Road to EU Climate Neutrality by 2050

Spatial Requirements of Wind/Solar and Nuclear Energy and Their Respective Costs

A Peer-Reviewed Publication for ECR Group and Renew Europe, European Parliament, Brussels, Belgium

Katinka M. Brouwer, LL.M., dr. Lucas Bergkamp (editor)

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- The ECR Group: "If the EU and its global partners really want to tackle issues such as climate change, recycling, waste, emissions and pollution, food quality and food security, then the EU needs to adopt sensible and sustainable measures which do not place unnecessary and costly burdens on businesses and Member States. Rather than unrealistic targets which will never be fulfilled or properly implemented, the ECR Group supports an ambitious, incremental, and sensible approach that all Member States can support." For further information, see https://ecrgroup.eu/

- Renew Europe: "We will invest in a sustainable continent. We do not have a Planet B, so we must make sure that we preserve the one we have for future generations. The Paris climate agreement of 2015 set out the roadmap, now it is time to deliver on the promises made and even go beyond them." For further information, see https://reneweuropegroup.eu/en/

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Foreword

The EU has endorsed the ambitious objective of achieving climate neutrality (i.e. net zero greenhouse gas carbon emissions) by 2050. An energy transition is necessary to achieve this objective. This report presents the results of a study that examines three issues that are key to the EU climate neutrality's ambition:

i. The effect of EU climate neutrality on the average global atmospheric temperature by 2050 and 2100;
ii. The spatial (land and sea) requirements for wind and solar energy versus nuclear energy in the Czech Republic and The Netherlands; and
iii. The cost of wind/solar energy and of nuclear energy for these two countries.

Summaries

Following this foreword, we have included two summaries, a brief Executive Summary, and a much longer Extensive Summary. While the Executive Summary gives the reader our answers to the main questions posed in this study, the illustrated Extensive Summary follows each main step in our analysis, so that the reader can discern the structure of our reasoning.

These summaries have been written in plain English, so that they are accessible to policy makers and interested citizens alike. The report itself uses also technical terms and abbreviations – a glossary and list of abbreviations have been added as annexes to this report to assist the reader.

Authors and Contributors

The authors of this study have been assisted by an interdisciplinary team of experts with academic qualifications and professional experience in a number of disciplines, including energy economics, modelling, engineering, business administration, natural sciences, climate science, and law and policy-making. Each of the key chapters has been reviewed by at least two peer reviewers with relevant academic qualifications and professional backgrounds. A list of these peer reviewers is attached to this report as Annex XIV.

Through a collaborative effort, the team has succeeded in bringing their extensive expertise to bear on the issues discussed in this report. The authors hope that this report will be judged on its merits, as they believe that it should play a key role in policy-making in connection with the EU's 2050 climate neutrality program. All professionals that have contributed to the completion of this report champion the cause of evidence-based energy- and climate policy-making. The authors are thankful to all of them for their indispensable contributions, scrutiny, comments, feedback, criticism, and guidance.

Evidence-Based Analysis: "Do the Numbers"

The EU is committed to evidence-based policy-making, also in the areas of energy and climate policies.[1] In this spirit, Commissioner Frans Timmermans has repeatedly emphasized that facts, science, and evidence-based analysis should inform policy-making, and encouraged interested parties to "do the numbers"[2] on nuclear energy.

The authors share Commissioner Timmermans 's views on the role of evidence in policy making. The research and analysis conducted in connection with this study have therefore been based on 'state-of-the-art' professional standards, academic literature, prior analyses, such as those conducted for the Dutch government and electricity network operators, and other relevant, reliable information. References to sources are provided throughout this report.

Of course, it would have been preferable had the European Commission itself done a comprehensive cost/benefit analysis of alternative policy options available to pursue the EU's climate neutrality objective. The fact that no such analysis has been conducted, despite the European Commission's '*Better Regulation,*' highlights the strong political forces and sense of urgency behind EU climate policy-making.[3]

This is not to say that the European Commission has not conducted any analysis relevant to the issues discussed in this report; it most definitely has. While Commissioner Timmermans appears to be focused very much on perceived disadvantages of nuclear energy, a 2016 Commission report succinctly sums up its advantages:

"Nuclear energy is a source of low-carbon electricity. The International Energy Agency (IEA) estimated for example that limiting temperature rise below 2 °C would require a sustained reduction in global energy CO_2 emissions (measured as energy-related CO_2/GDP), averaging 5.5 % per year between 2030 and 2050. A reduction of this magnitude is ambitious, but has already been achieved in the past in Member States such as France and Sweden thanks to the development of nuclear build programmes.

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[1] European Commission, Evidence-based policy making in the European Commission, available at https://ec.europa.eu/jrc/en/publication/evidence-based-policy-making-european-commission

[2] "Timmermans acknowledged the benefits nuclear power can bring in the transition to a zero-carbon economy but pointed to "serious disadvantages," such as uranium imports and treatment of radioactive waste. "The second disadvantage I need to mention is that it's very expensive," Timmermans said. "It's very, very expensive." … "Do the numbers and then draw your own conclusions, that's my only plea," he said." Frédéric Simon, Brussels 'won't stand in the way' of new nuclear plants, says EU climate chief, EURACTIV, 26 okt. 2020 (updated: 27 okt. 2020), available at https://www.euractiv.com/section/energy/news/brussels-wont-stand-in-the-way-of-new-nuclear-plants-says-eu-climate-chief/ Cf. Interview with Frans Timmermans on the EU Green Deal, New Mobility News, 3 Feb 2020, available at https://newmobility.news/2020/02/03/interview-frans-timmermans-on-the-eu-green-deal/

[3] European Commission, Better regulation: why and how, available at https://ec.europa.eu/info/law/law-making-process/planning-and-proposing-law/better-regulation-why-and-how_en

Nuclear energy also contributes to improving the dimension of energy security (i.e. to ensure that energy, including electricity, is available to all when needed), since:

a. fuel and operating costs are relatively low and stable;

b. it can generate electricity continuously for extended periods; and

c. it can make a positive contribution to the stable functioning of electricity systems (e.g. maintaining grid frequency).

Finally, nuclear can play an important role in reducing the dependence on fossil fuel energy imports in Europe."[4]

Since this data is from before 2016, Commissioner Timmermans may be right, and the cost of nuclear energy may be higher than the cost of other electricity-generating technologies. With this study, we intend to find out.

Holistic, Constructive and Innovative Approach

Analysis for purposes of policy-making is typically limited to specific aspects relevant to a policy issue. Such specialized analysis often is useful to address an issue in depth from the perspective of a particular discipline, be it economics, energy transition science, climate science, political science, or law. At the level of policy-making, however, all such disciplines have to be integrated into a holistic whole. Unfortunately, there is a lack of integrated, holistic analysis useful to policy makers; specifically, the Summaries for Policy Makers (SPMs) prepared by the IPCC do not provide it, and are silent on such critical issues as spatial requirements and costs of power generation technologies. The issues addressed in this report lend themselves very well to an integrated assessment, which is what the authors have aimed to provide.

Further, analysis and advice for policy makers is often colored by a selective or subjective perspective on the relevant issues. Further, much analysis and tools for policy makers incorporate value or normative judgments that remain hidden in the technical details. As discussed in this report, the analyses done for the Dutch government are examples. This applies also to tools, such as the *Energy Transition Model* (ETM).[5] By generating nuclear variants on the scenarios for the Dutch government in the ETM, however, this study demonstrates that even in a model that is not designed to treat nuclear on equal footing with renewable energy, nuclear energy is not necessarily inferior to wind and solar.

The authors of this report have attempted to clarify the key issues for policy makers, without making subjective or value judgments or at least making any such judgments explicit. Many issues arose that required thinking 'outside the box.'

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[4] European Commission, STAFF WORKING DOCUMENT Accompanying the Communication from the Commission: Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty for the opinion of the European Economic and Social Committee, Brussels, 4.4.2016, SWD(2016) 102 final, available at https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v10.pdf

[5] Energy Transition Model, available at https://energytransitionmodel.com/

For instance, the team identified the limitations of the so-called 'levelized cost of electricity' methodology as applied to nuclear and renewable energy for purposes of policy-making. In addition, it has unraveled the complexities around the market-based weighted cost of capital or 'WACC.' The WACC, as typically used in energy studies, reflects government-related risk in addition to commercial risk. For purposes of this study, the team developed a method to extract the government-related portion to arrive at a realistic WACCs reflective of only commercial risk. Team members have also pioneered a novel way to avoid the common, but controversial, practice of discounting the electricity output of alternative generation technologies for purposes of policy advice. This 'synchronized lifetime analysis' is described further in this report; the authors believe that it may become the standard for comparing electricity-generating technologies.

To Conclude for Now

As this study demonstrates, the argument that "nuclear energy is extremely expensive," which Commissioner Timmermans has entertained, requires qualification. Likewise, his concerns about uranium imports and nuclear waste management need to be weighed against not only the advantages of nuclear energy, but also the disadvantages of renewable energy.

In light of the spatial and economic consequences of renewable energy relative to nuclear energy, the EU is well advised to consider a "*Nuclear Renaissance*" program. Under this program, the EU would create a level playing field for all electricity generation technologies.

The authors hope that this study will be widely distributed and read. The people of Europe deserve it and the energy transition needs it.

Brussels, December 2020

Executive Summary

The EU is committed to achieving **climate neutrality** (i.e. net zero greenhouse gas emissions) by 2050. Electrification of the energy system is a key component of this strategy. This implies that the electricity (or power) system must be completely 'decarbonized' over the next three decades.

This study analyses and compares **two climate-neutral power-generating technologies** that can result in decarbonization of the electricity system[6] -- **wind/solar** and **nuclear**. We assess the amount of **space** necessary for each technology to deliver the power required, and the **costs** of the power thus generated. This analysis has been done for two EU member states: **The Netherlands**, a country along the North Sea with abundant wind, and the **Czech Republic**, a landlocked country with no access to sea and less wind. This study also assesses the **effectiveness of EU climate neutrality**.

Space demand

We found that amount of space required to provide annually 3000 PJ of power in The Netherlands by wind and solar power[7] in 2050 would range from 24,538 to 68,482 km². To put this in perspective:

- 24,538 km² is roughly the size of the **five largest provinces** of The Netherlands combined (Friesland, Gelderland, Noord-Brabant, Noord-Holland, and Overijssel); and
- 68,482 km² corresponds to about **1.8 times the entire land territory** of The Netherlands.

To generate the same amount of energy, **nuclear power** would require, on average, no more than 120 km², which is **less than half the size of the city of Rotterdam**. Thus, due to their low power density, **wind energy requires at least 266 (offshore) to 534 (onshore) times more land and space than nuclear** to generate an equal amount of electricity; for solar on land, at least **148 times more land** is required (disregarding, in all cases, the additional land required for the necessary network expansion and energy storage or conversion solutions).

For the Czech Republic, the amount of space required to generate 1,800 PJ by **wind and solar**[8] would range from 14,630 km² to 43,758 km². To put that into perspective, that covers **19 % and 55 % of the Czech Republic's available land**. Achieving the same level of electricity output with nuclear power would require no more than **269km²**.

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[6] These technologies only result in decarbonization if fossil fuel power generation infrastructure is effectively replaced and decommissioned in parallel.

[7] Based on 1/3 of each of onshore wind, offshore wind, and solar on land, and 100 % electrification.

[8] Based on ½ onshore wind and ½ solar on land with 100 % electrification.

> **//** While nuclear requires a tiny bit of land to provide a whole lot of power at a low cost, wind and solar require a whole lot of land to provide a tiny bit of power at a high cost. **//** **From: 'Road to EU Climate Neutrality'**

Costs

The **cost of nuclear is generally lower** than the cost of wind/solar, in most scenarios by a significant margin. In the best-case scenario for wind/solar, the cost of nuclear is still slightly lower. In the worst-case scenario for wind/solar, **nuclear cost only one fourth as much as wind/solar, i.e. wind/solar cost four times as much**. For an average Czech household,[9] this means an annual electricity bill of that is at least €50 more expensive for wind/solar compared to nuclear; for the Dutch,[10] it implies an **annual electricity bill that is at least €165 more expensive for wind/solar compared to nuclear**. In reality, the **cost of wind/solar is even higher** because these technologies require other expenses to bring the power where it is needed and to maintain the integrity of the electricity system (so-called integration- and system-related costs).

Based on ETM modelling for The Netherlands, we found **additional integration cost for wind/solar at levels of up to 18 %**, further deteriorating the economic case for wind/solar.

Effectiveness of EU Climate Neutrality

EU 2050 climate neutrality, if achieved, will likely cause only a very small decrease in the global average atmospheric temperature increase. Relative to current policies, **2050 EU carbon neutrality will add no more than between 0.02 and 0.06 °C average temperature reduction in 2050** and between 0.05 and 0.15 °C in 2100, **if no carbon leakage occurs**, which the EU cannot prevent. For the EU to achieve carbon neutrality in 2050, it must begin now deploying **renewable energy at a rate at least 4 – 7 times higher than the average rate** over the last 12 years. Even if the EU can do so

> **//** EU climate neutrality is an ideal that may never become reality in our interdependent world. The reality is that the EU cannot limit emissions in the whole world, and that the proposed solution, renewable energy, is an ideal with serious side effects. **//** **From: 'Road to EU Climate Neutrality'**

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[9] Based on average per capita electricity usage of 5,800 kWh per annum, or 32,200 kWh per household.

[10] Based on household of 4, https://www.engie-energie.nl/energieadvies/gemiddeld-energieverbruik.

> **//** The EU needs a realistic 'no regrets' solution to the climate problem. The nuclear solution is as climate-effective as the renewable solution, but is much less space-demanding, significantly cheaper, and has fewer, lesser side effects. **//** **From: 'Road to EU Climate Neutrality'**

over three decades, there still is a very high likelihood that other countries will not limit their emissions, thus frustrating the EU's efforts.

To exclude this unfortunate outcome, the EU would have to curb also carbon emissions from outside EU territory. A relatively certain way for the EU to prevent carbon dioxide emissions in the rest of the world would be acquiring the current estimated reserves of fossil fuels.[11] Such a purchasing program would impose a **minimum cost of €560,000.00 per household, or a total expense of €109,200,000,000,000**, which is approximately 7 times the entire EU's annual GDP and thus would be **prohibitively expensive**. This number not only gives us an idea of the economic value of fossil fuels, but also shows that a sure way to prevent the EU's climate neutrality efforts from being futile, is unrealistic. Put differently, the enormous cost of buying up all fossil fuels casts **doubt over the practicality of EU climate neutrality policy**.

'No regrets' solutions

The ineffectiveness of the EU climate neutrality program gives policy makers a good reason to consider space- and cost-effective '***no regrets***' **solutions**, such as nuclear power. Nuclear power can also play a role in the evolving **hydrogen technology**, which is another part of the EU's climate neutrality strategy. At the same time, an **unambiguous choice for the nuclear** power option would meet the EU policy objectives of ***energy security, affordability***, and ***social acceptability***.[12] EU energy policy-making, however, should also consider impacts of various power generation technologies on other EU policies and interests, such as **environmental and health policies**. In many areas, nuclear energy would appear to perform well relative to renewable energy.

Policy Recommendations

Thus, to realize its climate neutrality ambition, the EU needs to end the unjustified discrimination of power generation technologies and create a technology-neutral[13] level playing field for decarbonized power generation technologies. To this end, the EU can adopt a '**Nuclear Renaissance**' program that places nuclear energy on equal footing with renewable energy. The study report provides **12 policy recommendations** for such a program.

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[11] Adverse substitution effects may occur, if, instead of fossil fuels, wood and other biomass are combusted for energy. If this results in deforestation, carbon dioxide will be added to the atmosphere, but not subsequently removed.

[12] Social acceptability of nuclear energy is an issue, as is social acceptability of renewable energy. As discussed in this report, while nuclear energy's social acceptability appears to be growing, that of renewable energy appears to be on the decline.

[13] As discussed in this report, current EU climate policy is not technology-neutral, because it favors renewable energy. There is nothing inherent to climate policy, however, that requires any such technology bias; policy could merely stipulate performance requirements.

Extensive Summary

The EU is committed to achieving climate neutrality (i.e. net zero greenhouse gas emissions) by 2050. Electrification of the energy system is a key component of this strategy. This implies that the electricity (or power) system must be completely 'decarbonized' over the next three decades.

This study assesses the effectiveness of EU climate neutrality, and analyses and compares two climate-neutral power-generating technologies that, if they effectively replace fossil fuel infrastructure, can result in decarbonization of the electricity system -- wind/solar and nuclear. We determine the amount of space necessary for each technology to deliver the power required, and the costs of the power thus generated. This analysis has been done for two EU member states: The Netherlands, a country along the North Sea with abundant wind, and the Czech Republic, a landlocked country with no access to sea and less suitable land.

Key Takeaways

The EU's 2050 climate neutrality strategy involves a high risk of ineffectiveness. The anticipated energy transition, however, can hedge against this risk by deploying 'no regrets' solutions that are resistant to climate-related ineffectiveness. Nuclear power is such a solution.

In addition, with respect to both spatial requirements (area of land required) and costs of electricity, nuclear power offers substantial advantages over renewable power (any combination of wind and solar). The cost advantage of nuclear power increases once system costs are added to the equation, and increases further with higher penetration rates of wind and solar.

These advantages have been recognized in the Czech Republic, but not (yet) by policy makers at the EU level and in The Netherlands.

Part I. Effect of EU Climate Neutrality

EU 2050 climate neutrality, if achieved, will likely cause only a very small decrease in the average global atmospheric temperature increase, estimated at between 0.05 °C and 0.15 °C in 2100, and no more than between 0.02 °C and 0.06 °C in 2050, assuming no carbon leakage occurs.

- Even if this can be achieved, this would mean that the average global temperature would still increase by some 3 °C[14] (assuming estimates are accurate).
- Electricity-generating technologies therefore should be evaluated for the degree to which they constitute 'no regrets' solutions.

a. The EU's plan to become the first climate-neutral continent in 2050 is merely aspirational; there is **no proven pathway** that will lead to this result.[15] Much depends on factors that the EU does not control, such as technological breakthroughs, demand for energy, the cost of moving towards climate neutrality, the general state of the economy (GDP), population growth, etc.

b. The **EU's share of global carbon emissions** has been **below 10 % for several years**. In 2050, the EU's share of global emissions will have declined further, due to strong emission growth in the rest of the world, which, in turn, is caused by economic growth in those countries (as mandated by the UN SDGs) and '**outsourcing**' of emissions from developed nations to developing nations.

Study	Temperature reduction due to 2050 EU CN in 2050	Temperature reduction due to 2050 EU CN in 2100
Lomborg (2016) [6] – number derived from author's numbers; for methodology see Annex VII	0.02 °C	0.05 °C
Rogelj (2016) [7] -- number derived from author's numbers; for methodology see Annex VII	0.06 °C	0.15 °C

Table 1.1

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[14] Note that this estimate is based on an assumption about climate sensitivity that was made at the time the research on which we rely was conducted (i.e. 2016).

[15] While this is an issue with respect to many polices adopted by governments, it is a particular troublesome issue in relation to climate policy because of its scale, lack of diversification, extent of central planning, and the many problems caused by it that are ignored.

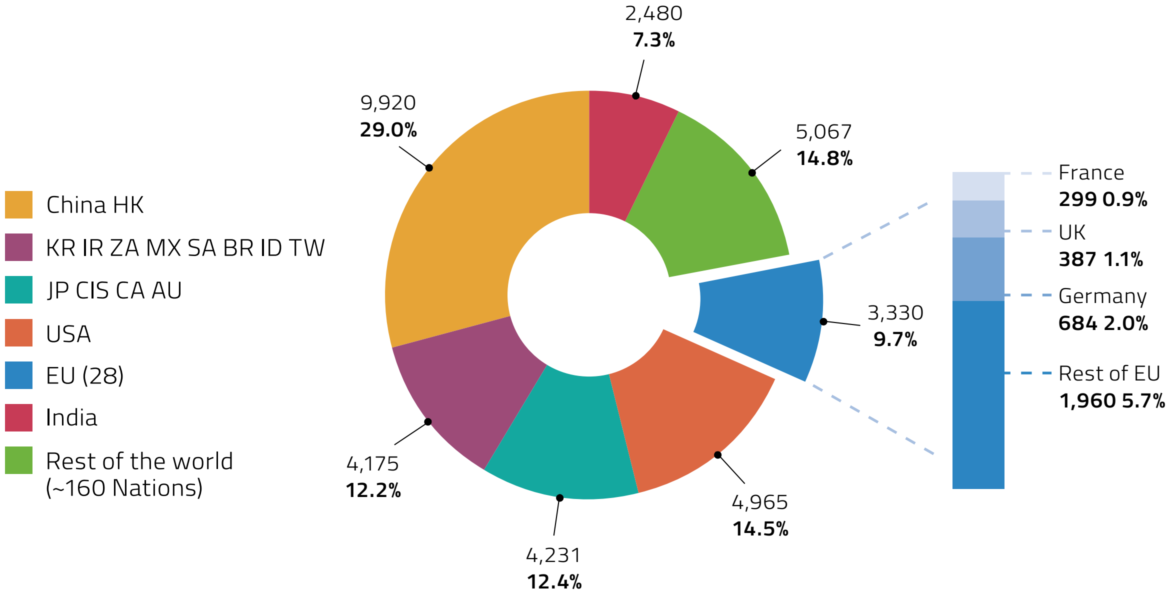


Figure 1.1. Annual CO_2 emissions 2019: in million tonnes - % global output *BP data 2020.*

Annual CO_2 emissions [1]

c. **CO_2 is only one of the greenhouse gases**, although it is the main one at approx. 75 % of the total. The GHGs covered by the EU climate legislation are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs) (Regulation 2018/1999, Annex V, Part 2). The potency, or **global warming potential (GWP), of GHGs differs**, however, and most GHGs have a GWP that (far) exceeds CO_2's GWP, which, by definition, is set at 1. **CO_2 equivalent** of a GHG is used to convert its GWP to that of CO_2 – the amount of CO_2 that causes the same warming as this GHG.

Global greenhouse gas emissions by gas [15]

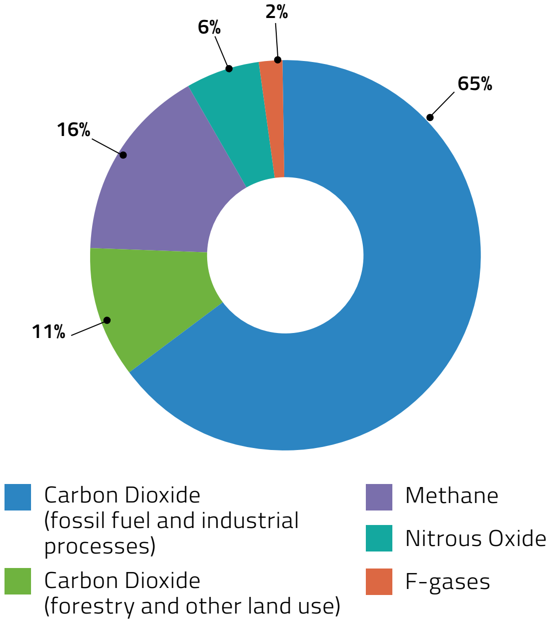


Figure 1.2. Global Greenhouse Gas Emissions by Gas.

Global greenhouse gas emissions by gas and source [14]

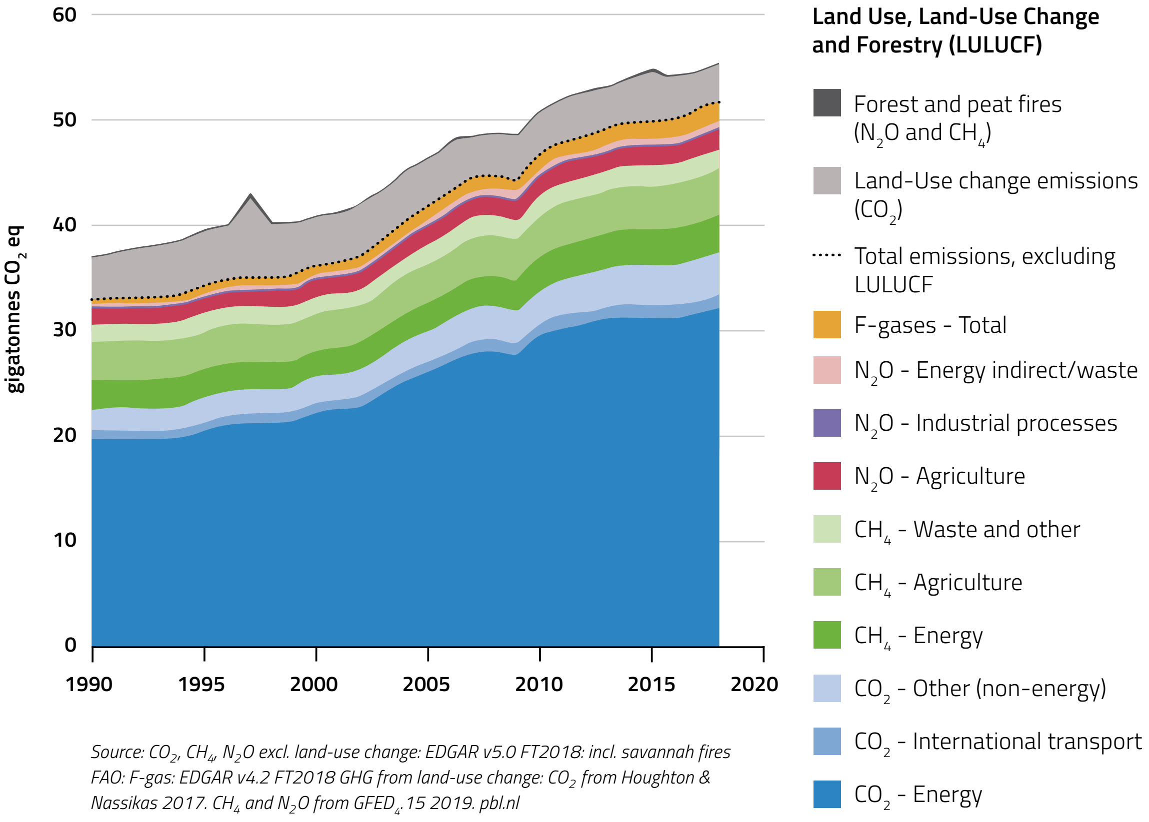
d. **Growth in global GHG emissions** (excluding those from land use change) in 2018 was the **highest since 2011**, **increasing at a rate of 2.0 %**, reaching 51.8 gigatonnes of CO_2 equivalent ($GTCO_2$ eq), with the developing world **steadily increasing**. [14]

   i. In 2018, the 2.0 % (1.0 $GTCO_2$ eq) increase in global GHG emissions was mainly due to a **2.0 % increase in global fossil CO_2 emissions** from fossil fuel combustion and those from industrial non-combustion processes including cement production.

   ii. Global emissions of **methane (CH_4)** and **nitrous oxide (N_2O)** increased by **1.8 %** and **0.8 %**, respectively. Global emissions of **fluorinated gases (F-gases)** continued to grow by an estimated 6 % in 2018, thereby also contributing to the 2.0 % growth in total GHG emissions.

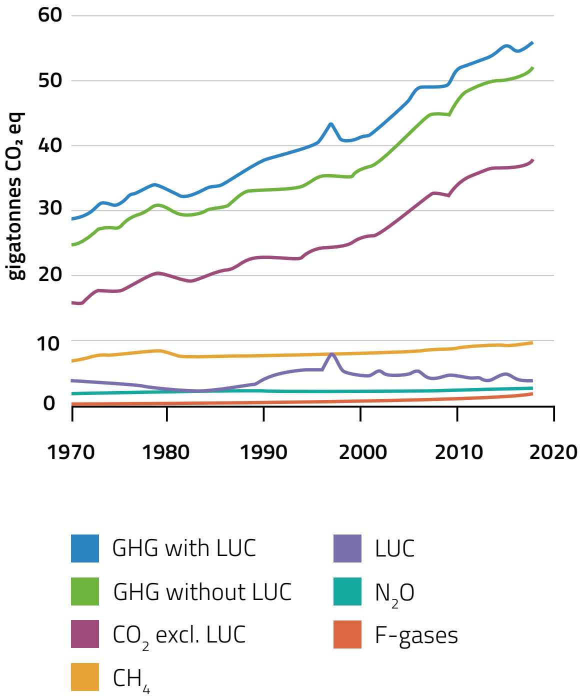
   iii. **Global consumption of oil products and natural gas continued to increase, by 1.2 % and 5.3 % in 2018**, led by increased consumption in China, the US, and Russia.

   iv. The 2018 increase in global emissions followed **trends in primary energy demand and in the energy mix**. In 2018, energy demand increased by 22 EJ, which was met for 50 % by fossil fuels and 50 % by nuclear and renewable power.



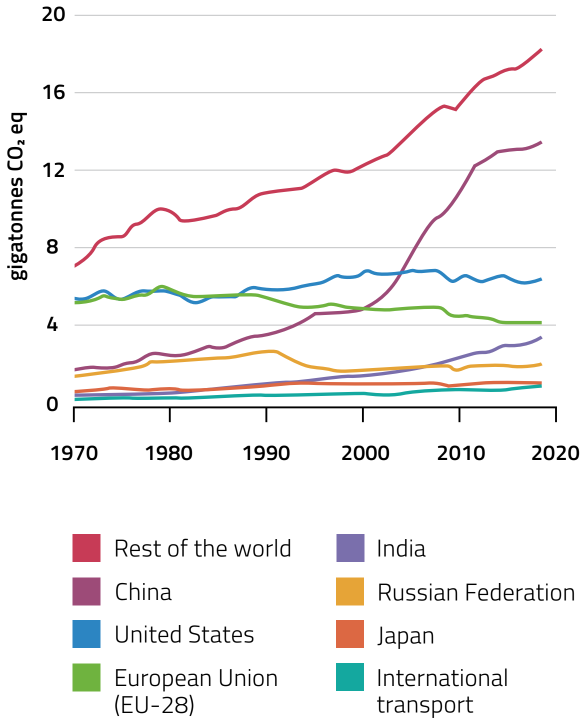
Source: CO_2, CH_4, N_2O excl. land-use change: EDGAR v5.0 FT2018: incl. savannah fires FAO: F-gas: EDGAR v4.2 FT2018 GHG from land-use change: CO_2 from Houghton & Nassikas 2017. CH_4 and N_2O from $GFED_4$.15 2019. pbl.nl

Figure 1.3. Global greenhouse gas emissions, per type of gas and source, including LULUCF.



LUC = Land-use change, GHG = greenhouse gas
Source: GHG excl. LUC EDGAR v5.0 FT2018
LUC: Houghton and Nassikas 2017
pbl.nl

Figure 1.4. Global greenhouse gas emissions: per type of gas.



Source: EDGAR v5.0 FT2018 (without land-use change). pbl.nl
both: F-gas: EDGAR v4.2 FT2018: incl. savanna fires.

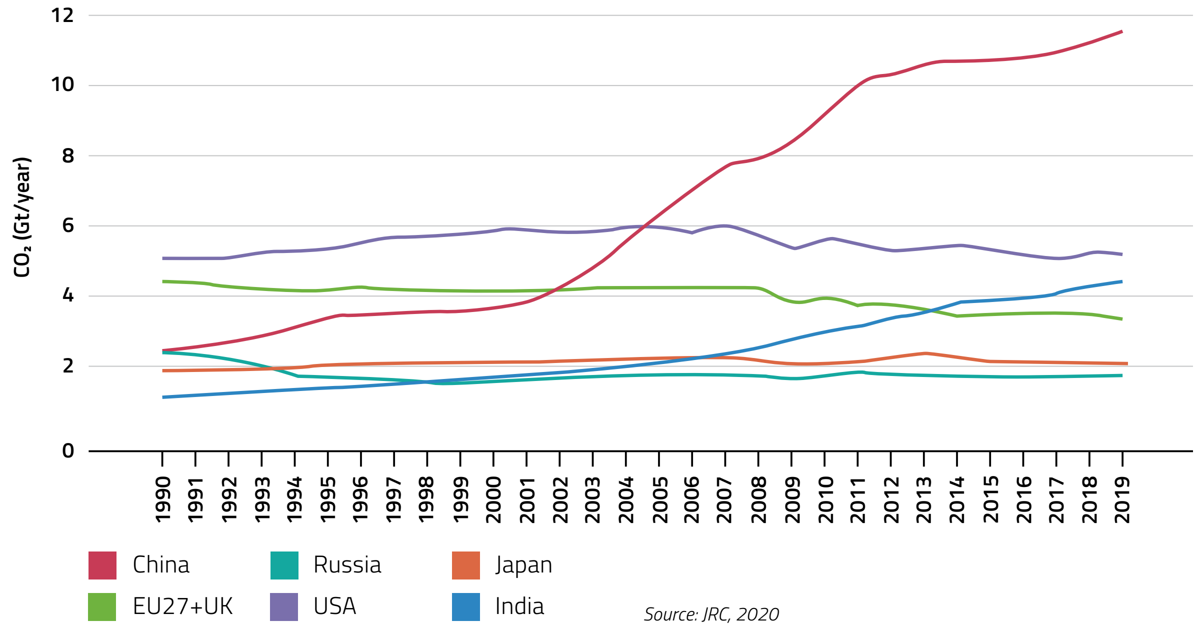
Figure 1.5. Global greenhouse gas emissions: top emitting countries and the EU.

Global GHG emissions by type of gas and country [14]

e. In the period 1990-2019, the ***EU has reduced emissions from fossil fuels by about 25 %***. In fact, the EU and Russia are the only industrialized economies that have significantly reduced their fossil CO_2 emissions relative to their 1990 levels. The US and Japan show increased CO_2 emissions since 1990 by 0.8 and 0.4 %, respectively. The ***emerging economies of China and India show strong emission growth*** with 2019 CO_2 emissions levels, respectively, 3.8 and 3.3 times higher than in 1990, due to rapid industrialization and 'outsourcing' effects. Power generation is the largest source of emissions.

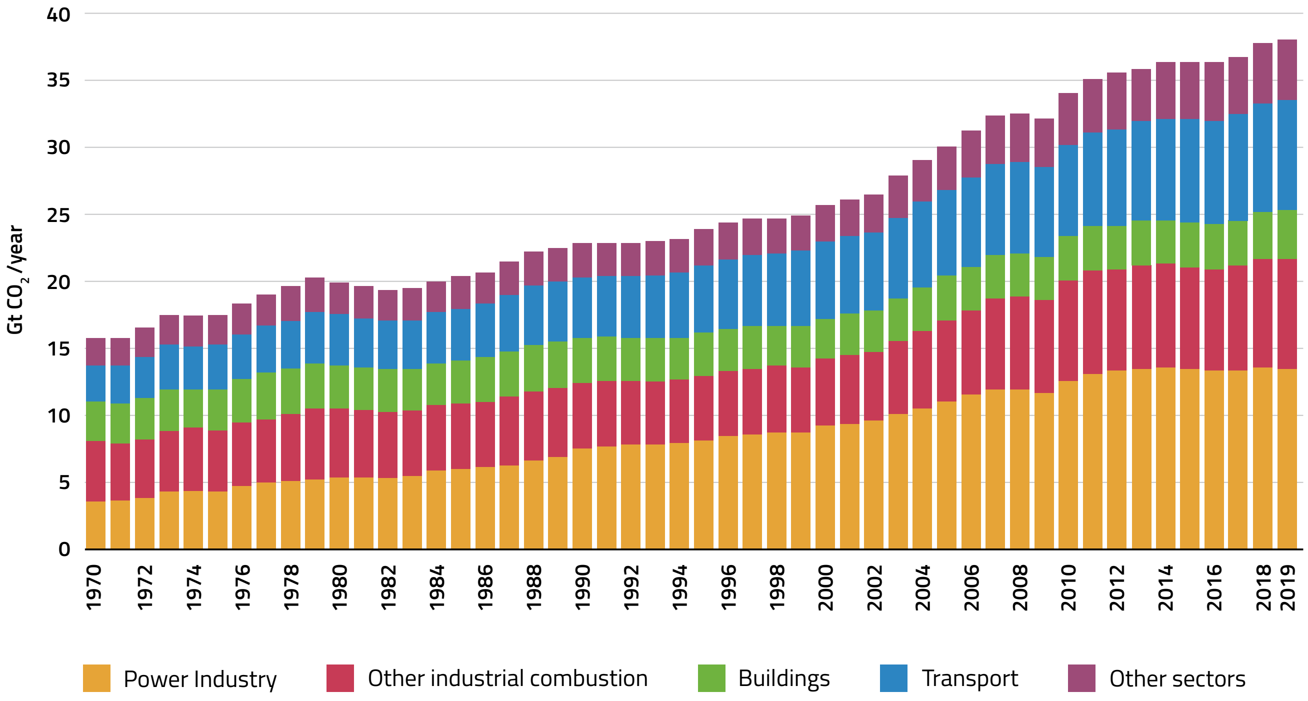
Fossil CO_2 emissions from major emitting economies and by sector [13]

f. The '**outsourcing**' effect of European climate policies (also known as '**carbon leakage**') can be demonstrated by accounting for both territorial emissions and the emissions associated with domestic consumption of imports.



Source: JRC, 2020

Figure 1.6. Fossil CO_2 emissions of the major emitting economies.



Source: JRC, 2020.

Figure 1.7. Total global annual emissions of fossil CO_2 in Gt CO_2/yr by sector. Fossil CO_2 emissions include sources from fossil fuel use, industrial processes and product use (combustion, flaring, cement, steel, chemicals and urea).

Decoupling of GDP per head from CO_2 emissions seems to have happened at the expense of outsourcing manufacturing [2]

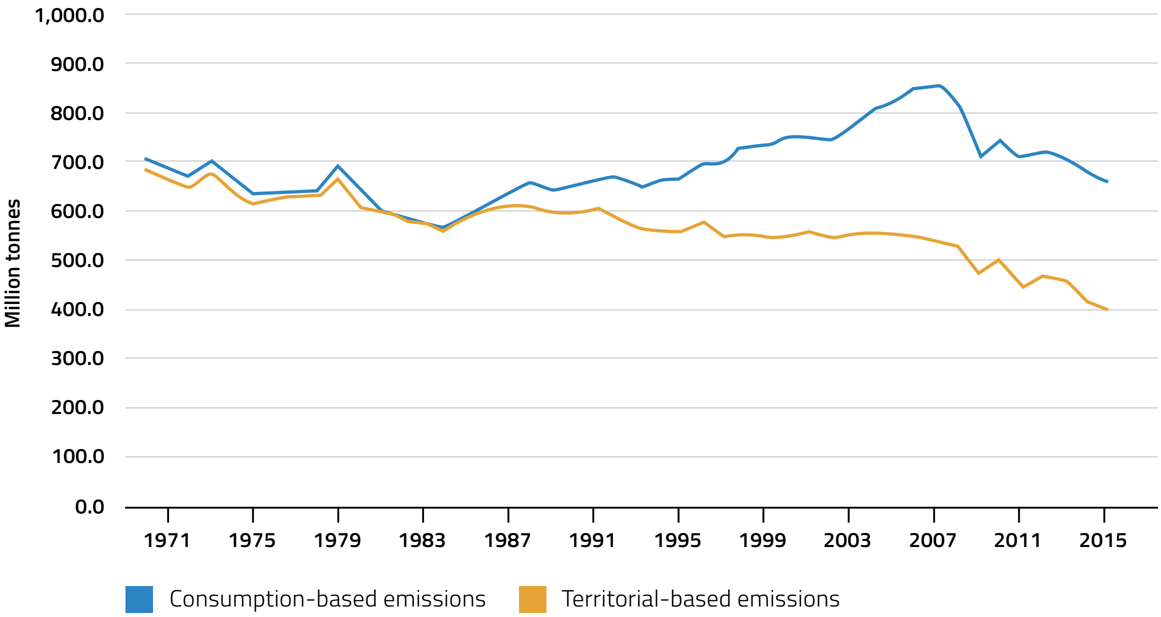


Figure 1.8. Different measures of CO_2 emissions, 1970 to 2015, UK.

Total GHG emissions associated with UK consumption [3]

g. In 2019, **global carbon emissions** from energy use **increased by at least 0.5 %, despite a decrease in the EU**.[16] According to JRC, the global emissions growth continued in 2019 with ***global anthropogenic fossil CO_2 emissions increasing by 0.9 %*** compared to 2018, reaching 38.0 Gt CO_2. [13] The increase was fueled by strong emission increases in China (2.6 %) and, to a lesser extent, India (1.8 %); JRC reports an even higher growth rate for China at 3.4 %. [13]

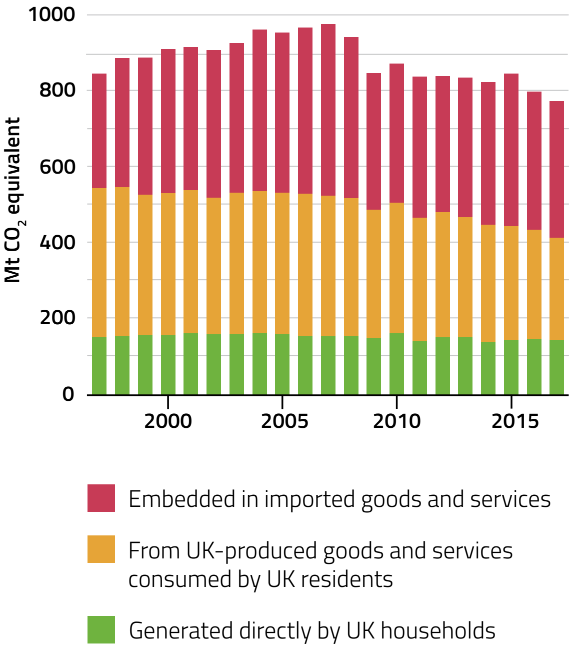


Figure 1.9. Total greenhouse gas emissions associated with UK consumption (DEFRA).

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[16] We do not discuss 2020 and the COVID-19, which has created an exceptional situation.

Annual Fossil CO_2 emissions 2019 [4]

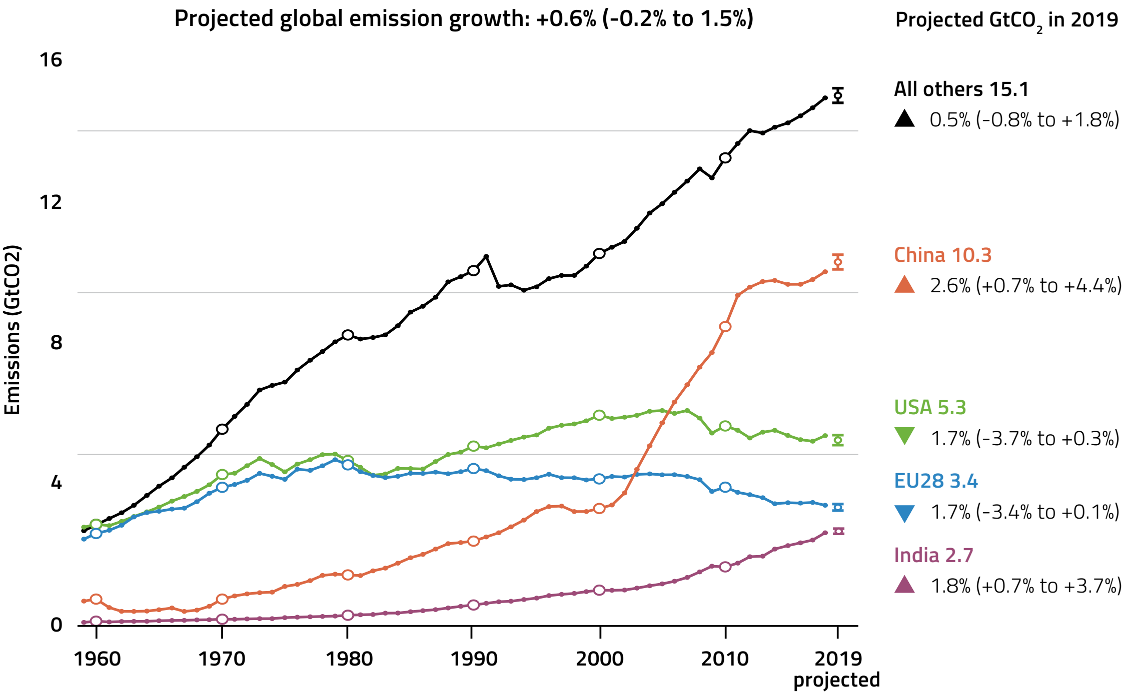
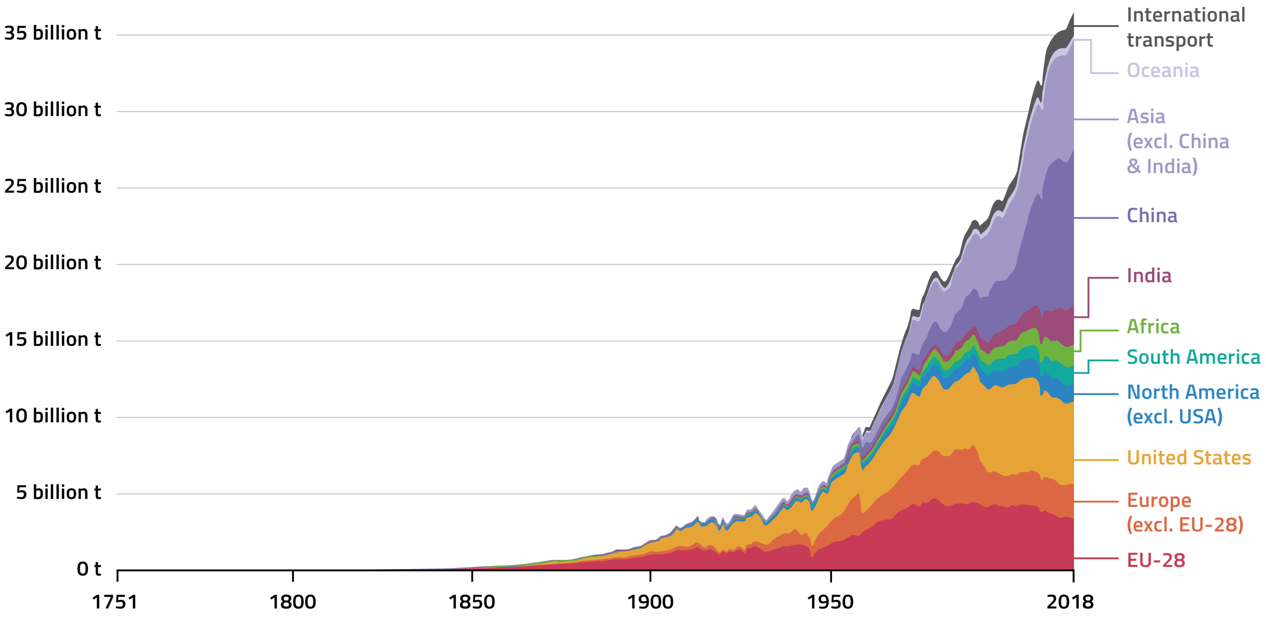


Figure 1.10. Annual fossil CO_2 emissions and 2019 projections

Annual Total CO_2 Emissions [8]

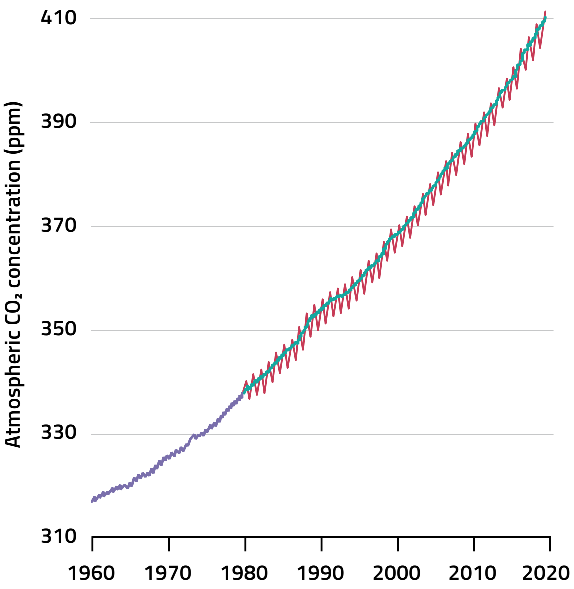


Source: Carbon Dioxide Information Analysis Center (CDIAC); Global Carbon Project (GCP)
Note: 'Statistical differences' included in the GCP dataset is not included here.
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions - CC BY

Figure 1.11. Annual total CO_2 emissions, by world region

h. The **atmospheric concentration of carbon dioxide continues to increase**. No peak concentration has been reached, and the CO_2 level shows no signs of peaking. This is **critically important**, because, according to conventional climate science, it is the atmospheric concentration of carbon dioxide that drives global warming and climate change, which is the problem the EU hopes to remedy through its climate neutrality policy.[17]

Atmospheric carbon dioxide concentration [5]



Seasonally corrected trend:

🟪 Scripps Institution of Oceanography (Keeling et al., 1976)

🟩 NOAA/ESRL (Dlugokencky and Tans, 2019)

Monthly mean:

🟥 NOAA/ESRL

Figure 1.12.

  i. EU climate neutrality will only have its intended favorable effect on reducing the average global atmospheric temperature increase, ***if and only if no 'carbon leakage' (or outsourcing) occurs, which thus far has occurred consistently***. Indeed, carbon leakage explains why global emissions continue to rise despite the significant (and costly) reductions in the EU.

  ii. Even if the EU is able to prevent carbon leakage and outsourcing, when it achieves carbon neutrality in 2050, it may still find that its efforts were in vain, because emissions from other countries increased. As discussed below, an effective way to prevent this unfortunate outcome (i.e. buying up all fossil fuels), is beyond the EU's reach. This state of affairs requires that ***the EU hedge against the risk of its efforts not achieving the desired effect*** by ***giving priority to 'no regret' solutions***.

i. This suggests that ***EU climate neutrality***, even if achieved, may have ***very little effect on the average global temperature increase***. Other, non-EU nations, including developing nations, have no obligation to reduce their emissions, and the EU has no way to force them to do so. Thus, the EU's efforts are vulnerable to potential failure.

  i. Given that the EU has very little or no control over non-EU nations' emissions, it can only use **diplomacy** and **economic incentives** to get them to change their policies; e.g. the EU can offer to pay for non-EU countries' reduction efforts, or impose carbon taxes on imports into the EU. Given the value of the world's fossil fuel reserves (see further below), there is no way that strong diplomacy and economic incentives created by the EU can have more than a **negligible influence**.

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[17] It is true that countries representing a substantial portion of global emissions are committed to a climate neutrality policy, but the question is how strong these commitments are. If the past is representative of the future, the expectations should be tempered. International climate policy since 1990 has not had the effect of reducing global emissions or the atmospheric carbon dioxide concentration.

ii. The EU and national policies have produced modest reductions in carbon emissions thus far, and emissions from the rest of the world continue to increase, with **no sustained evidence of a peak, let alone of the necessary decrease**.[18] Thus, there is a substantial risk that the EU's efforts, even if successful, will not have the desired effect.

iii. International climate policy has a **poor track record**. Since the adoption of the UNFCCC in 1992, global carbon emissions have steadily increased, despite the Kyoto Protocol and the Paris Agreement. In fact, the international mitigation efforts have **not produced a drop** in global emissions. ***On what principle is it that, when we look we see nothing but failure behind us, we are to expect nothing but improvement before us?***

Global carbon emissions and international climate policy [10]

j. Another way to assess the EU climate neutrality ambition is to ask: what is the **necessary rate of deployment of renewable energy** to arrive at zero emissions in 2050 in the EU and worldwide? Taking the average rate of addition of renewable energy over the last 12 years, assuming a linear trajectory, the following requirements would have to be met:

i. For the world to achieve a **45 % reduction in 2030**, it needs to increase the rate of annual addition of renewables by a **factor of 16**;

ii. For the world to achieve a 45 % reduction in 2050, it needs to increase the annual addition of renewables by a factor of 10;

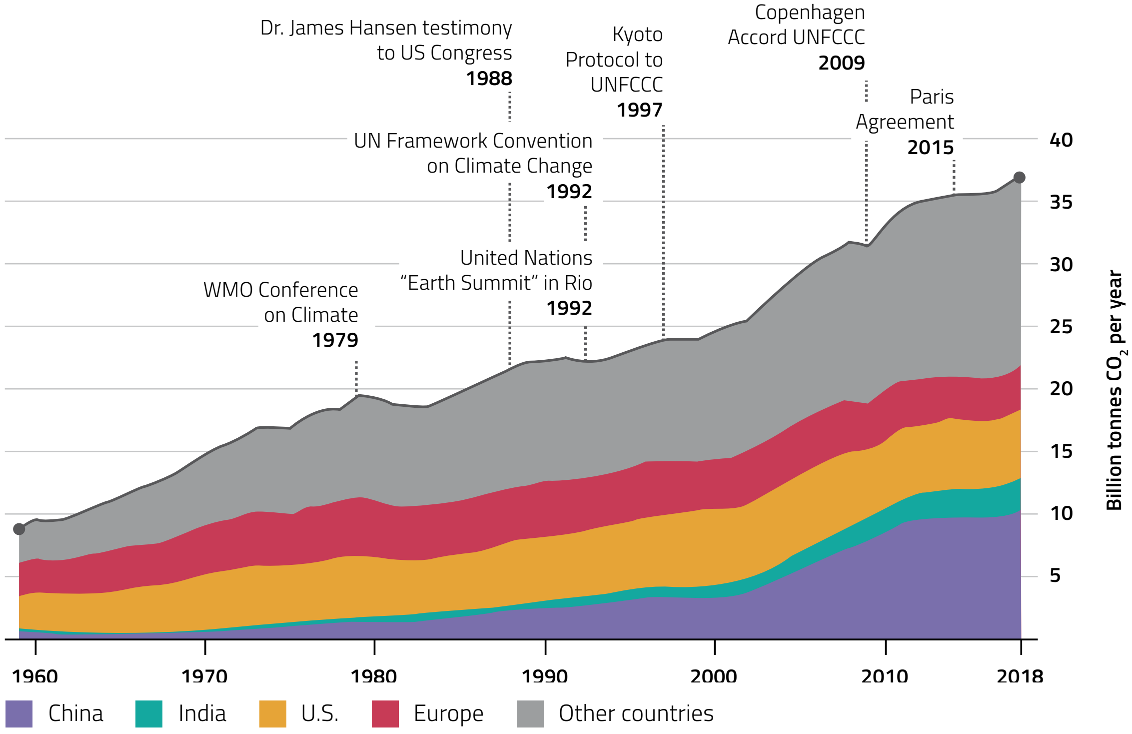

Figure 1.13. Global Carbon Emissions

Source: Global Carbon Budget 2018 ▪ Get the data

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[18] Research by Burgess et al. suggest that 2019 was a peak, but it is too early to treat it as such. Cf. Burgess, Matthew G., Justin Ritchie, John Shapland, and Roger Pielke Jr., IPCC baseline scenarios have over-projected CO_2 emissions and economic growth, Environmental Research Letters (ERL, forthcoming), available at https://osf.io/preprints/socarxiv/ahsxw/

EU climate neutrality, even if achieved, may have very little effect on the average global temperature increase. Other, non-EU nations have no obligation to reduce their emissions, and the EU has no way to force them to do so. Developing nations have a right to develop their economies. Thus, the EU's efforts run a substantial risk of not achieving their objective.

iii. For the EU to achieve zero emissions by 2050, it needs to increase the annual addition of renewables by a factor of 4, assuming the energy demand drops by 0.7 % annually.

iv. For the **EU to achieve zero emissions by 2050**, it needs to **increase the annual addition of renewables by a factor of 7**, assuming the energy demand increases by 1.2 % annually.

k. Even though this is a huge mountain to climb, the biggest problem may not even be the expansion of the renewable energy system. The biggest problem probably will be **retiring fossil fuels within the same time frame, including in the EU itself,** in particular if intermittent renewable energy continues to expand and nuclear energy declines. The humungous cost associated with buying up the global fossil fuel reserves demonstrates that EU climate neutrality is unlikely to be effective.

i. Thus far, the EU's emissions reduction efforts have not caused a corresponding drop in global emissions, because the **use of fossil fuels continues unhindered in large parts of the world** (and, to a lesser extent, within the EU). In the EU, the necessity of back-up for intermittent renewable electricity generation, combined with an averseness to nuclear energy, prevents the rapid phase-out of fossil fuel power generation.

ii. With the demand for fossil fuel in the Western world declining, prices on the world markets are likely to drop (all else equal) and fossil fuels will become more affordable for developing countries. This will allow them to consume more fossil fuels, and grow their economies as mandated by the UN SDGs, which, in turn, will further fuel the demand for fossil fuels.[19]

iii. To prevent carbon emissions in the rest of the world with a high degree of certainty,[20] over the period from now to 2050, the EU could **buy up all fossil fuels (oil, gas, coal/lignite) and retire them definitively**.

iv. If there are no fossil fuels other than the currently known reserves, at current market price levels, the total cost of this purchasing program will be **at least €109,000,000,000,000**, which is

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[19] Cf. Sinn, Hans-Werner, The Green Paradox: A Supply-Side Approach to Global Warming, MIT Press, 2012.

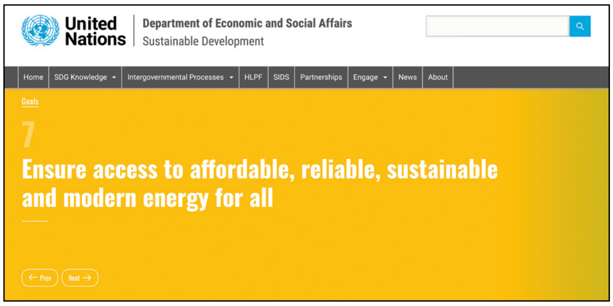
[20] Adverse substitution effects may occur, if, instead of fossil fuels, wood and other biomass are combusted for energy. If this results in deforestation, carbon dioxide will be added to the atmosphere, but not subsequently removed.

approximately **7 times the entire EU's annual GDP** and equal to €560,000 per EU household.[21]

v. Assuming the buying will be linear over 30 years, the **EU would have to spent approximately a quarter of its GDP on fossil fuel purchasing** every year, which is **more than 20 times the 2019 EU budget (of €165 billion), every year, starting in 2021 up to and including 2050**.

vi. These numbers not only give us an idea of the **economic value of fossil fuels**, but also show that a known certain way to prevent the EU's climate neutrality efforts from being futile, is unrealistic. Put differently, the enormous cost of buying up all fossil fuels casts doubt over the practicality of EU climate neutrality policy. Thus, there is a high probability that **EU climate neutrality will not have the desired effect**.

vii. But even if such a program were feasible, it would raise serious concerns from **developing nations**. Under the United Nations Sustainable Development Goals, developing nations have been promised an **end to poverty and hunger**, "**access to affordable, reliable, sustainable and modern energy for all**"[22] and **industrialization**.[23] All of these goals are ranked higher than the fight against climate change.[24]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Goals

7

Ensure access to affordable, reliable, sustainable and modern energy for all

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Goals

9

Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

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viii. The international law framework (UNFCCC, Paris Agreement) recognizes the **rights of nations, in particular developing economies, to exploit their own resources and develop their economies**, and does not require that they pursue emissions reductions (also referred to as 'differentiated responsibilities').

ix. Given developing nations' right to develop and the immense opportunity cost of foregoing development, it is unlikely that they will refrain from doing so, or that the developed nations can persuade them otherwise or prevent them from doing so.

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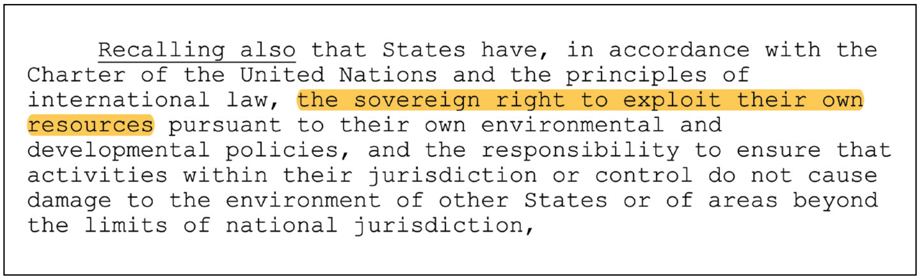
[21] There are approx. 195 million households in the EU. Eurostat, Household composition statistics, available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Household_composition_statistics. On a per capita basis, given that the EU has approximately 450 million citizens, this represents an expense of roughly €250,000 per citizen. World Bank, https://data.worldbank.org/region/european-union, population statistics as of 2019.

[22] United Nations, SDG number 7, available at https://sdgs.un.org/goals/goal7 UN SDG number 1 is 'end poverty' and number 2 is 'end hunger.'

[23] United Nations, SDG number 9, available at https://sdgs.un.org/goals/goal9 ("Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.)

[24] United Nations, SDG number 13, available at https://sdgs.un.org/goals/goal13

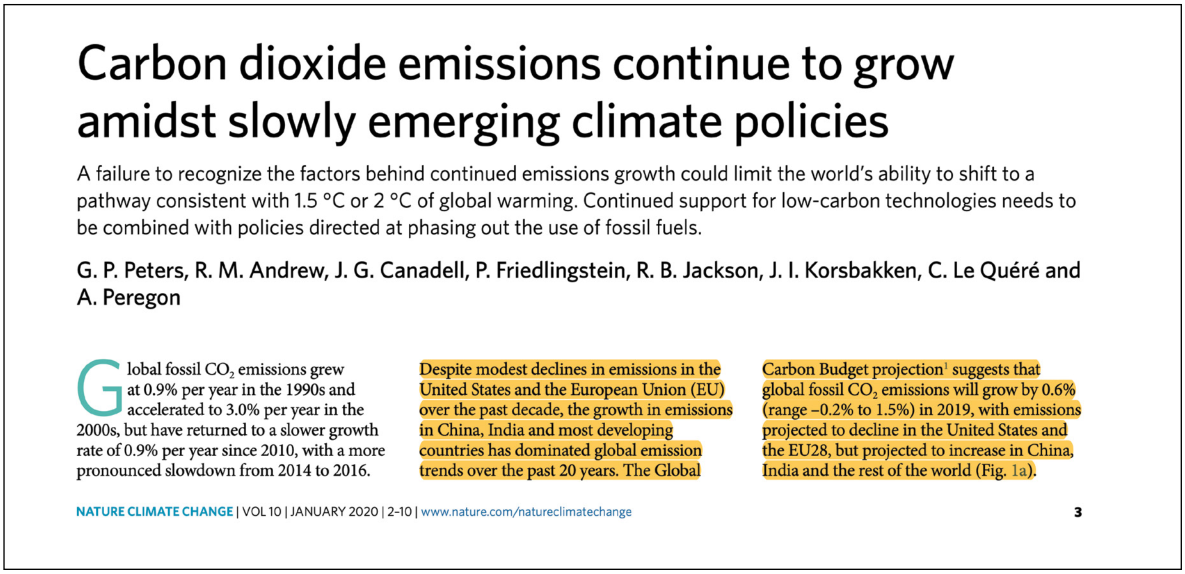
UN Framework Convention on Climate Change [9]



Recalling also that States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction,

x. Thus, even if the EU member states can achieve zero emissions by 2050, there is a **substantial risk that emissions from other nations more than compensate for the EU's reductions** and **no positive effect on the global climate will materialize**.

From Nature Climate Change, January 2020 [4]



Carbon dioxide emissions continue to grow amidst slowly emerging climate policies

A failure to recognize the factors behind continued emissions growth could limit the world's ability to shift to a pathway consistent with 1.5 °C or 2 °C of global warming. Continued support for low-carbon technologies needs to be combined with policies directed at phasing out the use of fossil fuels.

G. P. Peters, R. M. Andrew, J. G. Canadell, P. Friedlingstein, R. B. Jackson, J. I. Korsbakken, C. Le Quéré and A. Peregon

Global fossil CO_2 emissions grew at 0.9% per year in the 1990s and accelerated to 3.0% per year in the 2000s, but have returned to a slower growth rate of 0.9% per year since 2010, with a more pronounced slowdown from 2014 to 2016. Despite modest declines in emissions in the United States and the European Union (EU) over the past decade, the growth in emissions in China, India and most developing countries has dominated global emission trends over the past 20 years. The Global Carbon Budget projection[1] suggests that global fossil CO_2 emissions will grow by 0.6% (range −0.2% to 1.5%) in 2019, with emissions projected to decline in the United States and the EU28, but projected to increase in China, India and the rest of the world (Fig. 1a).

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xi. In a 2018 interim special report pursuant to the Paris Agreement on Climate Change, the IPCC has mapped out a pathway to limiting the temperature increase in 2100 to 1.5 °C. [17]
  - This pathway, which explicitly includes nuclear energy as an option, requires that the **entire world reaches climate neutrality around 2050**.
  - Limiting warming to 1.5 °C requires **drastic emission reductions** by 2030 and **carbon neutrality** by around 2050. This would entail **unprecedented transformations of energy, land, urban, and industrial systems**, including measures to achieve "negative emissions" by removing carbon from the atmosphere.
  - There is **no plausible, feasible plan or pathway** to achieve global climate neutrality by 2050, however. It is merely an aspiration.

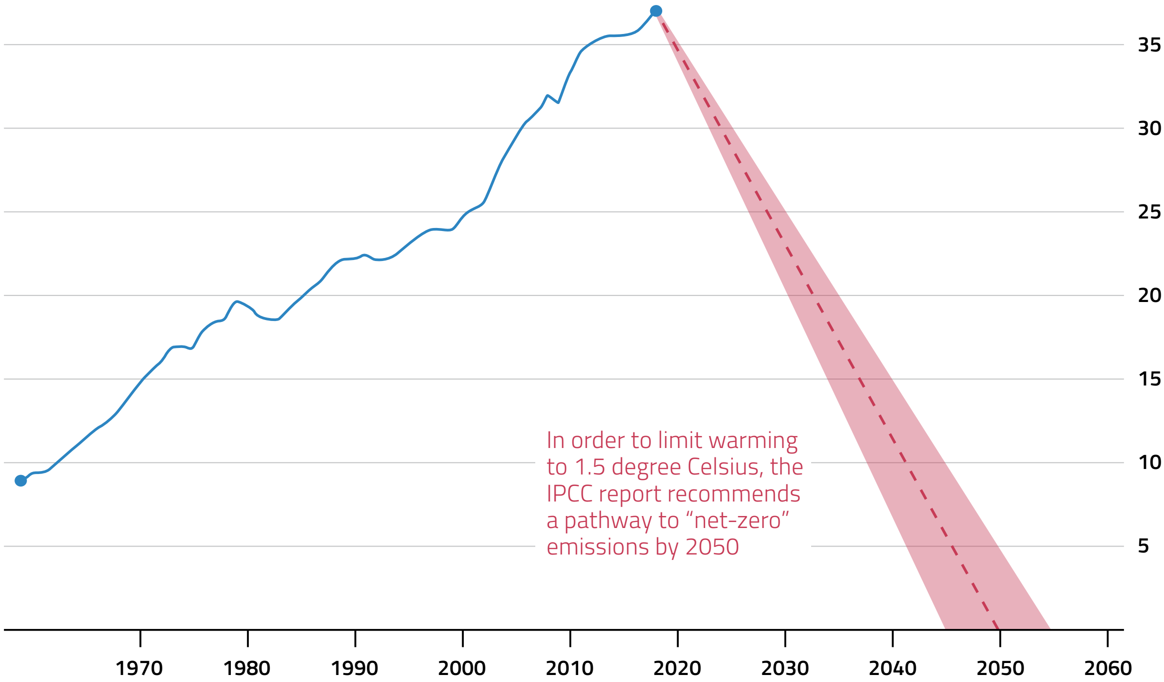


Figure 1.14. IPCC carbon emission pathway to limit warming to 1.5 degrees

Billion tonnes CO_2 per year

Source: Global Carbon Budget 2018 ▪ Get the data

IPCC Special Report -- Limiting warming to 1.5 °C requires drastic emission reductions by 2030 and carbon neutrality by around 2050. This would entail unprecedented transformations of energy, land, urban, and industrial systems, including measures to achieve "negative emissions" by removing carbon from the atmosphere.

IPCC carbon emission pathway to limit warming to 1.5 degrees

xii. Compared to where policies are now, the **changes would have to be unrealistically radical**. Even for the more modest target of 2 °C the required policy changes do **not appear realistic**.

Global greenhouse gas emissions as implied by INDCs compared to no-policy baseline, current-policy and 2 °C scenarios [7]

xiii. If we look at all emissions from energy use (not only electricity), it becomes clear that achieving net zero in a few decades by deploying currently

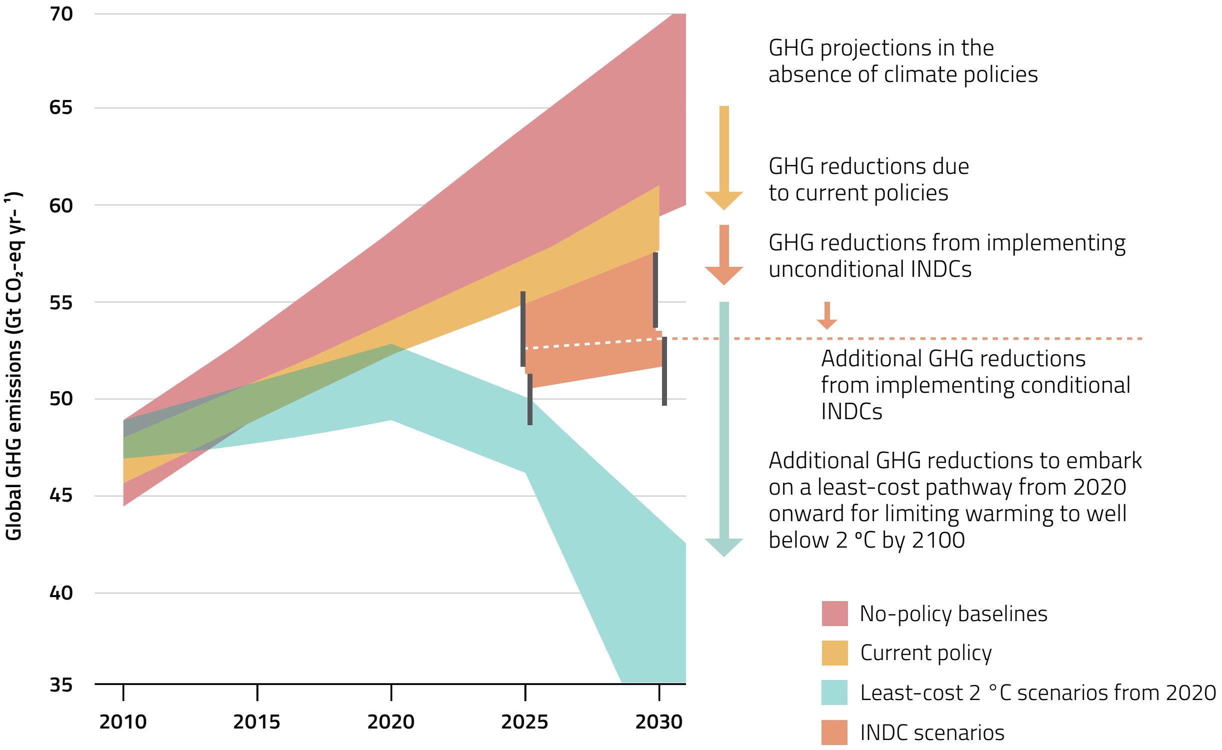


Figure 1.15.

Source: Joeri Rogelj et al., Paris Agreement climate proposals need a boost to keep warming well below 2 °C, Nature, volume 534, pp. 631–639 (2016).

available technologies is impracticable. It has been calculated that getting to net zero in 2035 requires **replacing approximately 0.1 EJ (exajoules) of fossil energy with renewable energy every day starting now.** [16] This is equivalent to approximately **2 nuclear plants or 3,000 wind turbines of 2.5 MW**. A corresponding amount of fossil fuel would have to be retired every day. **All new, additional energy use would have to be carbon-free**. Reality is entirely at odds with these requirements.

xiv. Thus, the **EU is not likely to achieve climate neutrality by 2050. There is no well-defined plan to get there**. No cost/benefit-analysis has been done on alternative policy options; not all policy options have been carefully considered, some viable options, most notably, nuclear power, are even virtually off the table, and the EU cannot afford to buy up all fossil fuel reserves in the world or any significant portion thereof, or otherwise prevent global emissions increases.

EU climate policy-making is led by **a desire to become climate neutral without a rational strategy and roadmap** that can lead the member states to this result. The EU's aspirational strategies and plans all pursue **derivative objectives**, such as renewable energy targets, and are **neither sufficient nor necessary** to achieving climate neutrality.

The Green Deal contemplates that the EU will continue to strengthen pre-existing policies, such as energy efficiency and renewable energy, while **betting on technological breakthroughs** in areas such as hydrogen, energy storage, and system integration. Meanwhile, the chief drivers of EU climate policy are targets set by the policy makers for

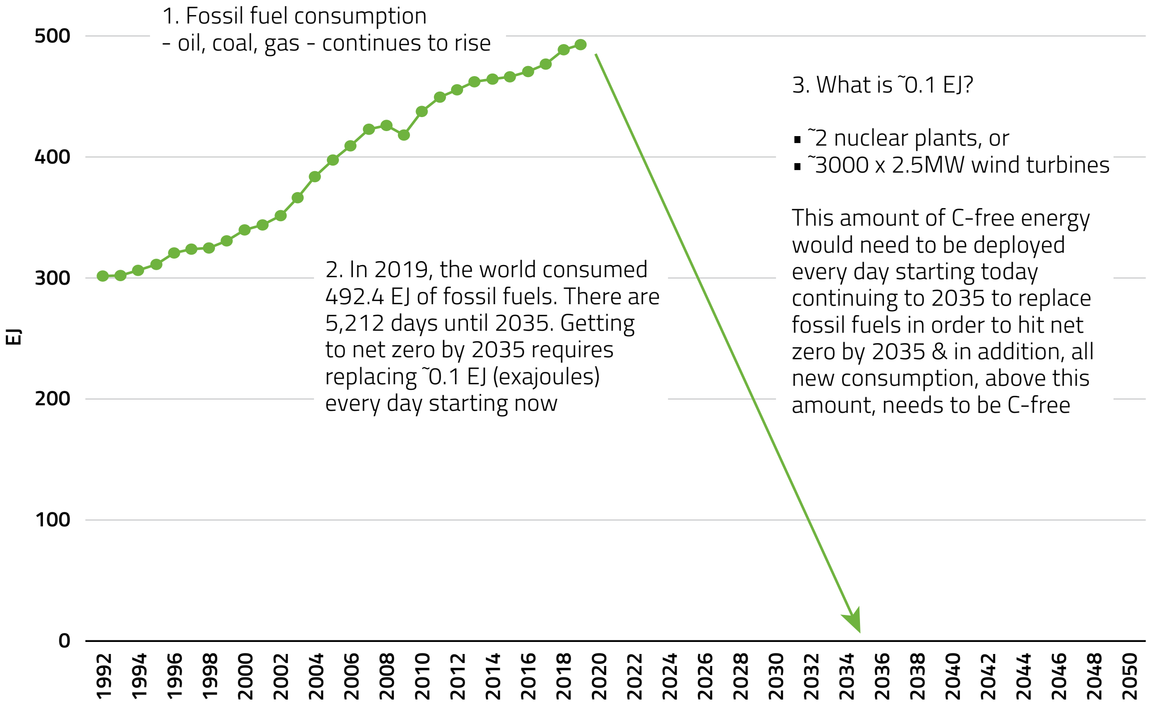


Figure 1.16. Global Fossil Fuel Consumtion

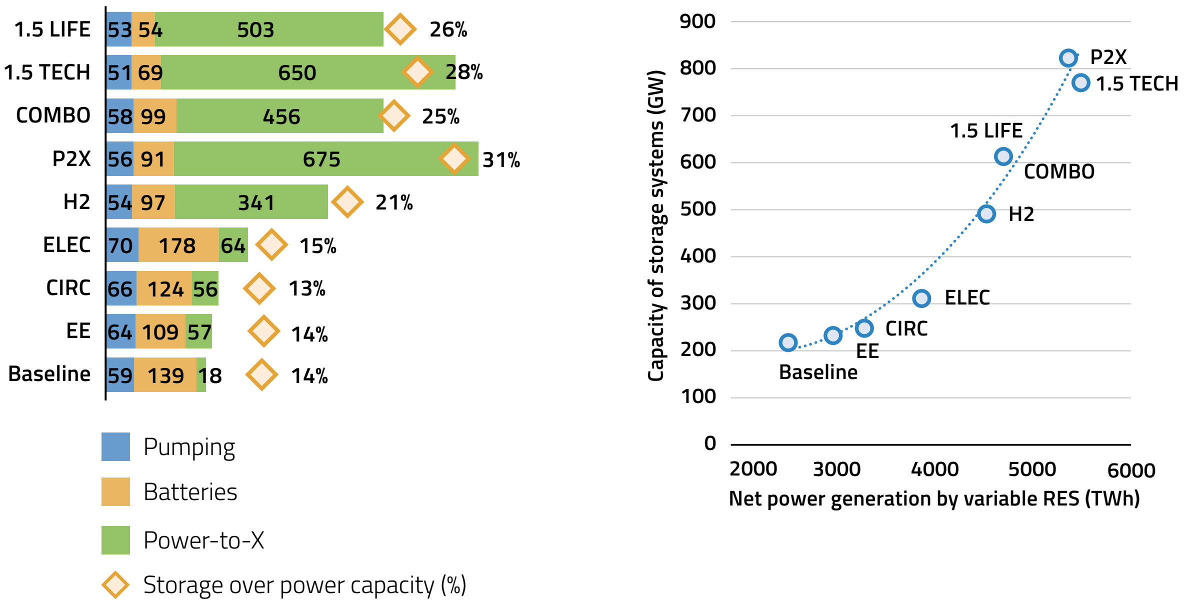
Source: BP 2020, R. Pielke Jr. , 24 Sept 2020

renewable energy and emissions reductions, and financial incentives for research and development, which **do nothing to address the root cause of the global emissions increase.**

xv. In short, there is a **high probability of failure** in that either (i) the EU will not achieve climate neutrality, because the necessary technologies are not ready for wide scale deployment or the costs turn out to be too high (note that the system-related cost of renewable energy increases with its penetration rate), or (ii) the rest of the world will not limit their emissions so that the EU's sacrifices are in vain.

Is climate-neutrality by 2050 in the EU viable and sustainable in the long run? [11]

Developing a power system with a high share of variable RES requires the development of storage technologies., demand response, mesh grids and an efficient multi-country integrated system and market, to share the resources that would enable the cost-effective balancing of variable RES generation. Large-scale storage of electricity (**Fig. 6**) with versatile features and seasonal cycles such as large-scale batteries, power-to-H_2 for chemical storage and compressed air electricity storage, depends on the technology readiness levels (TRL) of those technologies that currently remain at a demonstration stage. Without the synergy between chemical storage



Source: PRIMES model.

Figure 1.17 . EU storage systems capacity (GW), share of total power capacity and correlation of power storage with variable RES generation. In these graphs, the abbreviations 'P2X', '1.5TECH', '1.5LIFE', 'COMBO, etc. refer to scenarios of energy mixes with a decreasing percentage of variable renewable energy.

and the production of hydrogen and synthetic fuels, the huge increase of the power system size, projected in the climate-neutral scenarios, would have been unmanageable. The non-linear increase of storage as a function of the volume of total generation can be depicted in the right-hand side chart shown in figure 1.17.

xvi. This reinforces the need for ***'no regrets'* solutions,** i.e. ***policies that confer benefits, and do not cause adverse impacts and negative externalities, irrespective of any positive effects they may have on the problem of climate change***.

xvii. **Power-generating technologies should be evaluated in terms of the extent to which they are '*no regrets*' solutions,** which is currently not done by the EU. Despite the obvious need, the EU has not conducted a cost/benefit analysis of the alternative electricity-generating technologies and electricity systems. This analysis, which should include 'no regrets' assessment, akin to application of the precautionary principle, should address **all benefits and costs of alternative power generation technologies**, such as those listed in Annex IX attached to the report.

xviii. **Two important features of power-generating technologies** that have not received much attention in EU and national policy-making are (i) **the land and space a technology requires**, and (ii) **its costs**. As this study has demonstrated, once these features are accurately reflected in policy-making, **nuclear energy appears to be an attractive, space-and cost-efficient option**.

Part II. Spatial Requirements of Power Generating Technologies

1. If electricity in The Netherlands and the Czech Republic is solely or chiefly provided by wind turbines and solar panels, these renewable energy technologies will take up very significant portions of the available land. This is due to the **low power density of wind and solar**, which is approximately **150 to 500 times lower** than the power density of nuclear power, on average (see further, below).

   a. Depending on variables such as electricity demand and capacity factors, in realistic scenarios, there is **not enough land to meet all power demand** if the Czech Republic and The Netherlands were to rely solely or predominantly on wind and solar power. In the Czech case, it is even **out of the question that the available land will be sufficient to cover all electricity demand**.

   b. In any event, the **spatial impact of high penetration of wind and solar** in the electricity system will be **very substantial** and will increase as a function of the percentage of wind and solar in the power mix.

      i. In The Netherlands, **offshore wind may alleviate the pressure on land somewhat**, but creates its own issues in terms of marine impacts, costs (see below), etc.

      ii. As the penetration of wind and solar increases, **competing land uses, landscape protection, and nature protection** will increasingly come under pressure, resulting in land price increases and deterioration of the living environment.

      iii. In the Czech Republic, if **only 30 % of the power is generated by renewables, all available land is occupied with wind and solar** at a power demand of only 1,000 PJ.

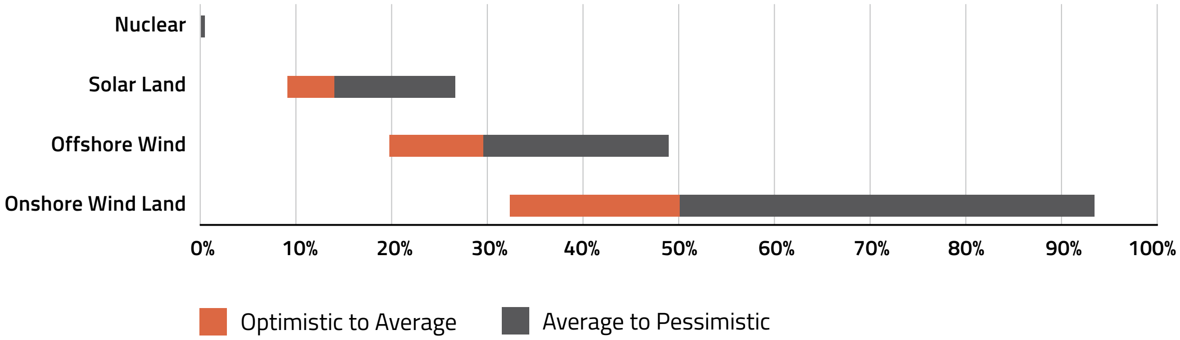
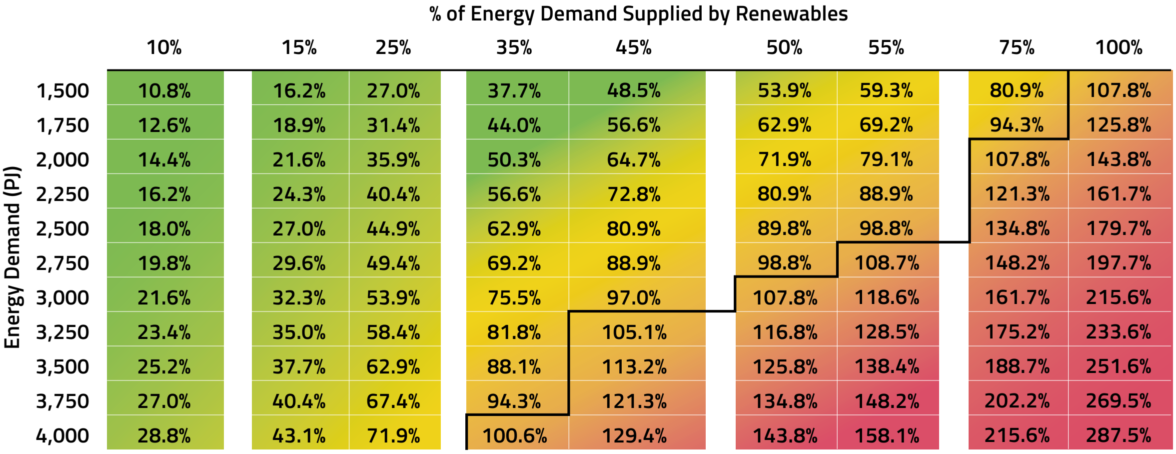


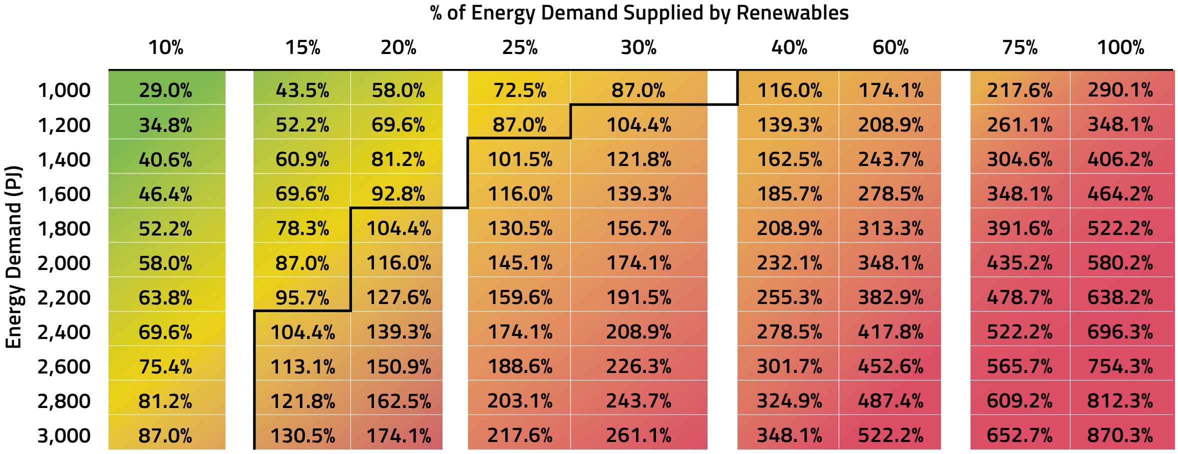
Figure 1.18. The Netherlands - Area Required if Each Source Provides 500 PJ in Energy Annually



% of Energy Demand Supplied by Renewables

Energy Demand (PJ)	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	10.8%	16.2%	27.0%	37.7%	48.5%	53.9%	59.3%	80.9%	107.8%
1,750	12.6%	18.9%	31.4%	44.0%	56.6%	62.9%	69.2%	94.3%	125.8%
2,000	14.4%	21.6%	35.9%	50.3%	64.7%	71.9%	79.1%	107.8%	143.8%
2,250	16.2%	24.3%	40.4%	56.6%	72.8%	80.9%	88.9%	121.3%	161.7%
2,500	18.0%	27.0%	44.9%	62.9%	80.9%	89.8%	98.8%	134.8%	179.7%
2,750	19.8%	29.6%	49.4%	69.2%	88.9%	98.8%	108.7%	148.2%	197.7%
3,000	21.6%	32.3%	53.9%	75.5%	97.0%	107.8%	118.6%	161.7%	215.6%
3,250	23.4%	35.0%	58.4%	81.8%	105.1%	116.8%	128.5%	175.2%	233.6%
3,500	25.2%	37.7%	62.9%	88.1%	113.2%	125.8%	138.4%	188.7%	251.6%
3,750	27.0%	40.4%	67.4%	94.3%	121.3%	134.8%	148.2%	202.2%	269.5%
4,000	28.8%	43.1%	71.9%	100.6%	129.4%	143.8%	158.1%	215.6%	287.5%

Figure 1.19. The Netherlands - % of Available Land Occupied in 100% Renewables Scenario (electricity only). Current annual energy use in The Netherlands is approximately 3100 PJ (see https://www.clo.nl/indicatoren/nl0052-energieverbruik-per-sector).



% of Energy Demand Supplied by Renewables

Energy Demand (PJ)	10%	15%	20%	25%	30%	40%	60%	75%	100%
1,000	29.0%	43.5%	58.0%	72.5%	87.0%	116.0%	174.1%	217.6%	290.1%
1,200	34.8%	52.2%	69.6%	87.0%	104.4%	139.3%	208.9%	261.1%	348.1%
1,400	40.6%	60.9%	81.2%	101.5%	121.8%	162.5%	243.7%	304.6%	406.2%
1,600	46.4%	69.6%	92.8%	116.0%	139.3%	185.7%	278.5%	348.1%	464.2%
1,800	52.2%	78.3%	104.4%	130.5%	156.7%	208.9%	313.3%	391.6%	522.2%
2,000	58.0%	87.0%	116.0%	145.1%	174.1%	232.1%	348.1%	435.2%	580.2%
2,200	63.8%	95.7%	127.6%	159.6%	191.5%	255.3%	382.9%	478.7%	638.2%
2,400	69.6%	104.4%	139.3%	174.1%	208.9%	278.5%	417.8%	522.2%	696.3%
2,600	75.4%	113.1%	150.9%	188.6%	226.3%	301.7%	452.6%	565.7%	754.3%
2,800	81.2%	121.8%	162.5%	203.1%	243.7%	324.9%	487.4%	609.2%	812.3%
3,000	87.0%	130.5%	174.1%	217.6%	261.1%	348.1%	522.2%	652.7%	870.3%

Figure 1.20. Czech Republic - % of Available Land Occupied in 100% Renewables Scenario (electricity only). Current annual energy use in the Czech Republic is approximately 1800 PJ.

2. If electricity in The Netherlands and the Czech Republic is solely or chiefly provided by nuclear power, **nuclear power plants will take up only a minute fraction of the land and space necessary for wind and solar**. This is due to the very high **power density** of nuclear, which is **at least 150 up to over 500 times higher** than the power density of wind and solar.
   a. Nuclear power plants can be sited at the same sites where fossil fuel-fired power plants are located, and require approximately the same area as such plants, which implies **savings on infrastructure** to connect to the network.
   b. These features **greatly reduce pressures on land availability, landscape protection and nature protection**, which is a significant advantage, in particular when competition for land increases.

	Average GWh / km²		Indexed to Nuclear (i.e. nuclear produces x times more electricity per km²)	
	NL	CZ	NL	CZ
Onshore Wind Land	13	13	534	534
Onshore Wind Water	14	n/a	506	n/a
Offshore Wind	26	n/a	266	n/a
Solar Roof	136	163	51	43
Solar Land	47	65	148	108
Nuclear	6,982	6,982	1	1

Table 1.2.

3. Compared to wind and solar, **nuclear power produces approx. 500 and 150 times more electricity per square kilometer**.

4. These numbers **exclude the additional land and space demand imposed by renewable energy**, which increases exponentially as renewable energy expands and makes up a larger share of the power mix. This additional land is required for the **additional infrastructure** necessary for the integration of renewable energy into the electricity system, such as **energy storage and conversion facilities**.

Part III. Cost of Power Generating Technologies and System Cost

1. In virtually **all realistic scenarios, nuclear** power **is cheaper than wind and solar** power in terms of € per MWh in both the Czech Republic and The Netherlands, both at market-based interest rates and at a zero interest rate.[25] These estimates are based on realized costs for each technology and do not factor in any future cost decreases.

€ / MWh	Nuclear	Solar	Onshore Wind	Offshore Wind
0 % WACC	35	72	47	59
3 % WACC	19	65	41	49

Table 1.3. The Netherlands

€ / MWh	Nuclear	Solar	Onshore Wind	Offshore Wind
0 % WACC	30	43	31	N.A.
4.2 % WACC	16	41	29	N.A.

Table 1.5. The Czech Republic

   a. While tables 1.4. and 1.5. only lists the **costs of generating the electricity**, the costs of the electricity system include both the (i) cost of electricity-generation (LCOE), and (ii) the cost of transmission, distribution, storage and conversion (integration and system-related cost). The integration- and system-related cost of nuclear energy is much lower than that of intermittent renewable energy, which, moreover, increases exponentially as the penetration rate of renewable increases.

   b. Each electricity-generating technology (wind, solar, nuclear) produces **both types of cost**, which, to a significant extent, are a function of (i) the extent to which a technology is deployed in a system (the power mix), and (ii) the pre-existing infrastructure.

2. The **main drivers of the LCOE for both wind/solar and nuclear** are, in order of importance:
   i. weighted average cost of capital (WACC)
   ii. capacity factor
   iii. capital cost
   iv. fixed O&M cost

The **WACC is the most influential**, but also the most controversial factor. Based on thorough analysis of this debate, our approach estimates the WACC for policy makers by **separating government risk** (which policy makers control) from **project risk** (which operators control to a great extent). In standard LCOE calculations, non-intermittent nuclear electricity is discounted more heavily than intermittent renewable

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[25] These estimates do not discount the energy produced to reflect intermittency or the time of generation. This is the default throughout the extensive summary, unless otherwise noted.

electricity, even though electricity is fungible and the economic value of intermittent energy is lower. Our method avoids this practice, but does not discount intermittent renewable electricity to account for its lesser economic value.

3. In part because the WACC is also used as discount rate, the WACC to be applied in planning decisions is not a given for policy makers. The choice of a WACC/discount rate is a value-laden decision, not a technical matter to be decided by experts. Deciding the appropriate discount rate for policy purposes involves political and moral debates as much as economic and technical issues. Given that policy making can influence WACCs directly, policy makers should scrutinize the WACCs used in any LCOE. Using a **policy-neutral WACC of 3 % for The Netherlands and 4.2 % for the Czech Republic,** we find that **in most plausible scenarios nuclear power is cheaper than all types of renewable energy (offshore wind, onshore wind, solar)** or any combinations thereof in both the Czech Republic and The Netherlands.
   a. Only if all or most variables turn out to be in favor of renewable and to the detriment of nuclear, some renewable power might have a lower LCOE, although not necessarily a lower total cost.
   b. Note that this cost comparison is based merely on LCOE and, thus, does not take into account **integration and system-related costs**, which are much **higher for renewable power** than for nuclear (see further below).
   c. **In most plausible scenarios nuclear power is cheaper than all types of renewable energy (offshore wind, onshore wind, solar) in both**

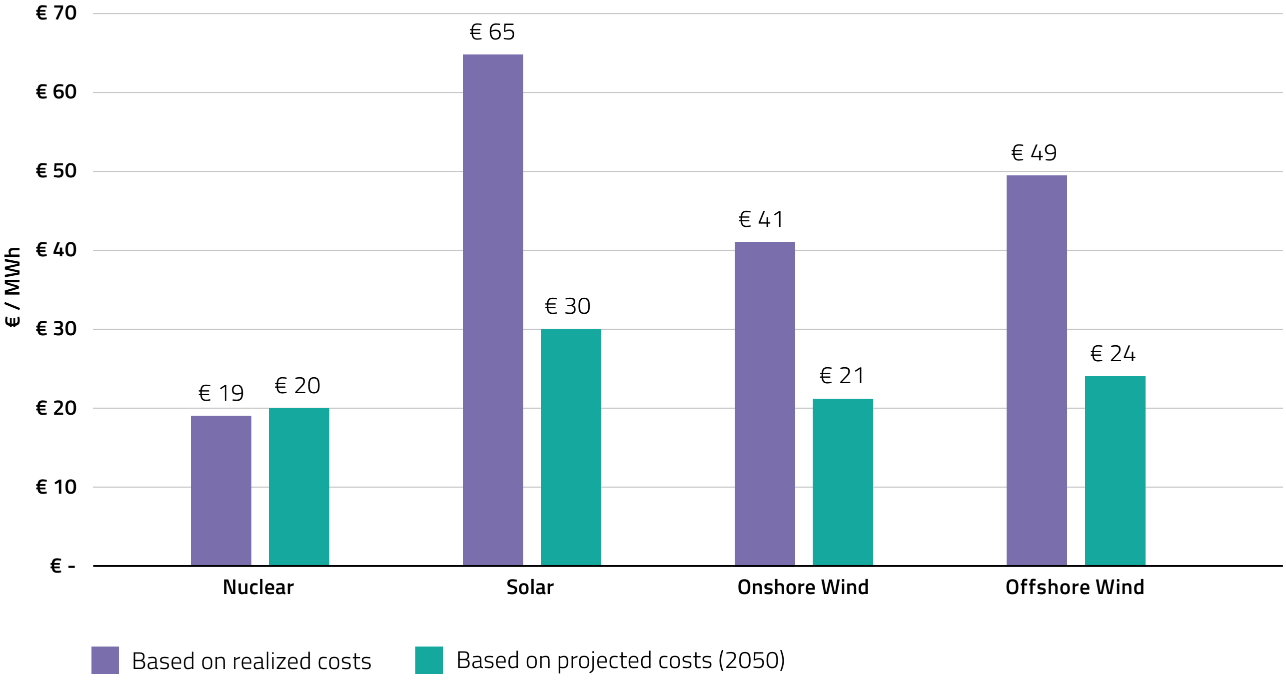


Figure 1.21. The Netherlands: LCOE Analysis

In most plausible scenarios nuclear power is cheaper than all types of renewable energy (offshore wind, onshore wind, solar) in both the Czech Republic and The Netherlands, even before integration- and system-related cost is added, which is much higher for renewables.

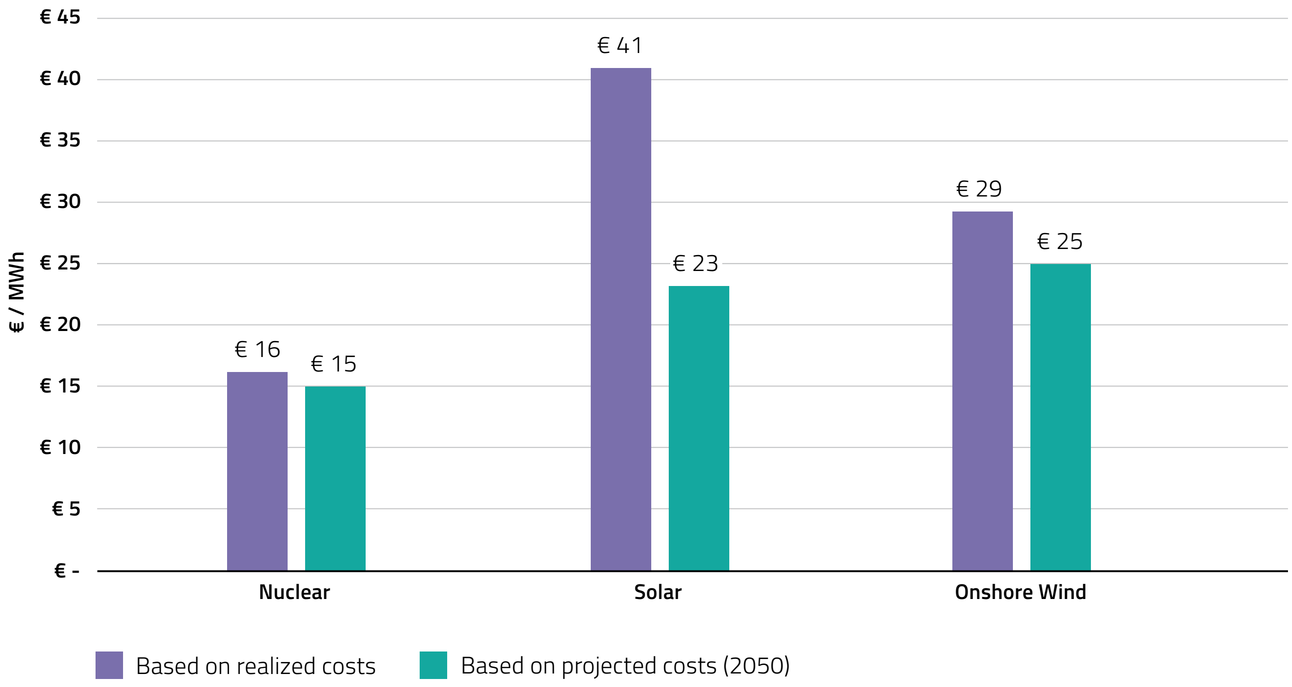


Figure 1.22. The Czech Republic: LCOE Analysis

the Czech Republic and The Netherlands, even before integration- and system-related cost is added, which is much higher for renewables (see further below).

   d. Likewise, spatial requirements are not taken into account in this analysis (refer to the discussion above).

4. We further **adapted the LCOE method** by developing a **synchronized lifetime analysis** as an additional point of reference. A synchronized lifetime analysis is the preferred method for comparing various power generating technologies, because it avoids the distorting effects of discounting projects with different lifetimes and different production schedules.

   This method confirms that **nuclear power is a more cost-efficient solution to meet chosen levels of electricity production over a given period of time, even before integration- and system-related costs are added.**

   a. As expected, the cost advantage of nuclear decreases as the WACC increases.
   b. This result is independent of the level of power output required. It is also independent of the time period over which the analysis is conducted, assuming the lifetime of the technology is exhausted.

Note: The time periods under consideration for The Netherlands and the Czech Republic are different due to different technical lifetimes of the renewable power technologies.

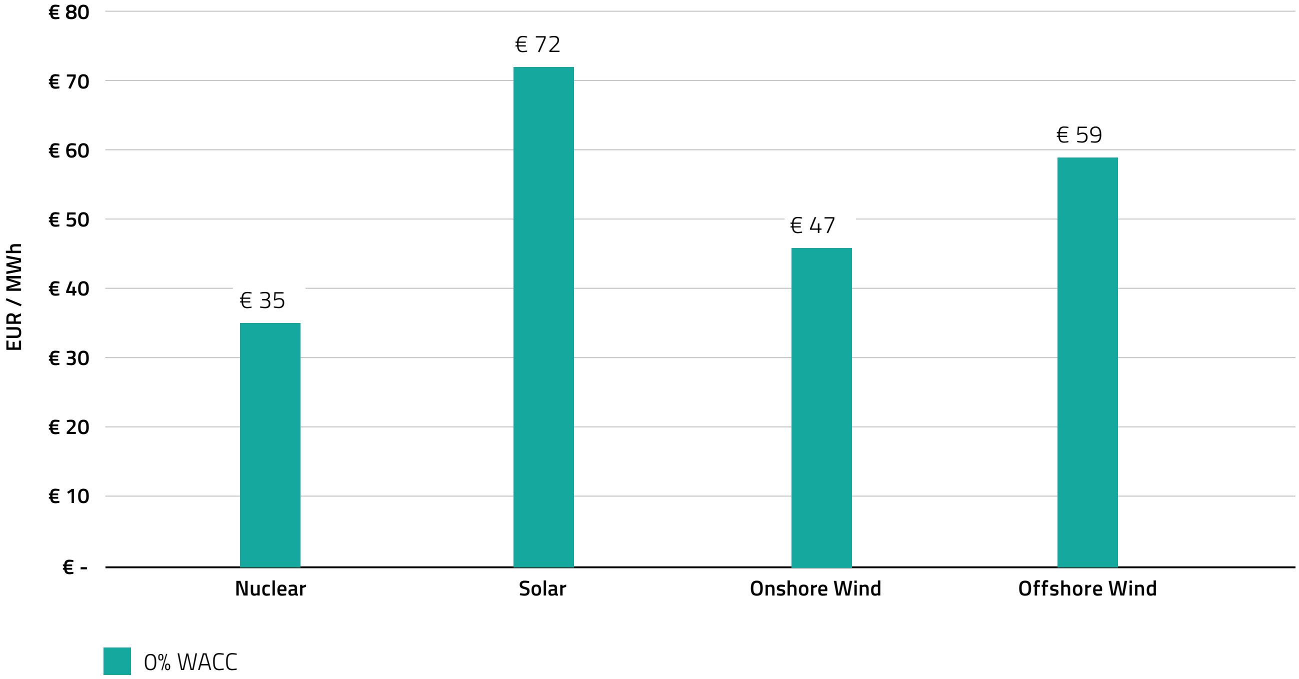


Figure 1.22. The Netherlands - Synchronized Lifetime Analysis (based on realized cost of levelized output and no discounting).

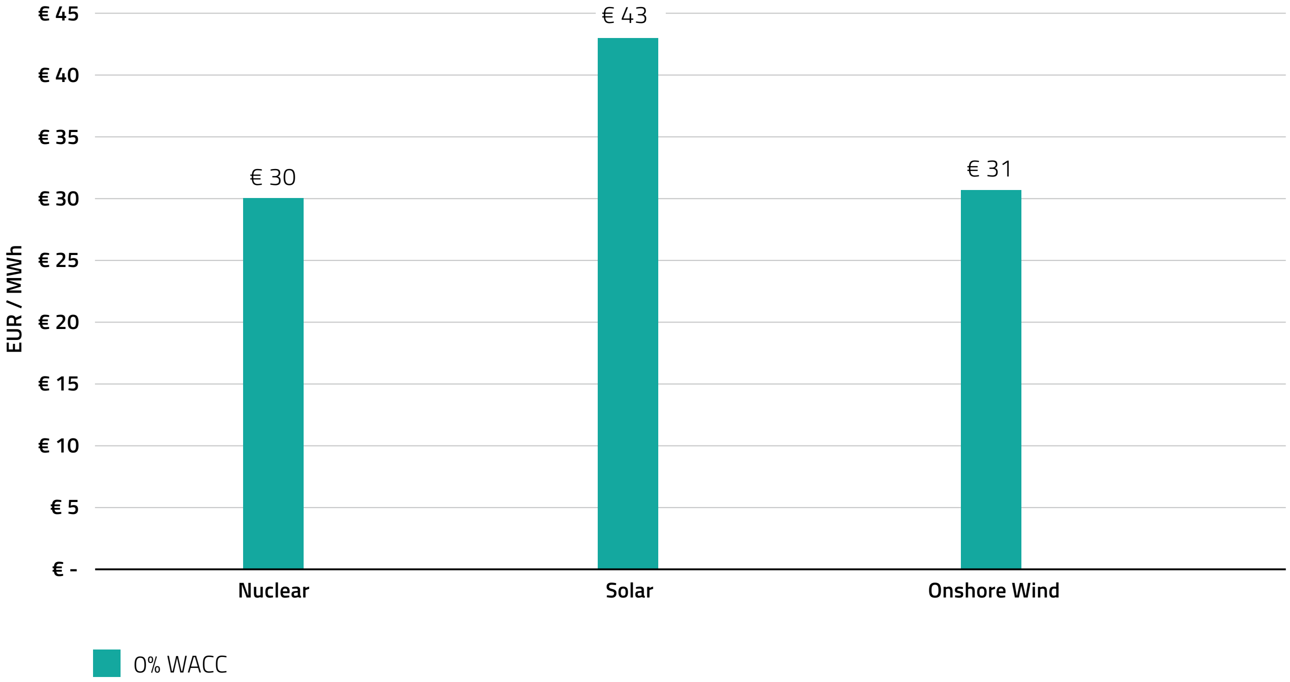


Figure 1.23. The Czech Republic - Synchronized Lifetime Analysis (based on realized cost of levelized output and no discounting).

	Nuclear	Solar	Onshore Wind	Offshore Wind
Present Value of Generation Costs at 0 % WACC, *Relative to nuclear*	1.0x	2.0x	1.3x	1.7x
Present Value of Generation Costs at 3 % WACC, *Relative to nuclear*	1.0x	1.9x	1.2x	1.5x

Table 1.6. The Netherlands - Synchronized Lifetime Analysis

	Nuclear	Solar	Onshore Wind
Present Value of Generation Costs at 0 % WACC, *Relative to nuclear*	1.0x	1.4x	1.0x
Present Value of Generation Costs at 4.2 % WACC, *Relative to nuclear*	1.0x	1.0x	0.7x

Table 1.7. The Czech Republic - Synchronized Lifetime Analysis

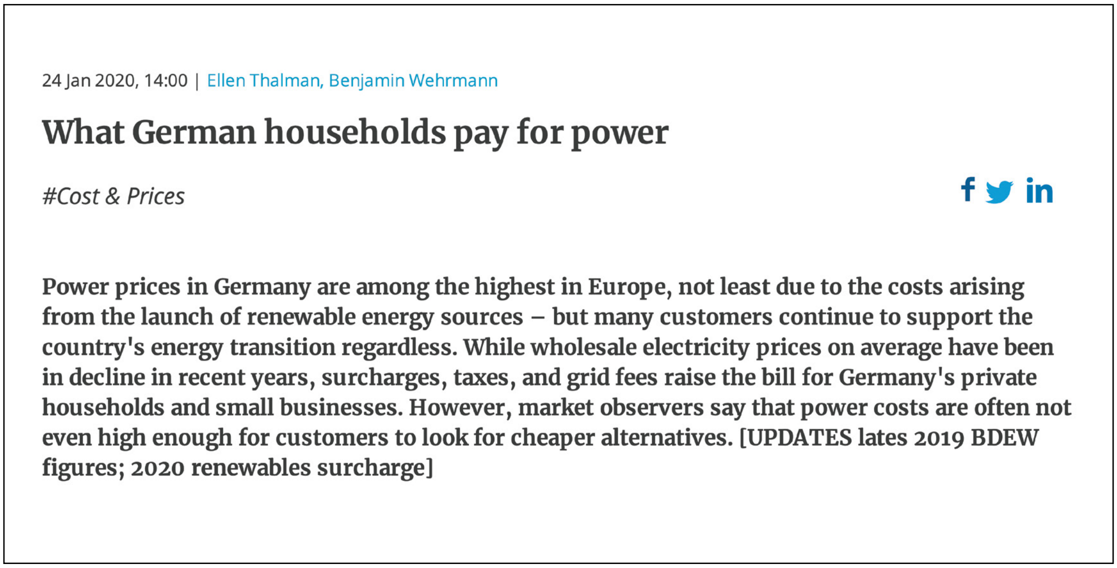
5. If the **integration and system-related costs** (profile cost, connection cost, balancing cost, grid cost) are included in the analysis, the **cost advantage of nuclear power over wind and solar power increases further**. This is true especially when wind and solar power achieve high penetration rates.

a. **Integration- and system-related costs are low for nuclear power, because nuclear power plants provide a constant output (no intermittency) and, to some extent, can adjust power production to fit demand (flexibility)**. Moreover, they can be located at the current sites of fossil fuel-powered electricity plants or similar, relatively small sites, close to the power infrastructure and close to where electricity is most needed.

b. **Integration- and system-related costs are high for wind and solar power, because this technology is intermittent (no constant output) and it is incapable of producing power on demand (stochastic, no flexibility)**. As renewable energy displaces conventional energy sources, integration- and system-related cost increases exponentially because the problem of intermittency increases, requiring more backup-, storage- and conversion facilities. Moreover, the sites for wind and solar facilities are often located at relatively remote areas, far away from the power infrastructure and from where electricity is most needed. This contributes further to higher integration costs as infrastructure needs to be built to connect these facilities to the existing grid and wind/solar are unable to replace conventional power generation facilities at a 1:1 ratio.

c. Based on modelling with the ETM, for The Netherlands, **total energy system costs could be reduced by as much as 18% by replacing renewable generation with nuclear generation,** with more cost savings for those scenarios that initially had more renewables in the energy mix. Importantly, **grid connection costs, only one part of the integration costs, were reduced by over 60 % in one scenario**, which would save the Dutch government almost EUR 10 billion per year.

d. Further evidence for the **price-inflating effect of renewable energy** is derived from Germany, where household electricity prices broke the **30 cents per kWh** barrier in recent years. These high prices have been contrasted with those in France, which relies much more on nuclear power, where in 2019, the average household electricity prices in France were **18 cents per kWh**. Interestingly, in scenario analysis for France, the scenarios with **60 % renewables** were **55 billion euros more expensive** than the scenario that kept nuclear power capacity constant and renewables at 35 %.

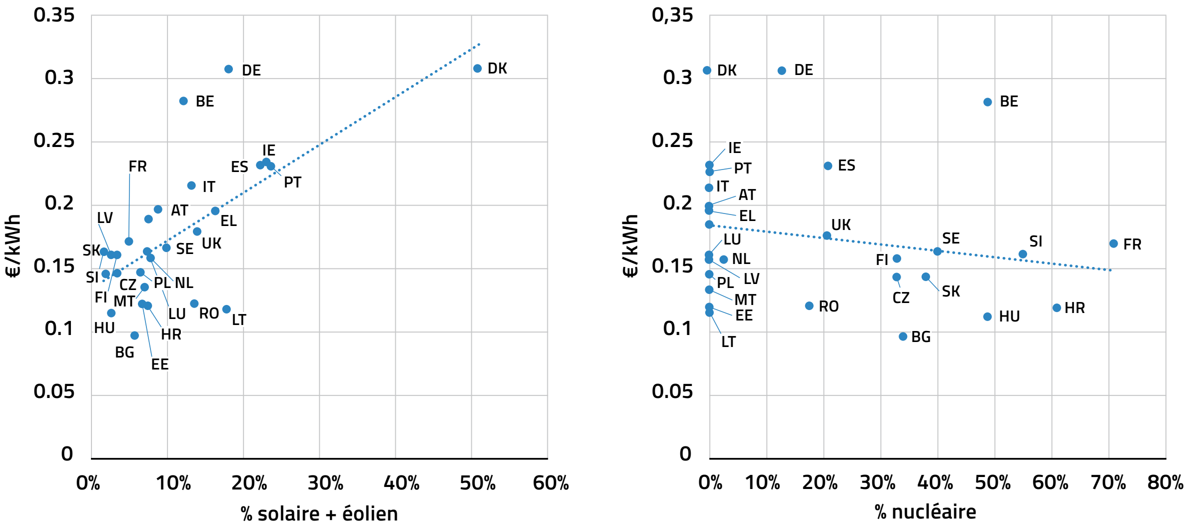


24 Jan 2020, 14:00 | Ellen Thalman, Benjamin Wehrmann

What German households pay for power

#Cost & Prices

Power prices in Germany are among the highest in Europe, not least due to the costs arising from the launch of renewable energy sources – but many customers continue to support the country's energy transition regardless. While wholesale electricity prices on average have been in decline in recent years, surcharges, taxes, and grid fees raise the bill for Germany's private households and small businesses. However, market observers say that power costs are often not even high enough for customers to look for cheaper alternatives. [UPDATES lates 2019 BDEW figures; 2020 renewables surcharge]



1.24. Price of electricity (household)

From: Prof. Samuel Furfari, Uinversite Libre de Bruxelles, 2019.

Source: Eurostat (Dec 2018)

e. Importantly, as the **rate of penetration of wind and solar power increases**, the **integration and system-related cost increase exponentially**, further widening the gap between the low cost of nuclear power and the high cost of renewable power.

f. As the figure 1.24. suggests, **higher renewable energy penetration rates are positively correlated to higher household electricity prices**, while **higher nuclear energy shares are positively correlated with lower electricity prices**.

Part IV. Policy Recommendations

Because current EU policies **favour renewable energy over nuclear energy**, assessment of the relative cost of both technologies can easily be led astray and reflect the **policy status quo**, rather than anything inherent to these technologies. Massive funding found its way into the development and deployment of wind and solar energy solutions. This had the effect of reducing the price of renewable energy, but it has also had a relative **inflating effect on the cost of nuclear power** and of the deployment thereof in the EU.

Given the advantages of nuclear power from spatial and economic viewpoints, however, Member State governments will likely **need to add nuclear power to their energy mixes** to stay on track in their attempts to meet the EU climate neutrality's objective.

1. Under the current EU and member state policies, the following **benefits are extended to renewable energy**, which are **not (or only to a much more limited extent) available to nuclear power**:

    a. **Direct subsidies (grants) for research and development** of renewable power technologies, including wind and solar technologies;
    b. **Direct subsidies (investments grants, loan guarantees, soft loans) for actual renewable power projects,** including wind and solar projects;
    c. **Indirect subsidies by paying for infrastructure** required specifically by renewable power projects out of general budget, tax revenues, or levies;
    d. **Mandatory, guaranteed minimum shares for renewable energy** in the energy mix imposed through minimum targets for renewable energy, with renewable energy defined to exclude a competing decarbonized technology;
    e. **Priority and privileged access to the energy market** through priority dispatch, feed-in tariffs (FiT), feed-in premiums (FiP), to the detriment of competing power generators, including decarbonized power producers;

f. **Quota obligations with tradable green certificates**, and similar minimum purchase requirements for renewable electricity;
g. **Tax incentives** available only to renewable power generation, not to other decarbonized power generation technologies;
h. **Tendering schemes** that favor renewable power generators over other decarbonized power generators;
i. **Expedient permitting and regulatory procedures** that reduce the risks for renewable power projects, but are not available to other decarbonized power projects;
j. **Procedures and rules relating to grid access and operation** that favor renewable generators or disadvantage other power producers;
k. **Other features of power market design, structure, and functioning** that favor renewable power projects;
l. **Land-related policies that keep the price of land use for renewable power projects low**, including, but not limited to, agricultural policies;
m. **Lack of obligation for renewable power generators to compensate property owners that suffer damage** (e.g. reduced property value) as a result of location of renewable power plants;
n. **No internalization of negative externalities** (e.g. adverse environmental impacts) into the price of renewable power generation; and
o. **Free riding on other technologies that keep the power system stable and flexible**, such as base load generators and flexibility providers.

2. To meet the public demand for nuclear power, the EU should place renewable and nuclear on equal footing and endorse a '***Nuclear Renaissance***' program. This program would comprise twelve key elements:

a. **Equal treatment**: All decarbonized power generation technologies (wind, solar, nuclear) receive equal treatment by the EU and member state governments.
b. **Generator pays principle**: Based on the principles of cost internalization and "polluter pays," all EU policies ensure that the fully loaded costs, including integration- and system-related costs as well as relevant externalities, are taken into account in policy making with respect to both renewable and nuclear power.
c. **No discriminatory subsidies**: All open and hidden subsidies, direct and indirect, in cash or in kind, and other advantages for renewable energy (e.g. targets, priority rules, higher or guaranteed feed-in tariffs, subsidized infrastructure necessary for wind on sea, deflated land use prices, etc.) are eliminated, so that nuclear can compete on a level playing field. Other EU policies are not skewed to provide benefits to renewable energy.
d. **Total system cost rules**: The electricity market is redesigned so that total system costs, rather than marginal cost of subsidized power generation technology, drives carbon-neutral investments.
e. **Differentiated electricity products**: Based on the idea that unequal cases are not treated the same way, the concept of 'energy only' is no longer construed in a way that favors the marginal cost of stochastic, demand-unresponsive electricity generation, but recognizes the fundamentally different nature of constant, on demand electricity supply, and demand-unresponsive electricity supply.
f. **Holistic assessment**: The extent to which power generation technology, whether wind, solar, or nuclear, has favorable or adverse effects on other EU interests and policies (such as habitat and species protection, toxic-free environment, agricultural policy, energy policy, etc.) and causes other externalities, is identified and objectively assessed in connection with policy making at EU and member state levels.

g. **Expedient regulatory procedures**: Like renewable energy, nuclear power equally benefits from expedited, efficient permitting and regulatory procedures, and the EU requires that the Member States eliminate privileged treatment of any power generation technology in their administrative procedures.

h. **Legal and policy certainty**: To encourage investment in the best power generation technology and keep the finance cost down, legal and policy certainty is guaranteed to both renewable and nuclear power.

i. **Adequate compensation of damage**: The EU requires that Member States provide for reasonable compensation for EU persons that suffer damage or harm, or are otherwise disadvantaged, by siting decisions in relation to power generation facilities and transmission lines.

j. **Access to finance on the merits**: Access to private and public finance is a function of the merits of power generation technologies. Privileges and discrimination in this area are eliminated.

k. **EU nuclear energy regulation for the new era**: EU nuclear energy regulations are reviewed and updated, as necessary, to ensure that they are fit for purpose and for the new era in power generation. Nuclear regulation is effective and efficient.

l. **EU nuclear liability and compensation program**: The EU enacts EU regulation on nuclear liability to ensure that there are additional incentives for prevention and that compensation is available if a nuclear accident were to happen.

Conclusions

1. The EU's 2050 climate neutrality strategy involves a high risk of policy failure. The anticipated energy transition, however, can hedge against this risk by deploying 'no regrets' solutions that are good investments, bring down emissions, and have little adverse impact. Nuclear power is such a solution.

2. With respect to both spatial requirements and costs, nuclear power offers substantial advantages over renewable power (wind, solar). These advantages have been recognized in the Czech Republic, but not (yet) by policy makers at the EU level and in The Netherlands.

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1

Introduction

Introduction

The EU is committed to achieving climate neutrality (i.e. net zero greenhouse gas emissions[26]) by 2050. Electrification of the energy system is a key component of this strategy. This implies that the electricity (or power) system must be completely 'decarbonized' over the next three decades.

The European Commission did not indicate, however, what effect the EU's climate ambition would have on the problem of climate change, specifically, the average global atmospheric temperature increase caused by human greenhouse gas emissions, nor did it attempt to assess the land use and space demands and total cost of the contemplated energy transition.

Study Subject

This study assesses the effectiveness of EU climate neutrality, and analyses and compares two climate-neutral power-generating technologies that can result in decarbonization of the electricity system (assuming effective replacement of fossil fuel power generation) – renewable energy (wind/solar) and nuclear energy. Geographically, the study focuses on two Member States on opposite side of the spectrum for wind energy potential: The Netherlands, a country along the North Sea with abundant wind, and the Czech Republic, a landlocked country with no access to sea and less suitable land.

In these countries, we are assessing the power generation technologies concerned, renewable (wind/solar) and nuclear, with respect to their demand for land/space to generate a specified amount of electricity. In addition, we determine their costs, both

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[26] Note that net zero greenhouse gas emissions require net negative CO_2 emissions to compensate for on-going emissions of other GHGs.

the cost of power generation and, to a more limited extent, the integration- and system-related cost.

Study Relevance

The contemplated energy transition is not without risks in terms of both climate effectiveness and economic effects. In this study, we engage several key questions relevant to ensuring a successful and affordable energy transition within the EU. Since achieving climate neutrality will require unprecedented investments and expenses, it is essential that the EU pursue the 2050 climate neutrality mission in a cost-effective and efficient manner.

If there is significant uncertainty about the effect on the climate problem, and the response by non-EU countries is not a given, '*no regret*' solutions become more appealing. These kinds of solutions serve as a hedge against the risks associated with these uncertainties, since they remain good investments, irrespective of any positive effect they may have on the problem of climate change, thus, also in case the effect of the EU's transition on climate change appears to be negligible, or the 2050 zero GHG target would need to be abandoned or postponed during the transition period.

Structure of Report

Following this introduction, Part 2 of this report discusses the EU policy background against which the issues discussed here arise. Through this background analysis, we attempt to place the key questions addressed in this study firmly in the context of EU policies and policy-making. This part reviews the overarching policy principles relevant to policymaking in the climate area, the EU climate and energy policies. In addition, we focus specifically on the renewable energy policy, the sustainable finance initiatives, and nuclear power regulation, which are all directly relevant to the issues discussed in this report.

Subsequently, the research questions and their background are reviewed (Part 3). In this part, we also describe the objectives of our research, as well as the methodologies and data we have used to answer the research questions. The scope and limitations of this study are briefly reviewed too.

Part 4 covers the topic of EU climate neutrality's effect on the average temperature. We assume that there is a relation between greenhouse gas emissions and global warming. By way of introduction, we begin by discussing scientific uncertainty and policy uncertainty in the context of climate change. The objective is not to engage the science or policies as such, but rather to lay the groundwork for understanding the challenges the EU faces in this area. We then proceed to review the existing literature relevant to greenhouse gas (GHG) emissions, the EU's current and projected contributions to global GHG emissions, and the effect thereof on the average global atmospheric temperature.[27] The analysis of the expected effect of EU climate neutrality on the temperature can inform the policy choices facing the EU. We assess also the rate of renewable energy dispersion necessary to achieve climate neutrality in 2050, and an alternative to the current policy, called 'taking climate neutrality seriously,' which does not hinge on the mitigation efforts of other countries. To complete this section, we discuss the international context and the limiting conditions and restrictions it imposes on the EU.

In the subsequent parts of the report, the focus shifts to the comparison of wind/solar power and nuclear

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[27] This part does not address the relation between the average temperature and other possible changes in the climate system, such as sea level rise, ocean acidification, and extreme weather.

power with respect to, first, spatial requirements (i.e. the surface areas required by these technologies to produce a given amount of electricity) and then the cost of electricity (i.e. the cost of generating a given amount of electricity produced by a particular technology). We developed models to compute spatial requirements and costs; note that our cost model estimates only the cost of electricity generation, not the system-related costs associated with power generation technologies. These models are fully transparent and allow for reproducibility of the results. The model inputs can be varied to reflect a range of possible scenarios, and thus accommodate uncertainties. We provide explanations and justifications for the inputs used for the model, and contrast our model with other existing models. Sensitivity analysis is also presented.

In Part 5, we present the results of our modelling of spatial requirements for the Czech Republic and The Netherlands for wind/solar and nuclear power. These two countries differ substantially in their potential for renewable power -- The Netherlands is a country at the North Sea with abundant wind, both on land and on the North Sea off shore area that is part of Dutch territory, while the Czech Republic is a landlocked country with no access to sea and less suitable land for wind power. Before the model outputs are presented, a brief introduction and description of the policy background are provided to give the reader additional context. In the case of The Netherlands, we also discuss recent studies done for the Dutch government on spatial requirements of various renewable technologies. We present conclusions and further reflections at the end of this part.

We then turn to the cost of wind/solar and nuclear power (Part 6). Following an introduction and description of our cost model, we first discuss the costs of renewable and nuclear power in the Czech Republic and then turn to The Netherlands. For each country and each type of technology, the discussion covers the levelized cost of electricity (LCOE) model outputs. Subsequently, we identify the main drivers of LCOE, and any uncertainties and model limits. A discussion of our findings concludes each section. To be able to make accurate comparisons of the cost of electricity across the spectrum of different technologies, we use a novel method that we call "synchronized lifetime analysis." This method involves a conventional levelized cost of electricity (LCOE) calculation, modified by replacing power discounting by synchronizing power delivery in equal quantities across technologies. This part of the report discusses also the synchronized lifetime analysis model outputs.

In Part 7, the analysis focuses on the relations between electricity generation technologies, the electricity system as a whole, and the economy and society. The LCOE is not the only cost associated with the electricity system; in addition, there is significant cost associated with integrating power generation technology and its output into the power system, and this integration cost differs between various power technologies. There are also differences in terms of the broader effects of power generation technologies on the economy and society. This part presents a qualitative and limited quantitative discussion of these issues for wind/solar and nuclear power. We estimate integration costs of wind/solar and nuclear for The Netherlands, and present a case study of integration costs based on electricity prices. The discussion of other system-related cost focuses on land use-related issues and is qualitative. In an annex, an overview is presented of a wide range of impacts and externalities associated with wind, solar, and nuclear energy. This overview is intended to complete the range of considerations relevant to policy makers.

Part 8 presents a series of policy recommendations based on the findings of the study, as presented in previous parts. Before laying out these recommendations, we first provide brief explanations of the basics of the electricity system, power generation technologies, power delivery through the electricity network, load dispatch and merit order, the electricity market and the so-called 'merit order effect', the electricity bill for consumers, investing in private electricity generation markets, and subsidies, free-riding, and externalities in power markets. In these reviews, we zoom in on aspects of renewable and nuclear energy that are salient to energy policy-makers. Our policy recommendations are aimed at establishing a technology-neutral, non-discriminatory framework for electricity generation.

The conclusions are set forth in the Part 9. We wish to point out here that the analysis of the relative spatial and cost requirements of wind/solar and nuclear energy does not depend on the merits of the EU climate neutrality policy; these parts of the study can be read as stand-alone assessments. Thus, the conclusions on the relative spatial and cost requirements of wind/solar and nuclear energy do not hinge or build on the conclusions on the effect of EU climate neutrality.

We have added a list of references as Part 10 and over a dozen annexes that provide further details and back-up relevant to the models utilized for this analysis and other topics. For the reader's convenience, a glossary and list of abbreviations are included, alongside a table that links the research questions to specific sections of this report.

This report is intended to assist the reader in understanding the key issues associated with wind, solar and nuclear energy. To achieve this objective, we had to cover a lot of ground. Not all readers will read it cover to back without putting it down. A detailed table of contents, a brief executive summary, and an extensive summary can help them to identify those parts in which they take specific interest.

Before getting into the substance, we wish to assure the reader that we, unlike some of the authors we criticize, have attempted consistently to avoid hidden value judgments and prejudging. This report lets facts and numbers speak without trying to massage and bend them to fit preconceived policy preferences. As such, it offers another perspective on the cost of nuclear power that is more realistic and respectful of the choices that policy makers face.

The report was finalized on 30 November 2020.

2

Relevant EU Policies

Relevant EU Policies

As discussed in the introduction, this study examines (i) the effect of EU climate neutrality on the average global atmospheric temperature by 2050, (ii) analyzes the land and space requirements for wind and solar electricity in the Czech Republic and The Netherlands, relative to the land required for the same amount of nuclear power, and (iii) compares the cost of wind/solar power to the cost of nuclear power for these two countries.

EU laws and policies are relevant to these issues in several ways, both directly and indirectly. In this section, we provide an introduction to these EU laws and policies. The objective of this analysis is to place the topics of this study in their policy context, which has a bearing on both answering the question posed and interpreting the answers to these questions.

The first section briefly discusses some overarching policy principles that have helped to shape the specific policy areas. The EU climate policy, including the Green Deal and EU Climate Law are reviewed in the second section. In the third section, we turn to the EU energy policy, including the EU Energy Union. The fourth part deals specifically with the EU laws and policy regarding renewable energy. Section five reviews the EU sustainable finance initiatives, which are also relevant to the financing of energy projects. In the sixth part, we discuss the EU regulatory framework for nuclear electricity. The final part presents some conclusions on these policies.

a. Overarching Policy Principles

Many of the EU's climate and energy policies, directly or indirectly, in one way or another, can be traced back to an undefined principle set out in the EU Treaty. The pertinent provision stipulates as follows:

"The Union shall establish an internal market. It shall work for the ***sustainable development*** *of Europe based on balanced economic growth and price stability, a highly competitive social market economy, aiming at full employment and social progress, and a high level of protection and improvement of the quality of the environment."*[28] *(emphasis supplied).*

The Treaty on the Functioning of the European Union works this out further by requiring that sustainable development be promoted by integrating environmental protection requirements into "the definition and implementation of the Union's policies and activities."[29]

In addition, the EU has adopted several generic policy principles that apply to all EU policies or, by their terms, only to environmental policies, although their scope of application may be broader. The former includes principles such as **proportionality, equality before the law, legal certainty, and subsidiarity**. Although these principles are relevant to the subject of this study, they are not further discussed here.

The EU's principles for environmental policy-making apply to all environmental, many health and safety, and most climate-related policies. They are intended to inform legislation and policy-making relating to environmental protection and sustainable development. There are five such principles:

- The ***precautionary principle***, which allows regulatory action to be taken even if a risk has not been established with full certainty, and is applied to manage risk in cases of scientific uncertainty.
- The ***prevention principle***, which aims to prevent environmental and climate-related damage, including harm to protected species, natural habitats, water and soil, or harm due to climate change.
- The ***rectification at source principle***, which seeks to prevent pollution at its source, rather than address it at the 'end-of-pipe' or remedy its effects.
- The ***polluter pays principle***, which implements the concept of 'internalizing negative externalities,' and requires that polluters pay for the costs of the pollution they cause.[30]
- The ***integration principle***, which requires that environmental protection requirements be integrated into other EU policies, in particular with a view to promoting sustainable development.[31]

Much can be said about each of these principles, but for purposes of this study a few comments suffice. The precautionary, prevention, and polluter pays principles have shaped the EU's climate policies in important ways. There is scientific uncertainty about the magnitude and seriousness of the impact of human activities on climate change, but the precautionary principle allowed the EU to move ahead with its ambitious programs despite the causal uncertainties. Obviously, some of the EU's climate-related policies are underpinned by the prevention principle, such as those relating to fluorinated gases. In relation to the polluter pays principle, it has been argued by a former top climate official of the European Commission that the theory of cost internalization has been the main instrument of EU climate policy.[32]

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[28] Article 3(3), Treaty on European Union.

[29] Article 11, Treaty on the Functioning of the European Union (TFEU).

[30] Article 191(2) of TFEU.

[31] Article 11, TFEU.

[32] "In the 1990s, economists were actively looking at how to improve environmental policymaking, and made a strong case for putting a price on the impacts of pollution that are not otherwise paid for by the polluter ("pricing environmental externalities")." Jos Delbeke and Peter Vis (editors), EU Climate Policy Explained, European Union, Brussel, 2016, available at https://ec.europa.eu/clima/sites/clima/files/eu_climate_policy_explained_en.pdf

The integration principle is perhaps the least visible in the EU policies at issue here. As discussed in the conclusions of this part and throughout this report, there appear to be tensions, if not conflicts, between the objectives and requirements of climate and environmental policies and those of other policies, but, remarkably, it is not necessarily so that the former always do a better job of promoting sustainable development.

b. EU Climate Policy

Climate change is believed by EU policy makers to pose serious risks to humanity and the survival of the plant, but is also viewed as an opportunity. At the presentation of the EU Green Deal, echoing the European Parliament's resolution,[33] Climate Commissioner Frans Timmermans even stated: *"We are in a climate and environmental emergency. The European Green Deal is an opportunity to improve the health and well-being of our people by* ***transforming our economic model****"*[34]. *(emphasis supplied)* The EU intends to "move fast and move first" in addressing climate change and becoming the world's first climate neutral continent.

Instruments

The EU's climate strategy has several main prongs: emissions trading under the '*cap and trade*' program established by the Emissions Trading System[35] (which covers power plants), energy and resource efficiency, renewable energy, energy saving (demand reduction), industry decarbonization, other mitigation strategies, and adaptation.[36] Other instruments to fight climate change include national targets for sectors outside emissions trading (such as transport, buildings and agriculture), forest and land policies, CO_2 emission standards for vehicles, increasing energy efficiency of buildings and products, promoting innovative low-carbon technologies, phasing down climate-warming fluorinated greenhouse gases and protecting the ozone layer, adapting to the impacts of climate change, and funding climate action.[37]

In its communication on *The European Green Deal*, the Commission envisions that the electricity sector in 2050 will be "*largely based on renewable sources.*"[38] More specifically, in 2018, the Commission predicted that "[b]y 2050, more than 80 % of electricity will be coming from renewable energy sources (increasingly located off-shore), … with a nuclear electricity share

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[33] European Parliament resolution of 28 November 2019 on the climate and environment emergency (2019/2930(RSP), available at https://www.europarl.europa.eu/doceo/document/TA-9-2019-0078_EN.pdf

[34] The European Green Deal sets out how to make Europe the first climate-neutral continent by 2050, boosting the economy, improving people's health and quality of life, caring for nature, and leaving no one behind, Press Release, 11 December 2019, available at https://ec.europa.eu/commission/presscorner/detail/e%20n/ip_19_6691

[35] Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC, OJ L 275, 25.10.2003, pp. 32–46, as amended. The ETS applies to emissions from approximately 11,000 heavy energy-using installations, including power stations & industrial plants, covering around 45% of the EU's greenhouse gas emissions.

[36] European Commission, Climate strategies & targets, available at: https://ec.europa.eu/clima/policies/strategies_en

[37] EU climate action and the European Green Deal, available at https://ec.europa.eu/clima/policies/eu-climate-action_en

[38] "A power sector must be developed that is based largely on renewable sources, complemented by the rapid phasing out of coal and decarbonising gas. At the same time, the EU's energy supply needs to be secure and affordable for consumers and businesses. For this to happen, it is essential to ensure that the European energy market is fully integrated, interconnected and digitalised, while respecting technological neutrality." European Commission, The European Green Deal, 2019, COM(2019) 640 final

In 2018, the Commission predicted that “by 2050, more than 80 % of electricity will be coming from renewable energy sources (increasingly located off-shore), … with a nuclear power share of circa 15 %.

of circ. 15 %.”[39] While emphasizing technological neutrality, the Commission did not analyze, however, how much land and space would be required for that much renewable energy production, how much these energy options could contribute towards achieving carbon neutrality, and how electricity prices would be affected. This study attempts to begin to fill these gaps.

A first of its kind, the proposed EU Climate Law,[40] would make the climate neutrality objective of the European Green Deal binding. Under this draft law, the EU member states jointly would have to achieve net zero greenhouse gas emissions by 2050. The law attempts to coordinate other relevant EU policies so that they contribute to this goal, and “to move in a fair and ***cost-effective*** manner towards the temperature goal of the 2015 Paris Agreement on Climate Change” ensuring “a socially-fair and ***cost-efficient*** transition”[41]. *(emphasis supplied).* Importantly, the proposed Climate Law requires that the EU and Member States, in taking measures to achieve the climate-neutrality goal, take into account:

> *“the contribution of the transition to climate neutrality to the* ***well-being of citizens****, the* ***prosperity of society*** *and the* ***competitiveness of the economy; energy security*** *and* ***affordability****; …* ***cost-effectiveness and technological neutrality*** *in achieving greenhouse gas emissions reductions and removals and increasing resilience.”*[42] *(emphasis supplied).*

The European Commission uses the term “climate neutrality” because it will likely be impossible to eliminate 100 % of fossil fuels; to achieve climate neutrality the CO_2 emitted by the remaining fossil fuel use must be “neutralised” either by storing it (so-called “carbon capture and storage” or CCS technology) or reuse it in a non-emitting application. Both of these solutions have not yet been demonstrated to be economically feasible at reasonable cost.

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[39] “The global expansion of renewable energy, instigated by EU leadership, led to massive cost decreases in the last 10 years, in particular in solar and on- and off-shore wind. Today, more than half of Europe’s electricity supply is free from greenhouse gas emissions. By 2050, more than 80 % of electricity will be coming from renewable energy sources (increasingly located off-shore). Together with a nuclear power share of ca. 15 %, this will be the backbone of a carbon-free European power system.” European Commission, A Clean Planet for All, 2018, COM(2018) 773 final

[40] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law), COM/2020/80 final (the “EU Climate Law”), available at https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588581905912&uri=CELEX:52020PC0080 Note that the term “Law” is strange, as the EU Treaty does not contemplate any “Law.” Article 288 of the Treaty on European Union provides that “[t]o exercise the Union’s competences, the institutions shall adopt regulations, directives, decisions, recommendations and opinions.” There is no reference to a “Law.”.

[41] Recitals 3 and 8, EU Climate Law.

[42] Recital 15, EU Climate Law. Cf. Article 3(3), which requires that the Commission, when setting a trajectory to transition towards climate neutrality, must consider “(a) cost-effectiveness and economic efficiency; (b) competitiveness of the Union’s economy; (c) best available technology; (d) energy efficiency, energy affordability and security of supply; (h) the need to ensure a just and socially fair transition; [and] (i)international developments and efforts undertaken to achieve the long-term objectives of the Paris Agreement and the ultimate objective of the United Nations Framework Convention on Climate Change.”

The proposed EU Climate Law requires that the transition to climate neutrality be fair and cost-effective, as well as cost-efficient, and contributes to prosperity, competitiveness, energy security, energy affordability, and technological neutrality. How the Climate Law would ensure that these conditions are met, is unclear.

Progress towards climate neutrality would be assessed every five years, in line with the 'global stocktake' exercise under the Paris Agreement. The proposed Climate Law, which references the EU's renewable energy initiatives,[43] is pending before the EU legislature under the ordinary legislative procedure.[44]

The Electricity Mix

Indeed, renewable energy has been a key element of the EU's climate policy, but it is not entirely uncontroversial. Renewable energy sources include wind electricity, solar electricity and biomass.[45] All three of these sources of energy utilize natural phenomena as energy, and two of them do not emit CO_2 during operation, but all three have drawbacks that affect their cost/benefit-ratio and, in some cases, limit their deployment.[46]

Although the Commission foresaw a 15 % nuclear electricity share in the total energy mix in its 2018 "A Clean Planet for All" communication, it did not address nuclear electricity in *The Green Deal*. Due to its high power density, nuclear power may offer advantages over renewable electricity as far as land usage requirements are concerned. The cost of electricity production, however, is also a main concern and "energy poverty" has become a concern of European policy makers (see further below). An evidence-based comparison of the land/space demand and cost of wind/solar and nuclear, which, as noted, has not yet been released by the EU, would aid policy makers.

c. EU Energy Policy

In addition to the EU climate policy, its energy policy shapes the transition to a carbon-neutral economy by 2050.

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[43] "The Union has, through the 'Clean Energy for All Europeans' package been pursuing an ambitious decarbonisation agenda notably by constructing a robust Energy Union, which includes 2030 goals for energy efficiency and deployment of renewable energy in Directives 2012/27/EU 30 and (EU) 2018/2001 31 of the European Parliament and of the Council, and by reinforcing relevant legislation, including Directive 2010/31/EU of the European Parliament and of the Council." Recital 9, EU Climate Law.

[44] The European Parliament's legal service has opined that the proposed delegation of powers to the European Commission under the Climate Law would be unlawful under the Treaty. See Non-paper on the choice of delegated acts to set out the trajectory for achieving climate neutrality in the proposal for a European Climate Law [2020/0036(COD)], 31 March 2020, available at https://www.politico.eu/wp-content/uploads/2020/04/Climate-law-paper-NON_PAPER.pdf?utm_source=POLITICO.EU&utm The Council's legal service has taken the same position.

[45] The official definition set forth in Article 2(1) of Directive 2018/2001 defines renewable energy as "energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas."

[46] Part 8 discusses the impacts of the various power generation technologies at issue in this study.

The Treaty on the Functioning of the EU defines the powers of the EU in relation to energy policy.[47] It also defines the powers that are reserved to the Member States, where it states that measures adopted by the EU legislature "shall not affect a Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply,"[48] except if measures are adopted unanimously, in which case they may "significantly affect a Member State's choice between different energy sources and the general structure of its energy supply."[49] Thus, EU measures that restrict the Member States' right to choose between energy sources and to structure the energy supply require unanimity.[50]

Under the heading of the 'Energy Union,' the EU is pursuing integration of the member states' energy markets, and policies to ensure energy security of supply, improve energy efficiency, and decarbonise the economy.[51] Through the Energy Union program, the EU attempts to ensure greater coherence in all policy areas to achieve a "***reliable, affordable and sustainable*** energy system"[52] *(emphasis supplied).*

Objectives

More specifically, the Energy Union is aimed at five objectives:

i. *integration of the EU internal energy market* (i.e. enabling energy to be transmitted throughout the EU through transmission and other infrastructure and without technical or regulatory barriers);

ii. *diversification of sources of energy* and ensuring *energy security*;

iii. *improving energy efficiency* to reduce energy consumption and lower emissions;

The Energy Union is aimed at diversification of sources of energy, ensuring energy security, improving energy efficiency, and ensuring energy affordability.

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[47] Article 194(1) TFEU provides as follows: "In the context of the establishment and functioning of the internal market and with regard for the need to preserve and improve the environment, Union policy on energy shall aim, in a spirit of solidarity between Member States, to: (a) ensure the functioning of the energy market; (b) ensure security of energy supply in the Union; (c) promote energy efficiency and energy saving and the development of new and renewable forms of energy; and (d) promote the interconnection of energy networks.

[48] Article 194(2), TFEU.

[49] Article 192(2)(c), TFEU.

[50] There is a legal issue as to whether all EU energy legislation meets this Treaty requirement, which is not further discussed here.

[51] "The energy union strategy …, a key priority of the Juncker Commission (2014-2019), aims at building an energy union that gives EU consumers - households and businesses - secure, sustainable, competitive and affordable energy." COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy, Brussels, 25.2.2015, COM/2015/080 final, available at https://eur-lex.europa.eu/resource.html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0001.03/DOC_1&format=PDF European Commission, ENERGY UNION PACKAGE: COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL, The Paris Protocol – A blueprint for tackling global climate change beyond 2020, Brussels, 25.2.2015, COM(2015) 81 final, SWD(2015) 17 final.

[52] European Union, Energy, available at https://europa.eu/european-union/topics/energy_en

iv. *decarbonization* of the energy system and broader economy; and

v. financial support for R&D into *low-carbon and clean energy* technologies to drive the energy transition.[53]

By its own terms, the 2019 EU Electricity Regulation, sets "the basis for an efficient achievement of the objectives of the Energy Union and in particular the climate and energy framework for 2030 by enabling market signals to be delivered for increased efficiency, higher share of renewable energy sources, security of supply, flexibility, sustainability, decarbonisation and innovation."

To ensure policy coherence, the EU attempts to coordinate energy policy also with other policies. Climate policy, of course, is an area that closely relates to energy policy. As noted above, one of the objectives of the EU's energy policy is to decarbonize the energy system. The EU electricity market legislation is also aimed at facilitating the objectives of the Green Deal by enabling further electrification of the energy system.[54] Conversely, the EU climate policy also refers back to the EU energy policy. In the 'Green Deal' Communication, for instance, the European Commission recognizes the importance of energy security and competitiveness.[55]

Energy security

Energy security, i.e. security of energy supply and delivery, is a key element of the EU energy policy. The shift toward renewable energy creates additional challenges for energy security, however. As the European Commission explains, "[a] key role is to encourage cross-border cooperation and interconnections to make energy flow more smoothly across the whole of the EU. When there is no sun or wind to produce electricity, it is key for an EU country to be able to rely on imports of electricity produced in a neighbouring EU country."[56] Of course, if there is significant statistical dependence between wind and solar strength in two neighboring countries, import will not be of much help in securing adequate supply.

In any event, expansion of cross-border transmission is a key element of the EU's electricity market policy. In order for that to work, the neighbouring EU Members States to which the Commission refers, should be able to deliver electricity to its neighbour at that time, which may be challenging if that country also overrelies on variable renewable electricity.[57] Needless to say, the expansion of the transeuropean transport infrastructure will involve substantial costs.[58]

Capacity mechanisms

In addition to increased cross-border transmission, to address the issue of the electricity supply becoming unreliable with the advance of renewable electricity,

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[53] European Commission, Energy union, available at https://ec.europa.eu/energy/topics/energy-strategy/energy-union_en?redir=1

[54] As the European Commission puts it, the EU electricity legislation contributes to "the EU's goal of being the world leader in energy production from renewable energy sources by allowing more flexibility to accommodate an increasing share of renewable energy in the grid. The shift to renewables and increased electrification is crucial to achieve carbon neutrality by 2050." European Commission, Electricity market design, https://ec.europa.eu/energy/topics/markets-and-consumers/market-legislation/electricity-market-design_ro#the-electricity-directive-and-electricity-regulation

[55] European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, The European Green Deal, Brussels, 11.12.2019, COM/2019/640 final ("[The EU] recognizes the need to maintain its security of supply and competitiveness …"

[56] European Commission, In focus: Energy Security in the EU, https://ec.europa.eu/info/news/focus-energy-security-eu-2020-avr-27_en

[57] The European Commission does not address this issue explicitly, but seems to suggest that energy storage could be a solution too.

[58] In addition to costs, there will be delays. This study does not address these issues.

Capacity payments distort markets and price signals, and add to the total costs of the power system. These payments help to alleviate the risks posed by an electricity market characterized by increasing penetration levels of variable renewable energy.

the EU uses several policy instruments aimed at maintaining a functioning electricity market with high penetration of variable renewable energy. An important instrument is the system of so-called '***capacity mechanisms***,' i.e., payments made to power plants to be available for generating electricity when needed, not for electricity generated. These mechanisms are highly relevant to an electricity system dominated by renewable energy. Recent EU electricity legislation[59] revised the eligibility criteria for power plants in order to be eligible for subsidies[60] for capacity mechanisms by imposing a maximum CO_2 emission limit.

Capacity payments can help to alleviate the risks posed by an electricity market characterized by increasing penetration levels of variable renewable energy.[61] These kinds of payments, however, are also bound to create inefficiencies by distorting markets and price signals,[62] and add to the total cost of the electricity system. To limit these adverse effects, the EU has put in place an EU-wide assessment process for such mechanisms.[63]

Demand response

To facilitate the transition to renewable electricity, member states may also use "demand response" measures, defined as "the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments."[64] For instance, to accommodate the intermittency of renewable electricity, member states may use financial incentives

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[59] Directive 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, pp. 125–199. Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, OJ L 158, 14.6.2019, pp. 54–124.

[60] Subsidies to generation capacity emitting 550gr CO_2/kWh or more are to be phased out.

[61] Bhagwat, Pradyumna C ; Marcheselli, Anna ; Richstein, Jörn C ; Chappin, Emile J.L ; De Vries, Laurens J, An analysis of a forward capacity market with long-term contracts, Energy policy, 2017, Vol. 111, pp. 255-267 ("Capacity markets can compensate for the deteriorating incentive to invest in controllable power plants when the share of variable renewable energy sources grows.")

[62] Article 3 of the Electricity Regulation provides that "prices shall be formed on the basis of demand and supply; market rules shall encourage free price formation and shall avoid actions which prevent price formation on the basis of demand and supply; [and] market rules shall facilitate the development of more flexible generation, sustainable low carbon generation, and more flexible demand." Article 3, Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, OJ L 158, 14.6.2019, p. 54–124

[63] This assessment should be based on the latest calculation of future supply-demand scenarios, and take into account the availability of renewable energy sources, demand side flexibility and cross-border infrastructure in times of system stress. Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, OJ L 158, 14.6.2019, pp. 54–124.

[64] Article 2, under 20, Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, p. 125–199.

(including selling electricity at a negative price) for consumers to use electricity when the sun shines or the wind blows, or disincentives (higher prices) when there is not enough electricity to meet all demand. These price fluctuations may pose challenges for some consumers, and adversely affect energy affordability.

In addition, demand response, in a broad sense, can also be utilized to help ***balance the grid***. For instance, when there is excessive production of wind and solar electricity, this electricity could be stored in the batteries of electric cars; consumers could be given incentives to permit this or even be required by law to permit it. Conversely, as a last resort, in times of low electricity production, consumers could be subject to power rationing or be cut off from the grid, with or without their permission.[65]

To fully implement these policies, the existing electricity grid will have to be reshaped. Although such a new "smart grid" is technically feasible, it will probably entail very substantial cost, which will have to be borne by consumers or tax payers. If governments choose to spare industrial consumers so as to maintain their competitiveness on global markets, the cost burden will have to be carried by households and other small consumers. As a result, the issue of energy poverty may become more acute and necessitate other support measures.

Energy independence

Energy dependence is viewed as a threat to the security of the energy supply. One author has called it "the biggest threat" and "the toughest challenge of all."[66] During the last couple of decades, energy dependence has typically been debated as an issue of dependence on Russian gas imports. The main sources of gas for the EU as a whole are imported LNG and Russian pipeline gas; these two will remain the two main sources of gas up to 2030. There will only be limited quantities of non-Russian pipeline available for the EU before 2025.[67] Nevertheless, the European Union has worked to expand gas interconnections to enable a more fluid and dynamic gas market.

EU energy independence can be enhanced by moving away from imports of fossil fuels, and increasing domestic production of fuels and electricity. The latter can be achieved by adding wind, solar, and nuclear capacity. Domestically produced biofuels can help to reduce the dependence on fossil fuels in transportation. In theory, nuclear electricity can also be used to produce hydrogen, when the demand for electricity is low (e.g. during night time).[68]
The EU's energy independence ambition, however, needs to be balanced against other objectives, such as diversification, affordability, and security.

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[65] In the UK, the concern is that consumers could be cut off without their consent: "The revelation that smart meters could allow energy networks to switch off central heating systems has sparked a debate on whether Britain's use of the appliances should be reviewed." 'They're a scam, we should follow the Swiss model', Telegraph, 21 September 2020, available at https://www.telegraph.co.uk/news/2020/09/21/scam-should-follow-swiss-model-telegraph-readers-smart-meters/

[66] Vladimir Urutchev, Energy Dependence: The EU's Greatest Energy Security Challenge?, European View (2014) 13:287–294, available at https://doi.org/10.1007/s12290-014-0319-1

[67] European Parliament, Policy Department A for the Committee on Industry, Research and Energy (ITRE), EU Energy Independence, Security of Supply and Diversification of Sources, Proceedings of a workshop, Brussels, 6 February 2017, IP/A/ITRE/2016-07, available at https://www.europarl.europa.eu/RegData/etudes/STUD/2017/595367/IPOL_STU(2017)595367_EN.pdf#:~:

[68] See, however, Samuel Furfari, The Hydrogen Illusion, September 2020 (arguing that "the use of hydrogen to store and then produce electricity, but also as a fuel, will not happen for obvious economic and safety reasons" and that "this illusion is, above all, a mistake used to cover up a previous mistake on intermittent renewable energies").

Technology neutrality

Although it has not been articulated as an overarching principle, technology neutrality has also shaped EU energy policy. This concept allowed EU member states to pursue different energy technologies within their territories, with countries such as France investing in nuclear power, and Eastern European countries investing in coal-fired power plants.[69]

With the drive towards decarbonization of the energy system, fossil fuel-fired power plants (without carbon capture, removal, or storage facilities) will have to be phased out in the EU. All carbon-neutral energy options, however, are open to the EU member states, although, as discussed below, renewable energy receives preferential treatment. Nevertheless, technology neutrality is still an important element of EU policies. As the Commission's Green Deal communication puts it:

> *"At the same time, the EU's energy supply needs to be secure and affordable for consumers and businesses. For this to happen, it is essential to ensure that the European energy market is fully integrated, interconnected and digitalised, while* ***respecting technological neutrality****."*

Indeed, technological neutrality is critically important to ensure that all carbon neutral technologies can compete on their own merits. In this respect, the Renewable Energy Directive, which excludes nuclear energy, raises questions.[70]

Reliability and risk

Reliability and resilience, of course, are also important objectives of the European electricity system. Reliability is essential for the entire system, from electricity generation and the transmission system to cross-border interconnections and the local grid.

Reliability requires, among other things, that operators are ready to address risks when they arise. The EU has realized that risk preparedness has become essential in an electricity market dominated by renewable electricity. In 2019, the Regulation on risk preparedness in the electricity sector was adopted.71 Under the Regulation, Member States are required to prepare plans for how to deal with potential future electricity crises, and put the appropriate tools in place to prevent, prepare for and manage these situations.72 These assessments must address seasonal and short-term adequacy, and cover, inter alia, "*variability of production of energy from renewable sources*" and "*the probability of the occurrence of an electricity crisis.*"

Energy Poverty

Energy poverty, of course, is closely related to energy affordability.[73] The EU made the ***prevention of energy***

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[69] As the Australian government stated in 2015 Energy White Paper, a 'technology-neutral policy and regulatory framework support[s] new energy sources and enable change, innovation and transformative technologies." Energy White Paper maps Australia's powerful future, 8 April 2015, available at https://www.minister.industry.gov.au/ministers/macfarlane/media-releases/energy-white-paper-maps-australias-powerful-future

[70] Current EU climate policy is not technology-neutral, because it favors renewable energy. There is nothing inherent to climate policy, however, that requires any such technology bias; policy could merely stipulate performance requirements.

[71] Regulation (EU) 2019/941 of the European Parliament and of the Council of 5 June 2019 on risk-preparedness in the electricity sector and repealing Directive 2005/89/EC, OJ L 158, 14.6.2019, pp. 1–21.

[72] Article 8 of Regulation 2019/941 requires that a methodology for short-term and seasonal adequacy assessments be adopted.

[73] A 2019 poll shows that 89 % of EU citizens agree that the EU must ensure access to affordable energy, such as ensuring competitive market prices, in particular to reduce the number of people unable to pay their energy bills. Special Eurobarometer 492 2019, available at https://op.europa.eu/en/publication-detail/-/publication/b891cfb7-d50f-11e9-b4bf-01aa75ed71a1/language-en?WT.mc_id=Searchresult&WT.ria_c=37085&WT.ria_f=3608&WT.ria_ev=search

poverty a policy priority in the 2019 'Clean Energy for all Europeans' package.[74] Energy poverty is defined with reference to adequate warmth, cooling, lighting and the energy to electricity appliances, which are regarded as essential services. The EU established an Energy Poverty Observatory to alleviate this issue.[75]

Pursuant to the Regulation on the governance of the energy union and climate action (EU/2018/1999), the Member States were required to submit National Energy and Climate Plans (NECPs) to the European Commission by the end of 2019. In addition to topics such as policies regarding energy efficiency, renewables, greenhouse gas emissions reductions, interconnections, and research and innovation, these plans are also to address energy poverty, including specific national objectives on energy poverty. The Czech NECP notes that energy poverty has been decreasing since 2005, and is lower than the EU average.[76] According to the Dutch NECP, "[a]lthough there is no specific policy in the field of energy poverty, there is a scheme that prevents people who cannot pay their energy bill (or pay it on time) from being disconnected."[77] These NECPs do not discuss whether, and, if so, to what extent, increasing the share of renewable energy sources in the electricity mix affects energy poverty.

Nuclear energy

Despite the fact that nuclear energy can be traced back to the origins of the EU,[78] the EU legislation on the electricity markets tolerates nuclear energy, but does not deal with it specifically. It only refers to nuclear in passing and in connection with fossil fuel power plant, where it refers to the past:

> *"Historically, the electricity system was dominated by vertically integrated, often publicly owned, monopolies with **large centralised nuclear or fossil fuel power plants**. The internal market for electricity, which has been progressively implemented since 1999, aims to deliver a real choice for all consumers in the Union new business opportunities and more cross-border trade, so as to achieve efficiency gains, competitive prices and higher standards of service, and to contribute to security of supply and sustainability."*[79]

d. EU Renewable Energy Policy

In the context of this study, an important piece of EU legislation is the 2009 Renewable Energy Directive (RED-I).[80] RED-I sets rules for the EU to achieve 20 % renewable energy by 2020 – by the end of this year, the EU as a whole must meet at least 20 % of its total energy needs with renewable energy by 2020. This EU-wide target has been achieved through the

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[74] European Commission, Clean Energy for all Europeans package, March 2019, available at https://op.europa.eu/en/publication-detail/-/publication/b4e46873-7528-11e9-9f05-01aa75ed71a1/language-en/format-PDF/source-164711015

[75] European Energy Poverty Observatory, available at https://www.energypoverty.eu/about/what-energy-poverty

[76] "The share of households that could not maintain sufficient thermal comfort decreased from 11 % in 2005 to 5 % in 2016 and the number of households with energy bill arrears fell from 5 % in 2005 to 2 % in 2016." Czech Republic, National Energy and Climate Plan 2021-2030, Nov. 2019, available at https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en#final-necps

[77] The Netherlands, National Energy and Climate Plan 2021-2030, Nov. 2019, available at https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en#final-necps

[78] Euratom is the European Atomic Energy Community. It was established in 1958 by the Treaty establishing the European Atomic Energy Community, which was one of the Treaties of Rome. Euratom was intended to create a common market for the development of the peaceful uses of atomic energy. Initially, this common market was limited to Belgium, France, West Germany, Italy, Luxembourg, and The Netherlands. Afterwards, Euratom was expanded to include all EU Member States; its powers have also been expanded over time. As with the other treaties, the European Commission is the guardian of the Euratom Treaty.

[79] Recital 2, Electricity Regulation.

[80] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, OJ L 140, 5.6.2009, p. 16–62.

The Renewable Energy Directive is intended to (i) provide long-term certainty for investors, (ii) speed up permitting procedures for renewable energy projects, (iii) increase market integration of renewable electricity, and (iv) accelerate the uptake of renewables in the heating/cooling and transport sectors.

attainment of individual national targets, which vary between member states as a function of their economic capabilities and their renewable energy potential. EU member states are also required to ensure that at least 10 % of their transport fuels come from renewable sources by 2020.

Following the Paris Agreement on Climate Change and as part of the 'Clean Energy for All Europeans' package, in December 2018, a revised Renewable Energy Directive (RED-II) entered into force.[81] RED-II sets a new binding renewable energy target for the EU for 2030 of at least 32 %, with a clause for a possible upwards revision by 2023.[82] It also imposes an increased 14 % target for the share of renewable fuels in transport by 2030, while amending the criteria for bioenergy sustainability so as to limit in particular the use of first generation biofuels. Pursuant to the Regulation on the Governance of the Energy Union and Climate Action,[83] the member states must submit a 10-year integrated national energy and climate plan (NECP) for 2021-2030 demonstrating how they will meet the new 2030 targets for renewable energy and for energy efficiency. The member states must transpose RED-II into national law by 30 June 2021.

Under RED-II, the EU framework for renewable energy pursues economic and financial policy objectives aimed at promoting renewable energy. The new framework is intended to (i) provide long-term certainty for investors, (ii) speed up permitting procedures for renewable energy projects, (iii) increase market integration of renewable electricity, and (iv) accelerate the uptake of renewables in the heating/cooling and transport sectors, and (v) encourage consumers to produce and consume their own renewable energy ("self-consumption") and to act jointly through "renewable energy communities."[84]

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[81] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ L 328, 21.12.2018, p. 82–209 ("RED-II").

[82] The Commission has initiated the revision process. EU renewable energy rules – review, https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12553-Revision-of-the-Renewable-Energy-Directive-EU-2018-2001

[83] Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council, OJ L 328, 21.12.2018, p. 1–77.

[84] RED-II. See also European Commission, Fact sheet The Revised Renewable Energy Directive, available at https://ec.europa.eu/energy/sites/ener/files/documents/directive_renewable_factsheet.pdf

By way of example, RED-II promotes renewable energy in the following ways:

- *Renewable support schemes* – To reach or exceed the renewable target, a member state may apply support schemes. Support schemes for electricity from renewable sources must provide incentives for and maximize the integration of electricity from renewable sources in the electricity market. Direct price support is to be granted in the form of a market premium.[85] The level of, and the conditions attached to, the support granted to renewable energy projects may not be revised in a way that negatively affects the rights conferred thereunder and undermines the economic viability of projects that already benefit from support; the level of support may be adjusted only in accordance with objective criteria set forth in the original design of the support scheme.[86]

- *Administrative procedures* – National rules regarding the authorization, certification and licensing procedures that are applied to renewable energy projects must be objective, transparent, proportionate and necessary. Administrative procedures are to be streamlined and expedited; predictable timeframes must be established. The particularities of individual renewable energy technologies are to be taken into account.[87] At the volition of applicants, a dedicated national contact person must provide guidance and facilitate the entire administrative permit application and granting process.[88]

It should be noted that RED-II defines "energy from renewable sources" as ''energy from renewable sources' or 'renewable energy', which means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas.[89] This definition, of course, does not cover nuclear electricity. Consequently, nuclear electricity projects do not benefit from the national support schemes and simplified and expedited administrative procedures.

While RED-I imposed an obligation on each Member State to reach an individualized target, RED-II works differently. RED-II imposes only an EU-wide obligation. Under other EU legislation, Member States are required to submit national energy and climate plans (NECPs) for 2021-2030, outlining how they will meet the new 2030 targets for renewable energy and for energy efficiency.[90]

e. EU Sustainable Finance Initiatives

Since financing plays a pivotal role in energy markets, the EU's initiatives on sustainable finance deserve attention. In March 2018, the European Commission adopted an Action Plan on financing sustainable growth.[91] This Action Plan is aimed at (i) reorienting capital flows towards sustainable investment in order to achieve sustainable and inclusive growth; (ii) manage financial risks stemming from climate change, resource depletion, environmental degradation and

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[85] Articles 4(1), 4(2) and 4(3), RED-II.

[86] Articles 6(1) and 6(2), RED-II.

[87] Article 15(1), RED-II.

[88] Article 16(1), RED-II.

[89] Article 2(1), RED-II.

[90] Regulation on the Governance of the Energy Union and Climate Action (EU) 2018/1999, OJ L 328, 21.12.2018, p. 1–77.

[91] COMMUNICATION FROM THE COMMISSION, Action Plan: Financing Sustainable Growth, COM/2018/097 final.

The Renewable Energy Directive defines "energy from renewable sources" as energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas."

This definition does not cover nuclear power, although nuclear energy is also decarbonized.

social issues; and (iii) foster transparency and long-termism in financial and economic activity.

In these three areas, the Action Plan sets out ten key actions, such as an EU taxonomy, i.e. a classification system for sustainable activities, creating an EU Green Bond Standard and labels for green financial products. In June 2020, the Taxonomy Regulation was published.[92] An economic activity qualifies as environmentally sustainable if it:

a. contributes substantially to one or more of the environmental objectives (climate change mitigation, climate change adaptation, the sustainable use and protection of water and marine resources, the transition to a circular economy, pollution prevention and control, the protection and restoration of biodiversity and ecosystems[93]);

b. does not significantly harm any of the environmental objectives;

c. is carried out in compliance with the minimum safeguards; and

d. complies with technical screening criteria established by the Commission.[94]

Under the Taxonomy Regulation, an economic activity qualifies as "contributing substantially to climate change mitigation where that activity contributes substantially to the stabilisation of greenhouse gas concentrations in the atmosphere at a level which prevents dangerous anthropogenic interference with the climate system consistent with the long-term temperature goal of the Paris Agreement through the avoidance or reduction of greenhouse gas emissions or the increase of greenhouse gas removals, including through process innovations or product innovations, by: (a) generating, transmitting,

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[92] Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088, OJ L 198, 22.6.2020, p. 13–43. As the Commission explains, "the EU sustainable finance taxonomy will guide investment in these activities to ensure they are in line with our long-term ambitions." European Commission, Communication, "Powering a climate-neutral economy: An EU Strategy for Energy System Integration", COM(2020) 299 final, Brussels, 8.7.2020, available at https://ec.europa.eu/energy/sites/ener/files/energy_system_integration_strategy_.pdf

[93] Article 9, Taxonomy Regulation.

[94] Article 3, Taxonomy Regulation.

storing, distributing or using renewable energy in line with Directive (EU) 2018/2001, including through using innovative technology with a potential for significant future savings or through necessary reinforcement or extension of the grid; … [or] (h) producing clean and efficient fuels from renewable or carbon-neutral sources."[95]

In the legislative process leading to the adoption of the Taxonomy Regulation, there has been much debate about nuclear electricity. The EU Technical Expert Group on Sustainable Finance addressed nuclear electricity in the Technical Annex[96] to its report.[97] Based on the '*do no harm*' requirement, nuclear opponents argued that it should not be included in the EU's sustainable finance program.[98] The regulation as adopted, however, leaves open whether nuclear electricity could qualify.[99] In this debate, the key issue appears to be whether nuclear waste can be managed without significant impact to the environment. According to the EU Technical Expert Group (TEG), "nuclear energy generation has near to zero greenhouse gas emissions in the energy generation phase and can be a contributor to climate mitigation objectives."[100] As the TEG found that "the evidence about nuclear energy is complex and more difficult to evaluate in a taxonomy context, … it was not possible for TEG, nor its members, to conclude that the nuclear energy value chain does not cause significant harm to other environmental objectives on the time scales in question. The TEG has therefore not recommended the inclusion of nuclear energy in the Taxonomy at this stage."

In a June 2020 FAQs document, the European Commission states that "[w]hile nuclear energy is generally acknowledged as a low-carbon energy source, opinions differ notably on the potential environmental impacts of nuclear waste."[101] To reach a decision on this issue, the Commission wants a "scientifically rigorous, transparent" assessment, based on a "balanced set of views" and reflecting "the principle of technological neutrality." The Commission has decided to request the Joint Research Centre for a technical report on the 'no significant harm' aspects of nuclear energy. This report will be the basis for further review and decision-making.[102] The JRC is expected to submit its opinion in the course of 2021.[103]

In the context of sustainable finance, attention should also be paid to the European Commission's Guidelines

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[95] Article 10(1), Taxonomy Regulation.

[96] Technical Annex: Taxonomy, Final report of the Technical Expert Group on Sustainable Finance, March 2020, available at https://ec.europa.eu/info/sites/info/files/business_economy_euro/banking_and_finance/documents/200309-sustainable-finance-teg-final-report-taxonomy-annexes_en.pdf

[97] Taxonomy: Final report of the Technical Expert Group on Sustainable Finance, March 2020, available at https://ec.europa.eu/info/sites/info/files/business_economy_euro/banking_and_finance/documents/200309-sustainable-finance-teg-final-report-taxonomy_en.pdf

[98] Frédéric Simon, 'Do no harm': Nuclear squeezed out of EU green finance scheme, EURACTIV, 06-12-2019, available at https://www.euractiv.com/section/energy-environment/news/do-no-harm-nuclear-squeezed-out-of-eu-green-finance-scheme/

[99] EU Taxonomy leaves low-carbon nuclear 'in limbo', admits climate adviser, World Nuclear News, 03 August 2020, available at https://www.world-nuclear-news.org/Articles/EU-Taxonomy-leaves-low-carbon-nuclear-in-limbo-adm

[100] Technical Annex: Taxonomy, pp. 210-211.

[101] European Commission, FREQUENTLY ASKED QUESTIONS about the work of the European Commission and the Technical Expert Group on Sustainable Finance on EU TAXONOMY & EU GREEN BOND STANDARD, June 2020, available at https://ec.europa.eu/info/sites/info/files/business_economy_euro/banking_and_finance/documents/200610-sustainable-finance-teg-taxonomy-green-bond-standard-faq_en.pdf

[102] "The JRC's report will be reviewed by experts on radiation protection and waste management under Article 31 of the Euratom Treaty, as well as by experts on environmental impacts from an equivalent Commission environmental group or committee." FAQs Taxonomy, p. 13.

[103] JRC to assess nuclear's inclusion in EU Taxonomy, World Nuclear News, 06 July 2020, available at https://www.world-nuclear-news.org/Articles/JRC-to-assess-nuclears-inclusion-in-EU-Taxonomy

The European Commission states that "while nuclear energy is generally acknowledged as a low-carbon energy source, opinions differ notably on the potential environmental impacts of nuclear waste."

The Joint Research Centre is preparing a technical report on the 'no significant harm' aspects of nuclear energy.

on State aid for environmental protection and energy 2014-2020.[104] These guidelines will soon have to be reissued, as they expire. Various types of aid relevant to the subject matter of this study are covered by the Guidelines, including (1) aid for energy from renewable sources; (ii) aid for energy efficiency measures, including cogeneration and district heating and district cooling; (iii) aid in the form of reductions in funding support for electricity from renewable sources; (iv) aid for energy infrastructure; and (v) aid for generation adequacy measures. There is no reference to nuclear energy.

The objective of environmental aid is stated to be "to increase the level of environmental protection compared to the level that would be achieved in the absence of the aid." The Guidelines note that "[a] low carbon economy with a significant share of variable energy from renewable sources requires an adjustment of the energy system and in particular considerable investments in energy networks." The primary objective of aid in the energy sector, therefore, is "to ensure a competitive, sustainable and secure energy system in a well-functioning Union energy market." Given the different stage of technological development of renewable energy technologies, the Guidelines permit technology specific tenders "on the basis of the longe term potential of a given new and innovative technology, the need to achieve diversification; network constraints and grid stability and system (integration) costs."

Because the full cost of carbon may not yet be internalized, the Commission assumes that a market failure persists and will permit state aid for renewable energy that contributes to "the achievement of the related, but distinct, Union objectives for renewable energy." The Guidelines define 'renewable energy sources' as "renewable non-fossil energy sources: wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases." Nuclear energy does not fall under this definition.

Under the Guidelines, for instance, state aid in the form of operating aid for the production of renewable electricity and/or combined production of renewable heat, is permissible under conditions. Tax

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[104] COMMUNICATION FROM THE COMMISSION, Guidelines on State aid for environmental protection and energy 2014-2020, 2014/C 200/01, 28.6.2014, OJ C 200/1.

The Commission will permit state aid for renewable energy that contributes to the achievement of the EU objectives for renewable energy. Under the Guidelines, state aid in the form of operating aid for the production of renewable electricity, is permissible under conditions. Tax exemptions, reductions from environmental taxes and exemptions from charges for the financing of energy from renewable sources do not have to be notified individually.

Thus, while the Guidelines clear the way for renewable support programs, the situation for nuclear energy remains opaque.

exemptions, reductions from environmental taxes and exemptions from charges for the financing of energy from renewable sources do not have to be notified individually. Thus, while the Guidelines clear the way for renewable support programs, the situation for nuclear energy remains opaque.

f. EU Nuclear Electricity Regulation

The EU, more specifically, ***Euratom***,[105] ***has extensively regulated nuclear electricity***. These regulations address (i) ***nuclear safety***, (ii) ***nuclear waste management***, (iii) ***radiation protection***, (iv) decommissioning of nuclear facilities, and (v) misuse protection. In addition, nuclear-related activities are covered by general regulations aimed at protecting the environment, public safety, occupational health, etc. There are also international treaties that impose ***strict liability on operators of nuclear facilities*** for damages resulting from nuclear accidents.[106] These treaties require that nuclear operators contract insurance (or present other financial security) to cover these liabilities.[107]

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[105] Euratom, or the European Atomic Energy Community, "regulates the European civil nuclear industry, which produces almost 30 % of energy in the EU. Euratom's work safeguards nuclear materials and technology, facilitates investment, research and development, and ensures equal access to nuclear supplies, as well as the correct disposal of nuclear waste and the safety of operations. Its main instruments are the Euratom Supply Agency, and its research and nuclear safeguard activities. Notably, Euratom is involved in developing atomic fusion technology which has the potential of delivering abundant sustainable energy in the future." European Parliament, European Atomic Energy Community (Euratom) – Structures and tools, Briefing, September 2017, available at https://www.europarl.europa.eu/RegData/etudes/BRIE/2017/608665/EPRS_BRI(2017)608665_EN.pdf

[106] Convention on Third Party Liability in the Field of Nuclear Energy of 29th July 1960, as amended by the Additional Protocol of 28th January 1964 and by the Protocol of 16th November 1982, available at https://www.oecd-nea.org/law/nlparis_conv.html

[107] Nuclear Energy Agency, Paris Convention on Nuclear Third Party Liability, available at https://www.oecd-nea.org/law/paris-convention.html

The ***EU Nuclear Safety Directive***[108] imposes "the highest standards of nuclear safety."[109] Nuclear safety involves both compliance with design and technical standards and management procedures. The directive requires that EU member states give the highest priority to nuclear safety at all stages of the lifecycle of a nuclear power plant, and that national regulatory authorities be independent and have sufficient staff and resources. ***Safety assessments*** are mandatory before the construction of new nuclear power plants; existing nuclear power plants must implement significant safety enhancements. A system of safety peer review has been established. At least once every 10 years, a ***safety re-evaluation*** of a nuclear power plant must be conducted.

Radioactive waste and spent fuel are also subject to regulation by the EU (Euratom). The management of any radioactive waste generated from the production of electricity in nuclear power plants is subject to the ***Radioactive Waste and Spent Fuel Management Directive***,[110] which requires that member states draw up and implement national programs for the safe management of these materials, including in the long-term. Responsible and safe management of spent fuel and radioactive waste is required to avoid imposing undue burdens on future generations. A ***high level of safety*** in spent fuel and radioactive waste management must be achieved to protect workers and the general public against the dangers arising from ionising radiation. A comprehensive and robust legal framework and a competent, independent regulatory body with sufficient resources, must be established. Every three years, member states are to submit to the Commission national reports on the implementation of the directive, and they must conduct self-assessments of their programs and invite international peer reviews of their national regulatory programs at least every ten years. Low level nuclear waste is managed safely is the EU.

Radiation protection regulation is intended to protect people from the dangers of ionising radiation. The EU regulatory framework establishes basic safety standards,[111] a prior authorization scheme for

Euratom has extensively regulated nuclear power.

These regulations address (i) nuclear safety, (ii) nuclear waste management, (iii) radiation protection, (iv) decommissioning of nuclear facilities, and (v) misuse protection.

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[108] Council Directive 2014/87/Euratom of 8 July 2014 amending Directive 2009/71/Euratom establishing a Community framework for the nuclear safety of nuclear installations, OJ L 219, 25.7.2014, p. 42–52.

[109] Recital 5, Nuclear Safety Directive.

[110] Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste, OJ L 199, 2.8.2011, p. 48–56.

[111] Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom, OJ L 13, 17.1.2014, p. 1–73.

The financial and regulatory incentives that the EU has created for renewable energy are withheld from nuclear power, while nuclear energy is subject to demanding EU and international regulations applying to the full life cycle of the plant, the fuel, and the spent fuel, from cradle to grave, and beyond.

The concept of technological neutrality, which the EU has endorsed, would appear to be inconsistent with prioritizing one carbon-neutral power generation technology over another one.

transport of radioactive waste,[112] and includes an emergency preparedness and response program. Before a member state permits the operation of a new nuclear plant, the Commission is to evaluate the potential health impact from the plant on the population of neighboring member states.[113]

Under the EU Directives on nuclear safety and on management of spent fuel and radioactive waste the ***decommissioning of nuclear power plants*** is a responsibility of member states. Each Member State must deal internally with its spent fuels. Finland, France and Sweden have selected sites for the deep geological disposal of intermediate and high level waste, which are due to open between 2024 and 2035.[114]

The decommissioning of a nuclear power plant must meet the ***highest safety standards***. It starts with the shutdown process, followed by the removal of nuclear material from the site, and the environmental restoration of the site. This process is complex and may take up to up to 30 years. The EU assists the Member States in addressing issues related to funding of nuclear decommissioning through a group of experts known as the Decommissioning Funding Group (DFG).[115]

g. Conclusions on Relevant EU Policies

This brief review of EU policies and regulations applying to renewable energy and nuclear energy suggests that this legislation is likely to have significant impacts on the ***relative competitiveness***

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[112] Council Directive 2006/117/Euratom of 20 November 2006 on the supervision and control of shipments of radioactive waste and spent fuel, OJ L 337, 5.12.2006, p. 21–32.

[113] COMMISSION RECOMMENDATION of 11 October 2010 on the application of Article 37 of the Euratom Treaty, OJ L 279/36, 23.10.2010.

[114] European Commission, Radioactive waste and spent fuel, https://ec.europa.eu/energy/topics/nuclear-energy/radioactive-waste-and-spent-fuel_en

[115] Commission Recommendation of 24 October 2006 on the management of financial resources for the decommissioning of nuclear installations, spent fuel and radioactive waste, OJ L 330, 28.11.2006, p. 31–35.

of these two electricity sources. The ***financial and regulatory incentives that the EU has created for renewable energy are withheld from nuclear power, while nuclear energy is subject to demanding EU and international regulations*** applying to the full life cycle of the plant, the fuel, and the spent fuel, from cradle to grave, and beyond.

In addition, the EU has set itself objectives to which nuclear electricity can contribute in significant ways. For instance, the EU fosters ***security of energy supply and energy affordability***, including the prevention of energy poverty. Nuclear energy is a source of abundant and secure energy, it is non-intermittent, and able to provide electricity when demanded. Energy independence, for one, may be greatly enhanced by nuclear energy. And, of course, nuclear energy can contribute to the EU's climate neutrality mission. The concept of ***technology neutrality***, which the EU has endorsed, would appear to be inconsistent with prioritizing one carbon-neutral electricity generation technology over another one.

Because the EU often omits to spell out in any detail how its specific initiatives contribute to the various objectives it has set for its climate, environmental and energy policies, it may not consistently make balanced policy decisions. The recent ***omission to include nuclear energy in the sustainable finance taxonomy*** illustrates this point – while renewable energy was deemed to qualify automatically without any meaningful assessment, nuclear energy was excluded without any sound, reliable assessment of its sustainability.

In the context of this study we merely note these ***discrepancies in policy and legislative treatment***. We have not attempted to detail and quantify the effects thereof on the competitiveness of the two technologies. On the basis of reports from the field, however, we believe that this is an issue that merits further analysis if the EU is serious about meeting the objectives of its climate, energy, environmental, and economic policies. It is in this space that this study can contribute to improving EU policy making going forward.

As noted above, the EU has paid surprisingly little attention to the issues of spatial requirements of electricity generation technologies and of the relative costs of such technologies.[116] The reason for this lack of attention is that the ***EU made a policy decision in favor of renewable energy without considering the relative pros and cons of all technologies***; once renewable electricity became a legal mandate, cost-benefit analysis of alternative options no longer was perceived as providing pertinent information. Likewise, although the EU pays ***lip service to cost-effectiveness, efficiency, and affordability***, it has not even attempted to come up with estimates of the cost of the energy transition necessary to achieve climate neutrality in 2050.

There is reason to believe that these issues (spatial requirements and relative costs) will feature more prominently on the EU agenda in the next decade. In this regard, it is interesting to note that citizens of The Netherlands believe that renewable electricity (wind turbines, solar) has a larger share than it actually has,[117] apparently because they either perceive the country to be already full of wind turbines or they

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[116] See, for instance, European Commission, IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773, A Clean Planet for all -- A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, Brussels, 28 November 2018, available at https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en

[117] Respondents thought that the share of wind energy was 16 % (actually, 2 %), of solar energy 17 % (actually, 1 %), and of bio-energy 12 % (actually, 5 %). NEDERLANDSE VERENIGING DUURZAME ENERGIE, NEDERLANDERS OVERSCHATTEN AANDEEL DUURZAME ENERGIE, 19 juli 2020, available at https://www.nvde.nl/nvdeblogs/nederlanders-overschatten-aandeel-duurzame-energie/

> The number of social conflicts related to wind power plants or solar energy plants is on an all-time high, but decarbonization of the power sector remains critical to achieving carbon neutrality. Energy affordability and the cost of electricity are more important than ever.
>
> The EU therefore cannot afford to continue to treat an important decarbonized power generation technology as a pariah.

expect renewable electricity to have greater efficiency than it actually has. Once people begin to understand the ***relative spatial requirements and efficiencies of alternative electricity generating technologies*** better, these issues are likely to become politically more salient. Clearly, both wind/solar and nuclear power are able to contribute towards the 2050 climate neutrality objective; ***the choice between the two therefore hinges on other factors***.

The two aspects of electricity generation covered by this study, spatial requirements and cost, are highly relevant to current policy debates for three reasons. First, in light of the conflicting demands made on land and space for a variety of purposes (residential use, industrial use, nature protection areas, recreational areas, sports, agriculture, forestry, fishery, transportation, infrastructure, etc.[118]), the ***issue of land use is regarded as increasingly critical*** by national and local governments;[119] and ***"the number of social conflicts related to wind power plants or solar energy plants is on an all-time high"***[120]. *(emphasis supplied)* . Second, since the electricity sector makes a substantial contribution to total EU carbon emissions, and the demand for electricity is bound to increase due to further electrification,[121] ***decarbonization of the electricity sector is critical to achieving carbon neutrality***;[122] not all technologies can contribute to this

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[118] Cf. Eurostat, Land use statistics, available at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Land_use_statistics

[119] "About 80 % of Europe's surface area is shaped by land use in cities, agriculture and forestry." European Environment Agency, Land use, available at https://www.eea.europa.eu/themes/landuse Siting of power plants is a particular sensitive issue.

[120] Bosch, Stephan ; Rathmann, Joachim ; Schwarz, Lucas, The Energy Transition between profitability, participation and acceptance – considering the interests of project developers, residents, and environmentalists, Advances in geosciences, 2019, Vol.49, pp. 19-29 ("In planning processes for Renewable Energy Technologies mostly economic approaches are chosen, but simultaneously the number of social conflicts related to wind power plants or solar energy plants is on an all-time high.")

[121] Electrification Strategy EU, available at https://electrificationstrategy.eu/#:~:text=The%20EU%20Electrification%20Strategy%20will%20be%20the%20key,decarbonise%20the%20transport%20and%20heating%20%26%20cooling%20sectors.

[122] European Environment Agency (EEA), CO_2 Intensity of Electricity Generation, available at https://www.eea.europa.eu/data-and-maps/data/co2-intensity-of-electricity-generation ("To date, power generation remains the largest GHG-emitting sector in Europe. Carbon dioxide (CO_2) is by far the most commonly-emitted GHG across the sector, being a product of combustion processes. An almost complete decarbonisation of the EU's electricity sector is needed in order to meet the EU's objective of becoming the first carbon-neutral continent by 2050. Electricity can play an increasing role in decarbonising energy use across a number of sectors, such as transport, industry and households.")

objective to the same extent.[123] Third, in light of the enormous cost incurred due to COVID-19 crisis and the electrification trend, ***energy affordability and the cost of electricity are more important than ever***.[124]

The importance of this study for EU policy making therefore can hardly be overstated. With the ambitious programs mapped out by the EU, spatial requirements and costs will become dominant considerations in the area of energy policy making at the European and national levels.

Given the findings presented in this report, the EU should redesign its policies so that the worst consequences of the current mandates are avoided. The EU must put climate and energy policy on a sustainable, 'no regrets' trajectory that does not cause massive adverse spatial and related impacts, respects Europe's landscapes and nature, and meets the people's need for secure, affordable electricity without attempting to change their lifestyle.

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[123] To determine the CO_2-emissions associated with a particular power generation technology, full life cycle analysis needs to be undertaken (from cradle to grave). See, e.g., Wolfram, Paul, Wiedmann, Thomas, Diesendorf, Mark, Carbon footprint scenarios for renewable electricity in Australia, Journal of Cleaner Production, 2016-06-15, Vol.124, pp. 236-245. ("In this paper, scenario-based hybrid Life-Cycle Assessment is applied to calculate the economy-wide carbon footprints of seven electricity generation technologies in scenarios with differing renewable electricity penetration. This work is the first to apply a full life-cycle approach to scenario analysis of electricity generation in Australia. The findings are at the higher end of previously reported carbon footprint intensity ranges and above median values.")

[124] Thomson, Harriet, Bouzarovski, Stefan, Snell, Carolyn, Rethinking the measurement of energy poverty in Europe: A critical analysis of indicators and data, London, England: SAGE Publications, Indoor + built environment, 2017, Vol.26 (7), pp. 879-901.

3

Research Questions, Scope, and Methodology

Research Questions, Scope, and Methodology

This part discusses the questions to be answered, and the methods we employ to answer those questions. It also provides some additional background and explanation. In Annex XI attached to this report, we point the reader to specific parts, sections, and pages of the report that address each of the research questions.

a. Background

Although the favorable effect on the climate is uncertain, the EU is committed to achieving climate neutrality by 2050. As part of this commitment, the EU will continue to promote renewable energy, specifically wind and solar energy. Wind and solar energy have known disadvantages, such as intermittency and the related necessity of back-up power, as well as environmental and health impacts. With the further deployment of wind and solar power as the EU moves toward climate neutrality, however, another disadvantage will become more acute – the demand for land and space.[125] It is to be expected that, increasingly, citizens in the member states will object to wind and solar projects.[126]

Given the limited availability of land and space, as the demands placed on land and space by wind and solar power increase, it is to be expected that other energy options will become more attractive. Energy technologies that use less land and space for the

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[125] Berenschot/Kalavasta, Klimaatneutrale energiescenario's 2050, Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, maart 2020, available at https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2020Z06737&did=2020D14346 Generation Energy, Ruimtelijke uitwerking Energiescenarios, maart 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/31/ruimtelijke-uitwerking-energiescenarios Kalavasta/Berenschot, Systeemeffecten van nucleaire centrales in Klimaatneutrale Energeiscenarios 2050, 9 maart 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-in-klimaatneutrale-energiescenarios-2050 For the related data sheets in English, see https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-in-klimaatneutrale-energiescenarios-2050

[126] See, for instance, Jess Shankleman and Lars Paulsson, As Wind Power Grows in Europe, So Does Resistance From Locals -- Communities object to new and bigger turbines, threatening efforts to reduce carbon emissions, Bloomberg Green, 19 June 2020, available at https://www.bloomberg.com/news/articles/2020-06-19/wind-power-and-turbines-are-facing-pushback-from-europe-s-locals See also 'As wind power grows in Europe, so does resistance from locals,' 19 June 2020, available at https://www.wind-watch.org/news/2020/06/19/as-wind-power-grows-in-europe-so-does-resistance-from-locals/

production of the same amount of energy, however, are also required to contribute to achieving climate neutrality. As land and space become scarcer and public opposition to the geographical footprint of wind and solar grows, nuclear power is an option that increasingly draws attention from policy makers. In addition to relative space requirements, relative costs also need to be taken into account for policy-making to achieve the EU's climate ambition and ensure a successful and affordable energy transition.

Thus, the objectives of this study are, in addition to quantifying the effect of EU climate neutrality, to develop a better, evidence-based understanding of the land and space requirements of wind/solar power and nuclear power, the cost of wind/solar power and nuclear power, and the factors that determine such cost. This study does not attempt to assess or quantify all costs and benefits of wind/solar and nuclear power; we do attempt to identify categories of impacts, externalities and costs, however, that are relevant to the choice between the power generation technologies at issue. Our study hence is narrow,[127] and broad at the same time, as the specific, detailed analysis of the space and financial requirements of wind/solar and nuclear are placed in the broader picture of the energy market.

b. Research Questions

This study examines the following questions. There are five main questions. Sub-questions and specifics for each question are identified below.

I. *What is the expected effect on global warming (i.e. average global atmospheric temperature) in 2050 and 2100 if the EU will achieve net zero greenhouse gas (GHG) emissions in 2050?*

a. This question is answered based on available studies/literature, and may involve a range. We include brief summaries of the findings.
b. We consider the effect of the assumption that the non-EU countries will comply with their INDCs pursuant to the Paris Climate Agreement, and will make proportional efforts in the period 2030-2050, and throughout the century. Other assumptions, unknown factors, and uncertainties are identified.
c. We consider the probability of the EU achieving zero GHG emissions by 2050 from several perspectives, including the concept of 'taking climate neutrality seriously.'
d. In answering these questions, we consider the EU and international policy contexts (including the Paris Agreement on Climate Change) within which the EU pursues its carbon neutrality objective. We pay attention to international climate-related obligations, and existing EU policies in the areas of climate and energy. Part 2 provides a summary of the key EU policies.
e. We provide a qualitative discussion of the issues relevant to answering this question, and the context within which carbon emission reductions are pursued, while reflect on the uncertainties inherent in answering this question, and the factors that impact the likelihood of success of the EU's emission reduction efforts.
f. In this context, we also comment on the relevance of the concept of 'no regrets' solutions.

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[127] Unlike, for instance, the studies conducted by Berenschot for the Dutch government, this study does not consider biomass, hydrogen (as feedstock and back-up), heat, green gas, CCS, or imports, as part of the energy mix. It focusses on wind and solar, which are projected to be the dominant technologies in the power mix in 2050, and compares these technologies to nuclear from the perspective of spatial requirements and generation costs.

As land and space become scarcer and public opposition to the geographical footprint of wind and solar grows, nuclear power is an option that increasingly draws attention from policy makers.

In addition to relative space requirements, relative costs also need to be taken into account for policy-making to achieve the EU's climate ambition and ensure a successful and affordable energy transition.

II. How much land/space is required, if wind/solar is used to deliver all required electricity by 2050, in The Netherlands and the Czech Republic?

a. This question is answered based on a model that uses available, reliable estimates of the total energy demand in 2050 for the Czech Republic and The Netherlands, utilizing a reasonable range of potential increases or decreases in energy demand. A description of the model is included in this report.

b. We assume the current state of the technologies and proven capacities; we address any plausible future innovation (e.g. the latest wind turbines for installation in sea) in brief comments or, in some cases, in a short qualitative discussion. Our analysis includes wind at sea, wind on land, wind on surface waters (rivers, lakes, etc.), solar on land, and solar on roofs.

c. With respect to the land/space required, we reference the maximal surface of the land/space currently available for wind/solar power recognizing technical/regulatory restrictions, and indicate the extent to which this available space will be utilized or even exceeded.

d. In relation to the wind/solar power, our model is able to accommodate a range of estimated plausible land/space requirements, and expected energy production per km^2.

e. We indicate also how our estimates vary as a function of the degree of electrification, capacity factors, and other key parameters.

f. We provide a description of our model, explain how it works, and how it differs from other existing models.

g. We do not analyze the issues and challenges related to the use of cross-border capacities and interconnections, and the import of electricity, but add some comments on these topics, where useful. It is clear, however, that expanded cross-border interconnections involve significant cost, and may not solve the problem of renewable energy's intermittency.

III. How much land/space is required, if nuclear power is used to produce all required electricity by 2050, in The Netherlands and the Czech Republic?

a. This question is answered based on the same model as referenced under II, above, using available, reliable estimates of the total energy demand in 2050 for the Czech Republic and The Netherlands as described under II.a, above; a range is stated.

b. We assume the current state of the technologies and proven capacities; in some instances, we briefly address plausible future innovations (e.g., small modular nuclear reactors) in a qualitative discussion and provide references for further reading.
c. With respect to the land/space required, we reference the surface of the land/space currently available for nuclear power recognizing technical restrictions, and indicate the extent to which this available space will be utilized or exceeded.
d. In relation to the nuclear power, we assume that state-of-the-art, well-performing, safe nuclear technology will be used. In the EU, as discussed in Part 2, above, there is extensive safety regulation of nuclear energy installations.
e. We identify the differences in land/space requirements between wind/solar and nuclear power, and add comments that are useful to understand these differences.
f. We conduct sensitivity analysis on the key model inputs, and explore land/space requirements for power mixes composed of wind/solar and nuclear power in various proportions. Given values for key inputs/parameters, we compute at which point there will be insufficient land to meet power demand through a particular power technology (wind, solar, nuclear).

IV. What is the cost of implementing the wind/solar option discussed under II, above, and the cost of the nuclear option discussed under III, above?

a. Our cost estimates are based on a model that uses fully loaded costs, including capital expense, operational expense, and other expenses. This implies, for instance, that the costs of maintenance and decommissioning are included; for nuclear, it means, for instance, that the cost of the longer lead time are reflected. The fully loaded costs include costs such as the year-round operation safety, for both wind/solar and nuclear power, insofar as these are included in the numbers we used, which we cannot always verify. In any event, if not included in the quantitative model, these costs are addressed qualitatively in the discussion. However, the external cost necessary to ensure integration into the electricity system and other system-related costs (including transmission, system stability, etc.) are discussed separately (see Part 8, below).
b. We assume the current state of the technologies and proven capacities; any plausible future innovation is addressed in a qualitative discussion.
c. We assume that wind/power and nuclear power are treated as equal alternatives, without any priority or preference for one over the other.
d. In relation to the weighted average cost of capital, we use the lowest currently available market-based rates for wind/power and nuclear (correcting for status quo bias), respectively, and also a 0 (zero) % interest rate for both wind/solar and nuclear.
e. We conduct sensitivity analysis on the key model inputs, consider which are the main factors affecting the cost of wind/solar and nuclear, respectively. In addition, we consider how some of these factors could be favorably influenced in The Netherlands and The Czech Republic.
f. As noted, our model does not incorporate integration and system-related costs, but we provide a qualitative discussion of the costs of integration of renewable power into the electricity system. We also comment on (the costs of) the adaptation of the electricity system (transmission, grid, etc.) that will be

necessary, if renewable energy (wind, solar) supply all of the power required, no other power generation technology is deployed as back-up, and other technologies are deployed extensively to address the problem of intermittency of renewable power.

V. Would a 50 % nuclear – 50 % wind and solar option have space or cost advantages over a 100 % solution of either technologies?

a. We assume an optimal location of wind/solar farms consistent with restrictions, and use numbers representative for currently operating wind/solar facilities, which have been built at attractive locations.
b. We consider briefly whether some other mix (e.g. 80/20 %) might have further advantages.
c. We assess the effects of the mixes we considered under b, above, on the costs of power in The Netherlands and The Czech Republic.

All of the research questions under I through IV, above, relate, in a direct way, to the costs and benefits of the energy transition and various options to effectuate this transition. As such, the answers are relevant to cost/benefit-analysis in relation to climate policy. The questions focus on issues that have not yet been researched extensively or exhaustively, although relevant literature is available and has been used to answer all four questions. Our analysis also informs the debate on the energy transition in countries other than the Czech Republic and The Netherlands.

The questions posed not only address costs in a strictly monetary sense; they also relate to the quality of the environment enjoyed by citizens, which are hard to quantify, let alone monetize. We have therefore not tried to express all answers to the questions in monetary terms, but have identified financial effects where doing so appeared useful to us. In other words, a qualitative analysis of the key issues supplements our quantitative analysis of the spatial requirements and costs of wind/solar power and nuclear power.

Below, some further comments are made on each of the individual research questions. These comments provide further details on how we interpreted the questions and how we proceeded to answer them.

i. Effect of EU Climate Neutrality Ambition

The research question in relation to the expected effect of the EU's 2050 climate neutrality ambition on the average atmospheric temperature (under I, above) presents stand-alone issues that do not directly affect the approach to answering the other research questions. On the other hand, the likely effect of EU climate neutrality on the global climate is important, because this information may be deemed relevant to both the level of resources dedicated to pursuing the objective and the means through which it is pursued. If the EU pursues its climate neutrality policy based on the anticipation that other nations will also take the required actions to reduce their GHG emissions, it is important to understand what contributions the EU and non-EU countries, respectively, make to global GHG emissions.

The Paris Agreement requests each country to submit its post-2020 climate actions, known as its intended nationally determined contribution or INDC; these INDCs are supposed to be replaced by NDCs which are due by the end of 2020. Jointly, these INDCs determine whether the aggregate emission reductions are achieved that are believed to be necessary to limit the long-term temperature increase to no more than 2 °c by 2100. In assessing the likely effect of the EU's climate neutrality policy, the INDCs of other countries provide a point of reference. We review literature that considers the effect of the assumption that the non-EU countries will comply with their INDCs pursuant to the Paris Climate Agreement, and will

The likely effect of EU climate neutrality on the global climate is important, because this information may be deemed relevant to both the level of resources dedicated to pursuing the objective and the means through which it is pursued. If the EU pursues its climate neutrality policy based on the anticipation that other nations will also take the required actions to reduce their GHG emissions, it is important to understand what contributions the EU and non-EU countries, respectively, make to global GHG emissions.

make proportional efforts in the period 2030-2050 and throughout the century.

As the research questionnaire requires, we assess also the probability of the EU achieving zero GHG emissions by 2050. Of course, there are many unknowns and uncertainties in relation to this issue; one approach to this assessment is to look at past track records of achieving climate goals. This, of course, raises the issue as to whether the past is representative of the future; while this is true, the past may be a more realistic measure than mere aspirations. Emission reduction, however, does not equate to effect on the climate, which complicates the analysis. We therefore use another method to eliminate the effect that other countries have on the climate, which we label 'taking climate neutrality seriously'.

To address this set of questions, the study analyzes existing literature on the effect of the INDCs, which sheds light on the key issues associated with the EU climate neutrality's likely effect. As the research questionnaire suggests, following a discussion of the quantitative literature on point, we provide a qualitative discussion of the relevant issues and the context within which carbon emission reductions are pursued. We tie the results of our analysis to the concept of 'no regrets' solutions in this context.

Before moving on, we note that there is an ongoing debate about the question how a choice for more renewable power or more nuclear in the power mix could affect the likelihood that a country will effectively achieve greater emission reduction.[128] A recent paper gave new fuel to this debate, and even suggested that

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[128] Aijun Li, Zhe Zhang, Aizhen Zhang, Why are there large differences in performances when the same carbon emission reductions are achieved in different countries?, Journal of Cleaner Production 103 (2015) 309-318 ("[T]here are large differences in performances among these unilateral climate policies, as evidenced by large differences in leakage rates and carbon emission abatement costs.")

renewable and nuclear tend to crowd each other out.[129] We do not engage in this debate. Both renewable and nuclear power are decarbonized, and instead of using them as proxies to examine other variables (such as carbon leakage, level of industrialization, etc.), we discuss these variables and their relations with renewable versus nuclear power directly, as necessary.

ii. Land/Space Use

The research questions under II and III, above, address land and space use for power generation (here also referred to as 'spatial requirements'). These questions have become acute for policy makers in light of three recent developments:

- There is a renewed push for the further expansion of wind and solar power to increase the share of renewables in the power mix in line with EU mandates.
- Compared to other technologies used to generate power, wind and solar power have relatively significant spatial (land, sea) impacts, both quantitatively and qualitatively, as well as impacts on the electricity system.
- The public's concerns about further expansion of wind and solar power generation are beginning to affect the planning of new renewable projects.[130]

Indeed, it is to be expected that, as the share of wind and solar power in the energy mix increases, the issues associated with land/space use are bound to become more significant and controversial.[131] The first wind farms were constructed in areas where not only the potential for power generation was good, but also the externalities of the wind farms were relatively small – far away from residential areas, not in nature reserves, etc. Additional wind farms involve larger turbines and may have to be constructed in areas closer to residences, thus increasing the potential for nuisance.

As a related matter, the projected electrification of the energy system in Europe will cause of power in the energy mix to continue to increase, even if total energy use will not grow any further. According to the European Commission:

"Electricity demand is projected to increase significantly on a pathway towards climate neutrality, with the share of electricity in final energy consumption growing from 23 % today to around 30 % in 2030, and towards 50 % by 2050… ***This growing electricity demand will have to be largely based on renewable energy. By 2030, the share of renewable energy in the electricity mix should double to 55-60 %,***

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[129] Benjamin K. Sovacool, Patrick Schmid, Andy Stirling, Goetz Walter and Gordon MacKerron, Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power, Nature Energy 2020, available at https://doi.org/10.1038/s41560-020-00696-3 ("We find that larger-scale national nuclear attachments do not tend to associate with significantly lower carbon emissions while renewables do. We also find a negative association between the scales of national nuclear and renewables attachments. This suggests nuclear and renewables attachments tend to crowd each other out.")

[130] See, for instance, Jess Shankleman and Lars Paulsson, As Wind Power Grows in Europe, So Does Resistance From Locals -- Communities object to new and bigger turbines, threatening efforts to reduce carbon emissions, Bloomberg Green, 19 June 2020, available at https://www.bloomberg.com/news/articles/2020-06-19/wind-power-and-turbines-are-facing-pushback-from-europe-s-locals See also 'As wind power grows in Europe, so does resistance from locals,' 19 June 2020, available at https://www.wind-watch.org/news/2020/06/19/as-wind-power-grows-in-europe-so-does-resistance-from-locals/ For The Netherlands, see, e.g., Folkert van der Krol, 'Advocaat ziet einde van windmolenparken naderen: 'Als mens niet wordt beschermd, is het foute boel', available at https://www.ad.nl/rotterdam/advocaat-ziet-einde-van-windmolenparken-naderen-als-mens-niet-wordt-beschermd-is-het-foute-boel~a4c6380d/

[131] For different reasons, land use and location issues may arise with respect to nuclear power plant location. As the Commission notes, "construction of a nuclear reactor or extensive electricity transmission lines, while identified as ***cost-effective*** by the model, might not happen because of consumer acceptance/land availability issues." European Commission, IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773, A Clean Planet for all -- A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, Brussels, 28 November 2018, available at https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en , p. 329.

> The European Commission states that that the growing electricity demand will have to be largely based on renewable energy. By 2030, the share of renewable energy in the electricity mix should double to 55-60%, and projections show a share of around 84% by 2050.

and projections show a share of around 84 % by 2050. The remaining gap should be covered by other low-carbon options."[132] *(emphasis supplied).*

Consequently, if wind and solar power begin to dominate the power system, the issues with respect to land/space use will increase in number and significance. The issues of tomorrow will differ from today's issues both quantitatively and qualitatively. More and different areas and landscapes and other land uses (residential, industrial, etc.) will be impacted by the expanding installed base of wind and solar farms, thus amplifying the relevance of relative spatial requirements of various power technologies. The possibility to move renewable power generation offshore (e.g. into the sea) will alleviate the pressure on land, but raise another set of issues around impacts on the marine environment, whales, birds, ship routes, fishing, etc.[133]

Remarkably, the spatial requirements of wind and solar power generation have not received much attention in the Commission's extensive studies relating to the future EU energy system. Its 2018 report, which runs close to 400 pages, discusses land demand in the context of biomass, but not wind and solar.[134] As the review in Part 2 demonstrated, EU policies do not provide much guidance in the area of land use; in anything, they aggravate the problem by establishing frameworks for making conflicting claims on the scarce lands of Europe for all sorts of purposes, such as farming, industry, renewable energy, nature protection, etc. This study addresses this blind spot.[135]

Where the research questions refer to 100 % renewable[136] and nuclear power, they could be viewed as the 'pure case'-scenarios with respect to land/space use for power generation. These scenarios are useful for purposes of comparison of spatial impacts. In reality, it

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[132] European Commission, Communication, "Powering a climate-neutral economy: An EU Strategy for Energy System Integration", COM(2020) 299 final, Brussels, 8.7.2020, available at https://ec.europa.eu/energy/sites/ener/files/energy_system_integration_strategy_.pdf, at p. 7.

[133] See, for instance, Slavik, Kaela ; Lemmen, Carsten ; Zhang, Wenyan ; Kerimoglu, Onur ; Klingbeil, Knut ; Wirtz, Kai W, The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea, Hydrobiologia, 2018, Vol.845 (1), p.35-53. Regina Bispo, Joana Bernardino, Helena Coelho, José Lino Costa (editors), Wind Energy and Wildlife Impacts: Balancing Energy Sustainability with Wildlife Conservation, Springer, 2019.Bergström, Lena ; Kautsky, Lena ; Malm, Torleif ; Rosenberg, Rutger ; Wahlberg, Magnus ; Åstrand Capetillo, Nastassja ; Wilhelmsson, Dan, Effects of offshore wind farms on marine wildlife—a generalized impact assessment, Environmental Research Letters, 2014-03-01, Vol.9 (3), p.34012. Kirchgeorg, T ; Weinberg, I ; Hörnig, M ; Baier, R ; Schmid, M.J ; Brockmeyer, B, Emissions from corrosion protection systems of offshore wind farms: Evaluation of the potential impact on the marine environment, Marine Pollution Bulletin, 2018-11, Vol.136, p.257-268.

[134] Id., pp. 181-187.

[135] We do not discuss land use for bioenergy production. Of course, with yet another demand for land, pressure on land allocation will only increase, and the efficiency of land use for power generation becomes more important.

[136] Cf. Jacobson, Mark Z. et al. 100 % Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World, Joule, 1, 108–121, September 6, 2017, available at http://web.stanford.edu/group/efmh/jacobson/Articles/I/CountriesWWS.pdf

is likely that the power system in 2050 will not include only wind/solar or only nuclear, but several electricity-generating technologies. In our modelling, as the research questionnaire contemplates, we also include scenarios with a power mix closer to options policy makers are more likely to consider. Wind at sea, wind on land, wind on surface waters (rivers, lakes, etc.), solar on land, and solar on roofs are covered in our model.

As explained above, we assume the current state of the technologies and proven capacities for purposes of the quantitative analysis; doing so is good practice, because it reduces the uncertainties and avoids the risk of adverse surprises. In fact, realized numbers are more reliable than expected numbers, simply because realized numbers have been able to withstand the test of reality and experience. In reality, expectations may not be met. In our model, we accommodate both realized numbers and expected numbers, but we use realized numbers for our own analysis.

Plausible future innovation is briefly discussed qualitatively. With respect to the land/space required, we express the spatial requirements of the various technologies as a percentage of the total maximal surface of the land/space currently available for wind/solar power recognizing technical/regulatory restrictions.

iii. Costs

The research questions in relation to costs (under IV, above) address other key issues in relation to the contemplated energy transition. The cost of the production of electricity, to a significant extent, determines the price of electricity, which, in turn, affects the share of their income that citizens spend on power, and the production cost of power-intensive industries; more generally, it has extensive spill-over effects into the economy.

The questions posed refers to fully loaded costs. Taken literally, this would mean that all direct and indirect costs, including subsidies and other advantages, should be reflected in the cost base of the power option concerned. We have chosen not to attempt to identify and quantify all such costs, subsidies and advantages. Doing so would be not only a substantial very task, but also involves a series of judgments about what is and is not a cost or a subsidy. However, this study discusses one important category of indirect cost, namely integration- and systems-related cost (see Part 7). Integration cost can be a very substantial part of the cost of a power generating technology, but differs widely between technologies.

As the questionnaire requests, our model includes costs such as capital expenses, operational expenses, and other expenses, such as the costs of maintenance and decommissioning. Since it reflects the cost of capital on a rolling basis from a project's inception, it accounts for longer lead time of a technology. As noted above, the external cost necessary to ensure effective transmission and system stability, etc. for both wind/solar and nuclear power, is not covered by our model, but addressed separately. In relation to the weighted average cost of capital, we use the lowest currently available market-based rates for wind/power and nuclear, if respectively, and also a 0 (zero) % interest rate for both wind/solar and nuclear. In determining market-based rates, however, we attempt to separate out policy-related risk, so as to avoid importing status quo bias into the analysis.

Our model assumes the current state of the technologies and proven capacities; plausible future innovation is addressed briefly in a separate qualitative discussion. Other models, such as the model used by the UK government, assume future innovation and base their cost estimates on such future improvements.[137] The studies conducted for the government of The Netherlands also reflects future innovation, in particular of wind power.[138] The disadvantage of taking possible future innovations into account is that it increases the margin of error and introduces subjectivity, as it calls on researchers to express beliefs in unproven technologies without a track record, and presents subjective choices; for instance, which innovations are taken into account for wind and which ones for nuclear? We avoid these choices, and, where useful, add comments about further developments and future innovation.

As requested by the questionnaire, we conduct sensitivity analysis in relation to the key model inputs. We consider the main factors affecting the cost of wind/solar and nuclear power, and how these factors could be favorably influenced in The Netherlands and the Czech Republic; part 8 presents our policy recommendations. Our model also compares scenarios with only nuclear and only renewable power, as well scenarios with different percentages of nuclear and wind/solar. The objective of these comparisons is to determine whether there are any cost advantages to power mixes other than a 100 % solution of either technology. We add a qualitative discussion of these issues impacting the answer to this question.

The disadvantage of taking possible future innovations into account is that it increases the margin of error and introduces subjectivity, as it calls on researchers to express beliefs in unproven technologies without a track record, and presents subjective choices.

For instance, which innovations are taken into account for wind and which ones for nuclear?

We avoid these choices, and, where useful, add comments about further developments and future innovation.

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[137] UK Department for Business, Energy & Industrial Strategy, BEIS Electricity Generation Costs, August 2020, available at https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020

[138] Berenschot/Kalavasta, Klimaatneutrale energiescenario's 2050, Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, maart 2020, available at https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2020Z06737&did=2020D14346 Generation Energy, Ruimtelijke uitwerking Energiescenarios, maart 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/31/ruimtelijke-uitwerking-energiescenarios Kalavasta/Berenschot, Systeemeffecten van nucleaire centrales in Klimaatneutrale Energeiscenarios 2050, 9 maart 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-in-klimaatneutrale-energiescenarios-2050 For the related data sheets in English, see https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-in-klimaatneutrale-energiescenarios-2050

c. Methods and Data

I. General

This research project focuses on several key questions that need to be answered to shape EU and national climate and energy policy-making, ensure its effectiveness and manage its cost. Answering these questions, however, requires trade-offs. Complexities arise at several levels and need to be identified and managed appropriately. The pros and cons of power generating technology options (wind/solar versus nuclear) depend on technical factors, economic factors, social factors, as well as local factors, such as wind patterns, the availability of land, etc. Technical factors tend to be independent of geography, although history, knowledge, experience, and existing networks play a role there too. Differences between countries in terms of wind and sun hours play a role in relation to the actual power generation by renewable technologies. Economic factors are many, some are geography dependent, many are technology-dependent.

To study the pros and cons of the power generating technologies wind/solar and nuclear, two EU member states have been selected on different sides of the spectrum for wind:[139] The Netherlands, a country along the North Sea with abundant wind,[140] and the Czech Republic, a landlocked country with no access to sea and less suitable land.[141] The two countries, however, also differ significantly in terms of their experience with nuclear power: the Czech Republic has invested in its nuclear power capacity and foresees an important role for nuclear in the energy transition,[142] while The Netherlands has little experience and is hesitant,[143] although that has recently, to some extent, changed.[144] The Czech Republic and The Netherlands are therefore two case studies that will give important insights into the issues that are the subject of this study.

In conducting this study, we have employed an evidence-based approach. We used existing studies, if they met methodological and data quality requirements, to the maximum extent possible. Beyond a literature search, additional research and analysis and data generation was necessary, however.

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[139] See, generally, Peter Enevoldsen, Finn-Hendrik Permien, Ines Bakhtaoui, Anna-Katharina von Krauland, Mark Z. Jacobson, George Xydis, Benjamin K. Sovacool, Scott V. Valentine, Daniel Luecht, Gregory Oxley, How much wind power potential does europe have? Examining European wind power potential with an enhanced socio-technical atlas, Energy Policy 132 (2019) 1092–1100.

[140] See, for instance, Verhees, Bram ; Raven, Rob ; Kern, Florian ; Smith, Adrian, The role of policy in shielding, nurturing and enabling offshore wind in The Netherlands (1973–2013), Renewable & Sustainable Energy Reviews, 2015-07, Vol.47, pp. 816-829 ("It is widely acknowledged that many renewable energy technologies cannot (yet) compete with incumbent (fossil fuel) options e.g. in terms of price."). Breukers, Sylvia ; Wolsink, Maarten, Wind energy policies in the Netherlands: Institutional capacity-building for ecological modernization, Environmental Politics, 2007-02-01, Vol.16 (1), pp. 92-112. ("The research question of this paper is how institutional conditions affected policy and planning processes for wind energy implementation.") Niesten, Eva ; Jolink, Albert ; Chappin, Maryse, Investments in the Dutch onshore wind energy industry: A review of investor profiles and the impact of renewable energy subsidies, Renewable & Sustainable Energy Reviews, 2018-01, Vol.81 (Part 2), pp. 2519-2525 (" The 2020 renewable energy targets have stimulated the debate on the efficacy of policy schemes.")

[141] See, for instance, Frantál, Bohumil ; Nováková, Eva, On the spatial differentiation of energy transitions: Exploring determinants of uneven wind energy developments in the Czech Republic, Moravian Geographical Reports, 2019-06-01, Vol.27 (2), p.79-91. ("[B]y a statistical analysis of data for districts in the Czech Republic. Unlike previous studies, we found that the installed capacity of wind energy cannot be well predicted by wind potential, land area and population density in an area.").

[142] Osička, Jan ; Černoch, Filip, Anatomy of a black sheep: The roots of the Czech Republic's pro-nuclear energy policy, Energy Research & Social Science, 2017-05, Vol.27, pp. 9-13. ("In this article we examine the main drivers behind the Czech Republic's enduring interest in nuclear energy.")

[143] Maarten J. Arentsen, CONTESTED TECHNOLOGY: Nuclear Power in the Netherlands, Energy & Environment, 2006, Vol.17 (3), p.373-382 ("Despite high ambitions nuclear technology hardly developed in the Netherlands. Already from the very start, nuclear technology was contested and became subject of power games.")

[144] 'Wiebes positief over kernenergie na onderzoek adviesbureau kernenergie,' 23 september 2020, available at https://joop.bnnvara.nl/nieuws/wiebes-positief-over-kernenergie-na-onderzoek-adviesbureau-voor-kernenergie

The two countries differ significantly in terms of their experience with nuclear power: the Czech Republic has invested in its nuclear power capacity and foresees an important role for nuclear in the energy transition, while The Netherlands has little experience and is hesitant, although that has recently, to some extent, changed.

In particular, we found existing models not fit for purpose, and the data inputs did not meet data quality requirements. Thus, we developed our own models. Through these models we generated further numbers, using existing, reliable data as inputs. This does not apply to the analysis of the effect of EU climate neutrality by 2050 on the climate, which is based entirely on a review of the relevant literature and analysis thereof.

In terms of data quality, we use realized numbers to compute things such as actual power generation and costs, because such numbers are more reliable than expected numbers, which have not been proven in reality. Research has found, for instance, that LCOEs (levelized cost of electricity) computed on the basis of audited accounts diverge substantially from costs computed using expected numbers.[145]

This study has been carried out by an interdisciplinary team of authors, who drafted and revised different parts of the report. To guarantee the report's scientific validity and quality, however, all parts of the draft report have been reviewed by at least two authors, and, in some cases, by all authors. The conclusions have been endorsed by the entire team of authors. We also received feedback and comments from peer reviewers, who have been invited by us based on their qualifications. The authors considered carefully all such feedback and comments, and, where necessary, conducted further research and analysis, and made the necessary amendments to the report.

A draft of this report was distributed to ECR Group and Renew for their review and comment on 12 October 2020. Before, on or shortly after 12 October 2020, the draft report was also made available to peer reviewers. The final version of report was submitted on 10 November 2020, and the final editing was concluded on 30 November 2020.

II. Scope and Limitations of Study

Before we dive into the substance of this study, it is useful to delineate its scope and place it in a broader context. The EU's ambition is for Europe's power generation in 2050 to be dominated by renewable energy. In practice, as the European Commission projects, this will mean that the energy sector will be dominated by wind and solar power, in particular now that biomass no longer receives broad support.

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[145] John Aldersey-Williams, Ian D. Broadbent, Peter A. Strachan, Better estimates of LCOE from audited accounts – A new methodology with examples from United Kingdom offshore wind and CCGT, Energy Policy 128 (2019) 25–35.

Each of renewable power and nuclear power have their own specific benefits/advantages and costs/disadvantages, or strengths and weaknesses; spatial requirements and costs are two important variables but not the only ones that count. While the bulk of this study focuses on those two variables, we discuss other significant advantages and disadvantages qualitatively in Part 8 of this report.

In this study, we are also unable to deal extensively with marginal effects, second order effects, and system effects, except for the integration- and system-related cost discussion in Part 8. To give the reader a flavor of these kinds of marginal effects that may be relevant to the analysis, by way of example, we review here the possible marginal effects of adding more wind/solar power. At the margin, the consequences of adding units of wind/solar power are not constant. As the share of wind/solar power increases, the following consequences are likely to become more acute:

- First, the problem of intermittency increases further, and conversion and storage capacity may need to be increased, or additional (cross-border) transmission infrastructure may have to be added to create larger networks. Grid-scale roll-out of electricity storage, however, presents serious engineering challenges and involves high cost. This is also the case for conversion technology and expanded transmission infrastructure.
- Second, land and space scarcity may increase, as a result of which the price of land is likely to increase. This effect may be limited as far as agricultural land is concerned, if there is no other demand for this land (and policies prevent other uses), but there may be spill-over effects on land for construction, as less land will be become available to this end. Land and space that is currently reserved for nature protection, recreation, etc. may increasingly have to be converted into land/space for wind and solar, with more and more valuable resources having to be sacrificed.[146] And with wind and solar parks extending into areas that are more valued for other uses, public opposition to wind and solar deployment is likely to increase significantly.[147]
- Third, the efficiency of wind and solar power may decrease further if the best locations and plots have been utilized first; offshore wind parks may have to be located farther away from the shore in deeper waters. On the other hand, improved technology may make wind and solar more efficient, generating more power and costing less.

These and other marginal, second order or system effects have not been systematically examined as part of this study, although we touch on quite a few of them as we go along. Further research can cover these kinds of effects more extensively.

Further, we note that our spatial model does not include underground space. It is to be expected that, in general, and all other things being equal, relative to nuclear, wind and solar are likely to require significantly more underground space (and more investment), because many more installations are required to produce the same amount of power.

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[146] European Environment Agency, Land in Europe: prices, taxes and use patterns, EEA Technical report No 4/2010, available at ("The root problem is that the societal value of open space (or other environmental service) is not reflected in its market value and would need to be identified through other means.")

[147] As the Dutch government advisory body PBL notes in a report on experience with wind-on-land, public acceptance of renewable energy projects is a critical element. David Evers, Pia Nabielek en Joost Tennekes, Wind-op-land: lessen en ervaringen: Een reflectie op de implementatie van windenergie vanuit een ruimtelijk perspectief, PBL, 's Gravenhage, 2019, available at https://www.pbl.nl/sites/default/files/downloads/pbl-2019-wind-op-land-lessen-en-ervaringen-3379.pdf ("Onze belangrijkste conclusie is dat de overgang naar een duurzame energievoorziening een dubbele opgave is: (1) de opgave om tijdig meer duurzame energie te realiseren in Nederland en (2) de opgave om duurzame energie in de dagelijkse leefomgeving in te passen op een manier die kan rekenen op zoveel mogelijk begrip.")

We use models to compute spatial requirements and cost of power generation for wind/solar and nuclear. In each case, we describe the models extensively. We discuss the model mechanics, data inputs and sources, user changes to inputs, model outcomes, and sensitivity for each of the spatial model and cost model.

Further, we are comparing several scenarios for wind/solar and nuclear based on range of key variables.

III. Models, Scenarios and Inputs

We use models to compute spatial requirements and cost of power generation for wind/solar and nuclear; we refer to these models as the "Space Model" and the "Cost Model." In each case, we describe the models extensively. We discuss the model mechanics, data inputs and sources, user changes to inputs, model outcomes, and sensitivity for each of the spatial model and cost model. In annexes, we provide further detail. In the case of The Netherlands, we contrast our models with the models used by consultants who recently conducted studies for the Dutch power network managers on the same or closely related subjects.

Further, we are comparing several scenarios for wind/solar and nuclear based on range of key variables. To arrive at ranges for these key variables, we surveyed the literature and selected well-documented, corroborated numbers. On that basis, we derive scenarios at the extremes, as well as for the mean. We referred to the scenarios at the extremes as pessimistic and optimistic scenarios. As noted above, we ignore the effects of further, unproven innovation, because its effects are not yet known. Where we do account for learning effects, we apply them to both wind/solar and nuclear technology. Given that substantial, widespread government backup of wind and solar over the last decade have propelled innovation in this sector, it is not likely that ignoring the effects of innovation affected the findings of the analysis to any significant extent.

In terms of other model inputs, energy demand, of course, is a key variable. To provide relevant and useful comparisons of energy technologies, reliable, realistic estimates of energy demand in 2050 are used. Instead of deriving energy demand in 2050 from policy choices in relation to the energy system, our model treats it as an exogenous variable. The energy demand estimates used in our modelling are discussed further in connection with the data inputs for the models. Key parameters that affect power demand in 2050 include population growth, improvements in energy efficiency (insulation, reduced power consumption of devices, etc.), the level of labor participation and remote working, etc., all of which are hard to predict. In addition, there are unknown factors, such as changes in consumption patterns, innovation, etc. Estimates of power demand in 2050 therefore are by necessity ranges, and we test for sensitivity to power demand.


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Effect of 2050 EU Climate Neutrality on the Climate

Effect of 2050 EU Climate Neutrality on the Climate

In this part, the effect of the EU's 2050 climate neutrality on the climate is discussed. Given that the climate system is global, not merely European, any effect on the climate can only be ascertained as a function of (1) the state of climate science, and (2) the aggregate global response, in particular whether non-EU countries will stop their emissions of GHGs and, if so, when. There is significant uncertainty around these two issues; in particular, as discussed below, nothing suggests that the global response will align with the EU's ambition. There is also uncertainty around the critical scientific issues, however.

The first section provides an introduction and the background necessary to understand the issue of EU's climate neutrality ambition against the background of the state of climate science and in an international context. In the second section, the question as to what the effect will be of the EU climate neutrality in 2050 on the temperature increase is addressed. The third section present conclusions and discusses the concept of '***no regrets***' solutions to the climate issue.

a. Introduction and background

Climate policy-making can be explained as an issue of political economy or public choice; political positions on the issue are a function of interest groups attempting to maximize their members' economic utility functions, as opposed to the general interest.[148] From this perspective, it is understandable that politicians tend to cherry-pick from climate science to support preconceived policy ideas – "policy-makers view the IPCC reports mainly as a source of quotes with which to legitimize their preferences."[149] In connection with the EU's climate neutrality desire, however, the question as to how climate science can support diverging political viewpoints is important. This is a

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[148] Paterson, Matthew ; P-Laberge, Xavier, Political economies of climate change, Climate change, 2018-03, Vol.9 (2), p.e506-n/a. Cf. Geoff Mann and Joel Wainwright, Climate Leviathan: a political theory of our planetary future, London: Verso Books, 2018 (arguing that two conditions are deemed to shape the coming political–economic system -- the first is whether society will continue to be dominated by capitalism; the second is whether a 'planetary sovereign', seen as a world-ruling single entity or organization, will emerge).

[149] Oliver Geden, Climate advisers must maintain integrity, Nature (London), 2015-05-07, Vol. 521 (7550), pp. 27-28.

broad question that cannot be answered in the context of this study. Below, we explore two closely related issues: scientific uncertainty and uncertainty in the international context.

I. Scientific uncertainty

Earth's climate system is complex. For over a century, scientists have attempted to unravel its workings.[150] The IPCC describes the climate system as "a coupled non-linear chaotic system."[151] Climate scientists have great difficulty to fully understand the climate system and its dynamics, and make accurate predictions of the future climate. As a result of the focus on anthropogenic climate change,[152] much climate science has focused on the relation between the level of atmospheric carbon dioxide[153] in the atmosphere, which has increased over the last couple of centuries and is currently at approximately 410 PPM,[154] and the increase in the global average atmospheric temperature, which has risen by a little more than 1° Celsius since 1880.[155]

To develop a better understanding of the climate system, scientists have developed climate models,[156] but there has been much debate about the lack of accuracy of the model projections.[157] In short, climate science cannot offer a complete understanding of the climate system, and much uncertainty remains.[158] As the IPCC puts it, there are degrees of certainty, or probability distributions, based on "the author teams' evaluations of underlying scientific understanding and expressed as a ***qualitative level of confidence*** (from very low to very high) and, when possible, probabilistically with a quantified likelihood (from exceptionally unlikely to virtually certain)."[159] Thus, an (inter)subjective evaluation of the weight of the evidence is deployed as a proxy for the strength of the evidence.

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[150] The first scientist to discuss the influence of carbon-based compounds on the climate was Svante Arrhenius, On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, Philosophical Magazine and Journal of Science, Series 5, Volume 41, April 1896, pp. 237-276.

[151] "[T]herefore," the IPCC concludes, "the long-term prediction of future climate states is not possible. Rather the focus must be upon the prediction of the probability distribution of the system's future possible states by the generation of ensembles of model solutions." IPCC, available at https://archive.ipcc.ch/ipccreports/tar/wg1/501.htm

[152] The objective of 1992 UNFCCC is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Article 2, UNFCCC. In one of its recitals, the UNFCCC recognizes that "that there are many uncertainties in predictions of climate change, particularly with regard to the timing, magnitude and regional patterns thereof."

[153] Carbon dioxide is one of the greenhouse gases ("GHGs"). Other GHGs include methane, fluorinated gases, and water vapor. See Jain, Atul K, Briegleb, Bruce P, Minschwaner, K, Wuebbles, Donald J, Radiative forcings and global warming potentials of 39 greenhouse gases, Journal of Geophysical Research: Atmospheres, 2000, Vol.105 (D16), pp.20773-20790.

[154] NOAA, Global Monitoring Laboratory, available at https://www.esrl.noaa.gov/gmd/ccgg/trends/monthly.html

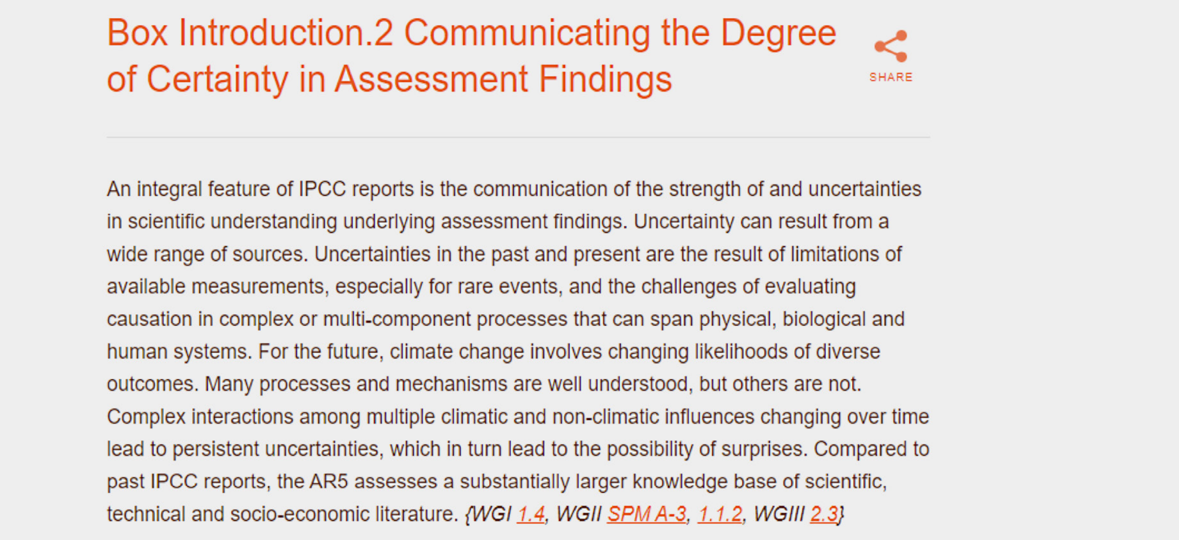
[155] NASA Earth Observatory, available at https://earthobservatory.nasa.gov/world-of-change/decadaltemp.php

[156] There are several types of climate models, including integrated assessment models. See, generally, IPCC, AR5 CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Chapter 9: Evaluation of Climate Models, available at https://www.ipcc.ch/report/ar5/wg1/evaluation-of-climate-models/ For an explanation of climate models for non-scientists, see Judith Curry, CLIMATE MODELS for the layman, London, GWPF, 2017, available at https://www.thegwpf.org/content/uploads/2017/02/Curry-2017.pdf

[157] There has been a heated scientific debate about the so-called 'global warming hiatus' between about 1998 and 2012. For an argument that "contradictory conclusions stem from different definitions of 'hiatus' and from different datasets," see Iselin Medhaug, Martin B. Stolpe, Erich M. Fischer & Reto Knutti, Reconciling controversies about the 'global warming hiatus', Nature, Volume 545, pp. 41–47 (2017).

[158] For a discussion of some of the key issues, see J. A. Curry, P. J. Webster, CLIMATE SCIENCE AND THE UNCERTAINTY MONSTER, Bulletin of the American Meteorological Society, 2011-12-01, Vol.92 (12), pp.1667-1682; and the response by Gabriele Hegerl, Peter Stott, Susan Solomon, Francis Zwiers, Comment on "Climate Science and the Uncertainty Monster" by J. A. Curry and P. J. Webster, Bulletin of the American Meteorological Society, 2011-12-01, Vol.92 (12), pp.1683-1685.

[159] IPCC, AR5, Synthesis Report, 2013, available at https://ar5-syr.ipcc.ch/topic_summary.php For a critique, see Curry, J. Reasoning about climate uncertainty. Climatic Change 108, 723 (2011). https://doi.org/10.1007/s10584-011-0180-z (arguing that the IPCC has oversimplified the issue of uncertainty in its Assessment Reports, which can lead to misleading overconfidence).



Box Introduction.2 Communicating the Degree of Certainty in Assessment Findings

An integral feature of IPCC reports is the communication of the strength of and uncertainties in scientific understanding underlying assessment findings. Uncertainty can result from a wide range of sources. Uncertainties in the past and present are the result of limitations of available measurements, especially for rare events, and the challenges of evaluating causation in complex or multi-component processes that can span physical, biological and human systems. For the future, climate change involves changing likelihoods of diverse outcomes. Many processes and mechanisms are well understood, but others are not. Complex interactions among multiple climatic and non-climatic influences changing over time lead to persistent uncertainties, which in turn lead to the possibility of surprises. Compared to past IPCC reports, the AR5 assesses a substantially larger knowledge base of scientific, technical and socio-economic literature. *{WGI 1.4, WGII SPM A-3, 1.1.2, WGIII 2.3}*

From: IPCC, AR5, Synthesis Report, 2013.

The degree of scientific uncertainty in climate science is downplayed or exaggerated as a function of policy preference, not strength of the evidence, which confirms that uncertainty is more than a scientific issue. Leaving that discussion aside, it is useful to identify the key issues of scientific uncertainty that hamper climate policy-making. Indeed, climate science cannot provide precise and certain answers to key questions about the human influence on the climate. The following key questions are still being investigated by climate scientists:

1. ***To what extent does the increase in atmospheric concentrations of carbon dioxide and other GHGs resulting from human activities cause global warming***, i.e. an increase in the average global atmospheric temperature (note that this does not equate to climate change and not to harm, which are separate issues, see below). This issue relates directly to the question around '*climate sensitivity*,' i.e. if the atmospheric carbon dioxide doubles, by how much will the average global atmospheric temperature increase?[160]

2. ***What is contribution of anthropogenic emissions of GHGs to climate change, relative to natural variability?*** Over the ages, the climate has changed in dramatic ways without any significant human influence; how can the human influence be separated from natural

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[160] Estimates of climate sensitivity differ widely, from a low of 1.5 °c to a high of 4.5 °c. S. Sherwood et al., An assessment of Earth's climate sensitivity using multiple lines of evidence, July 2020, available at https://climateextremes.org.au/wp-content/uploads/2020/07/WCRP_ECS_Final_manuscript_2019RG000678R_FINAL_200720.pdf See also Lewis, N., Crok, M., A Sensitive Matter: How the IPCC Burried Evidence Showing Good News About Global Warming, The Global Warming Policy Foundation, 2014.

causes of climate change?[161] If we reduce greenhouse gas emissions, will we prevent climate change?

3. ***What are the effects, both adverse and favorable, of higher atmospheric carbon dioxide concentrations and higher average global atmospheric temperatures?*** In particular, do higher average global atmospheric temperatures produce a higher frequency and/or higher intensity of extreme weather events (tornados, floods, droughts, etc.)?[162] Where and when will these impacts occur? Will these adverse effects be prevented if we drastically reduce greenhouse gas emissions?

Despite innovative attempts such as 'attribution'[163] and 'fingerprinting,'[164] no certain answers to these questions can currently be given. In the absence of strong evidence supporting unambiguous answers, as a panacea, the reliability of answers is framed in terms of the level of confidence of climate scientists,[165] which shifts the focus from the evidence to the authority of scientists, a different matter altogether. The concept that broad-scale impacts of physical climate change are "scientifically well-understood," but "specific estimates of these impacts are associated with uncertainty,"[166] is simply not satisfactory to the proverbial man of science.[167] Put in different terms, scientists tend to be "uncomfortable with the inherently

The concept that broad-scale impacts of physical climate change are "scientifically well-understood," but "specific estimates of these impacts are associated with uncertainty," is simply not satisfactory to the man of science.

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161 "Climate change in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change, where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods." IPCC, AR4, Summary for Policymakers, 2007: In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.available at https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-spm-1.pdf Cf. "Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use." IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5 °c. An IPCC Special Report on the impacts of global warming of 1.5 °c above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

162 Pielke, Roger, Economic 'normalisation' of disaster losses 1998–2020: a literature review and assessment, Environmental Hazards, 2020-08-05, pp. 1-19 (finding little evidence to support claims that any part of the overall increase in global economic losses documented on climate time scales is attributable to human-caused changes in climate").

163 Naveau, Philippe ; Hannart, Alexis ; Ribes, Aurélien, Statistical Methods for Extreme Event Attribution in Climate Science, Annual review of statistics and its application, 2020. Cf. Attribution Science: Climate Change & Extreme Weather, available at https://www.sciline.org/evidence-blog/climate-attribution

164 DelSole, Timothy ; Trenary, Laurie ; Yan, Xiaoqin ; Tippett, Michael K, Confidence intervals in optimal fingerprinting, Climate Dynamics, 2018, Vol.52 (7-8), pp.4111-4126 .

165 IPCC, AR5, Synthesis Report, 2013, available at https://ar5-syr.ipcc.ch/topic_summary.php

166 Editorial, Scientific uncertainty, Nature Climate Change, volume 9, p.797 (2019), available at https://www.nature.com/articles/s41558-019-0627-1

167 "If it disagrees with experiment, it's wrong. In that simple statement is the key to science." — Richard Feynman.

subjective or personalistic nature of the probabilities in climate science."[168]

Furthermore, the solutions that have been proposed to remedy climate change, raise a series of non-scientific, value-laden, and political issues, including issues around the costs and benefits of both climate change and the proposed remedies.[169] To try to move the policy debate, some scientists posit 'tipping points' and 'runaway' climate change,[170] but in the absence of empirical evidence to support these hypotheses,[171] they merely tend to politicize the debate further. For these reasons, the problem of climate change has been called a 'wicked' problem[172] -- ***the facts are uncertain, the relevant values are disputed, and the stakes are high***.[173] Indeed, the problem of global climate change presents overwhelming factual, analytical, and normative challenges.[174] Uncertainty, complexity, and dissent, as one scholar explains, make ***climate change hard to tackle with normal scientific procedures***.[175]

II. Policy Uncertainty in the International Context

Right before the UN COP25 Climate Change Conference in December 2019, the European Parliament adopted a resolution declaring "a climate and environmental emergency" in Europe and globally.[176] Referring to the IPCC's Special Report, the Parliament states that "immediate and ambitious action is crucial to limiting global warming to 1,5° C." The actions of the EP both before and after the adoption of the resolution, however, do not reflect the same sense of urgency, and the EU's 2050 climate neutrality objective pushes most actions into the future. Once again, the iron law of climate politics has been confirmed: In climate policy-making, politicians say what they believe to be scientifically necessary and politically possible, but they do what they believe to be politically necessary and scientifically possible.

To understand how the EU's climate neutrality ambition has become a policy uncertainty issue, the

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[168] Rougier J., Crucifix M. (2018) Uncertainty in Climate Science and Climate Policy. In: A. Lloyd E., Winsberg E. (eds) Climate Modelling. Palgrave Macmillan, Cham. https://doi-org.kuleuven.ezproxy.kuleuven.be/10.1007/978-3-319-65058-6_12

[169] William Nordhaus was awarded the Nobel Prize in economics for "integrating climate change into long-run macroeconomic analysis. Barrage, Lint, The Nobel Memorial Prize for William D. Nordhaus, The Scandinavian journal of economics, 2019-07, Vol.121 (3), pp. 884-924.

[170] See, e.g., Timothy M. Lenton, Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen & Hans Joachim Schellnhuber, Climate tipping points — too risky to bet against, Nature, 27 NOVEMBER 2019, available at https://www.nature.com/articles/d41586-019-03595-0 ("The growing threat of abrupt and irreversible climate changes must compel political and economic action on emissions.") Richard W. Erskine, Do tipping points mean runaway climate change, 5 Nov. 2019, available at https://essaysconcerning.com/2019/11/05/do-tipping-points-mean-runaway-global-warming-after-12-years/

[171] Hillebrand, Helmut, Ian Donohue, W. Stanley Harpole, Dorothee Hodapp, Michal Kucera, Aleksandra M. Lewandowska, Julian Merder, Jose M. Montoya and Jan A. Freund, Thresholds for ecological responses to global change do not emerge from empirical data, Nature Ecology & Evolution, https://doi.org/10.1038/s41559-020-1256-9.

[172] Frank P. Incropera, Climate Change: A Wicked Problem: Complexity and Uncertainty at the Intersection of Science, Economics, Politics, and Human Behavior, Cambridge University Press, 1st ed., 2016.

[173] S. O. Funtowicz and J. R. Ravetz, "Science for the postnormal age," Futures,25, 739–755, 1993. Krauss, Werner ; Storch, Hans, Climate science in a postnormal context, Eos, 2012-03-06, Vol.93 (10), pp. 108-108

[174] Adam B. Jaffe ; Suzi Kerr, The Science, Economics, and Politics of Global Climate Change: A Review of "The Climate Casino" by William Nordhaus, Journal of Economic Literature, 2015-03-01, Vol.53 (1), pp. 79-91.

[175] Jeroen van der Sluijs, Uncertainty and dissent in climate risk assessment, a post-normal perspective, Nature and culture (2012), pp. 174-195, available at http://www.nusap.net/downloads/Van_der_Sluijs_2012_PNS_NC.pdf van Der Sluijs J (2005) Uncertainty as a monster in the science–policy interface: four coping strategies. Water Sci Technol 52(6):87–92. https://doi.org/10.2166/wst.2005.0155 Mehta, L., Adam, H.N. & Srivastava, S. Unpacking uncertainty and climate change from 'above' and 'below'. Reg Environ Change 19, 1529–1532 (2019). https://doi.org/10.1007/s10113-019-01539-y

[176] European Parliament resolution of 28 November 2019 on the climate and environment emergency (2019/2930(RSP), available at https://www.europarl.europa.eu/doceo/document/TA-9-2019-0078_EN.pdf

In climate policy-making, politicians say what they believe to be scientifically necessary and politically possible, but they do what they believe to be politically necessary and scientifically possible.

international context should be understood. The EU is a party to the Paris Agreement on Climate Change, and played a key role in the negotiations leading to the adoption of the agreement. In accordance with the international dimension of the EU's climate policy, the EU has been working with other countries and regions to achieve its goals.[177] The Paris Agreement's core objective is reduce "the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius."[178] To implement the Paris Agreement within the EU, the EU has adopted a series of policies intended to reduce the emission of greenhouse gases (GHG).

The Commission communication presenting the EU Green Deal frames the problem inherent in the Paris arrangements as follows: "The EU will continue to ensure that the Paris Agreement remains the indispensable multilateral framework for tackling climate change. As the EU's share of global emissions is falling, comparable action and ***increased efforts by other regions will be critical*** for addressing the global climate challenge in a meaningful way."[179] Indeed, since climate change is a global, not a regional, issue, GHG emission reductions only in the EU cannot solve the problem. Very substantial GHG emission reductions by many nations are necessary to achieve the Paris Agreement's objective of limiting the temperature increase by 2100 to well below 2 °c or even 1.5 °c.

This raises an issue and exposes a major weakness of the Paris Climate Agreement. The Paris Agreement has created a ***wide gap between ambition and obligation*** by adopting ambitious temperature targets without specifying the means to reach them. Although the Paris Agreement has much to say about mitigation, it does not impose any emission reduction obligations on industrialized countries[180] or major emerging economies. There is no agreed roadmap for limiting GHG emissions. This is not a minor point, because the absence of such a roadmap may undermine the intended useful effects of all other activities.

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[177] In addition, as the Commission explains, the EU "promotes ambitious climate action in multilateral fora and in its bilateral cooperation with countries outside the EU. The EU is also a top provider of international climate finance to support developing countries in their efforts to tackle climate change." European Commission, EU climate action and the European Green Deal, available at https://ec.europa.eu/clima/policies/eu-climate-action_en

[178] The Paris Agreement on Climate Change, available at https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[179] European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal, COM/2019/640 final, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN

[180] To avoid Congressional approval (which is required for treaties), the US insisted on a last minute change to Article 4(4), which now reads "should" rather than "shall." ("Developed country Parties should continue taking the lead by undertaking economy-wide absolute emission reduction targets.")

A key concept of the Paris deal is the program of ***nationally determined contributions*** (NDCs). These are national climate action plans. Importantly, the Paris Agreement sets little or no substantive criteria for NDCs. A country is free to set its own level of ambition, which may be close to zero, and adopt the specific mix of measures it intends to pursue, which may include solely innovation policies and no emission reduction measures. Upon ratification, parties must submit their NDCs[181] to the Paris secretariat,[182] which are entered in a public registry.[183] National plans submitted after the agreement's entry into force may or may not be binding;[184] once a country has submitted an unqualified NDC, there is a good case to be made that it has entered into a legally binding agreement to perform its commitment,[185] subject to the conventional defenses and exceptions applicable under international law.

By 2020, the parties are requested to communicate new NDCs, and the Conference of the Parties periodically assesses the collective progress towards achieving the Agreement's purpose (also called the ***"global stocktake***"[186]), for the first time in 2023[187] and every five years thereafter unless otherwise decided.[188] Successive national plans should be more ambitious.[189] Further, a party is free to withdraw[190] from the agreement at any time after three years from the agreement's entry into force.[191] The United States of America have withdrawn from the agreement, with effect in November 2020.[192] As of 1 September 2020, 189 countries have ratified the Paris Agreement.[193]

Thus, the Paris Agreement imposes no obligations on countries to adopt any specific climate policy or emission reduction targets. Objectively viewed, the Paris Agreement would appear to be no more than a procedural framework for future, flexible "bottoms-up"[194] climate policy-making by the parties to it, dressed up with some non-binding language that emphasizes ambition and progression. Global

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[181] In accordance with the COP-21's Decision, such a plan should cover all sources of anthropogenic emissions and must explain why any categories not included have been excluded. COP-21 Decision, under 31(c) and (d).

[182] Article 4(2), Paris Agreement.

[183] Article 4(12), Paris Agreement.

[184] The agreement entered into force, once 55 ratifications from states representing 55 % of global emissions have been submitted. Article 21(1), Paris Agreement. This happened on 4 November 2016.

[185] Some commentators disagree, however. See, for instance, Philip Lloyd, The Paris 'Agreement' – chock full of noble intentions, December 21, 2015, http://wattsupwiththat.com/2015/12/21/the-paris-agreementchock-full-of-noble-intentions/

[186] The outcome must inform the update and enhancement of national plans. Article 14(1) and (3), Paris Agreement.

[187] Despite the EU's initial insistence on a first review of nationally determined contributions before 2020, the Paris Agreement imposes a more relaxed timeframe. Europa moet inbinden op klimaatconferentie, De Standaard, 11 december 2015, http://www.standaard.be/cnt/dmf20151210_02015644

[188] Article 14(1) and (2), Paris Agreement.

[189] Article 4(3), Paris Agreement.

[190] UNFCC, On the Possibility to Withdraw from the Paris Agreement: A Short Overview, 14 June 2017, available at https://unfccc.int/news/on-the-possibility-to-withdraw-from-the-paris-agreement-a-short-overview

[191] Article 28(1), Paris Agreement.

[192] Valerie Volcovici, Trump administration begins Paris climate pact exit, 4 November 2019, available at https://www.reuters.com/article/us-usa-climate-paris-idUSKBN1XE21K

[193] UNFCC, Paris Agreement - Status of Ratification, available at https://unfccc.int/process/the-paris-agreement/status-of-ratification

[194] Richard Stewart, Benedict Kingsbury & Bruce Rudyk (Eds.), Climate Finance Regulatory and Funding Strategies for Climate Change and Global Development, NYU Press, 2009.

There are no assurances whatsoever that other countries will match the EU's efforts. To the contrary, there are indications that they will not do so.

emissions should peak "as soon as possible," but peaking may take longer for developing countries.[195] As the share of GHG emissions from developing nations continues to grow towards 2050, their emissions will become the drivers of the global atmospheric temperature increase. Consequently, the EU's climate neutrality ambition is pursued in an international setting that leaves the total global emissions of GHG wide open. There are ***no assurances whatsoever that other countries will match the EU's efforts***. To the contrary, there are indications that they will not do so. Developing nations need access to abundant and cheap energy to pursue economic development, and end poverty and hunger. A further complication arises from the fact that countries are impacted by climate change in very different ways, with ***some countries benefitting from climate change***, at least in the short term.[196] Until developing nations, including those in Africa and Asia, reach a Western standard of living, their priorities will likely continue to differ from our priorities; concern about fossil fuel use and climate change may well take a back seat in those regions until then.[197]

In other words, the EU's mitigation approach involves a high risk of not achieving the global temperature objective, and, therefore, 'no regrets' options to become climate neutral should be attractive to the EU. The next section reviews the literature on the effect of the EU's climate policies on the global temperature. The final section of this chapter discusses the concept of 'no regrets' options in more detail.

b. EU Emissions, Global Emissions, and Average Global Atmospheric Temperature

In this section, we review the effect of EU climate neutrality on the average global atmospheric temperature in 2050 and 2100. First, the relevant literature is analyzed to determine by how much EU climate neutrality will reduce the global average temperature. The reference point for this analysis is derived from the INDCs submitted by all countries that participate in the Paris Agreement on Climate Change.[198]

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[195] Article 4(1), Paris Agreement.

[196] David Herring, Are there positive benefits from global warming?, January 23, 2014, available at https://www.climate.gov/news-features/climate-qa/are-there-positive-benefits-global-warming Cf. IPCC (2012), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA

[197] If the world will need to adapt to climate change, actions may have to be taken against a real and present threat, not a possible future threat. If most of our resources have been invested in mitigation measures that turned out to be futile, we may lack the resources for effective adaptation. This should be a major concern to countries that emphasize large scale mitigation exercises now.

[198] Note that an INDCs has become a NDC (without the "intended") upon ratification of the Paris Agreement by a country. By now, most party countries have ratified the agreement. To signal that the research we discuss dates back from before ratfication, however, we use the term INDCs, as the original research did. We use 'NDC 'where we refer to the period following the Paris COP and the EU's ratification of the Paris Agreement.

Thereafter, the attention shifts to the problems and uncertainties related to EU climate neutrality's effect on the temperature. The problem of 'outsourcing' of emissions, also known as 'carbon leakage,' is discussed here. We also review the issues relating to the EU's declining emissions and the emission increases in key non-EU countries. Next, to put the EU's climate neutrality ambition to the test, we assess it based on the proposition that the EU must not only expand renewable energy, but also effectively prevent the combustion of fossil fuels anywhere in the world. We conclude this section with some additional observations on the international context of the climate problem.

I. Review of Literature on EU Contribution to Reduction of Global Temperature Increase

In connection with the Paris Agreement, several direct scientific assessments have been made of the expected effect of mitigation on the average global atmospheric temperature.[199] The findings of these studies diverge, predominantly as a result of diverging assumptions.

In this section, we focus on two peer-reviewed publications from opposite sides of the spectrum: a study by Lomborg, and an article by Rogelj et al. Each of these two studies is reviewed in turn. Thereafter, we use their findings to derive an estimate of the effect of EU climate neutrality on the average global temperature.

Lomborg Study

In a peer-reviewed article in a scientific journal, Lomborg investigated the temperature reduction impact of major climate policy proposals implemented by 2030.[200] To do so, he used the standard MAGICC climate model. An earlier analysis by Wigley of the effect of the now defunct Kyoto Protocol had found that the emissions reductions promised until 2030 will do little to stabilize the climate and their impact will be undetectable for many decades.[201] Lomborg's main conclusions included the following:

- "Based on climate model simulations, the emission cuts that have been proposed by the US, the EU, China and the rest of the world will reduce temperature increases by the end of the century, but almost all of the expected warming will still take place by 2100."

- "Even optimistically assuming that promised emission cuts are maintained throughout the century, the impacts are generally small:
  - The impact of the US Clean Power Plan (USCPP) is a reduction in temperature rise by 0.013 °c by 2100. The full US promise for the COP21 climate conference in Paris, its so-called Intended Nationally Determined Contribution (INDC) will reduce temperature rise by 0.031 °c.
  - The EU 20-20 policy has an impact of 0.026 °c, the EU INDC 0.053 °c, and China INDC 0.048 °c.
  - All climate policies by the US, China,[202] the EU and the rest of the world, implemented from

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[199] For an overview, see Zeke Hausfather, Analysis: Meeting Paris pledges would prevent at least 1C of global warming, Carbon Brief, 6 June 2017, available at https://www.carbonbrief.org/analysis-meeting-paris-pledges-would-prevent-at-least-one-celsius-global-warming For

[200] Bjorn Lomborg, Impact of Current Climate Proposals, Global Policy, Volume 7, Issue 1, February 2016, pp. 109-116.

[201] Wigley, T. M. L. (1998) 'The Kyoto Protocol: CO_2, CH_4 and Climate Implications', Geophysical Research Letters, 25 (13), pp. 2285–2288.

[202] A 2014 study on China's found that "after 2020, the role of renewables is sensitive to both economic growth and technology cost assumptions. Importantly, we find that the CO_2 emissions reductions due to increased renewables are offset in each year by emissions increases in non-covered sectors through 2050. We consider sensitivity to renewable electricity cost after 2020 and find that if cost falls due to policy or other reasons, renewable electricity share increases and results in slightly higher economic growth through 2050. However, regardless of the cost assumption, projected CO_2 emissions reductions are very modest under a policy that only targets the supply side in the electricity sector." Qi, T., X. Zhang and V.J. Karlpus, The energy and CO_2 emissions impact of renewable energy development in China, Energy Policy, 68(2014): 60-69.

> the early 2000s to 2030 and sustained through the century will likely reduce global temperature rise about 0.17 °c in 2100."[203]

The study by Lomborg provides a table 4.1. that is reproduced. As Lomborg observes, "because the climate policy impacts from individual countries are almost additive, they can be almost perfectly partitioned."[204]

In a recent book, Lomborg shared further insights on the effects of the Paris Agreement on the global atmospheric temperature. In this book, Lomborg answers the question *'what will happen if nations meet their promises under Paris'* as follows:

"The United Nations organizers of the Paris Agreement once in 2015 (and never since) released an estimate of the total maximum impact of all carbon dioxide cuts promised by all nations. It provides the absolutely best-case scenario that we can hope for. This estimates a total reduction of 64 Gt carbon dioxide through to 2030. According to the UN's estimate of 0.8F per 1,000 Gt carbon dioxide, this translates to a reduction in temperature by the end of the century of about 0.05F. *(emphasis supplied).*

What this tells us is that even in an optimistic scenario, the Paris Agreement isn't going to come anywhere close to solving global warming. It will have a miniscule impact on the temperature by 2100."[205]

Rogelj et al. Study

A group of academics headed by Rogelj assessed the effect of (then) current Intended Nationally Determined Contributions (INDCs) on reducing aggregate greenhouse gas emissions, and its implications for achieving the temperature objective of the Paris climate agreement.[206] They found that the INDCs collectively lower greenhouse gas emissions compared to where current policies stand, but still imply a median warming of 2.6–3.1 degrees Celsius by 2100, so above the Paris target of "well below 2 degrees Celsius."

Change in temperature		
°C year 2100	**Pessimistic**	**Optimistic**
US INDC *US CPP*	0.008 *0.004*	0.031 *0.013*
EU INDC *EU 2020*	0.017 *0.007*	0.053 *0.026*
China INDC	0.014	0.048
RoW INDC	0.009	0.036
Global INDCs	0.048	0.170

Table 4.1. Impact of climate policies, optimistic and pessimistic, for RCP8.5, using MAGICC, summary of finds described throughout the text

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[203] Lomborg notes that "[t]hese impact estimates are robust to different calibrations of climate sensitivity, carbon cycling and different climate scenarios." Cf. Bjorn Lomborg, Paris climate promises will reduce temperatures by just 0.05 °C in 2100 (Press release), available at http://www.lomborg.com/press-release-research-reveals-negligible-impact-of-paris-climate-promises

[204] Lomborg, o.c., pp. 116-117.

[205] Bjorn Lomborg, False Alarm: How Climate Change Panic Costs Us Trillions, Hurts the Poor, and Fails to Fix the Planet, Basic Books, 2020.

[206] Joeri Rogelj, Michel den Elzen, Niklas Höhne, Taryn Fransen, Hanna Fekete, Harald Winkler, Roberto Schaeffer, Fu Sha, Keywan Riahi & Malte Meinshausen, Paris Agreement climate proposals need a boost to keep warming well below 2 °C, Nature, volume 534, pp. 631–639 (2016).

> // What this tells us is that even in an optimistic scenario, the Paris Agreement isn't going to come anywhere close to solving global warming. It will have a miniscule impact on the temperature by 2100. // **B. Lomborg**

The authors note that it is conceivable that "more can be achieved, because the agreement stipulates that targets for reducing greenhouse gas emissions are strengthened over time, both in ambition and scope."[207] Because countries do not spell out their emission reduction intentions for the entire period up to 2100, but only for the short term (typically, 10 to 15 years), researchers assessing the impact of NDCs on global warming over the entire century need to make assumptions about the levels of emission reductions during the period -that is not covered by NDCs. As Rogelj et al. explain, ***"[s]everal conceptual approaches can be followed to extend INDCs into the future, which basically assume that climate action stalls, continues or accelerates."***[208] Each of these assumptions leads to different global temperature outcomes based on the same INDC assessment for 2030. "It is therefore essential to spell out post-2030 assumptions to understand global temperature projections for the twenty-first century based on the INDCs," they conclude.

RESEARCH PERSPECTIVE

Scenario	Global-mean temperature rise by 2100 (in °C) that is not exceeded with the given probability		
	50%	66%	90%
No-policy baseline	4.1 (3.5-4.5) [3.1-4.8]	4.5 (3.9-5.1) [3.4-5.4]	5.6 (4.8-6.3) [4.2-6.8]
Current policy	3.2 (3.1-3.5) [2.7-3.8]	3.6 (3.4-3.7) [2.9-4.1]	4.4 (4.2-4.6) [3.6-5.2]
INDC (unconditional)	2.9 (2.6-3.1) [2.2-3.5]	3.2 (2.9-3.4) [2.4-3.8]	3.9 (3.5-4.2) [2.8-4.7]
INDC (conditional)	2.9 (2.6-3.1) [2.2-3.5]	3.0 (2.7-3.1) [2.2-3.6]	3.7 (3.3-3.9) [2.6-4.4]

For each scenario, temperature values at the 50%, 66% and 90% probability levels are provided for the median emission estimates, as well as the 10th -90th pecentile range of emissions estimates (in parentheses) and the same estimates when also including scenario projection uncertainly (in brackets). Temperature increases are relative to pre-industrial levels (1850-1900) and are derived from simulations with a probablistic set-up with the simple model MAGICC (refs 10, 68-70, Supplementary Text3)

Table 4.2. Estimates of global temperature rise for INDC and other scenarios categories

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[207] The Paris Agreement stipulates that in five-yearly intervals countries have to come forward with increasingly ambitious NDCs. These NDCs generally focus on the short term (about 1 decade to 15 years into the future). If one wants to estimate the long-term warming until 2100 from these short term NDCs, one needs to make assumptions on what happens after the time period for which the NDCs are explicit.

[208] Rogelj et al., o.c., p. 634 ("Stalling action is often modelled by assuming that emissions return to a no-climate-policy trajectory after 2030; continuing action by assuming that the level of post-2030 action is similar to pre-2030 action on the basis of a metric of choice (for example, extrapolating INDC trends in terms of carbon-price development or emissions intensity of the economy); and accelerating action by post-2030 action that goes beyond such a level.")

The literature reveals a wide range of estimates of future emissions under nominally similar scenarios. Possible confounders include modelling methods, input data and assumptions regarding country intent.

The authors distinguish between ***conditional and unconditional INDCs*** to reflect the fact that many countries subject their INDCs to conditions, such as the explicit requirement of financing being made available through the Paris Agreement's mechanisms. Assuming that climate action continues after 2030 at a level of ambition that is similar to that of the INDCs, the 2030 unconditional-INDC emission range is roughly consistent with a median warming relative to pre-industrial levels of 2.6–3.1 °c (median, 2.9 °c), with warming continuing its increase afterwards.

This should be compared to the current-policy baseline scenario, which suggests about 3.2 °c (median) of temperature rise by 2100 and the no policy scenario which projects about 4.0 °c (median) of temperature rise by 2100.

Thus, Rogelj et al. find that all of the unconditional INDCs jointly, ***assuming their stated near-term actions are continued with similarly ambitious targets through the entire century***, would result in a 0.3 °c reduction in temperature rise by 2100 compared to current policy, and a 1.1 °C reduction by 2100 compared to no policy.[209] If all conditional INDCs are successfully implemented, there could be an additional 0.2 °C reduction in temperature rise.

The authors warn that their numbers may be inaccurate due to confounding factors. They observe that any estimate of the impact of NDCs is uncertain. As they put it, "***the literature synthesized in this assessment reveals a wide range of estimates of future emissions under nominally similar scenarios***." Possible confounders include modelling methods, input data and ***assumptions regarding country intent***.[210] For example, a researcher may have to make assumptions related to the inclusion of land-use-related CO_2 removals in countries' NDCs.[211] A follow-up study[212] identified avenues to reduce this uncertainty through technical clarifications, but highlighted that some uncertainties depend on ***political choices about how NDCs are defined*** and can therefore not be easily eliminated.

The numbers reported by Rogelj et al. apply to all INDCs jointly, including the EU's contribution. Further, the EU's INDC is less ambitious than current policy, so we need to correct also for the EU's increased ambition. This what we do in the next section.

Derived Effect of EU Climate Neutrality on Average Global Temperature

Our focus is on assessing the **additional temperature reduction due to EU climate neutrality compared to current policy**, not total global warming (for which

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[209] Rogelj et al., o.c., p. 634.

[210] Rogelj et al., o.c., p. 633.

[211] Rogelj et al., o.c., p. 633.

[212] Rogelj, J., Fricko, O., Meinshausen, M., Krey, V., Zilliacus, J.J.J., Riahi, K., 2017. Understanding the origin of Paris Agreement emission uncertainties. Nature Communications 8, 15748. https://doi.org/10.1038/ncomms15748

the EU's historical CO_2 emissions are of importance). To compute the effect of the EU's climate neutrality ambition from the numbers presented above, we assume that the decrease in temperature will be linearly related to avoided cumulative carbon emissions and that emissions from various countries are additive. These assumptions are made throughout the literature, so we regard them as safe.

We also assume that there will be no 'carbon leakage' from the EU. If and to the extent that EU reductions are compensated by increases outside the EU due to EU production being moved to outside the EU, which, as discussed in this part of the report, is plausible if not likely, the EU efforts, of course, will have no or only a smaller reducing effect on the global temperature.

While Lomborg breaks out the EU effect, Rogelj et al. do not do so. This means that we need to allocate a share of the global effect to the EU. The EU's approximate current share of global emissions has been no more than 10 % since 2015 (the reference year used in the above-referenced publications).[213] This does not mean, however, that the EU contributes only up to 10 % to the global temperature reduction. If the EU contributes more than 10 % to the emission reductions resulting from the INDCs, its share of the global temperature reduction will be greater. Thus, we need to know how much the EU contributes to the INDCs. To estimate the EU's contribution, we use the ratio of 33 % based on Lomborg.[214]

The EU's INDC provides for 40 % emission reduction by 2030 (relative to 1990 levels). Under the proposed Climate Law, the EU would commit to 100 % reduction by 2050. Thus, assuming that the 20-year difference (2050 compared to 2030) has no effect,[215] EU climate neutrality will cause an additional temperature reducing effect of 100/40 = 2.5 times the EU INDC's share of total global reduction, minus the temperature-reducing effect arising from the EU INDC.

While Lomborg breaks out the EU's contribution to the global temperature reduction, Rogelj et al. do not. Using the 2100 global reduction computed by Rogelj as a starting point, we first need to compute the EU's share using Lomborg's ratio[216] and then increase that share, *pro rato*, to reflect the increased ambition (a factor of 2.5). From that number, we subtract the temperature reduction resulting from the EU INDC to arrive at the additional effect of EU climate neutrality. We can then linearly pro-rate these numbers to a 2050 reduction. To go from 2100 to 2050, we pro rate, linearly, with 2015 as baseline (as the research is as of 2015), thus, we pro rate at 35/85, with 35 = 2050-2015 and 85= 2100-2015.

Annex VII attached to this report provides further details on the numbers we used and the calculations. This annex also sets forth a verification of our results that is based on a different methodology, i.e. it assesses the amount of CO_2 reduction in tonnes and multiplies that amount by the temperature

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[213] Thus, if the EU reduces emissions in the same proportion as the global average reduction, the EU's contribution to the total temperature reduction will be no more than 10 %. The EU's share of global emissions is bound to drop, however, as the EU, being a developed nation, is expected to do more than developing nations, which will likely see their emissions rise.

[214] Bjorn Lomborg, Impact of Current Climate Proposals, Global Policy, Volume 7, Issue 1, February 2016, pp. 109-116. We acknowledge that the assumptions underlying the extrapolation emissions in the Lomborg study are not compatible with the assumptions in the Rogelj et al. study. Importantly, Rogelj et al. assume increasingly more ambitious climate action, while Lomborg does not make this assumption.

[215] Because the temperature outcome is defined by the global cumulative emissions over time, a 20 year period may be relevant. Note, however, that by ignoring this difference in timing we over-estimate, not under-estimate, the EU's contribution to average global temperature reduction, as we effectively assume that EU climate neutrality is achieved in 2030, so 20 years earlier than planned.

[216] As noted, the Lomborg study does not make the assumption that climate action will be increasingly more stringent, and, therefore, the two studies therefore are not comparable. For purposes of the calculations made here, however, the EU's ratio computed by Lomborg can provide us with a number derived from the Rogelj et al. study that is ballpark correct.

reducing effect per tonne, using two values for climate sensitivity.[217]

Based on this methodology, we arrive at the following main conclusions:

- ***EU 2050 climate neutrality, if achieved, will likely cause an additional decrease in the average global atmospheric temperature increase estimated at between 0.05 °C and 0.15 °C in 2100, and between 0.02 °C and 0.06 °C in 2050, assuming no carbon leakage occurs.***

Please refer to Table 4.3.

- Even if the EU achieves climate neutrality, under the then current policy scenario[218] used in this study, the global average atmospheric temperature would still increase with **approximately 3° C** (50 % probability).[219]

As noted above, like all estimates, these estimates are based on a series of assumptions.

It should be noted here too that the EU's plan to become the first climate-neutral continent in 2050 is merely aspirational; there is **no proven pathway** that will lead to this result.[221] Much depend on factors that the EU does not control, such as technological breakthroughs, demand for energy, the cost of moving towards climate neutrality, the general state of the economy (GDP), population growth, etc. So, the temperature-reducing effect presented will likely turn out not be realizable.

To fully grasp both ***the enormity and futility of the EU climate neutrality ambition***, however, the efforts required by EU and the global emission trends need to be understood in their international context. These are the topics of the several sections.

Study	Temperature reduction due to 2050 EU CN in 2050	Temperature reduction due to 2050 EU CN in 2100
Lomborg (2016) – number derived from author's numbers; for methodology see Annex VII of this report	0.02°C	0.05°C
Rogelj (2016) – number derived from authors' numbers; for methodology see Annex VII of this report	0.06°C	0.15°C

Table 4.3. Derived Temperature Reducing Effect of EU Climate Neutrality Relative to Current Policy[220]

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[217] Ideally, one would explicitly sketch out the assumed emissions path until 2100 starting from the current NDC and then compare this to a path where the EU gets to net zero GHGs in 2050 and continues that level until the end of the century. If the latter includes a sustained level of net CO_2 removal for part of the century, there may be a further EU contribution to reducing warming. The difference in cumulative CO_2 emissions between the current NDC path and the path indicated by the EU's 2050 net zero GHG goal can then be used to estimate the temperature reducing effect by multiplying it with the TCRE (i.e., the transient response to cumulative emissions of carbon). Annex VII pursues this calculation to verify the estimates through the 'rough and dirty' method employed there.

[218] We acknowledge that since the EU stated its intent to become climate neutral, other Paris Agreement signatories, including China, have issued similar statements. Whether their aspirations will be achieved, will not be known for a long time. Climate Action Tracker's assessment of China's most recent policy intentions is as follows: "President Xi Jinping has announced in September 2020 that China will strengthen its 2030 climate target (NDC), peak emissions before 2030 and aim to achieve carbon neutrality before 2060. China's COVID-19 response contains elements of a green recovery, showing an improved strategic deviation from the post-2008 financial crisis, but as yet lacks the policies and direction to set China on a low-carbon trajectory." Climate Action Tracker, China: Country Summary, available at https://climateactiontracker.org/countries/china/

[219] Note that this estimate is based on an assumption about climate sensitivity that was made at the time this research was conducted (i.e. 2016).

[220] The numbers set forth in this table are derived from numbers presented in the studies referenced, but have been calculated independently.

[221] While this is an issue with respect to many polices adopted by governments, it is a particular troublesome issue in relation to climate policy because of its scale, lack of diversification, extent of central planning, and the many problems caused by it that are ignored.

EU 2050 climate neutrality, if achieved, will likely cause a decrease in the average global atmospheric temperature increase estimated at between 0.05 °C and 0.15 °C in 2100, and between 0.02 °C and 0.06 °C in 2050, assuming no carbon leakage occurs.

II. EU Emissions, Global Emissions, and Carbon Leakage

The assessment of the reducing effect of EU climate neutrality on the average global temperature presented in the previous section assumed no carbon leakage – the EU's efforts will have its intended favorable effect on reducing the average global atmospheric temperature increase, if and only if no '**carbon leakage**' or 'outsourcing' occurs. There is a question, however, as to whether this assumption is realistic, since, thus far, carbon leakage seems to have occurred consistently. Indeed, carbon leakage might help to explain why global emissions continue to rise despite the significant (and costly) reductions in the EU.[222]

Even if the EU is able to prevent carbon leakage, when it achieves carbon neutrality in 2050, it may still find that its efforts were in vain, because **emissions from other countries increased due to development**, industrialization, and increased fossil fuel use in those countries. In this section, trends in global emissions of carbon dioxide and total greenhouse gases are reviewed, both for the EU and internationally. The objective is to develop a sound understanding of how these trends are likely to affect the EU's ambition to become the world's first climate neutral continent.

Global and EU Emissions

The **EU's share of global carbon emissions** has been **below 10 % for several years**.[223] According to the latest annual report by BP, the EU's share in 2019 was 9.7 %. Figure 4.1, shows a pie chart of the main emitters and their share of global emissions. In 2050, the EU's share of global emissions will likely have declined further, due to strong emission growth in the rest of the world, which, in turn, is expected based on economic growth in those countries and '**outsourcing**' of emissions from developed nations to developing nations. It is also important to realize that carbon dioxide is not the only concern.

CO_2 is only one of the greenhouse gases (GHGs) about which the EU is concerned. It is the main GHG at approx. 75 % of the total global emissions of GHGs. The GHGs covered by the EU climate legislation are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), nitrogen trifluoride (NF_3), hydrofluorocarbons (HFCs), and perfluorocarbons

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[222] "The European Union's Green Deal risks becoming a bad deal for the planet." Fuchs, Richard, Calum Brown & Mark Rounsevell, Europe's Green Deal offshores environmental damage to other nations, Nature, Vol. 586, October 2020, pp. 671-673.

[223] BP Statistical Review of World Energy 2019, https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

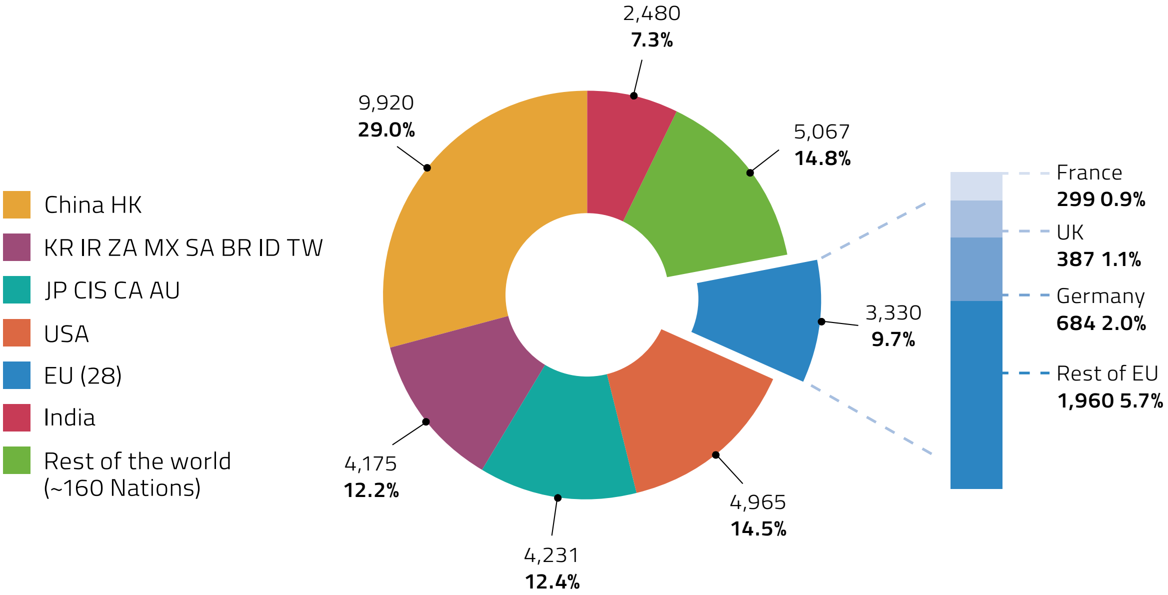

Figure 4.1. Annual CO_2 emissions[224]

(PFCs).[225] Figure 4.2., shows the approximate shares of each GHG. Figure 4.3., shows global greenhouse gas emissions by gas and source.

The potency, or **global warming potential (GWP), of GHGs differs**, however, and most GHGs have a GWP that (far) exceeds CO_2's GWP, which, by definition, is set at 1. The **CO_2 equivalent** of a GHG is used to convert its GWP to that of CO_2 – the amount of CO_2 that causes the same warming as this GHG is its CO_2 equivalent.

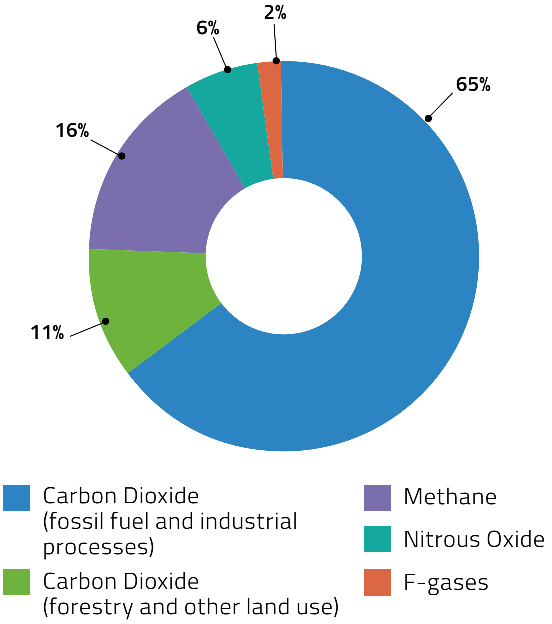

Figure 4.2. Global greenhouse gas emissions by gas:[226]

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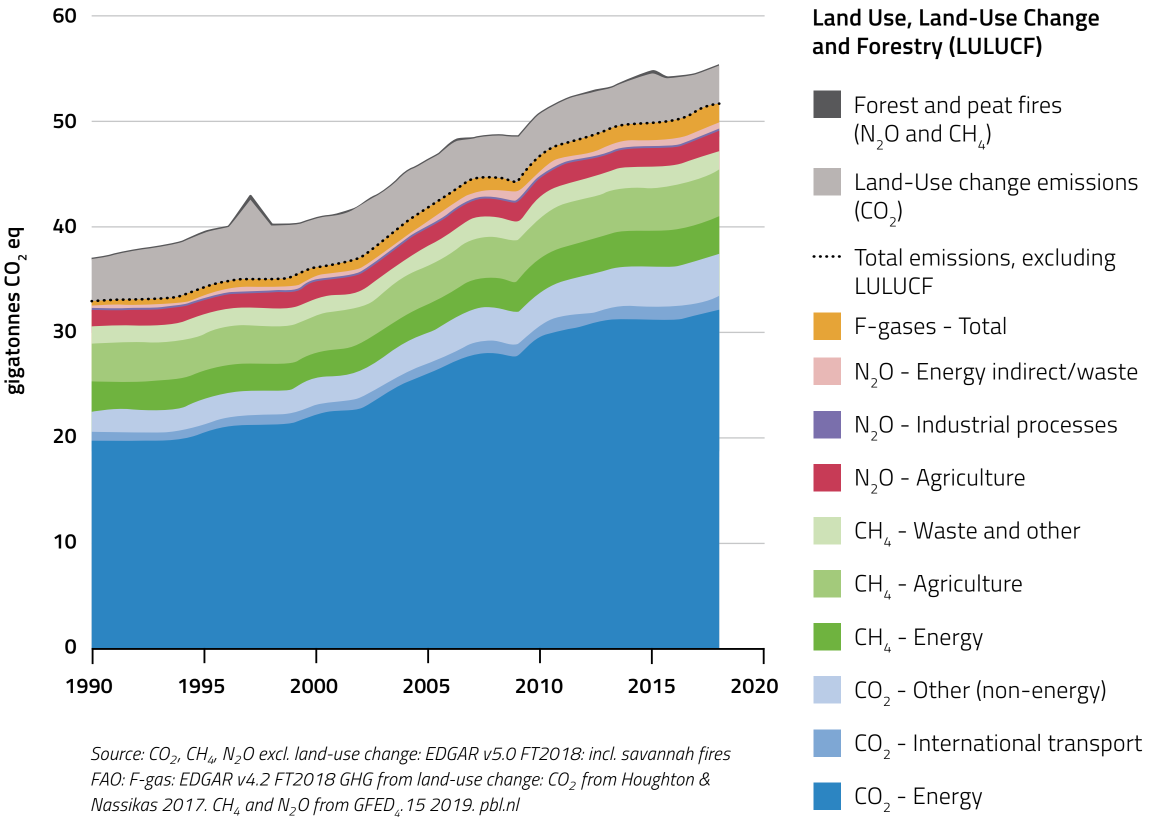
[224] Based on BP data

[225] Regulation 2018/1999, Annex V, Part 2.

[226] From: IPCC (2014) (based on global emissions from 2010), Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.



Source: CO_2, CH_4, N_2O excl. land-use change: EDGAR v5.0 FT2018: incl. savannah fires FAO: F-gas: EDGAR v4.2 FT2018 GHG from land-use change: CO_2 from Houghton & Nassikas 2017. CH_4 and N_2O from GFED$_4$.15 2019. pbl.nl

Figure 4.3. Global greenhouse gas emissions by gas and source:[227]

The trends in global GHG emissions are not favorable to the EU. Growth in global GHG emissions (excluding those from land use change) in 2018 was the **highest since 2011, increasing at a rate of 2.0 %,**[228] reaching 51.8 gigatonnes of CO_2 equivalent (GTCO$_2$ eq), with the **developing world steadily increasing.**[229]

- In 2018, the 2.0 % (1.0 GTCO$_2$ eq) increase in global GHG emissions was mainly due to a **2.0 % increase in global fossil CO_2 emissions** from fossil fuel combustion and those from industrial non-combustion processes including cement production.
- Global emissions of **methane (CH_4)** and **nitrous oxide (N_2O)** increased by **1.8 %** and **0.8%**, respectively. Global emissions of **fluorinated gases (F-gases)**[230] continued to grow by an estimated **6%** in 2018, thereby also contributing to the 2.0% growth in total GHG emissions.

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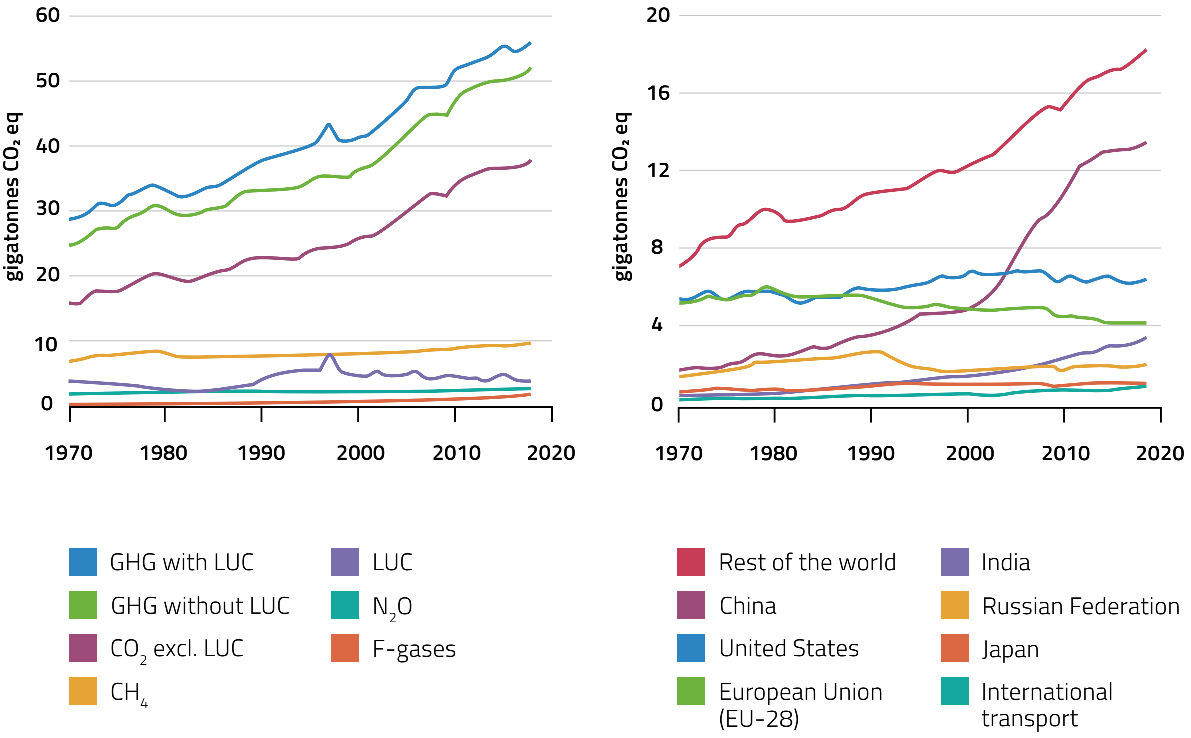
[227] J.G.J. Olivier and J.A.H.W. Peters, TRENDS IN GLOBAL CO_2 AND TOTAL GREENHOUSE GAS EMISSIONS -- 2019 Report, PBL, May 2020.

[228] OPEC predicts that “oil will remain the fuel with the largest share of the global energy mix until 2045,” “natural gas will be the fastest-growing fossil fuel between 2019 and 2045,” and “coal will be the only primary fuel for which demand declines between 2019 and 2045,” while renewables (including wind and solar) “retain the position of fastest growing source of energy in both relative and absolute terms.” Organization of Petroleum Exporting Countries (OPEC), World Oil Outlook 2020, available at https://woo.opec.org/pdf-download/index.php

[229] J.G.J. Olivier and J.A.H.W. Peters, TRENDS IN GLOBAL CO_2 AND TOTAL GREENHOUSE GAS EMISSIONS -- 2019 Report, PBL, May 2020.

[230] F-gases are regarded as very potent GHGs with high warming potential, and have been regulated by the EU. Regulation 517/2014 of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006, OJ L 150, 20.5.2014, pp. 195–230

The trends in global GHG emissions are not favorable to the EU. Growth in global GHG emissions (excluding those from land use change) in 2018 was the highest since 2011, increasing at a rate of 2.0%.



Global greenhouse gas emissions: per type of gas.

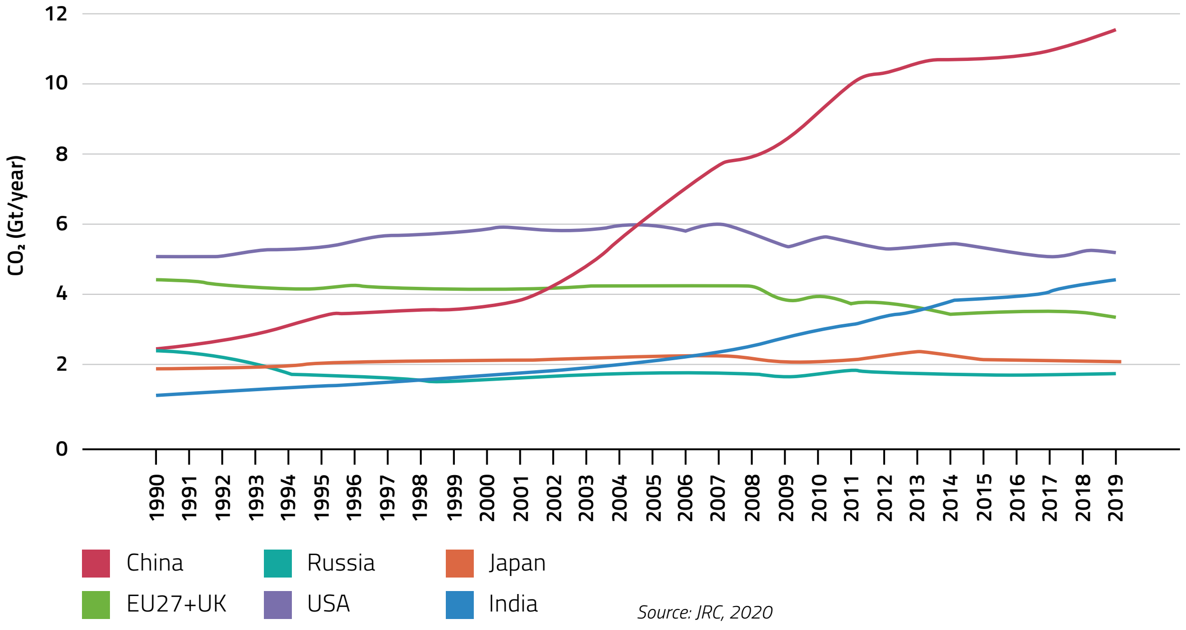
LUC = Land-use change, GHG = greenhouse gas
Source: GHG excl. LUC EDGAR v5.0 FT2018
LUC: Houghton and Nassikas 2017
pbl.nl

Global greenhouse gas emissions: top emitting countries and the EU.

Source: EDGAR v5.0 FT2018 (without land-use change). pbl.nl
both: F-gas: EDGAR v4.2 FT2018: incl. savanna fires.

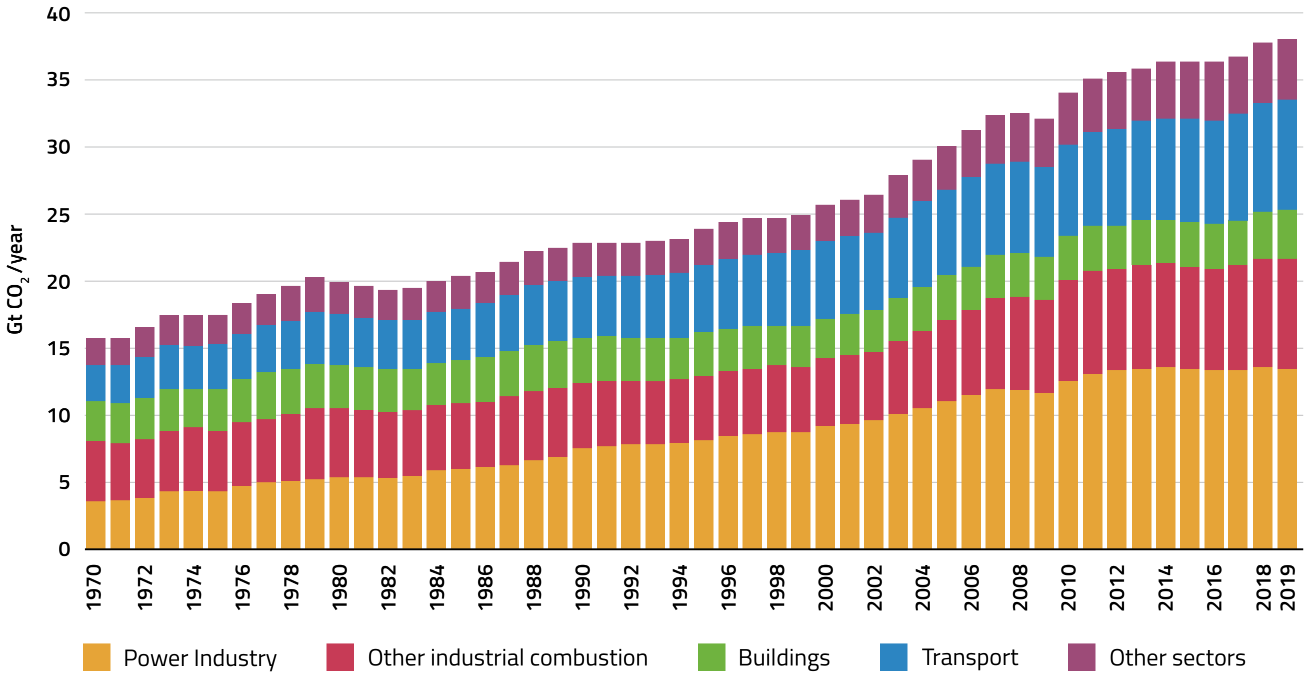
Figure 4.4. Global GHG emissions by type of gas and country:

- **Global consumption of oil products and natural gas continued to increase, by 1.2% and 5.3% in 2018**, led by increased consumption in China, the US, and Russia.
- The 2018 increase in global emissions followed **trends in primary energy demand and in the energy mix**. In 2018, energy demand increased by 22 EJ, which was met for 50% by fossil fuels and 50% by renewable and nuclear power.



Source: JRC, 2020

Figure 4.5. Fossil CO_2 emissions of the major emitting economies.

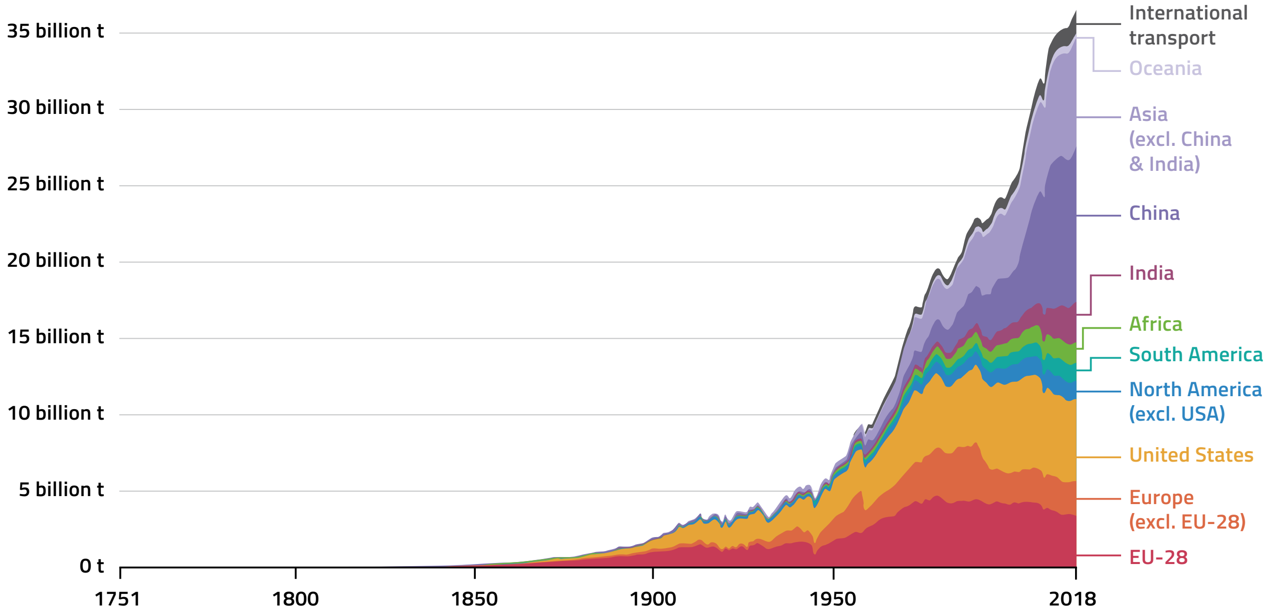


Total global annual emissions of fossil CO_2 in Gt CO_2/yr by sector. Fossil CO_2 emissions include sources from fossil fuel use, industrial processes and product use (combustion, flaring, cement, steel, chemicals and urea). *Source: JRC, 2020.*

Figure 4.6.Fossil CO_2 emissions from major emitting economies and by sector[231]

The EU can claim some success in the implementation of its policies, however. In the period 1990-2019, the ***EU has reduced emissions from fossil fuels by about 25%***. In fact, the EU and Russia are the only industrialized economies that have significantly reduced their fossil CO_2 emissions relative to their 1990 levels. The US and Japan show increased CO_2 emissions since 1990 by 0.8 and 0.4%, respectively. The ***emerging economies of China and India show strong emission growth*** with 2019 CO_2 emissions levels, respectively, 3.8 and 3.3 times higher than in 1990, due to rapid industrialization and 'outsourcing' effects. **Power generation is the largest source of emissions**.

In 2019, **global carbon emissions** from energy use **increased by at least 0.5%, despite a decrease in the EU**. According to JRC, the global emissions growth continued in 2019 with **global anthropogenic fossil CO_2 emissions increasing by 0.9%** compared to 2018, reaching 38.0 Gt CO_2. The increase was fueled by strong emission increases in **China (2.6%)** and, to a lesser extent, **India (1.8%)**; JRC reports an even higher growth rate with **China at 3.4%**.[232] Global CO_2 emissions have not yet peaked.



Source: Carbon Dioxide Information Analysis Center (CDIAC); Global Carbon Project (GCP)
Note: 'Statistical differences' included in the GCP dataset is not included here.
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions - CC BY

Annual total CO_2 emissions, by world region

Figure 4.6. Annual Total CO_2 Emissions [233]

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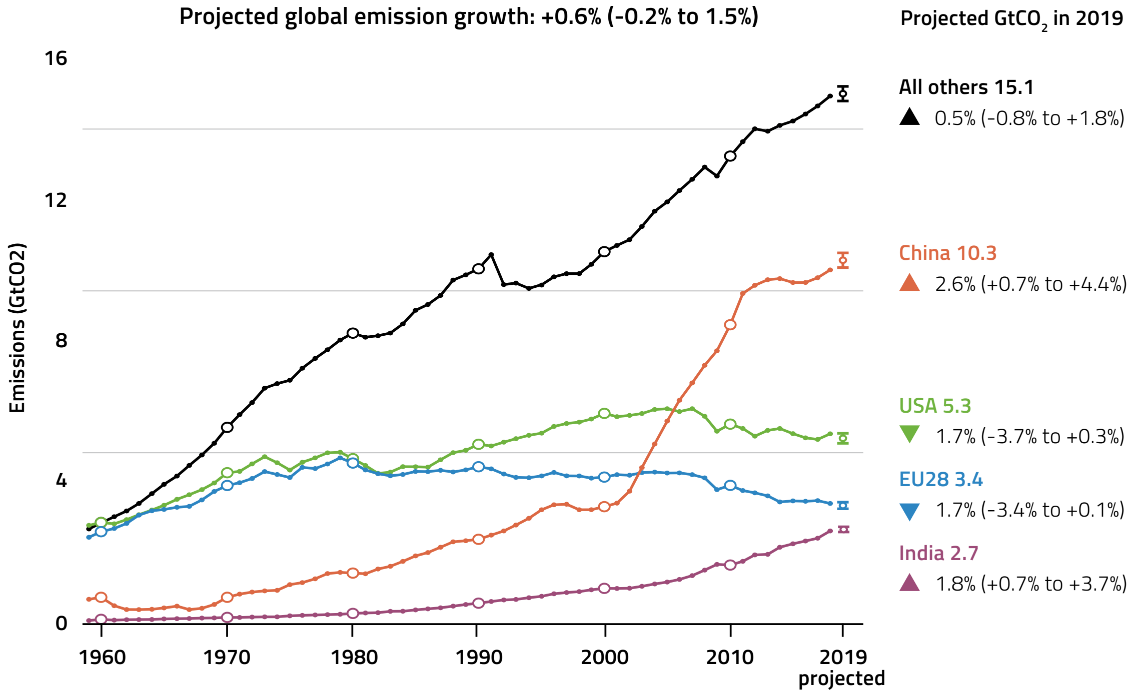
[231] Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J.G.J., Vignati, E., Fossil CO_2 emissions of all world countries - 2020 Report, EUR 30358 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-21515-8, doi:10.2760/143674, JRC121460.

[232] Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J.G.J., Vignati, E., Fossil CO_2 emissions of all world countries - 2020 Report, EUR 30358 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-21515-8, doi:10.2760/143674, JRC121460.

[233] Global emissions have not yet peaked, Our World in Data, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions



Annual fossil CO_2 emissions and 2019 projections

Figure 4.7. Annual Fossil CO_2 emissions 2019.[234]

Currently, as noted above, the EU's share of global carbon emissions is no more than 10%, and decreasing, while emissions from other countries are, in some cases rapidly, increasing, thus more than compensating for the EU's reductions. According to Global Carbon Budget, in the period 2000-2018, the EU's emissions decreased by 16%, but **China's emissions have tripled (+208%), and India's more than doubled (+155%)** (see Figure 4.8.).

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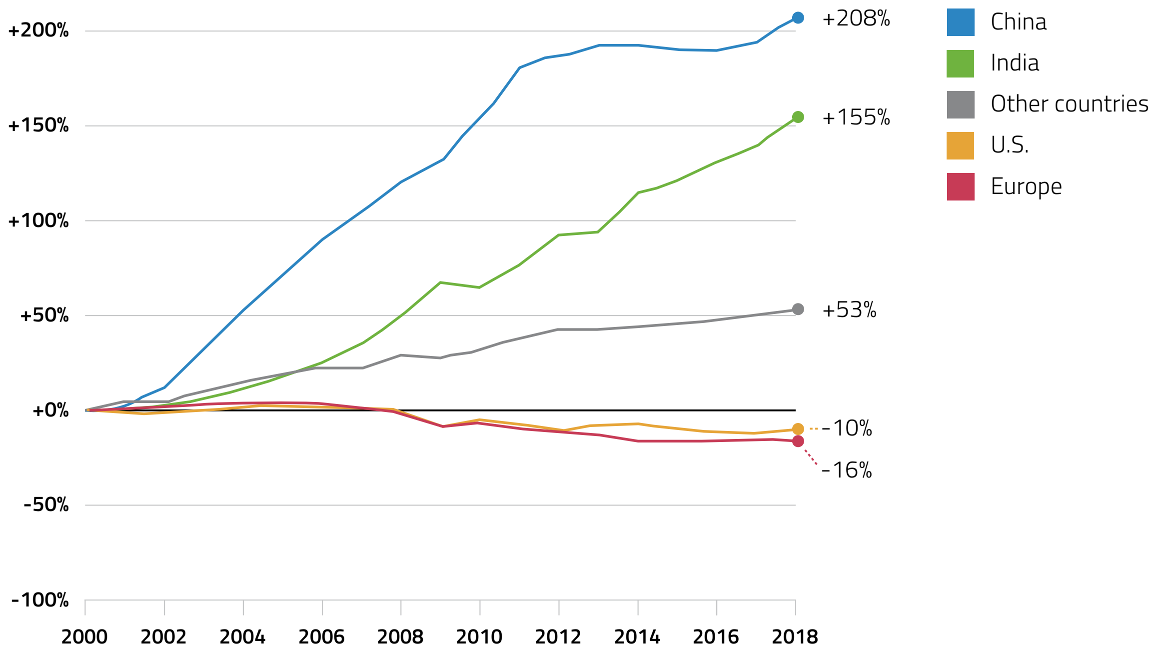
[234] G.P. Peters et al., Carbon dioxide emissions continue to grow amidst slowly emerging climate policies, Nature Climate Change, Vol. 10, January 2020, pp. 2–10.



How Carbon Emission Changed Since 2000 *Source: Global Carbon Budget 2018 ▪ Get the data*

Figure 4.8. Carbon emission changes by country since 2000.[235]

As a consequence of the continuing increase in global emissions, the **atmospheric concentration of carbon dioxide continues to increase**. This is a major concern, because a higher level of atmospheric carbon dioxide causes more forcing and thus higher atmospheric temperature. No peak concentration has been reached, and the CO_2 level shows no signs of peaking.

Since the increased atmospheric concentration of carbon dioxide, which is the main driver of global warming and climate change, is the problem the EU hopes to remedy through its climate neutrality policy, **this trend does not bode well for the EU's ambition**.[236]

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[235] Corinne Le Quéré et al., Global Carbon Budget 2018, Earth Syst. Sci. Data, 10, 2141–2194, 2018, https://doi.org/10.5194/essd-10-2141-2018

[236] It is true that countries representing a substantial portion of global emissions are committed to a climate neutrality policy, but the question is how strong these commitments are. If the past is representative of the future, the expectations should be tempered. International climate policy since 1990 has not had the effect of reducing global emissions or the atmospheric carbon dioxide concentration (see further below).

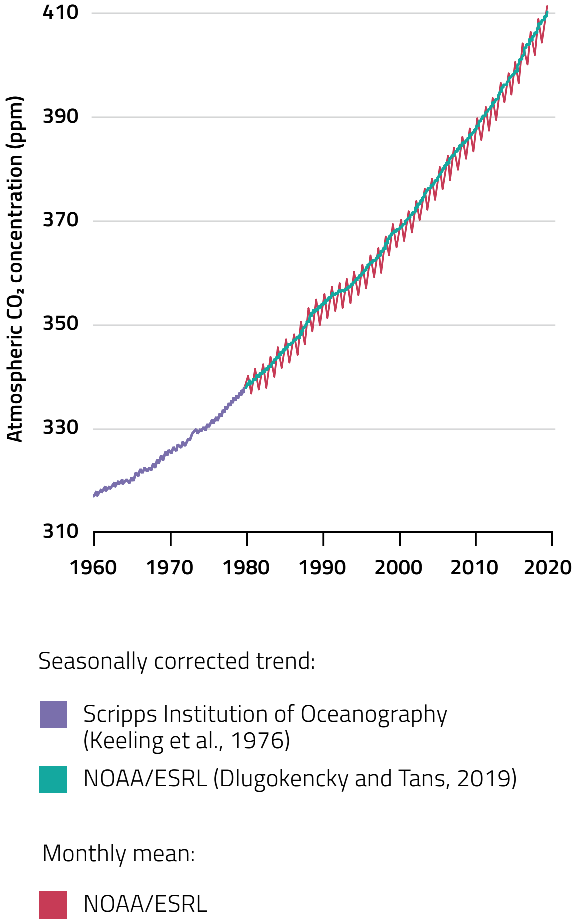

Figure 4.9. Atmospheric carbon dioxide concentration

MIT Research

We find further confirmation of these tentative findings in other climate science. As part of the MIT Joint Program on the Science and Policy of Global Change, a large group of climate scientists and other scholars regularly publishes outlook reports that assess global change, including climate change.[237] This group also estimates the impact of GHG emission reductions on the average global atmospheric temperature.[238] To project the global environmental impacts of COP21 and model emissions scenarios consistent with the 2 °c target, these researchers use a linked set of computer models designed to simulate the global environmental changes that arise due to human causes, and the latest U.N. estimates of the world's population. The models have been revised over time,[239] so the reports cannot easily be compared from year to year. Below, we review some pertinent findings of the Outlook reports from 2015, 2016, and 2018, which is the latest published report.

In its 2015 Outlook report, the MIT group states: "Assuming the proposed [COP21] cuts are extended through 2100 but not deepened further, they result in **about 0.2 °c less warming by the end of the century** compared with our estimates, under similar assumptions, for Copenhagen–Cancun."[240] Thus, their estimate is in line with the estimates discussed above.[241]

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[237] Massachusetts Institute of Technology, MIT Joint Program on the Science and Policy of Global Change, available at https://globalchange.mit.edu/

[238] Massachusetts Institute of Technology, The Joint Program on the Science and Policy of Global Change, 2016 Global Outlook: Exploring Global Challenges, MIT 2016, available at https://globalchange.mit.edu/publications/signature/2016-food-water-energy-climate-outlook

[239] Massachusetts Institute of Technology, The Joint Program on the Science and Policy of Global Change, 2018 Outlook: Food, Water, Energy, Climate, MIT 2018, available at https://globalchange.mit.edu/sites/default/files/newsletters/files/2018-JP-Outlook.pdf

[240] They added that "[o]ther adjustments in our economic projections resulted in another 0.2 °c reduction in warming," but their model recalibrations resulted in 0.2 °c more warming by 2100. Massachusetts Institute of Technology, The Joint Program on the Science and Policy of Global Change, 2015 Energy and Climate Outlook, MIT 2015, available at https://globalchange.mit.edu/publications/signature/2015-energy-and-climate-outlook

[241] The MIT's 0.2 C figure reflects the incremental effect of Paris in addition to previous commitments.

The 2016 Outlook report projected that global emissions will rise to 64 Gt carbon dioxide-equivalent (CO_2-eq) by 2050 and 78 Gt by 2100 (a 63% increase relative to 2010). This results in emissions projections for CO_2 concentrations at approximately 710 ppm by 2100, "with no sign of stabilizing."[242] **If Paris pledges are met and retained** in the post-2030 period, the authors predict, "**future emissions growth will come from the other G20 and developing countries**." Specifically, **by 2050, the developed countries account for approximately 15% of total global emissions**.[243] Thus, by 2050, the EU's emissions will not be a main driver of global warming, irrespective of whether the EU achieves carbon neutrality.

The researchers noted also that, "if nothing beyond the COP21 proposals is implemented, with high climate sensitivity, the **2 °c target may be exceeded in as little as 15 to 20 years from now**. Even with low climate sensitivity, on this path, the 2 °c target will be passed shortly after midcentury."[244]

In their latest report, 2018 Outlook, they repeat that the Paris pledges are inadequate by themselves to stabilize climate[245] – even if these pledges are met and retained in the post-2030 period with further emissions reductions, **future emissions growth will come from the Other G20 and developing countries**.[246] Consequently, even

Figure 2.0 GHG annual emissions by major group

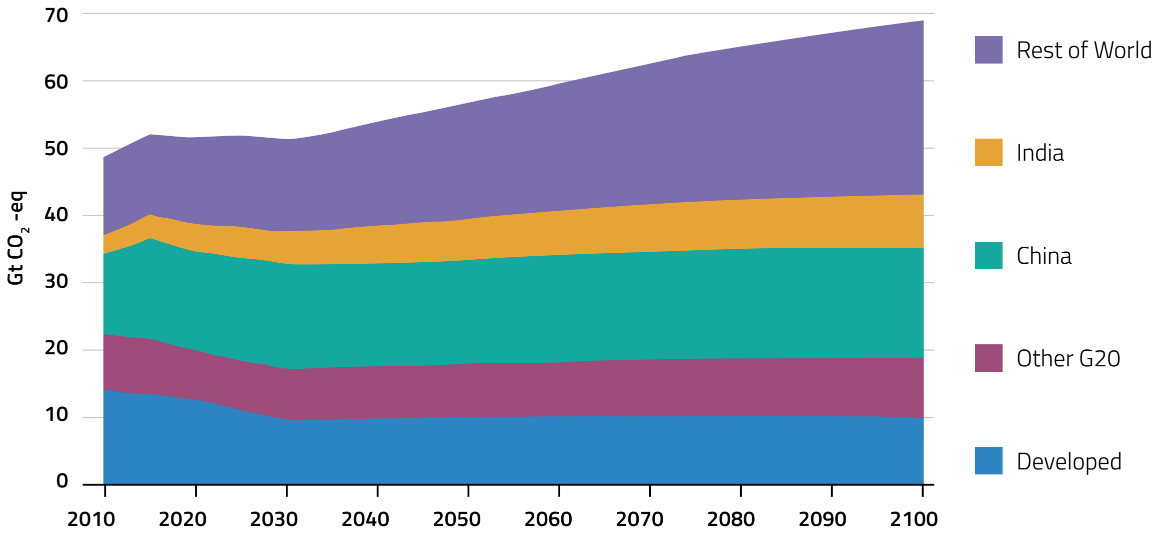

Figure 4.10. GHG Annual Emissions by Major Group (from: MIT 2018 Outlook)

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[242] 2016 Outlook, p. 9.

[243] 2016 Outlook, p. 5.

[244] 2016 Outlook, p. 5.

[245] "Given the representation of future technology in our model, we would deem the Paris pledges as inconsistent with even the 2 °c with a 50-50 chance. … It is hard to imagine a political process that would deliver this as a global policy, and if implemented, the sharp drop would leave stranded assets and likely cause other economic disruptions." 2018 Outlook, p. 6.

[246] "Global primary energy use rises to about 730 exajoules (EJ) by 2050, up from about 550 EJ in 2015. The share of fossil energy (coal, oil, gas) drops from about 84% in 2015 to 78% by 2050." 2018 Outlook, p. 5.

if current NDCs are extended throughout the century, “annual emissions of the major greenhouse gases are projected to increase from 52 gigatons (Gt) CO_2-e in 2015 to just under 69 Gt by 2100.”[247]

The projected median increase[248] in global mean surface temperature for Europe by 2100, is around **4 °c**. This is very far away from the 1.5 or 2 C target that the Paris Agreement has set.

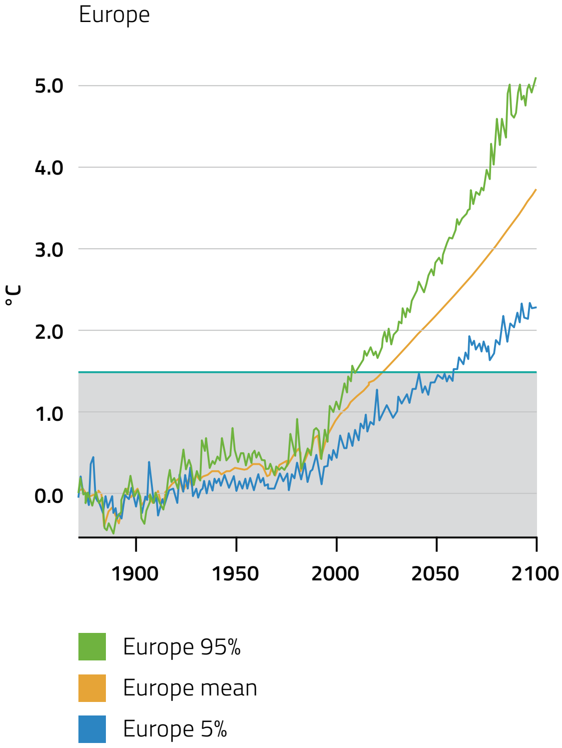

Figure 4.11. Annual mean surface air temperature for different regions relative to the 1861–1880 mean (from: MIT 2018 Outlook)

With respect to **energy technology** and **nuclear power**, the 2016 Outlook correctly emphasized the **role of innovation and government policy** on energy technology, where it stated:

“Depending on technological advances, the regulatory environment and public acceptance, a variety of different energy technologies could play a dominant role. The ***world could rely heavily on nuclear,*** renewables, biomass or carbon capture and storage (CCS), *or* ***some combination thereof.***”

They warn against putting all eggs in one basket, recommending “a **portfolio of research and development is needed** because we cannot predict which technologies may prove most successful.”[249] The 2016 Outlook contains a couple of figures showing what the global primary energy sources and electricity generation will look like “under a 2 °c scenario with base (median) assumptions about the costs of all technologies (as well as median climate response).” **Under these assumptions, the report demonstrates, nuclear energy becomes the dominate source of electricity across the globe**.[250]

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[247] 2018 Outlook, p. 5. “Annual emissions are fairly flat through 2030, and they gradually increase after that as regions of the world that have not adopted absolute emissions constraints see emissions increases.” “Global primary energy use rises to about 730 exajoules (EJ) by 2050, up from about 550 EJ in 2015. The share of fossil energy (coal, oil, gas) drops from about 84% in 2015 to 78% by 2050.”

[248] Above the 1861-1880 mean value.

[249] 2016 Outlook, p. 5.

[250] 2016 Outlook, p. 25.

Box 11.

Nuclear and the 2°C Challenge

Figures 27 and 28 show global primary energy and electricity generation under a 2°C scenario with base (median) assumptions about the cost of all technologies (as well as median climate response). Under these assumptions, nuclear energy becomes the dominate source of electricity across the globe. While such a rapid expansion of nuclear may seem unattainable, in fact we have seen such rapid expansion in the U.S. in tje 1970-80s as well as France in the 1980-90s. Of course, to reach this level globally, nuclear would need to overcome the many challenges addressed above. Even if the basic economics and technological issues around safety and proliferation with nuclear are resolved, society-at-large would likely need to be convinced that nuclear was a safe option, enabling streamlining of regulations for approving, sitting and construction "next generation" technology.

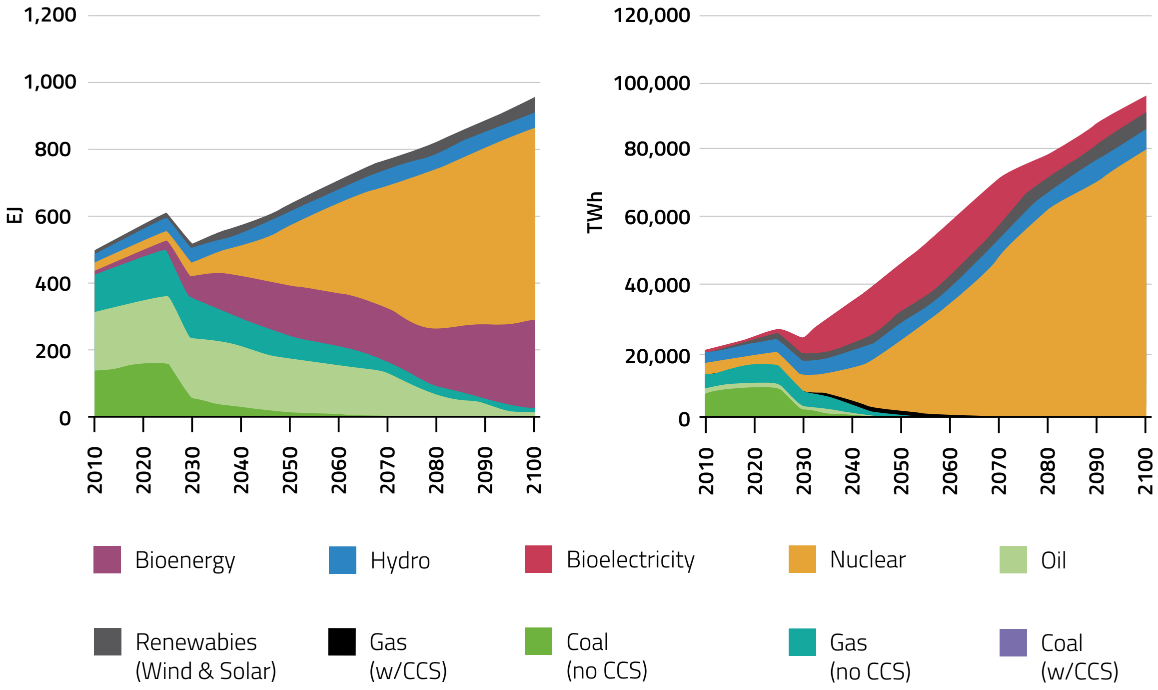
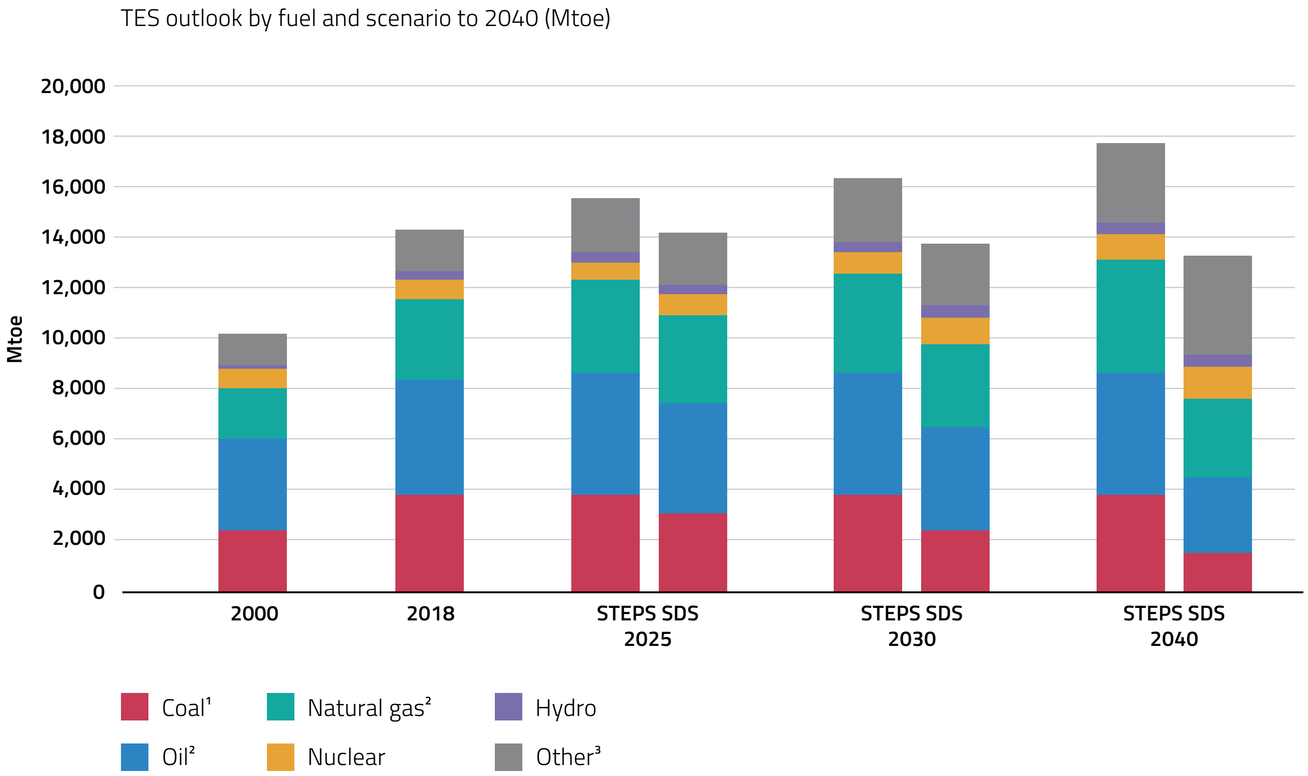


Figure 27. Global Primary Energy (exajoules) under the 2°C scenario with median assumptions about technology costs & median climate response

Figure 4.12. Nuclear and the 2 C Challenge (Box 11 from: MIT 2016 Outlook)

International Energy Agency
Another piece of corroboration comes from the International Energy Agency (IEA). In its World Energy Model, the IEA confirms that, based on existing and announced policies, which are described in the IEA Stated Policies Scenario (STEPS), "the world is not on course to achieve the outcomes of the UN SDGs most closely related to energy: to achieve universal access to energy (SDG 7), to reduce the severe health impacts of air pollution (part of SDG 3) and to tackle climate change (SDG 13)."[251] For 2025, 2030 and 2040, **the stated policies are way off from what these SDGs require** (see Figure 4.13.). Note that the first two SDGs require that poverty and hunger be ended, which implies economic development and, thus, the use of efficient power generation technologies.


TES outlook by fuel and scenario to 2040 (Mtoe)

STEPS: Stated Policies Scenario
Incorporates existing energy policies as well as an assessment of the results likely to stem from the implementation of announced policy intensions.

SDS: Sustainable Development Scenario[4]
Outlines an integrated approach to achieving internationally agreed objectives on climate change, air quality and universal access to modern energy.

Figure 4.13. IEA, Total Energy Supply (TES): [252]

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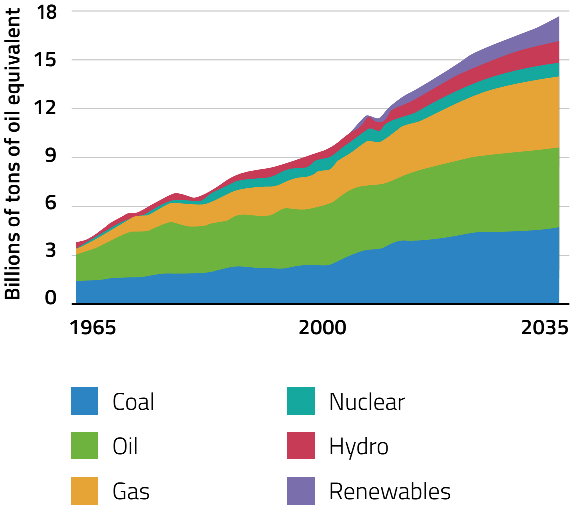
[251] IEA, World Energy Models, https://www.iea.org/reports/world-energy-model/sustainable-development-scenario

[252] International Energy Agency (IEA), Key World Energy Statistics 2020, available at https://www.iea.org/reports/world-energy-outlook-2019

Under current policies, the **IEA foresees a 26% increase of global energy consumption up to 2040**. This growth is expected to occur chiefly in India and Southeast Asia, while OECD countries are expected to stagnate in terms of energy consumption, and in Europe will likely even decrease.[253]

The ***drivers of global energy demand*** are ***population growth, urbanization (mega-cities), economic development, and related welfare increases***. As Kelly has pointed out, fossil fuels have continued to grow steadily at a rate about 7 to 8 times that of renewable technologies over the last 20 years.[254] The World Bank expects a further increase in the world population of 2.5 billion by 2035. With more and more people advancing to the middle classes,[255] ***global energy demand is bound to increase substantially***. As the figure 4.14., shows, ***BP estimates a further 40% growth in energy demand by 2035***, and ***most of this energy will be provided by fossil fuels***, with renewables only delivering about 10% of energy demand, which is less than one sixth of fossil fuel provision.



Source: BP.

Figure 7: Energy supply by type

From: Kelly, M., Energy Utopias and Engineering Reality

Figure 4.14. Energy by fuel/source

Intergovernmental Panel on Climate Change (IPCC)

The IPCC, which has been established pursuant to the UNFCCC, publishes assessment reports (ARs) on climate change, its causes, potential impacts and response options. Its next AR, AR6, is due to be released in 2021. The latest AR is AR5, which was published in 2014. The IPCC's findings also confirm the ineffectiveness of climate policy.

According to AR5, "human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history"[256] (see Figure 4.15.). Apparently, the IPCC could not discern any positive trend in global emissions of GHGs. It notes that "[l]imiting climate change **would require *substantial and sustained reductions*** in greenhouse gas emissions," but it could **not find evidence of any such reductions**.

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[253] IEA, World Energy Outlook 2019, November 2019, available at https://www.iea.org/reports/world-energy-outlook-2019 ("The Current Policies Scenario shows what happens if the world continues along its present path, without any additional changes in policy. In this scenario, energy demand rises by 1.3% each year to 2040, with increasing demand for energy services unrestrained by further efforts to improve efficiency. While this is well below the remarkable 2.3% growth seen in 2018, it would result in a relentless upward march in energy-related emissions, as well as growing strains on almost all aspects of energy security.")

[254] Kelly, Michael, Lessons from technology development for energy and sustainability, MRS Energy and Sustainability 2016, Vol. 3, pp. 2-13.

[255] A person in the middle class uses 3 to 4 as much energy as a poor person. Kelly, Michael, Energy Utopias and Engineering Reality, The Global Warming Policy Foundation 2019 Annual Lecture, London, 11 November 2019.

[256] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Mitigation and adaptation, AR5 states, could limit climate change risks. Thus far, however, mitigation has not had any desired effect. The reason for this lack of success is that the increases in anthropogenic greenhouse gas emissions since the pre-industrial era, are **"driven largely by economic and population growth,"** which are independent of climate policy. In this century, most of the growth is likely to occur in **developing nations**, which are **not required to reduce their emissions** and have **no incentives** to do so voluntarily, given the adverse impact on development.

The IPCC does not predict how GHG emissions will evolve in the course of this century, but it provides scenario projections. As AR5 states, "[p]rojections of greenhouse gas emissions vary over a wide range, depending on both **socio-economic development and climate policy**," and "[s]urface temperature is projected to rise over the 21st century under all assessed emission scenarios" (see Figure 4.16.). Thus, there is a **serious question over the effectiveness of climate policy**.

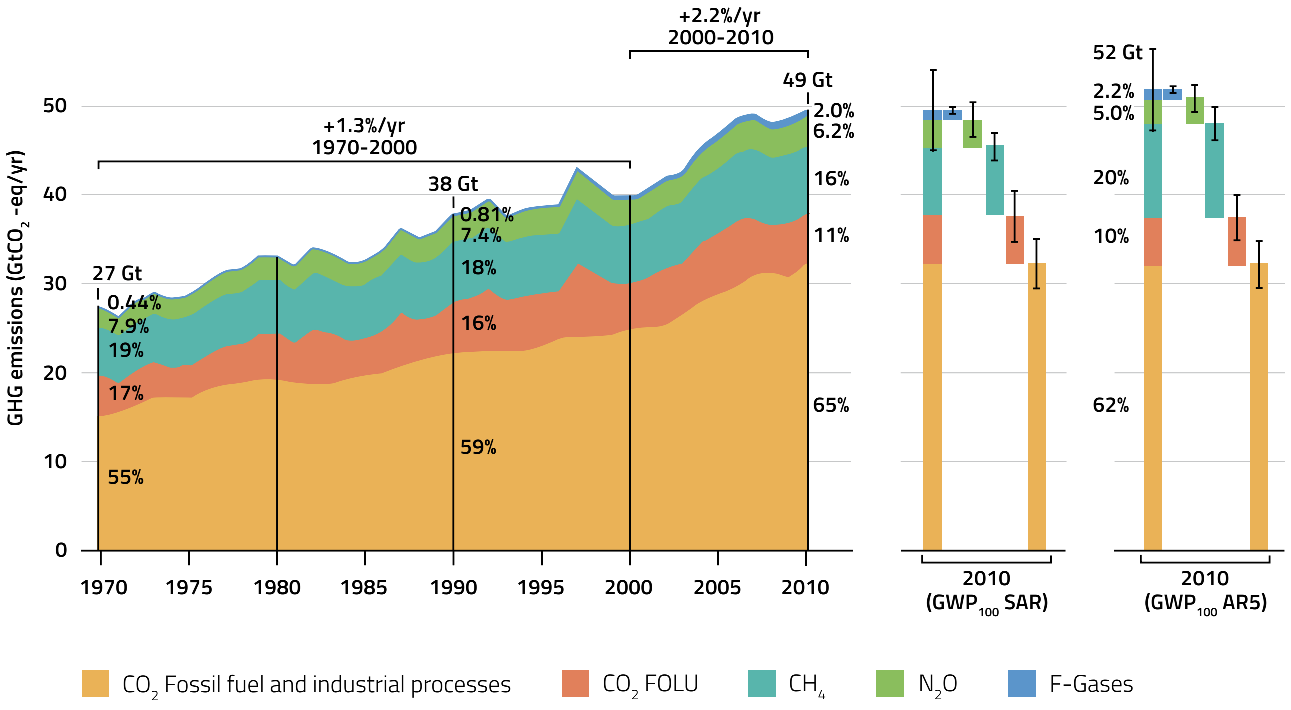
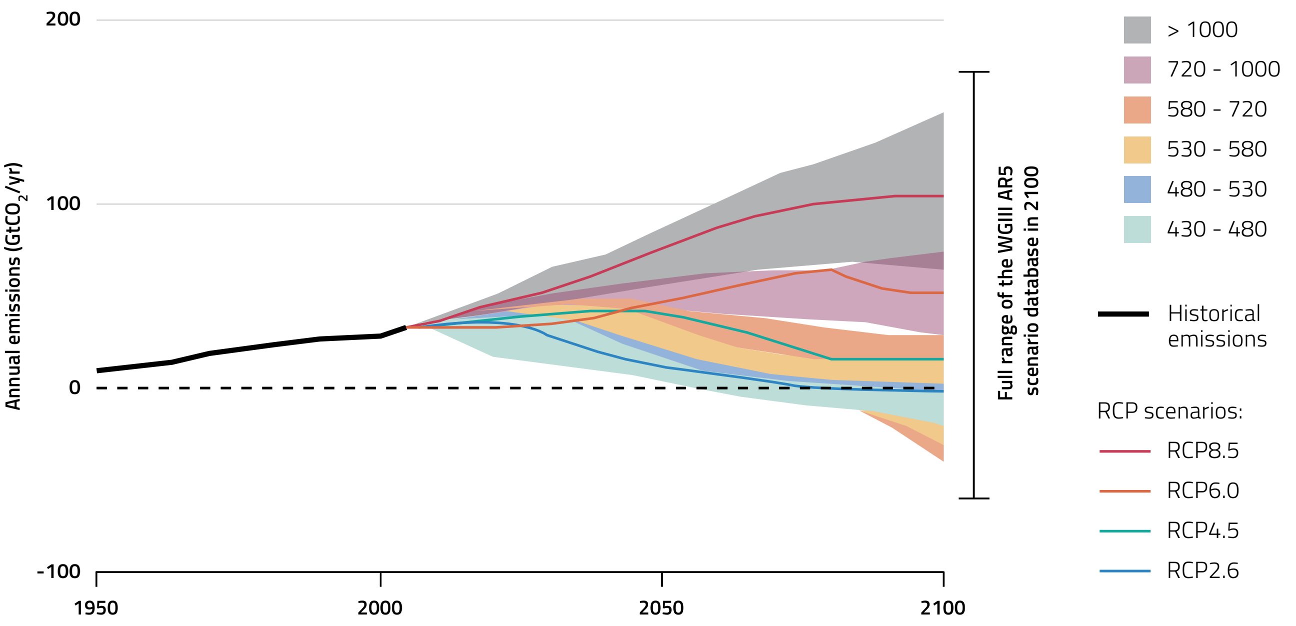


Figure SPM.2 | *Total annual anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO$_2$-equivalent per year, GtCO$_2$-eq/yr) for the period 1970 to 2010 by gases: CO$_2$ from fossil fuel combustion and industrial processes; CO$_2$ from Forestry and Other Land Use (FOLU); methane (CH$_4$); nitrous oxide (N$_2$O); fluorinated gases covered under the Kyoto Protocol (F-gases). Right hand side shows 2010 emissions, using alternatively CO$_2$-equivalent emission weightings based on IPCC Second Assessment Report (SAR) and AR5 values. Unless otherwise stated, CO$_2$-equivalent emissions in this report include the basket of Kyoto gases (CO$_2$, CH$_4$, N$_2$O as well as F-gases) calculated based on 100-year Global Warming Potential (GWP$_{100}$) values from the SAR (see Glossary). Using the most recent GWP$_{100}$ values from the AR5 (right-hand bars) would result in higher total annual GHG emissions (52 GtCO$_2$-eq/yr) from an increased contribution of methane, but does not change the long-term trend significantly. (Figure 1.6, Box 3.2)*

Figure 4.15. Anthropogenic Emissions of GHGs

(a) Annual anthropogenic CO_2 emissions



(b) Warming versus cumulative CO_2 emissions

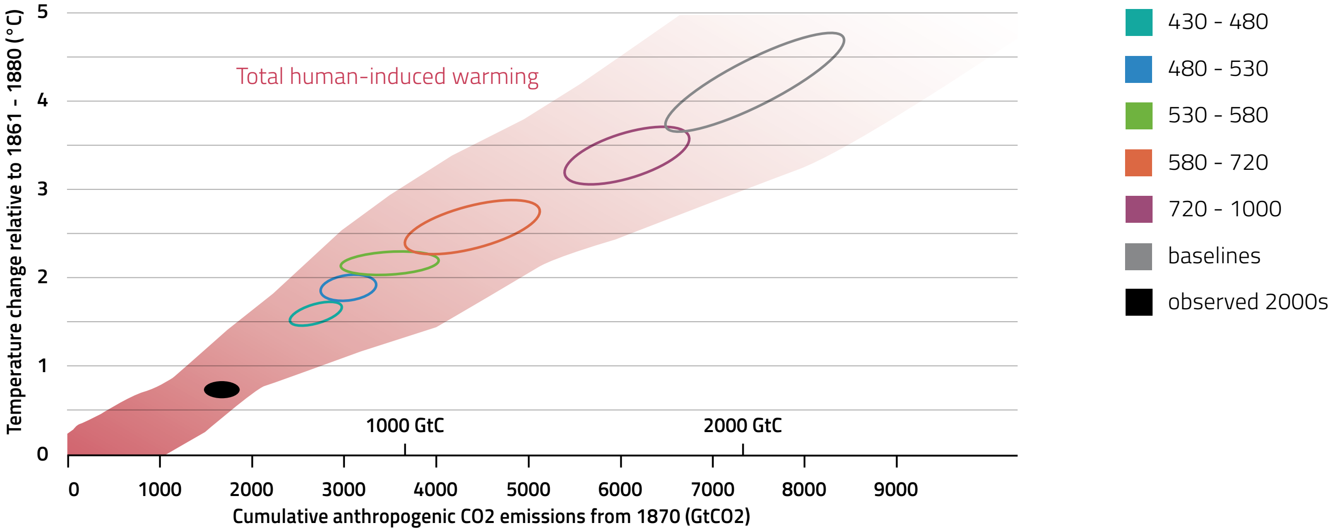


***Figure SPM.5** | **(a)** Emissions of carbon dioxide (CO_2) alone in the Representative Concentration Pathways (RCPs) (lines) and the associated scenario categories used in WGIII (coloured areas show 5 to 95% range). The WGIII scenario categories summarize the wide range of emission scenarios published in the scientific literature and are defined on the basis of CO_2 -eq concentration levels (in ppm) in 2100. The time series of other greenhouse gas emissions are shown in Box 2.2, Figure 1. **(b)** Global mean surface temperature increase at the time global CO_2 emissions reach a given net cumulative total, plotted as a function of that total, from various lines of evidence. Coloured plume shows the spread of the past and future projections from a hierarchy of climate-carbon cycle models driven by historical emissions and the four RCPs over all times out to 2100, and fades with the decreasing number of available models. Ellipses show total anthropogenic warming in 2100 versus cumulative CO_2 emissions from 1870 to 2100 from a simple climate model (median climate response) under the scenario categories used in WGIII. The width of the ellipses in terms of temperature is caused by the impact of different scenarios for non-CO_2 climate drivers. The filled black ellipse shows observed emissions to 2005 and observed temperatures in the decade 2000-2009 with associated uncertainties. (Box 2.2, Figure 1: Figure 2.3)*

Figure 4.16. GHG emissions and temperature increase

UNEP Emissions Gap

For the last 10 years, the United Nations Environment Program (UNEP) has been keeping track of the so-called '***emissions gap***,' i.e. the gap between where greenhouse gas emissions are heading against where they need to be. Its Emissions Gap Report 2019 presents the latest data on the expected gap in 2030 for the 1.5 °c and 2 °c temperature targets of the Paris Agreement.[257] In September 2019, UNEP published a special report on the lessons from a decade of emissions gap assessments, which reached the bleak conclusion that ***countries collectively failed to stop the growth in global GHG emissions***.[258]

The Emissions Gap Report 2019 reports that ***GHG emissions have risen at a rate of 1.5 per cent per year in the last decade***, stabilizing only briefly between 2014 and 2016.[259] Total GHG emissions, including from land-use change, reached a record high of 55.3 GTCO$_2$e in 2018. FAs expected, fossil CO$_2$ emissions, which dominate total GHG emissions, also grew 2.0 per cent in 2018, and reached a record 37.5 GTCO$_2$ per year. According to UNEP, there is **no sign of GHG emissions peaking in the next few years**, adding that "every year of postponed peaking means that deeper and faster cuts will be required."[260]

The report observes that **economic growth** has been much stronger in non-OECD countries, which grew at over 4.5 per cent per year in the last decade compared with 2 per cent per year in OECD countries. As a result of their stronger economic growth, non-OECD members have had stronger growth in primary energy use (2.8 per cent per year) than OECD members (0.3 per cent per year).

Under the heading "a decade lost," UNEP correctly observes that "[t]he current level of global GHG emissions is by now almost exactly at the level of emissions projected for 2020 under the business-as-usual, or no-policy, scenarios used in the Emissions Gap Reports, which are based on the assumption that no new climate policies are put into place from 2005 onwards." In other words, UNEP continues, "**essentially there has been no real change in the global emissions pathway in the last decade**. The effects of climate policies have been too small to offset the impact of key drivers of emissions such as economic growth and population growth."[261]

Carbon Leakage

The '**carbon leakage**' (or '**outsourcing**') effect of European climate policies should be distinguished from emission increases outside the EU that are not directly caused by EU climate policy. Put differently, emissions outside the EU can increase due to (i) the replacement of emitting industry in the EU by emitting industry outside the EU as a result of EU policies, and (ii) economic development, industrialization, welfare increase, and other causes unrelated to EU policies. In some cases, it might be hard to decide whether it is one or the other, but, in general, the distinction might have some validity.

Whether carbon leakage occurs can be demonstrated by accounting for both territorial emissions and the emissions associated with domestic consumption of imports. This has been done for the EU as a whole (see Figure 4.17.), and for the UK (see figures 4.18. and 4.19.). As the UK analysis demonstrates, much

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[257] UNEP, Emissions Gap Report 2019, available at https://www.unenvironment.org/resources/emissions-gap-report-2019

[258] UNEP, Lessons from a decade of emissions gap assessments, UNEP 2019, available at https://wedocs.unep.org/bitstream/handle/20.500.11822/30022/EGR10.pdf

[259] UNEP, Emissions Gap Report 2019, available at https://www.unenvironment.org/resources/emissions-gap-report-2019

[260] According to UNEP, "by 2030, emissions would need to be 25 per cent and 55 per cent lower than in 2018 to put the world on the least-cost pathway to limiting global warming to below 2°C and 1.5 °c respectively."

[261] UNEP, Lessons from a decade of emissions gap assessments, UNEP 2019, available at https://wedocs.unep.org/bitstream/handle/20.500.11822/30022/EGR10.pdf

of the emission reduction within the UK is undone by emission increases outside the UK associated with the production of goods for the UK market. Specifically, while in 2017, emissions relating to the consumption of goods and services produced in the UK were 31 per cent lower than in 1997, **GHG emissions relating to imports rose 49 per cent from 1997 to a peak in 2007, and in 2017 were 18 per cent higher than in 1997.**[262] In 2017, emissions relating to the consumption of goods and services produced in the UK were 31 per cent lower than in 1997.

For the EU as a whole, data are reported by UNEP.[263] The UNEP Emissions Gap Report 2019 provides "consumption-based emission estimates, also known as a carbon footprint, that adjust the standard territorial emissions for imports and exports." As expected, this data shows that "the net flow of embodied carbon is from developing to developed countries." The consequence of this flow is that "even as developed countries reduce their territorial emissions this effect is being partially offset by importing embodied carbon."[264] In simple terms, **once corrected for import-related emissions, EU per capita emissions go up, and Chinese per capita emissions go down**.

Figure ES.3. CO_2 emissions allocated to the point of emissions (territorial) and the point of consumption, for absolute emissions (left) and per capita (right)

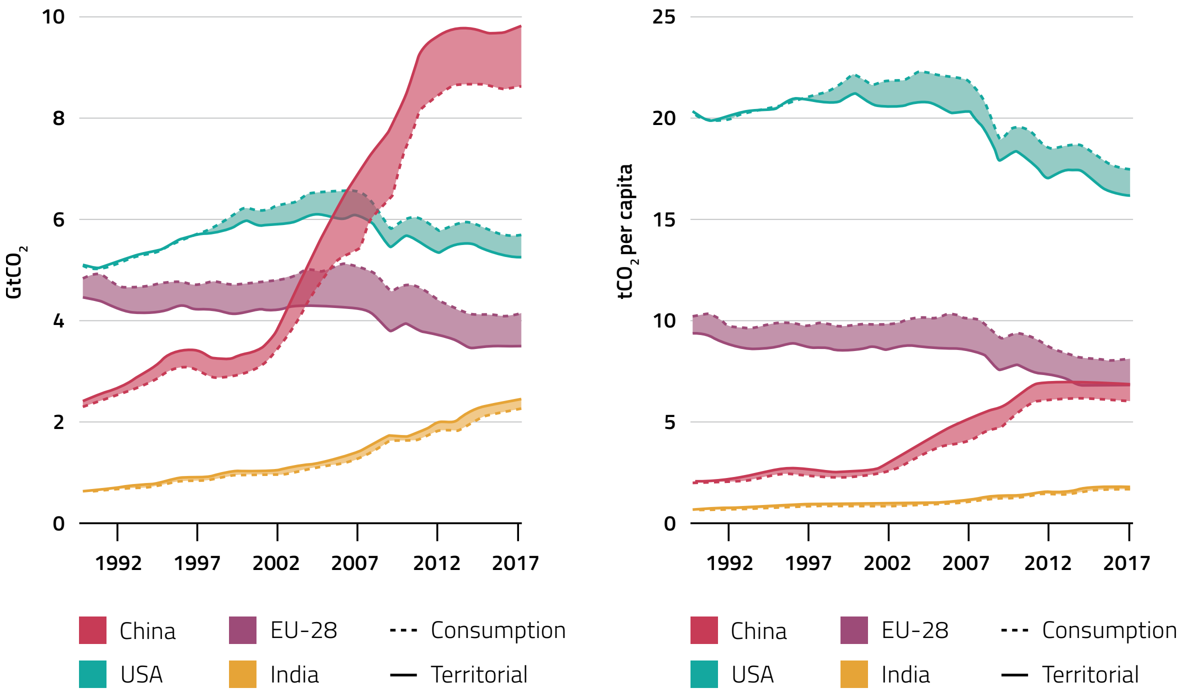

Figure 4.17. Import-Related CO_2 Emissions

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[262] Emissions associated with imports from China also showed a peak in 2007. In 2017 they were 260 per cent higher than in 1997. Id. Cf. Brunel, Claire, Pollution Offshoring and Emission Reductions in EU and US Manufacturing, Environmental and Resource Economics, 2017-11, Vol.68 (3), pp. 621-641.

[263] UNEP, Emissions Gap Report 2019, available at https://www.unenvironment.org/resources/emissions-gap-report-2019

[264] UNEP, Emissions Gap Report 2019, available at https://www.unenvironment.org/resources/emissions-gap-report-2019

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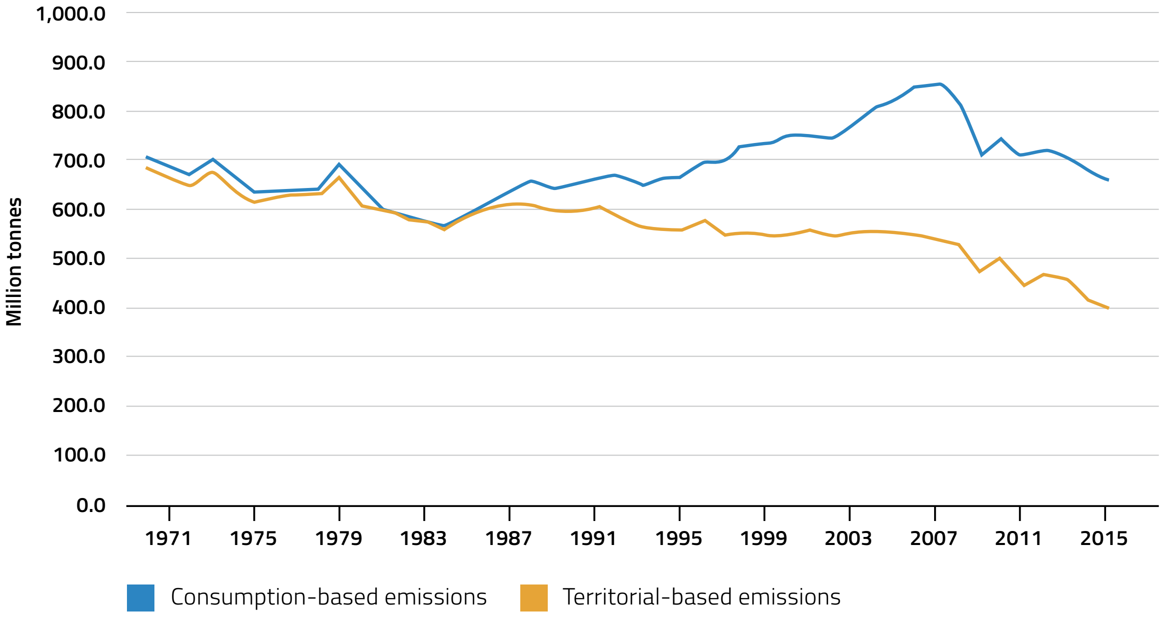

Figure 4.18. Decoupling of GDP per head from CO_2 emissions seems to have happened at the expense of outsourcing manufacturing:[265]

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[265] UK Office for National Statistics, The decoupling of economic growth from carbon emissions: UK evidence, https://www.ons.gov.uk/economy/nationalaccounts/uksectoraccounts/compendium/economicreview/october2019/thedecouplingofeconomicgrowthfromcarbonemissionsukevidence

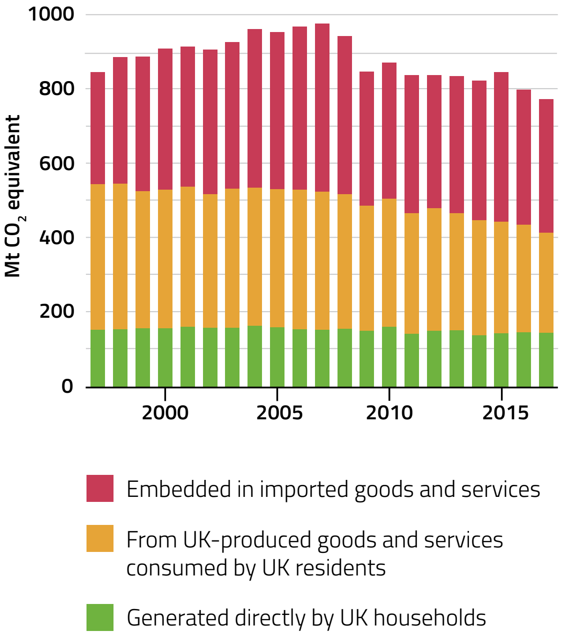

Figure 4.19. Total GHG emissions associated with UK consumption[266]

Rather than merely moving emissions to outside the **EU, carbon leakage may result in emission increases** per unit of production. For instance, in the UK, all but one of the aluminium smelters that used gas-fired electricity were closed, but the UK then started importing aluminium from China where the smelters use coal-based sources of energy.[267] As a result, **while the UK emissions decreased, global emissions increased**.

In addition to the carbon leakage effect, as discussed above, economic development in non-EU countries may add to their emissions. This suggests that ***EU climate neutrality***, even if achieved, will have ***very little effect on the average global temperature increase***. Other, non-EU nations, including developing nations, have no obligation to reduce their emissions, as further discussed below, and the EU has no way to force them to do so.

Thus, the EU's efforts will probably not achieve their objective. Given that the EU has very little or no control over non-EU nations' emissions, it can only use **diplomacy** and **economic incentives** to get them to change their policies; e.g. the EU can offer to pay for non-EU countries' reduction efforts, or impose carbon taxes on imports into the EU (the so-called "***carbon border adjustment tax***"). Given the enormous value of economic development of major economies in Asia, Africa, the Middle East, and South America, there is no way that diplomacy and economic incentives can be

EU climate neutrality, even if achieved, will have very little effect on the average global temperature increase. Other, non-EU nations have no obligation to reduce their emissions, and the EU has no way to force them to do so. Developing nations have a right to develop their economies. Thus, the EU's efforts will probably not achieve their objective.

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[266] UK Defra, UK's Carbon Footprint 1997-2017, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/918325/Consumption_emissions_March_20_fullycompatible.pdf

[267] Kelly, Michael, Lessons from technology development for energy and sustainability, MRS Energy and Sustainability 2016, Vol. 3, pp. 2-13.

expected to have more than a **negligible influence**. Thus, as the EU and national policies have produced modest reductions in carbon emissions thus far, and emissions from the rest of the world continue to increase, with **no peak in sight**, there is a substantial risk that the EU's efforts, even if successful, will have little or no effect.

III. Renewable Energy and the Road to Climate Neutrality

We can look at the issue of EU climate neutrality also from a different angle. The EU contemplates that the energy transition will imply total decarbonization and an energy system composed almost entirely of renewable energy sources, to be achieved by 2050. We take this ambition as point of reference and ask:

What is the necessary rate of deployment of renewable energy to arrive at zero CO_2 emissions in 2050 in the EU and worldwide?

This should give us a good idea of the road ahead, and whether it looks like the objective is achievable.

To answer the question, we take the average rate of addition of renewable energy over the last 12 years, and assume a linear trajectory. Under these assumptions, the following requirements would have to be met for the EU and the rest of the world to have an entirely renewable energy system by 2050:

- For the **world to achieve a 45% reduction in 2030**, it needs to increase the rate of annual addition of renewables by a **factor of 16**, i.e. each year, 16 times as much renewable must be added annually as has been added on average during the last 12 years;

- For the world to achieve a **45% reduction in 2050**, it needs to increase the annual addition of renewables by a **factor of 10**;

- For the **EU to achieve zero emissions by 2050**, it needs to increase the annual addition of renewables by a **factor of 4**, assuming the energy demand drops by 0.7% annually (which is not a given);

- For the **EU to achieve zero emissions by 2050**, it needs to increase the annual addition of renewables by a **factor of 7**, assuming the energy demand increases by 1.2% annually (which is a realistic possibility).[268]

Even though this is a huge mountain to climb, the biggest problem may not even be the expansion of the renewable energy system. The ***biggest problem probably will be retiring fossil fuels within the same time frame***. Because there probably can be no climate neutrality unless the combustion of fossil fuels stops completely by 2050. This is the topic of the next section.

Before we move on, we note a further complication here -- the dynamics of the world economy. Even if the rest of the world also installs high levels of renewable energy quickly, it does not follow that, in a dynamic economy, GHG emissions will drop and, thus, the temperature increase will be limited to the wishes of the parties to the Paris Agreement on Climate Change. This is so because the effects outside the energy system, in the broader economic system, may offset any savings made through the deployment of renewable energy. As a 2019 study demonstrated,

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[268] Based on the BP Statistical Review of World Energy, published in June 2020, we calculated for both the world and Europe, the compound annual growth rate of primary energy consumption over specific time periods. Based on those growth rates, we projected primary energy consumption into the future. Looking at the 2019 levels of primary energy consumption from fossil fuels and renewables, we were able to estimate how much more renewables need to be added. Based on the average addition of renewable energy sources over the last twelve years, we estimated the rate of acceleration in renewable energy addition annually to meet the objectives. See BP, Statistical Review of World Energy, 2020, available at https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf.

both renewable and nonrenewable energy contribute to carbon dioxide emissions in the countries studied in the long run.[269] Economic growth and urbanization have negative effects on carbon dioxide emissions – specifically, 1% of GDP growth leads to increases of 1.3% and 1.82% in emissions in the short, respectively long run.[270]

IV. Taking Climate Neutrality Seriously: Fossil Fuel Purchase Program

Thus far, the EU's emissions reduction efforts have been ineffective, because the **use of fossil fuels continues unhindered in large parts of the world** and, to lesser extent, within the EU itself. In the EU, the necessity of back-up for intermittent renewable electricity generation, combined with an averseness to nuclear energy, prevents the rapid phase-out of fossil fuel power generation. With the demand for fossil fuel in the Western world declining, prices on the world markets are likely to drop (all else equal) and fossil fuels will become more affordable for developing countries. This will allow them to consume more fossil fuels, and grow their economies, which, in turn, will further stimulate the demand for fossil fuels.[271]

If the EU is serious about climate neutrality, an effective remedy would be purchasing the world's reserves of fossil fuels so that they can be retired definitively. After all, emission increases in non-EU countries can only be effectively prevented if no fossil fuels are available to these countries. To be sure, we do not want to suggest that any policy maker has made a proposal to this effect. That is not the point we want to make. Rather, the cost associated with purchasing the world's fossil fuels should give us a good idea of ***the (minimum) cost of a probably effective climate neutrality program***.[272] In addition, it also demonstrates the ***economic value of fossil fuels***, which helps to explain why it is so hard to retire them.

We proceed to determine the cost of this fossil fuel purchase program. The program's objective is to prevent fossil fuel emissions anywhere in the world by buying up, over the period from now to 2050, **all fossil fuels (oil, gas, coal/lignite), and retiring them definitively**. Annex VIII attached to this report provides the details of our calculations. These are the main conclusions:

- If there are no fossil fuels other than the currently known reserves, at current market price levels, the total cost of this purchasing program will be **at least €109,000,000,000,000**, which is approximately **7 times the entire EU's annual GDP** and equals to €560,000 per EU household.[273]

- Assuming the buying will be linear over 30 years, the **EU would have to spent approximately a quarter of its GDP on fossil fuel purchasing** every year, which is **more than 20 times the 2019 EU budget (of €165 billion), every year, starting in 2021 up to and including 2050**.

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[269] Samuel Adams, Christian Nsiah, Reducing carbon dioxide emissions; Does renewable energy matter?, Science of the Total Environment 693 (2019) 133288.

[270] Samuel Adams, Christian Nsiah, Reducing carbon dioxide emissions; Does renewable energy matter?, Science of the Total Environment 693 (2019) 133288.

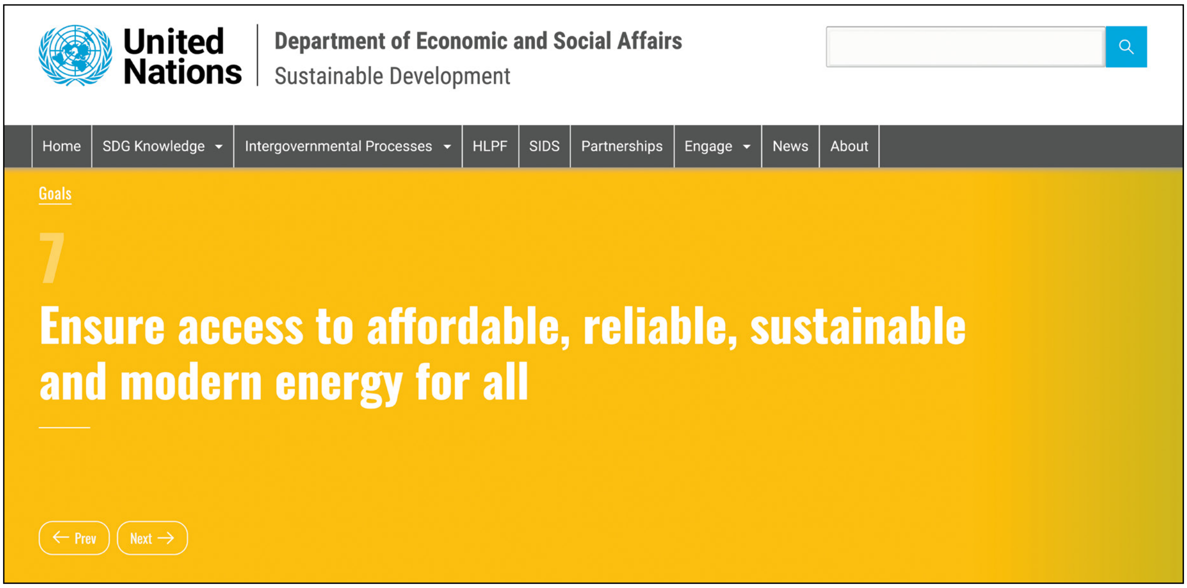
[271] Cf. Sinn, Hans-Werner, The Green Paradox: A Supply-Side Approach to Global Warming, MIT Press, 2012.

[272] Adverse substitution effects may occur, if, instead of fossil fuels, wood and other biomass are combusted for energy. If this results in deforestation, carbon dioxide will be added to the atmosphere, but not subsequently removed, undermining EU climate neutrality objectives.

[273] There are approx. 195 million households in the EU. Eurostat, Household composition statistics, available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Household_composition_statistics. On a per capita basis, given that the EU has approximately 450 million citizens, this represents an expense of roughly €250,000 per citizen. World Bank, https://data.worldbank.org/region/european-union, population statistics as of 2019.

The humungous cost of such a program demonstrates that achieving global climate neutrality will be problematic. Given that economic value of fossil fuels renders any purchasing program wholly unrealistic, there is a high probability that **EU climate neutrality will not have the desired effect,** assuming that developing nations will not voluntarily abstain from using fossil fuels (which is a safe assumption).[274]

Even if such a program were feasible, however, it would raise serious concerns from **developing nations**. Under the United Nations Sustainable Development Goals, developing nations have been promised an end to poverty and hunger, "**access to affordable, reliable, sustainable and modern energy for all**"[275] and **industrialization**.[276] These goals are ranked higher than the fight against climate change.[277] Given the relative costs and efficiency of technological options, fossil fuels contribute much more to economic development than renewable energy, begging the question as to why developing nations should forego these benefits without compensation.



Ensure access to affordable, reliable, sustainable and modern energy for all

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274 We do not believe that precedents such as the successful international programs against whaling and for the phase-out of CFCs pursuant to the Montreal Protocol, are representative for the situation we face with versatile fossil fuels. Much more so than CFCs and products derived from whales, fossil fuels are drivers of economic development in a number of key areas. Cf. Epstein, Alex, The Moral Case for Fossil Fuels, Penguin, 2014.

275 United Nations, SDG number 7, available at https://sdgs.un.org/goals/goal7

276 United Nations, SDG number 9, available at https://sdgs.un.org/goals/goal9 ("Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.)

277 United Nations, SDG number 13, available at https://sdgs.un.org/goals/goal13

Taking Climate Neutrality Seriously – If the EU is serious, it should purchase all world reserves of fossil fuels and retire them indefinitely.
At current market price levels, the total cost will be at least €109,000,000,000,000, which is approximately 7 times the entire EU's annual GDP and equals €560,000 per EU household.
Assuming the buying will be linear over 30 years, the EU would have to spent approximately a quarter of its GDP on fossil fuel purchasing every year, which is more than 20 times the 2019 EU budget (of €165 billion), every year, starting in 2021 up to and including 2050.

Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

From: United Nations, Sustainable Development Goals[278]

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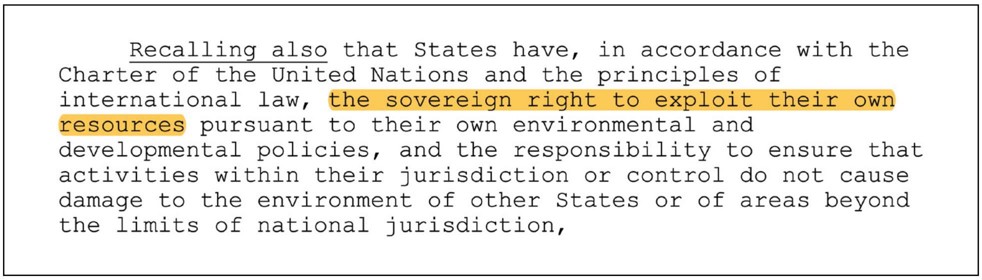
[278] United Nations, SDG, available at https://www.un.org/sustainabledevelopment/

In the next section, we consider how the international context is likely to affect EU attempts to force non-EU countries to reduce their emissions. After all, given the value of economic development, it is unlikely that they will forego the benefits of fossil fuels voluntarily.

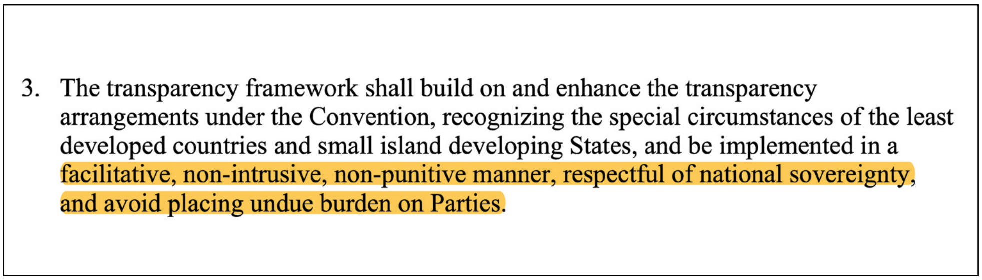
V. International Context

International law recognizes the rights of nations to develop their economies. For instance, the international climate law framework established by the UNFCCC and Paris Agreement recognizes the **rights of nations, in particular developing economies, to exploit their own resources and develop their economies**,[279] and does not require that they pursue emissions reductions.[280] Given their right to develop and the immense cost of foregoing development, it is unlikely that they will refrain from doing so, or that the developed nations can prevent them from doing so. Moreover, since emissions related to products consumed in another country are imputed to the exporting country, arguably, developing nations are placed at a disadvantage.



Recalling also that States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction,

UN Framework Convention on Climate Change (1992)[281]



3. The transparency framework shall build on and enhance the transparency arrangements under the Convention, recognizing the special circumstances of the least developed countries and small island developing States, and be implemented in a facilitative, non-intrusive, non-punitive manner, respectful of national sovereignty, and avoid placing undue burden on Parties.

Paris Agreement on Climate Change (2015), Article 13(3)[282]

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[279] Recital, UNFCCC.

[280] This is the concept of 'differentiated responsibilities.' Recital, Paris Agreement on Climate Change.

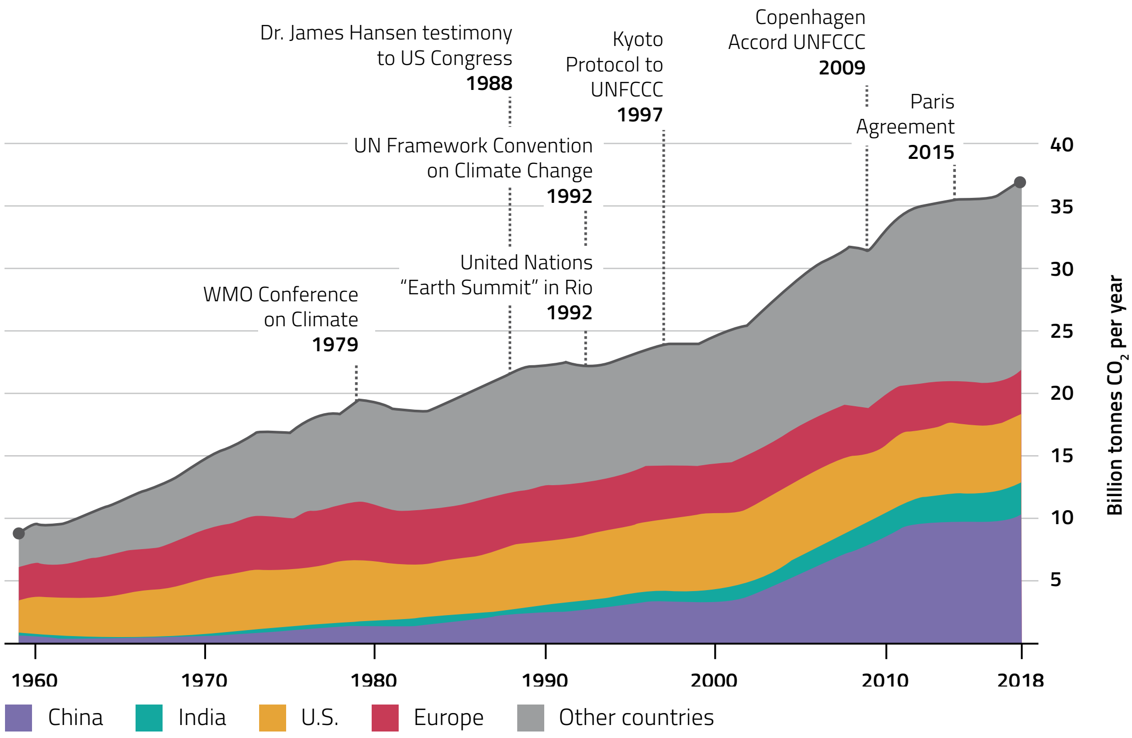
[281] United Nations Framework Convention on Climate Change, https://unfccc.int/resource/docs/convkp/conveng.pdf

[282] United Nations Framework Convention on Climate Change. The Paris Agreement on Climate Change. Available at https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Possibly, this conclusion could be regarded as premature, if the international climate policy framework is able to facilitate change in those countries as a result of which they no longer need to rely on fossil fuels. Unfortunately, however, **international climate policy** has a **poor track record**.

Since the adoption of the UNFCCC, global carbon emissions have steadily increased, despite the Kyoto Protocol and the Paris Agreement. In fact, the international mitigation efforts have **not produced a drop** in global emissions (see Figure 4.20.).

There is no reason to expect that this has changed with the Paris Agreement. The Kyoto Protocol established a 'cap-and-trade' program that could have been effective if all other countries had implemented it the same way the EU has done through the ETS scheme. Outside the EU, however, the level of enthusiasm to do so, was low.



Global Carbon Emissions

Source: Global Carbon Budget 2018 ▪ Get the data

Figure 4.20. Global carbon emissions and international climate policy:[283]

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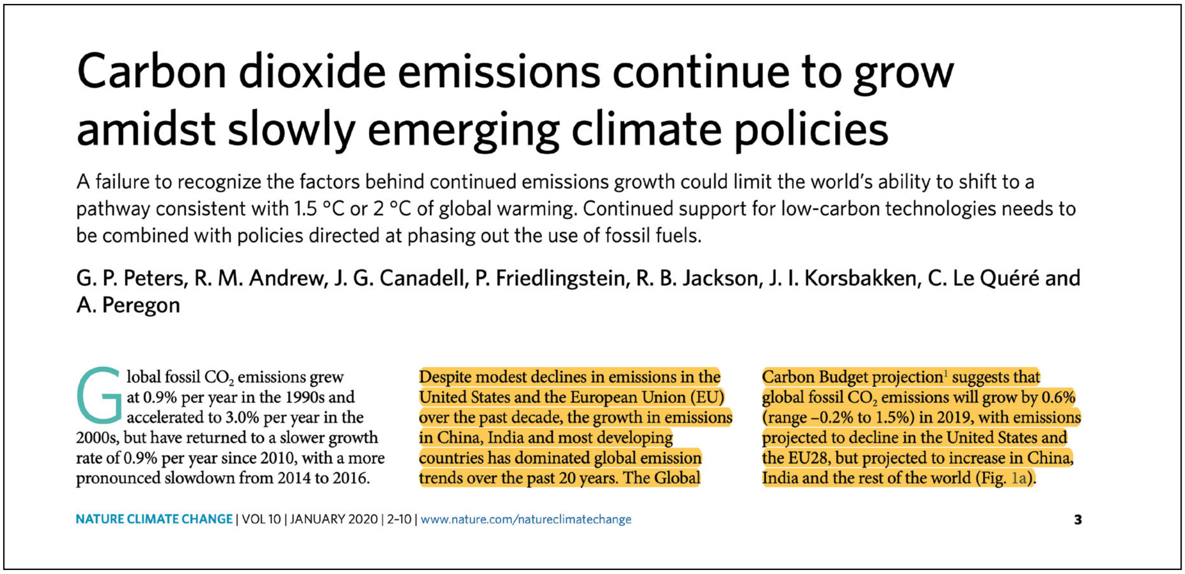
283 Based on: Corinne Le Quéré et al., Global Carbon Budget 2018, Earth Syst. Sci. Data, 10, 2141–2194, 2018, https://doi.org/10.5194/essd-10-2141-2018



Carbon dioxide emissions continue to grow amidst slowly emerging climate policies

A failure to recognize the factors behind continued emissions growth could limit the world's ability to shift to a pathway consistent with 1.5 °C or 2 °C of global warming. Continued support for low-carbon technologies needs to be combined with policies directed at phasing out the use of fossil fuels.

G. P. Peters, R. M. Andrew, J. G. Canadell, P. Friedlingstein, R. B. Jackson, J. I. Korsbakken, C. Le Quéré and A. Peregon

Global fossil CO_2 emissions grew at 0.9% per year in the 1990s and accelerated to 3.0% per year in the 2000s, but have returned to a slower growth rate of 0.9% per year since 2010, with a more pronounced slowdown from 2014 to 2016. Despite modest declines in emissions in the United States and the European Union (EU) over the past decade, the growth in emissions in China, India and most developing countries has dominated global emission trends over the past 20 years. The Global Carbon Budget projection[1] suggests that global fossil CO_2 emissions will grow by 0.6% (range –0.2% to 1.5%) in 2019, with emissions projected to decline in the United States and the EU28, but projected to increase in China, India and the rest of the world (Fig. 1a).

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From Nature Climate Change, January 2020.[284]

Thus, even if the EU member states can achieve zero emissions by 2050, there is a **substantial risk that emissions from other nations more than compensate for the EU's reductions** and **no positive effect on the global climate will materialize**.

While the emissions continue to increase, the policy makers continue to work on ever more ambitious plans, pushing ever more emission reductions into the future, setting ever higher targets, and betting ever more on technology (such as carbon removal) to provide solutions.

In a 2018 interim special report requested by the Paris Agreement, the IPCC has mapped out a pathway to limiting the temperature increase in 2100 to 1.5 °C. This pathway requires that the **entire world reaches climate neutrality around 2050**. Limiting warming to 1.5 degrees C requires **dramatic emission reductions by 2030** and complete carbon neutrality by around 2050. This would entail **unprecedented transformations** of energy, land, urban, and industrial systems, including measures to achieve "**negative emissions**" by removing carbon from the atmosphere. However, there is **no plausible, feasible, and effective strategy, plan or pathway** to achieve any of these objectives; it is entirely **unrealistic** (see Figure 4.21.).

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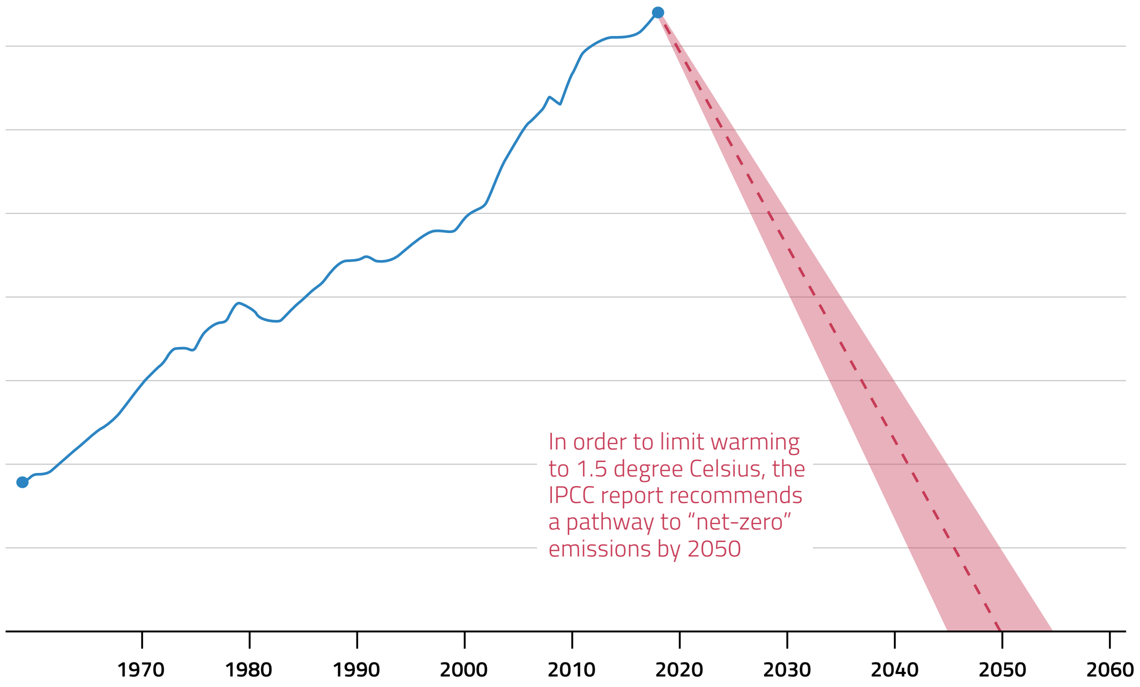
[284] G.P. Peters et al., Carbon dioxide emissions continue to grow amidst slowly emerging climate policies, Nature Climate Change, Vol. 10, January 2020, pp. 2–10.



Billion tonnes CO_2 per year
Source: Global Carbon Budget 2018 ▪ Get the data

IPCC carbon emission pathway to limit warming to 1.5 degrees

Figure 4.21. IPCC carbon emission pathway to limit warming to 1.5 degrees:

Interestingly, as an aside, the IPCC's Special Report does contemplate a **role for nuclear power** in the transformations that are needed (see further under c.ii,).

In short, compared to where policies are now, the **changes necessary to achieve 1.5 °C would have to be unrealistically radical**. Even for the more modest target of 2 °C the required policy changes do **not appear realistic** (see Figure 4.22.).

IPCC Special Report -- Limiting warming to 1.5°C requires dramatic emission reductions by 2030 and carbon neutrality by around 2050. This would entail unprecedented transformations of energy, land, urban, and industrial systems, including measures to achieve "negative emissions" by removing carbon from the atmosphere.

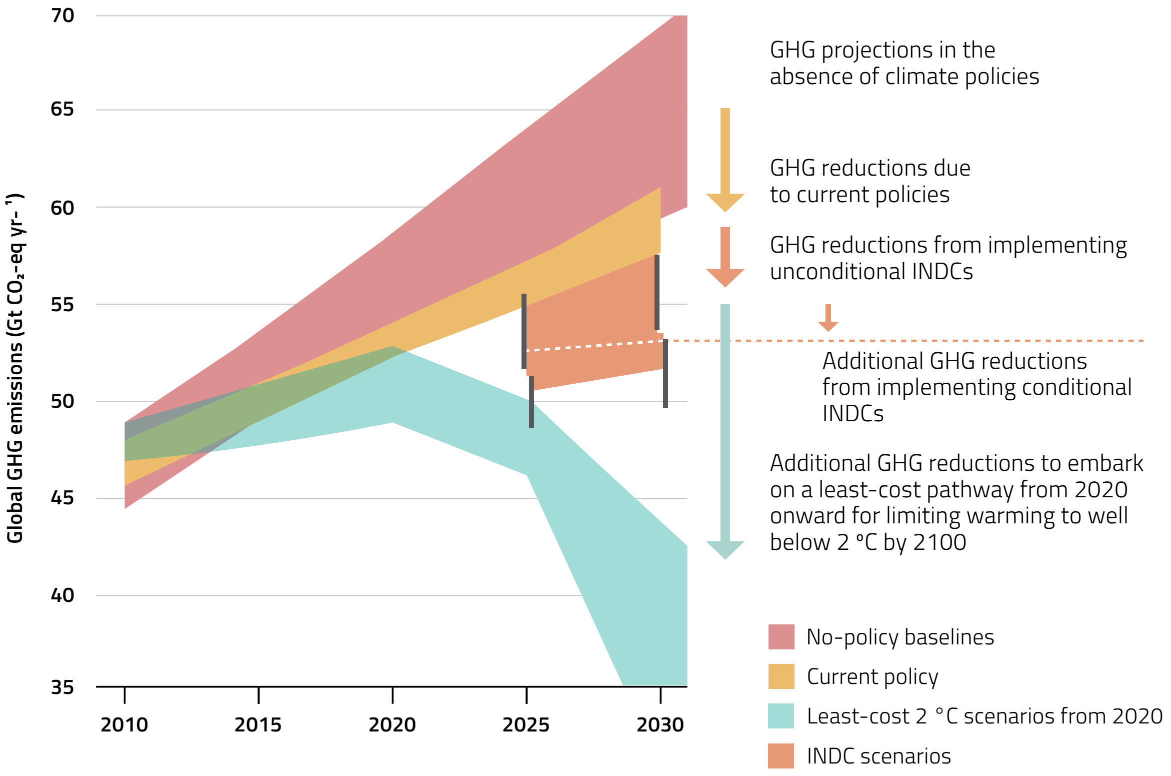


Figure 4.22. Global greenhouse gas emissions as implied by INDCs compared to no-policy baseline, current-policy and 2 °C scenarios:[285]

That the international targets are unrealistic is confirmed by further practical work by a US climate scholar, who has calculated that in order to get to net zero in 2035 requires **replacing approximately 0.1 EJ (exajoules) of fossil energy with renewable energy every day starting now**.[286] This is equivalent to approximately **2 nuclear plants or 3,000 wind turbines of 2.5 MW**. A corresponding amount of fossil would have to retired every day. **All new, additional energy use would have to be carbon-free**.

VI. The EU's 2030 Target

As discussed, the EU has the ambition to achieve climate neutrality in 2050, but it does not have a clear plan and pathway to get there. Possibly, however, the EU could develop plans to achieve interim targets, such as the 2030 target of 55% carbon dioxide reduction by 2030. Through three of such plans, the EU could get to climate neutrality in 2050.

Under current EU policy, however, planning is done by the Member States through the NECPs, with the Commission in a reviewing role. Based on an assessment of the plans, the European Commission

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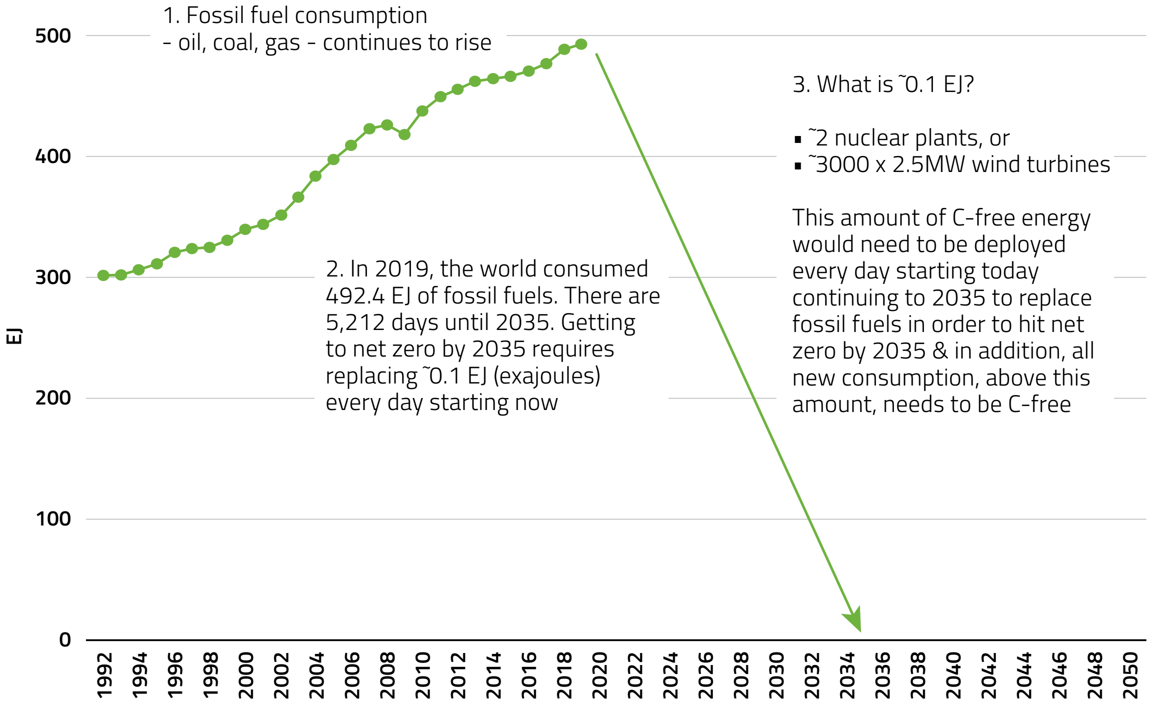
[285] Joeri Rogelj, Michel den Elzen, Niklas Höhne, Taryn Fransen, Hanna Fekete, Harald Winkler, Roberto Schaeffer, Fu Sha, Keywan Riahi & Malte Meinshausen, Paris Agreement climate proposals need a boost to keep warming well below 2 °C, Nature, volume 534, pp. 631–639 (2016).

[286] Pielke, R. (2019) "The World Is Not Going To Halve Carbon Emissions By 2030, So Now What?" https://www.forbes.com/sites/rogerpielke/2019/10/27/the-world-is-not-going-to-reduce-carbon-dioxide-emissions-by-50-by-2030-now-what/#5679ccc33794.

concluded that “the full implementation of the plans would lead Europe to overachieve the current 2030 greenhouse gas emissions reduction target,” with the share of renewable energy reaching 33.1 to 33.7% in 2030 at EU level, thus exceeding the target of at least 32%.[287] In September 2020, however, the Commission also noted that this target is “insufficient, and has recommended a 55% emissions reduction target.”[288] In November 2020, Ember published its review of the NECPs submitted by the Member States to assess progress towards the proposed 2030 target, specifically focussing on the power sector.[289]

Ember concluded that the EU is not on track to deliver the European Commission’s recommended 55% reduction in total emissions by 2030. Insufficient progress will be made in seven key countries,[290] which account for 80% of the total emissions in the power sector. In these countries, wind and solar deployment plans fall short by a third.



1. Fossil fuel consumption
- oil, coal, gas - continues to rise

2. In 2019, the world consumed 492.4 EJ of fossil fuels. There are 5,212 days until 2035. Getting to net zero by 2035 requires replacing ~0.1 EJ (exajoules) every day starting now

3. What is ~0.1 EJ?

- ~2 nuclear plants, or
- ~3000 x 2.5MW wind turbines

This amount of C-free energy would need to be deployed every day starting today continuing to 2035 to replace fossil fuels in order to hit net zero by 2035 & in addition, all new consumption, above this amount, needs to be C-free

Figure 4.23.

Source: BP 2020, R. Pielke Jr. , 24 Sept 2020

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[287] European Commission, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, An EU-wide assessment of National Energy and Climate Plans: Driving forward the green transition and promoting economic recovery through integrated energy and climate planning, COM(2020) 564 final, Brussels, 17.9.2020, available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=COM:2020:564:FIN

[288] European Commission, COMMISSION STAFF WORKING DOCUMENT, IMPACT ASSESSMENT Accompanying the document: COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS, Stepping up Europe’s 2030 climate ambition, Investing in a climate-neutral future for the benefit of our people, Brussels, 17.9.2020, SWD(2020) 176 final, available at https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/impact_en.pdf

[289] Ember, Vision or Division?: What do National Energy and Climate Plans tell us about the EU power sector in 2030?, November 2020, available at https://ember-climate.org/wp-content/uploads/2020/10/Vision-or-Division-Ember-analysis-of-NECPs.pdf

[290] In five Member States, limited or no progress will be made – these are Belgium, Bulgaria, Czechia, Romania and Poland. In two Member States with large economies, Germany and Italy, slow progress is projected. Id., p. iv.

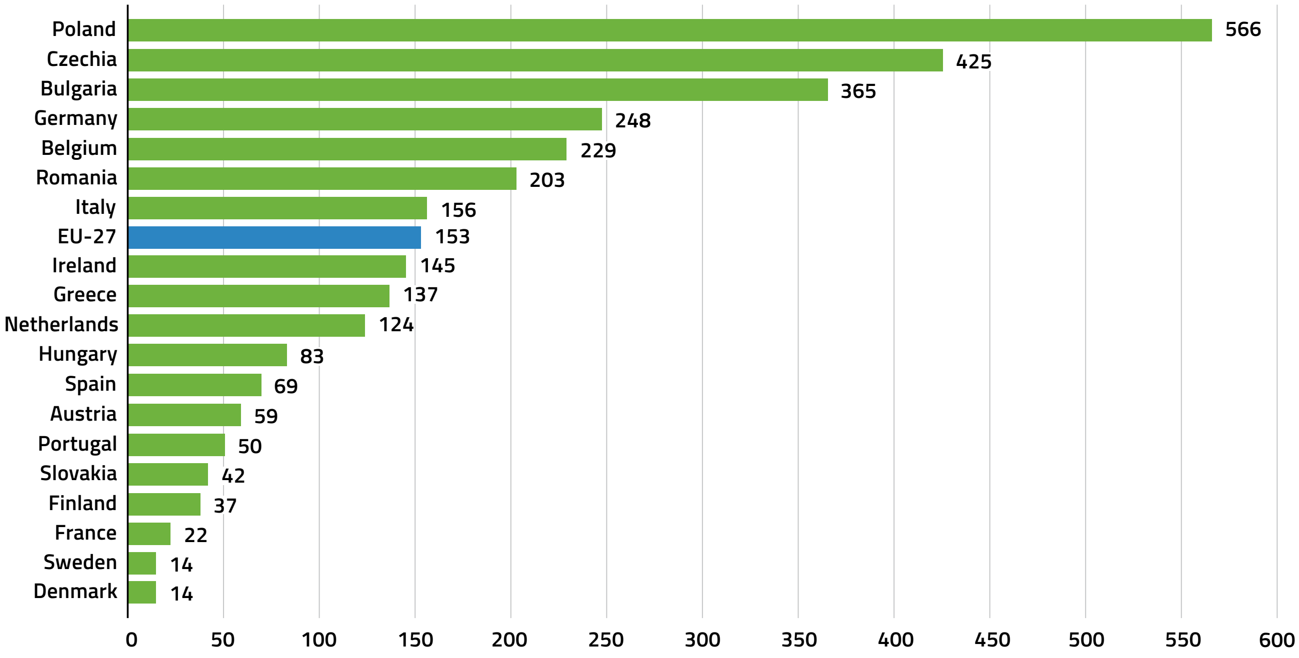

Figure 4.24. Progress needs to be made in secen key countries with the dirtiest electricity in 2030. *Expected emissions intensity of electricity production in 2030 (gCO*$_2$*/KWh)*

Source: Ember, Vision or Division, available at https://ember-climate.org/project/necp7/

As Ember observes, although nuclear power is a source of zero carbon electricity, the NECPs indicate that total electricity generated from nuclear power plants in the EU-27 is expected to fall by almost 20% by 2030.[291] In Germany, all nuclear power plants are to be phased out by the end of 2022. Only a few Member States intend to build additional nuclear capability (see figure 4.25.).

This is an assessment of plans, not of actual results. Thus, even if the plans are implemented as drafted, the target will not be achieved. There, of course, is no guarantee that they will be fully implemented, in particular in light of the fact that the costs of doing so is not known and has not been assessed accurately. If these costs turn out to be much higher than the body politic can bear, Member States may well be unable to deliver on their plans. Thus, at the very least, there is significant uncertainty about Member States' ability to deliver on the 2030 target of 55% emission reduction.

c. Policy-Making Process and 'No Regrets' Solutions

I. Better Regulation?

As discussed above, the track record of international and EU policymaking is not stellar. Both in terms of effectiveness and costs, policies have left much to be desired. EU climate policy making is not much better; indeed, the EU has been a staunch supporter of the international process, even if that meant bending internal

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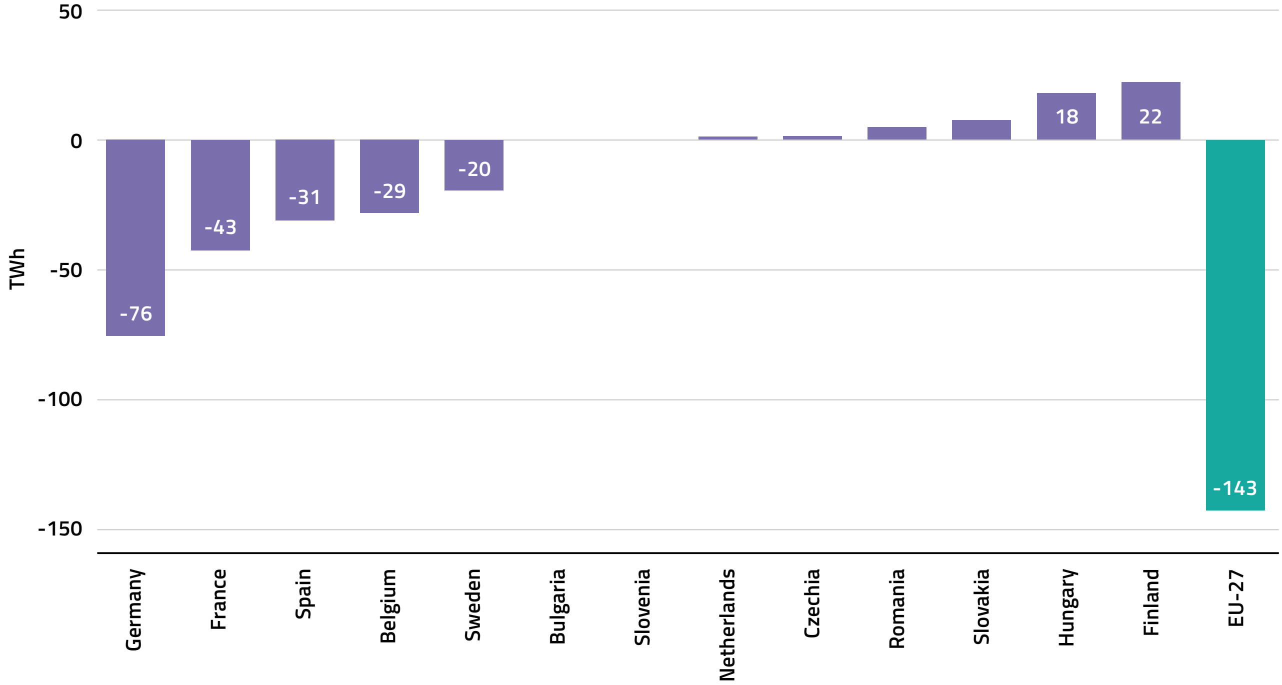
[291] Id., p. 11. Nuclear power generation would go down to 619 TWh in 2030, from 762 TWh in 2018.



Source: National Energy & Climate Plans (NECPs), Ember calculations.

Figure 4.25. EU-27 nuclear output expected to fall by ~ 19% by 2030. Germany leads the declines. *Change in gross electricity production from nuclear from 2018 to 2030 (TWh)*

Source: Ember, Vision or Division, available at https://ember-climate.org/project/necp7/

procedures. Indeed, EU climate policy making **is not the poster child of 'better regulation**,'[292] to put it mildly:

- Pursuant to the regular process of risk regulation, the EU would first conduct a **risk assessment**. As the Scientific Committees of the European Commission have stated, "[s]ound scientific advice is vital to ensure a high level of health and environmental protection. Before making a legislative proposal, the European Commission asks the Scientific Committees to ***assess the potential risks; namely the probability and the severity of an adverse effect, in relation to the hazard and to the exposure***."[293] There is no such risk assessment for climate change.
- As part of the 'Better Regulation' agenda, the EU is supposed to conduct a **cost-benefit analysis (called 'impact assessment'[294]) of relevant risk management options**. In the case of climate change,

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[292] "The better regulation agenda is about designing and evaluating EU policies and laws transparently, with evidence, and backed up by the views of citizens and stakeholders." European Commission, Better Regulation, available at https://ec.europa.eu/info/law/law-making-process/planning-and-proposing-law/better-regulation-why-and-how_en

[293] Scientific Committees of the European Commission, Risk assessment, available at https://ec.europa.eu/assets/sante/health/scientific_committees/risk_assessment/index_en.htm

[294] "Impact assessments examine whether there is a need for EU action and analyse the possible impacts of available solutions." European Commission, Impact Assessment, https://ec.europa.eu/info/law/law-making-process/planning-and-proposing-law/impact-assessments_en. We do not discuss the (possible) differences between cost-benefit analysis and impact assessment, as they are not relevant to the argument made here.

the EU could refer to international commitments to effectively sidestep this process; at best, it is treated as 'check box' exercise.

- After a policy has been enacted, an "**ex-post evaluation**" should be conducted. Such an evaluation provides "an evidence-based assessment of the performance of policies and legislation."[295] A serious ex-post evaluation of climate policy would verify whether the policy had any measurable impact on the climate, not whether it promoted some proxy, such as renewable energy. ***No such evaluation of effectiveness*** has been conducted.

Thus, EU climate policy, by and large, is implementation by the EU of international climate policy, and is made without risk assessment, cost-benefit analysis, and ex post evaluation. These deficiencies likely hamper the effectiveness of EU climate policy.

II. 'No Regrets' Solutions

An important manifestation of the inadequate climate policy making process is the neglect of the possibility of policy failure.[296] In light of the uncertain and small effect of the EU's climate neutrality objective on the actual climate in 2050, the choice from the range of possible policy options should be informed by this concept. As the UNFCCC Secretariat stated as early as 1999.

*"Policymakers can encourage energy efficiency and other climate-friendly trends in both the supply and consumption of energy. … Efficiency can be improved in large part by providing an appropriate economic and regulatory framework for consumers and investors. This framework should promote cost-effective actions, the best current and future technologies, and "**no regrets" solutions that make economic and environmental sense irrespective of climate change**."*[297]

EU policy makers have forgotten this early lesson of climate policy making. No regrets solutions are attractive because there is a business case to be made for them independent of climate change and the effectiveness of climate policies. The former IAEA Director-General Dr. Hans Blix has suggested that nuclear power is such a no regret climate solution, saying: "The cost of the nuclear option is such that it will not cause us to regret using it, even if global warming were to turn out not to be a risk. ***Nuclear power is a no-regret solution***."[298] Given the spatial impacts of the current push for renewables, which the EU did not analyze in much detail, nuclear power would appear to be an option that should be part of the climate policies.

In light of the EU Treaty's **precautionary principle**,[299] in designing policies (or managing risk), the EU is to consider both the ***(possible) risks associated with not acting and the (possible) risks associated with***

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[295] "Its findings support political decision-making and inform the design of new interventions. For this reason, and notably under the EU's Better Regulation agenda, evaluation has become a key policy-making tool at EU level." European Parliamentary Research Service, Evaluation in the European Commission: Rolling check-list and state of play, Brussel, July 2020, available at https://www.europarl.europa.eu/RegData/etudes/STUD/2020/654170/EPRS_STU(2020)654170_EN.pdf

[296] "Faulty policy design can stem from many causes: a poor understanding of the problem; insufficient knowledge of the implementation context; unclear and even contradictory goals; poor quality evidence; and an absence of political backing." Bob Hudson, David Hunter & Stephen Peckham (2019) Policy failure and the policy-implementation gap: can policy support programs help?, Policy Design and Practice, 2:1, 1-14, DOI: 10.1080/25741292.2018.1540378

[297] UNFCCC, PRESS RELEASE, Talks to build global consensus for post-2000 action on climate change, 1999, available at https://unfccc.int/cop5/media/cop5kit.html

[298] IAEA Director-General Dr. Hans Blix, Statement, last updated 26 Nov 2019, available at https://www.iaea.org/newscenter/statements/nuclear-power-prospects-revival

[299] While Article 191 of the Treaty on the Functioning of the European Union lays down the precautionary principle, it does not define it. The precautionary principle, as commonly interpreted, relates to decision-making under conditions of uncertainty; its aim is to ensure that protective policies are put in place, also where risk is uncertain.

The more resources the energy transition requires, the fewer resources are left over to meet other needs. Climate change is one of many major public policy ends. So, the more efficient the climate issue is addressed, the more resources are available for other important public policies, such as health care and education.

acting.[300] Both renewable energy and nuclear energy are decarbonized power generation technologies, so both offer a possible solution to the issue of carbon emissions associated with power generation. That being the case, a decision as to which technology to promote, is to be informed by the ***positive and negative impacts of each technology***. There is no doubt that renewable energy has become a large industry on the wings of the climate movement; without the focus on climate, it would not have grown exponentially. Policy makers have not asked, however, what happens if we go down the current policy route and realize after one or two decades that we will not be able to complete the whole project, or even a significant part thereof, and that this prevents the system from working as designed? If that happens, ***the scale of the stranded assets will be astronomical***.

From a precautionary perspective, it is important also to look at the cost of the energy transition as a question of the allocation of scare resources. The public purse may be large, but it may not be as deep as the renewable energy revolution will require. ***The more resources the energy transition requires, the fewer resources are left over to meet other needs.*** Climate change is one of many major public policy ends. So, ***the more efficient the climate issue is addressed, the more resources are available for other important public policies, such as health care and education***. Even at the level of threats to humanity, climate change may not be the greatest threat, as the COVID-19 pandemic illustrates. In addition to infectious diseases, financial system collapse, terrorism, cyberattacks, natural catastrophes, antibiotic resistance, and the demise of democracy, are also seen by many as major threats that are deserving of additional public resources.[301]

Maybe due to the low power density of renewable energy, the tide seems to be turning, however. In its Special Report, the IPCC intentionally left the options wide open, and recommended for any 1.5 °c pathway “growth in the share of energy derived from low-carbon-emitting sources (including renewables, ***nuclear and fossil fuel with CCS***).” It also recommended a “rapid decline in the carbon intensity of electricity generation simultaneous with further electrification

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[300] Communication from the Commission on the precautionary principle, COM/2000/0001 final, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52000DC0001

[301] For an overview of some of these threats, see the special issue of Futures, Baum, Seth D, Tonn, Bruce E, Confronting future catastrophic threats to humanity, Futures: The Journal of Policy, Planning and Futures Studies, 2015-09, Vol.72, pp.1-3.

of energy end-use."[302] The increase in nuclear energy, the IPCC stated, can be realized through "existing mature nuclear technologies or new options (generation III/IV reactors, breeder reactors, new uranium and thorium fuel cycles, small reactors or nuclear cogeneration)."[303]

Thus, the IPCC reinforced the need for policy makers to consider all decarbonized power generation technologies. The pros and cons of each option are part of that decision-making process, which is guided by a preference for ***'no regrets'* solutions**, i.e. **policies that confer benefits, and do not cause adverse impacts and negative externalities, irrespective of any positive effects they may have on the problem of climate change**. While the EU has not rejected nuclear power entirely, it clearly favors wind and solar power as the main pathway to achieving climate neutrality. This policy preference is not based on a careful, full comparison of wind/solar and nuclear, however.

Two important features of power-generating technologies that have not received much attention in EU and national policy-making are (i) **the land and space required by a technology**, and (ii) **its costs**. This study addresses these two features, which to a significant degree determine whether a technology constitutes a 'no regrets' solution.

d. Conclusions

Under the current aspirational policies, the EU is not likely to achieve climate neutrality by 2050. There is no well-defined, pragmatic plan or roadmap to get there. The EU's strategies may realize short-term emission reductions (if the outsourcing effect is ignored), but fail to give the EU a good chance at achieving the ultimate objective. ***Renewable energy is viewed as a panacea, although public resistance against its deployment is growing. At the same time, the solutions to remedy its deficiencies, such as battery storage and hydrogen, are not yet deployable at scale and have their own weaknesses (and costs)***. No cost/benefit-analysis has been done on alternative policy options. Not all policy options have been carefully considered, and some viable options, most notably, nuclear power, are not being seriously considered.

The EU regularly increases its climate ambitions, throws vast resources at the problem, and actively engages in climate diplomacy on an unprecedented scale. Despite all of these efforts, global emissions continue to rise, without showing a sign of peaking. The reason is that other countries, as they develop, need fossil fuels to power their economies; they simply cannot afford renewable energy to any significant extent and the EU cannot afford to subsidize them. In theory, there is a solution -- the EU could buy up all fossil fuel reserves in the world, but, as discussed, this would be unaffordable and unrealistic. The EU could not even acquire a significant portion of these reserves, and there is no other way it can prevent global emissions increases. **Developing nations have a right to sovereignty, a right to develop their economies, and industrialize – international law,**

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[302] IPCC, Special Report 1.5, 2019, available at https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf

[303] IPCC, 2018: Annex I: Glossary [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

including the UNFCCC, recognizes these rights. Given the size of the benefits derived from fossil fuels,[304] an EU carbon border adjustment tax or any climate diplomacy are unlikely to cause these countries to forego development.

A key issue is 'carbon leakage' (or 'outsourcing'). EU climate neutrality will have its intended favorable effect on reducing the average global atmospheric temperature increase, **if and only if no 'carbon leakage' occurs, which thus far has consistently occurred**. Indeed, carbon leakage explains why global emissions continue to rise despite the significant (and costly) reductions in the EU. But, as noted above, even if the EU is able to prevent carbon leakage, when it achieves carbon neutrality in 2050, it will likely still find that its **efforts were in vain, because emissions from other countries increased**. With the only effective way to prevent this unfortunate outcome (i.e. buying up all fossil fuels) beyond the EU's reach, the chances of success for the EU are extremely dim.

The root cause of the wide aspiration/reality gap in EU climate policy-making is that the policy-making is led by a desire to become climate neutral without a rational plan and effective pathway that can lead to this result. The EU's aspirational strategies and plans all pursue derivative objectives, such as renewable energy targets, which are neither sufficient nor necessary to achieve climate neutrality. The Green Deal contemplates that the EU will continue to strengthen pre-existing policies, such as energy efficiency and renewable energy, while betting on technological breakthroughs in areas such as hydrogen, energy storage, and system integration, and playing on demand response.[305] The chief drivers of EU climate policies are **targets set by the policy makers for renewable energy and emission reductions**, and financial incentives for research and development, which **do nothing or very little to address the cause of the global emissions increase**. It is as if the EU prefers to ignore that it is not an island, and to forget that achieving climate neutrality in an overwhelmingly climate positive world is inutile.

Thus, there is a **high probability of policy failure** in that either (i) the EU will not achieve climate neutrality (e.g., because the necessary technologies are not ready for wide scale deployment or the costs turn out to be too high[306]), or (ii) the rest of the world will not limit their emissions so that the EU's sacrifices are in vain. **For this reason, the EU is well advised to evaluate power-generating technologies in terms of the extent to which they are '*no regrets*' solutions**. Despite the obvious needs, the EU has not conducted a relative cost/benefit analysis of the alternative electricity-generating technologies and electricity systems. In such an analysis, **'no regrets' assessment**, akin to application of the precautionary principle, is incorporated, and **all benefits and costs of alternative power generation technologies**, are identified and assessed.

This study is aimed at filling this gap to some extent. We now proceed to assess the spatial requirements of wind/solar and nuclear energy in the Czech Republic and The Netherlands.

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[304] When activists claim that the World Bank, despite its commitment to the Paris Agreement, continues to spent much of its financial resources on fossil fuel projects, they are right, but the World Bank simply responds to the economic reality and the strong desires of the developing nations they are to support. See, e.g., Mainhardt, Heike, World Bank Group Financial Flows Undermine the Paris Climate Agreement, Frankfurt, Urgewald, October 2020, available at https://urgewald.org/shop/world-bank-group-financial-flows-undermine-paris-climate-agreement

[305] European Commission, A European Green Deal, available at https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[306] Cf. Pantelis Capros, Georgios Zazias, Stavroula Evangelopoulou, Maria Kannavou, Theofano Fotiou, Pelopidas Siskos, Alessia De Vita, Konstantinos Sakellaris, Energy-system modelling of the EU strategy towards climate-neutrality, Energy Policy 134 (2019) 110960.

5

Spatial Requirements of Wind/Solar and Nuclear Energy

Spatial requirements of wind/solar and nuclear energy

This chapter discusses the land and space use requirements for nuclear, wind, and solar power in both the Czech Republic and The Netherlands. To provide context, before we address the land/space demand, a brief introduction and description of the relevant policy frameworks are provided. Following the presentation of the model outputs, we discuss the results.

Pursuant to the EU Regulation on the governance of the energy union and climate action,[307] the member states submitted national energy and climate plans (NECPs) covering the period 2021-2030. NECPs set forth national plans on, inter alia, what a member state intends to do to reduce emissions and increase the production of renewable energy. Much of the policy information presented below is derived from the Czech and Dutch NECPs.

As discussed in Part 3 of this report, we developed a model to assess the land/space impact of wind/solar and nuclear power. We ran the model for the Czech Republic and The Netherlands under varying scenarios, and present the results below. Our model is briefly described in this section. Here, we provide the key assumptions. A full model description can be found in Annex I attached to this report. In this annex, we provide back-up for the general and country-specific sources we used, and other model inputs.

As discussed below, there are significant differences between the Czech Republic and The Netherlands with respect to their wind/solar and nuclear baselines, and their plans for further development of power infrastructure, in particular the extent to which nuclear power is viewed as a critical element of the power

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[307] Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council, OJ L 328, 21.12.2018, p. 1–77.

There are significant differences between the Czech Republic and The Netherlands with respect to their wind/ solar and nuclear baselines, and their plans for further development of power infrastructure, in particular the extent to which nuclear power is viewed as a critical element of the power mix.

mix. The data for the policies of the two countries are derived from their National Energy and Climate Plans and other sources.

a. Summary of Model Mechanics

The model estimates the area across land, waters, sea, and roofs required to meet a portion of the country's electricity demand. It is able to estimate the required area for a given mix of renewable and nuclear power.

The model explicitly incorporates onshore wind, offshore wind, solar (both on land and on roof), and nuclear energy. For each of these technologies, the model requires two user inputs:

- **Capacity factor**: MWh electricity generated annually as a percentage (%) of capacity
- **Density factor**: MW of nameplate capacity per square km

In addition to these two parameters, for each of the energy technologies, the model takes three exogenous parameters: total country energy demand (PJ), share of energy demand served by electricity (%), and the required electricity generation mix (e.g. offshore wind accounts for 20% of electricity generated). Based on those inputs, the model estimates how many power plants of each technology need to be built and, in turn, how much of the available space they occupy.

Note that all of these variables are country-specific – for example, solar does not have the same capacity factor in The Netherlands as it does in the Czech Republic. For each country, we provide a range for the capacity factor and the density factor to account for potential extremes.

In terms of our inputs, our model relies as much as possible on **historical, realized data**. In other words, **instead of using expected numbers**, our model prefers numbers on what has so far been realized with today's technologies (according to the authors of the studies used). We do not take into account any projections, as these are inherently uncertain.[308] While we believe that the data we use constitutes the best information readily available, we realize that actual empirical data may prove that this data is inaccurate. For instance, in the case of offshore wind, the seabed space necessary for cabling may not be included; in the case of solar and wind on land, the underground space demand for cabling is typically ignored. In the UK, this **additional space demand has been shown to be substantial**;

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[308] It has been shown that realized, proven numbers can differ significantly from expected, unproven numbers. See, for instance, Aldersey-Williams J, Broadbent ID, Strachan PA. Better estimates of LCOE from audited accounts – A new methodology with examples from the United Kingdom offshore wind and CCGT. Energy Policy, Vol. 128 (2019), pp. 25 – 35.

> In the case of offshore wind, the seabed space necessary for cabling may not be included; in the case of solar and wind on land, the underground space demand for cabling is typically ignored. In the UK, this additional space demand has been shown to be substantial; for three offshore wind farms up to 66% of additional seabed space is needed for the cable corridors. There is no reason as to why this would be any different in The Netherlands.

for three offshore wind farms up to 66% of additional seabed space is needed for the cable corridors.[309] There is no reason as to why this would be any different in The Netherlands.

For more details and a full discussion of the model mechanics, we direct the reader to Annex I. That said, the results presented in this chapter can be interpreted without reading the annex.

b. Czech Republic

i. Policy framework

The Czech Republic strives for self-sufficiency in electricity generation based on advanced conventional technologies and renewables.[310] Electricity security of supply is regarded as important, and the Czech do not want to depend on imports.[311] Advanced conventional technologies include nuclear energy, which is regarded as an emission-free source (see further in this section, below). In the electricity sector, the Czech Republic intends to ensure diversification of primary energy sources in accordance with the target corridors of the State Energy Policy of the Czech Republic, which, inter alia, means the continued development of nuclear energy in the Czech Republic.[312] Nuclear power should gradually replace coal in the electricity mix.

Pursuant to EU Regulation 2018/842, the emission reduction target for 2030 for the Czech Republic is 14 % compared to 2005. No emission target has yet been agreed for 2050.[313]

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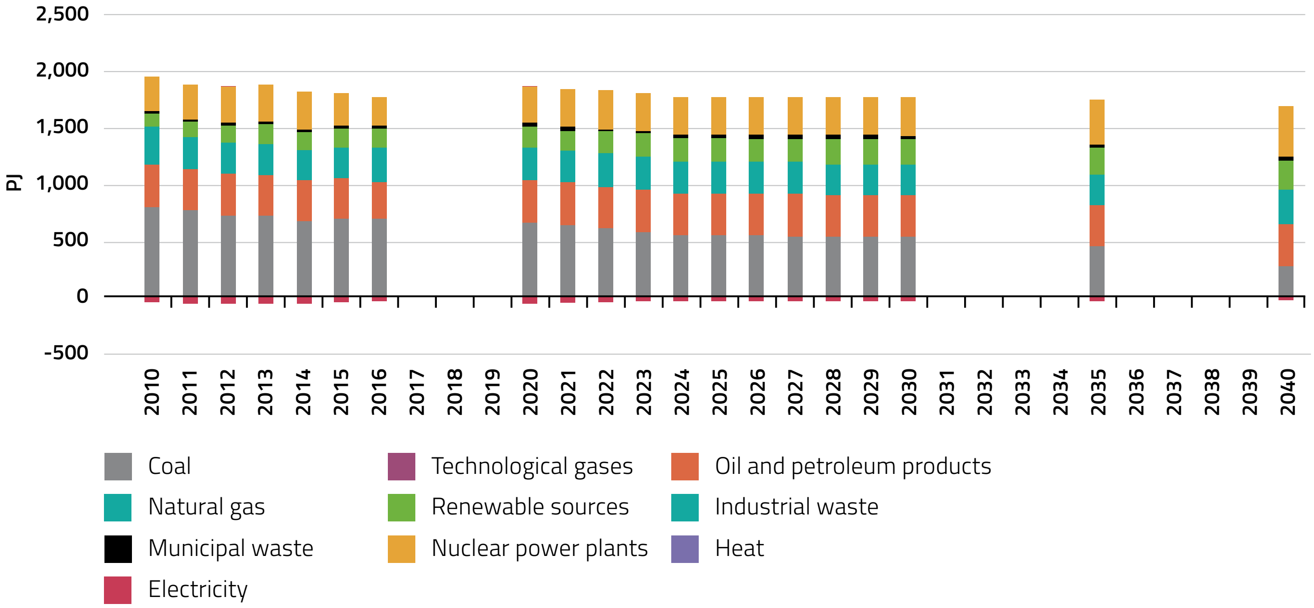
[309] The Triton Knoll offshore project demands 135 km2 of seabed, excluding the cable corridor, which needs roughly 90 km2, i.e. an additional 66% for cabling and related purposes. A recent extension of the Clyde Wind Farm in Scotland required 28 km2 plus 14 km2 for the cable corridor (50%). Another nearby site demands a nominal 11 km2, and 5 km2 for cabling (45%). Thus, for these offshore wind farms cabling requires additional seabed of between 45% and 66% of the seabed required for the wind turbines. Personal Communication with Professor Gordon Hughes, School of Economics, University of Edinburgh, 5 November 2020.

[310] National Energy and Climate Plan of the Czech Republic, November 2019 ("Czech NECP"), available at https://ec.europa.eu/info/energy-climate-change-environment/overall-targets/national-energy-and-climate-plans-necps_en, p. 57.

[311] OTE, Expected Electricity and Gas Balance Report 2019, p. 72, available at https://www.ote-cr.cz/en/about-ote/files-annual-reports/expected_balance_report_2019.pdf

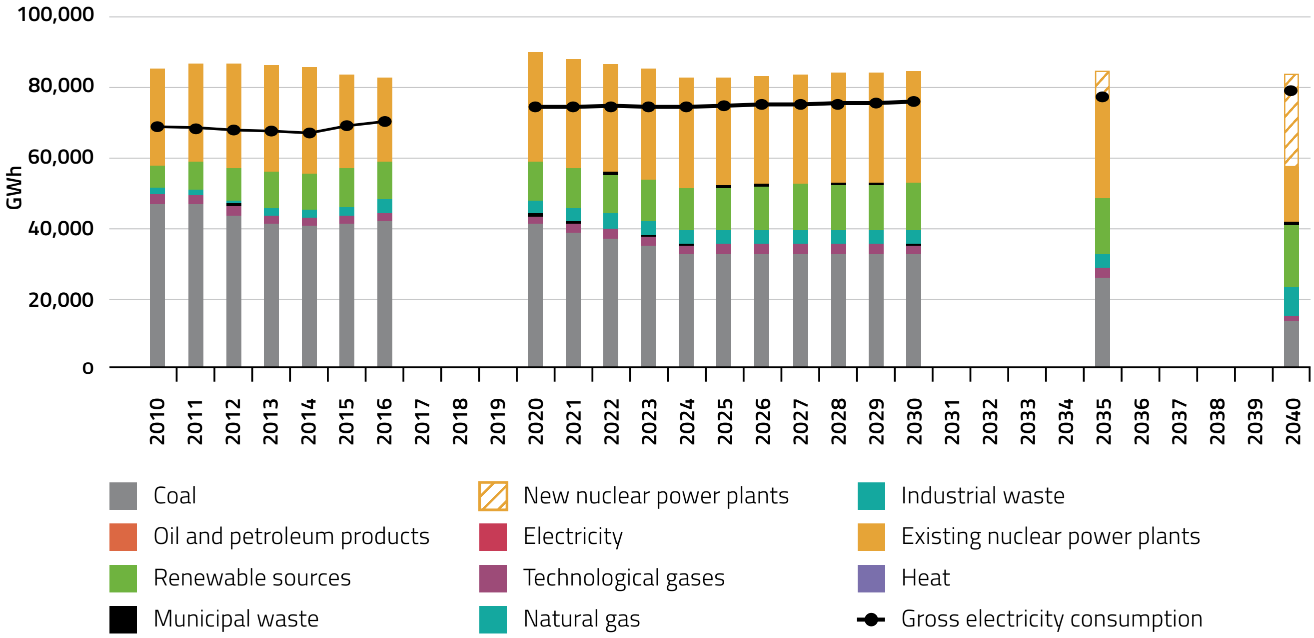
[312] Czech NECP, p. 57.

[313] Cf. Rečka, Lukáš ; Ščasný, Milan, Brown coal and nuclear energy deployment: Effects on fuel-mix, carbon targets, and external costs in the Czech Republic up to 2050, Fuel (Guildford), 2018, Vol.216, pp. 494-502 ("the 2050 80% reduction target may not be achievable in any case").



Source: Ministry of Industry and Trade

Figure 5.1. Expected evolution of the energy mix at the primary energy source level



Source: Ministry of Industry and Trade

Figure 5.2. Expected development of gross electricity production and electricity consumption

The Czech NECP, however, warns that the renewable target may appear to be unachievable without continued subsidies and that the high share of renewable energy contemplated in 2030 may cause blackouts.

Renewable energy

The Czech Republic aims for 22 % renewable energy by 2030, up 9% from its 2020 target set at 13%.[314] The **priority** of the Czech government is **solar energy**, not wind energy,[315] although the share of wind will increase towards 2030.[316] To achieve this target, the Czech Republic has amended Act No 165/2012 on supported energy sources. This act establishes a new support scheme for renewable or supported energy sources after 2020.[317]

After 2030, the Czech government **does not anticipate that the share of renewable energy will continue to increase**; it projects that renewable energy and secondary sources will amount to 17-22% of the total primary energy sources in 2040.[318] The costs required for the development of renewable energy sources amount to CZK 900 billion; note, however, that this number represents a cost at the level of state aid, the total investment will be higher.[319]

The Czech NECP, however, warns that the renewable target may appear to be unachievable without continued subsidies and that the high share of renewable energy contemplated in 2030 may cause blackouts, where it states:

"However, this increase does not take into account the fact that the Czech Republic will also have to 'cope' with the ***potential decrease in energy from RES after around 2028 in the case of electricity plants that are claiming and receiving operating support today****, where the production of energy from renewable energy sources may terminate after the end of the current operating support for these plants, because without any operating support there is a risk that these plants will shut down.*[320] *The risk of plant*

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[314] "This national target of the Czech Republic was already achieved in 2013 and in 2016 the Czech Republic reached the share of energy from RES to total final energy consumption of 14.89 %. Between 2021 and 2030, at least a 7 % increase in the share of energy from RES to final energy consumption will have to be achieved."

[315] "Development in the use of wind energy should be aimed at solutions to reduce losses (gearing, etc.) and trouble-free integration into the electricity grid." Czech NECP, p. 154.

[316] Czech NECP, p. 151. ("Developing economically efficient solar, geothermal energy, and biomass"). Table 15, p. 32.

[317] National Energy and Climate Plan of the Czech Republic, November 2019 ("Czech NECP"), available at https://ec.europa.eu/info/energy-climate-change-environment/overall-targets/national-energy-and-climate-plans-necps_en

[318] Czech NECP, p. 14.

[319] Czech NECP, p. 3.

[320] A study on renewable energy investment and job creation found that the jobs created in the renewable energy sector strongly depend on the continuation of financial incentives. Dvořák, Petr ; Martinát, Stanislav ; der Horst, Dan Van ; Frantál, Bohumil ; Turečková, Kamila, Renewable energy investment and job creation; a cross-sectoral assessment for the Czech Republic with reference to EU benchmarks, Renewable & Sustainable Energy Reviews, 2017, Vol.69, pp.360-368.

> " Around 2028 … the production of energy from renewable energy sources may terminate after the end of the current operating support for these plants. "

shutdowns and terminations may mean that without any further measures to maintain and motivate these plants to stay in operation, ***certain types of outages may occur.****"* [321]

Given the intermittent nature of solar and wind power plants, the Czech NECP contemplates that "gaseous fuels can play an important role, partly because of their technological possibilities for countering imbalances in the electricity system and because of the possibility of converting electricity into gaseous fuels."[322] Such gases include biogas, biomethane, and hydrogen.

	2016 level	2040 target level
Coal and other solid non-renewable fuels	40%	11-17%
Oil and petroleum products	20%	14-17 %
Gaseous fuels	16%	18-25 %
Nuclear energy	15%	25-33 %
Renewable and secondary energy sources	10%	17-22 %

Source: State Energy Policy of the Czech Republic (2015)

Table 5.1. Share of individual fuels in total primary energy sources (excluding electricity)

	2016 level	2040 target level
Coal and other solid non-renewable fuels	50%	11-21 %
Nuclear energy	29%	46-58 %
Natural gas	8%	5-15 %
Renewable and secondary energy sources	13%	18-25 %

Source: State Energy Policy of the Czech Republic (2015)

Table 5.2. Share of individual fuels in gross electricity generation

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[321] Czech NECP, p. 84 ("The scope of support will only be for non-fuel sources (except PVPP) and landfill or sludge gas. Fuel sources were redirected to heat support to ensure the achievement of the RES target in the heating and cooling sector. The form of support for new electricity plants will be applied by an hourly green bonus, with a division into electricity plants, which will compete for the support in an auction. For sources up to 1 MW (6 MW for wind power) support will be provided in the form of a green bonus laid down in an ERO price decision and for sources above 1 MW, the support will be provided by means of auctions in the form of the 'auction bonus'. The duration of the support will remain unchanged – over the lifetime (20 or 30 years)"). See also Czech NECP, p. 35 ("It is apparent that for wind farms, only about 32 % of the sources that were in operation in 2016 can be in operation in 2030. In the case of photovoltaic power plants, this value is 78 %. However, the table also shows the year 2035, where the dropout of sources that are currently in operation is already quite noticeable. Therefore, in order to achieve the installed capacity (see Table 18), it is necessary for these sources to be upgraded and to remain in operation, or to be compensated by new sources.")

[322] Czech NECP, p. 209.

Nuclear energy

In 2015, the Czech government adopted a 'National Action Plan for the Development of Nuclear Energy in the Czech Republic. As part of this plan, the Czech intend to invest also in nuclear research and development.[323]

Currently, 6 nuclear power units in the Temelín power plant and the Dukovany power plant are in operation in the Czech Republic. Maintaining the current share of nuclear energy in the energy mix and its further development is regarded as crucial for achieving the long-term low-emission commitments of the Czech Republic. The State Energy Policy of the Czech Republic therefore requires that the share of nuclear energy in primary energy be increased.[324]

Since uranium is no longer mined in the Czech Republic, nuclear fuels are imported. The Czech government envisages adopting measures to ensure the security of long-term supplies of nuclear materials and fuels.[325]

ii. Model Inputs

The Czech Republic's potential to build renewable power sources is relatively limited: they cannot build offshore wind farms, given that they have no jurisdiction over any seas, and their internal waters are also not sufficiently sizable to warrant onshore wind farms on internal waters.

Most of the inputs for the Czech Republic's model have been sourced from their Department of Energy, who provided us with historic, realized data. As discussed in Annex I attached to this report, we have attempted to corroborate that data as much as reasonably possible with other sources.

Table 5.3., summarizes the data inputs for the Czech Republic.

For the area available in the Czech Republic, we have relied on two Czech studies conducted to estimate the potential for wind[326] and solar.[327] General limitations

	Capacity Factor		MWe / km^2	
Technology	**Pessimistic**	**Optimistic**	**Pessimistic**	**Optimistic**
Onshore Wind	20%	25%	4	9
Solar Roof	10%	14%	134	176
Solar Land	10%	14%	35	88
Nuclear	85%	93%	250	1,541

Table 5.3. Model Data Inputs for the Czech Republic

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[323] Czech NECP, p. 158, 159, et seq.

[324] Czech NECP, p. 80.

[325] Czech NECP, p. 123, 244, et seq.

[326] POTENCIÁL VÝSTAVBY VTE V ČR A MOŽNOSTI ELEKTRICKÝCH SÍTÍ PRO JEJICH PŘIPOJENÍ, available at http://www.ueen.feec.vutbr.cz/images/Veda_a_vyzkum/Produkty/Total_potential/s4_01.pdf

[327] STUDIE „POTENCIÁL SOLÁRNÍ ENERGETIKY V ČESKÉ REPUBLICE", available at http://files.odpady.webnode.cz/200006128-0d90a0e8a8/CZEPHO%20-%20potenci%C3%A1l%20sol%C3%A1rn%C3%AD%20energetiky%20v%20%C4%8CR%20-%20FINAL%201.1.pdf

Maintenance of the current share of nuclear energy in the energy mix and its further development is regarded as crucial for achieving the long-term low-emission commitments of the Czech Republic. The State Energy Policy therefore requires that the share of nuclear energy in primary energy be increased.

that have been accounted for include national parks, roads, other infrastructure, military areas, etc. Under current policies, this would translate into 5,738 square km of land available for wind and solar and 78 square km of roof for solar.

The **available space is much lower** than that in The Netherlands. Notably, the Czech Republic has no access to the sea, so it cannot build any offshore wind, and has predominantly rivers as its internal waters, which are not suitable for wind energy. The Czech Republic has generally been more neutral in the nuclear and renewables trade-off, and hence has been able to draw clearer lines as to which land is available for energy technologies.

However, these conclusions align directionally with the available research. Two studies in particular, one that estimates the potential of wind power[328] and one that estimates the potential of solar power[329] in Europe, use high-resolution land cover maps and spatial raster datasets (where available) to estimate the potential land and roof available. The studies point to available space in the Czech Republic that is about twice as high, i.e. roughly 10,000 km^2 of available land and 185 km^2 of available rooftop. Given that the Czech studies are a more conservative and are accepted by the Czech government, we use those figures. Estimates based on high-level data, including maps, are likely to overestimate the available space given their insensitivity to potential protected status of pieces of land, land spaces that are used for other purposes (e.g. military exercises) but look otherwise free, etc.

We treat **energy demand as an exogenous variable**, and, as such, will perform sensitivity analysis with broad ranges. In general, the Czech Republic has a lower energy demand than The Netherlands. As such, the range for our sensitivity analysis will not be as broad as it is for The Netherlands. Energy demand was roughly 1,800 PJ in 2018 and is expected by the government to decline to around 1,000 PJ in 2050, with electrification rates of 20 and 27%, respectively. For our sensitivity analysis, we model energy demand between 1,000 and 3,000 PJ and electrification rates of 10% to 100%.

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[328] How much wind power potential does Europe have? Examining European wind power potential with an enhanced socio-technical atlas" by Enevoldsen et al, 2019

[329] A high-resolution geospatial assessment of the rooftop solar photovoltaic potential in the European Union," Bodis et al., 2019

As discussed above, what determines the amount of nuclear and renewables capacity necessary is the electricity demand. To simplify the analysis, we make the assumption that nuclear and renewables (wind, solar) are the only sources generating electricity.[330]

iii. Model Outputs

We present the model outputs in several ways to illustrate the various ways in which the issue of land usage can be approached. In order, we present the following model outputs:

1. Comparison of the various technologies to establish the space trade-offs involved in choosing between technologies
2. Spatial restraints to assess maximum power capacity of the Czech Republic for the power technologies concerned
3. Impact of increasing share of renewables on land usage
4. Sensitivity analysis of a 100% renewables scenario
5. Sensitivity analysis of a 75% / 25% nuclear and renewables scenario
6. Sensitivity analysis of a 100% nuclear scenario

Comparing Technologies

As a first exploratory step, we compare the technologies by imposing the same energy demand requirements on each technology. In our first scenario, we require that each technology meet 100% of the electricity demand. In this scenario, total energy demand supplied by electricity is **700 PJ per annum**, which represents roughly 40% of the total energy demand of 1,800 PJ per annum, in-line with the Czech Republic's 2019 primary energy usage. The outcomes are presented in Table 5.4.

Explanation

- As mentioned earlier, we employ ranges for each of capacity and density factors. Given that we use ranges with minima and maxima, we effectively have two corner points that represent extremes for the required land. The pessimistic corner point uses the minima for both the capacity and density factors, whereas the optimistic corner point uses the maxima for both those factors. We also represent an "average" scenario that corresponds to the simple average of both the capacity and density factors.

- In other words, if solar roof installations must produce 700 PJ of electricity annually, it would require at least 1.157% of the available roof space. Thus, at this level of demand, solar roof far exceeds the available roof space. More realistically, if the full demand is met through solar on land, at least 31% and up to 110% of the available area is required. On the other hand, if nuclear is to meet 700 PJ of electricity

	Area Required (km^2)			Area1 Required (% of Available)		
Technology	**Pessimistic**	**Average**	**Optimistic**	**Pessimistic**	**Average**	**Optimistic**
Onshore Wind Land	27,746	14,864	9,574	484%	259%	167%
Solar Roof	1,653	1,194	903	2119%	1530%	1157%
Solar Land	6,288	3,005	1,806	110%	52%	31%
Nuclear	104	28	15	2%	0%	0%

Table 5.4. Area Required At Full Demand Met By Specific Power Technology

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[330] Thus, we exclude other potential power sources, such as H_2, gas, or import.

	Area Required (km^2)			Area1 Required (% of Available)		
Technology	**Pessimistic**	**Average**	**Optimistic**	**Pessimistic**	**Average**	**Optimistic**
Onshore Wind Land	6,937	3,716	2,393	121%	65%	42%
Solar Roof	413	298	226	530%	383%	289%
Solar Land	1,572	751	451	27%	13%	8%
Nuclear	26	7	4	0%	0%	0%

Table 5.5. Area Required By Each Technology If Each Produces Equal Share of Total Electricity Demand

demand, it would require at most 104 square km of land. This scenario, of course, is not realistic, because it is unlikely that policy makers would want only one power technology to supply all power, but it is useful to illustrate the relative land/space demand.

The absolute and relative space demands can be more realistically illustrated by requiring that each technology supply an equal share of the demand. Specifically, if each of the four technologies is to generate 25% of the annual 700 PJ of electricity demand, the areas required are set forth in Table 5.5.

Thus, ***for onshore wind and solar on roof, the scenario whereby all the available space is exceeded is within our reasonable range of possible outcomes***.

Table 5.6., summarizes the impact on the total land and roof usage for this scenario of equal share:

As the table shows, a **perfectly equal power mix** implies that the **space demand of onshore water and roof space could exceed the available space**. Thus, this mix might not be feasible. However, this exercise allows us to get a better feel for the impact of each technology on their spatial environment.

Spatial Restraints and Power Produced

A scenario that takes restraints into account is probably more relevant to policy makers who by necessity operate under restraints. Under this kind of scenario, policy makers, confronted with conflicting demands on land and space, ex- or implicitly set limits on any land or space demand by an activity, be it residential, industrial, power generation, agriculture, fishery, recreation, nature protection, landscape, horizon and silence protection, transportation or yet another demand.

In the scenario that is explored here, the model operates under the following restraints: (i) 100% of any available space may be used for power generation, and (ii) priority should be given to the various technologies in the following hierarchical order, which is based on

	Area Required (km^2)			Area1 Required (% of Available)		
Technology	**Pessimistic**	**Average**	**Optimistic**	**Pessimistic**	**Average**	**Optimistic**
Onshore Land	8,535	4,474	2,849	149%	78%	50%
Roof	413	298	226	530%	383%	289%

Table 5.6. Impact on Space If Each Technology Produces Equal Share of Total Electricity Demand

> The expected electricity production if we use 100% of the available space for renewable would be about 670 PJ per annum. For context, the Czech Republic's primary energy demand for 2019 was just over 1,800 PJ, and hence renewable would generate no more than 40% of its energy demand.

space efficiency, with the more efficient ranked higher:

- solar roof (few competing uses)
- solar land (many competing uses)
- onshore wind land (many competing uses)

In this scenario, nuclear is not regarded as an option, and is added only for purposes of comparison. Furthermore, we are operating in the pessimistic case.

The hierarchy demands that the higher ranked technology be exhausted first up to the 100% space limit before the next technology is added. We first explore how much power is produced if all of these technologies, except nuclear, are fully utilized up to maximum limit; we then add nuclear up to 100% of the space to compare with renewable. Table 5.7., presents the results.

Thus, ***the expected electricity production if we use 100% of the available space for renewable power in this scenario would be about 670 PJ per annum***. For context, the Czech Republic's primary energy demand for 2019 was just over 1,800 PJ, and hence renewable would generate **no more than 40% of its energy demand**.

A maximum space utilization of 100% for power generation is an enormous portion of available space allocated to power generation. Given other competing uses of space, a maximum percentage that is politically probably more realistic and feasible is 50%. The model now determines how much power is generated by renewable power under this constraint, and then compares to nuclear. Table 5.7., presents the results.

Technology	Land	Roof	Electricity Production (PJ p.a.)
Solar Roof	-	100%	33
Solar Land	100%	-	640
Onshore Wind	n/a (full)	-	0
Total Renewable	100%	100%	**673**
Nuclear (as alternative)	100%		**38,500**

Table 5.7. Area Required If Restraints Are Put in Place (no more than 100% of space, hierarchical order for technology)

Technology	Land	Roof	Electricity Production (PJ p.a.)
Solar Roof	-	50%	16.5
Solar Land	50%	-	320
Onshore Wind	n/a (full)	-	0
Total Renewable	**50%**	**50%**	**336.5**
Nuclear (as alternative)	50%		**19,250**

Table 5.8. Area Required If Restraints Are Put in Place (no more than 50% of space, hierarchical order)

With total power generated at 337 PJ per annum, ***power production would be insufficient to meet the power demand in a conservative scenario of 1,500 PJ per annum and 25%*** electrification, which results in a power demand of 375 PJ per annum.

Space Impact of Increasing Share of Renewables

We now proceed to explore the space impact of renewable power more systematically. To illustrate the impact of increasing the share of renewables on area usage, we plot the percentage (%) of available land utilized for energy (the y-axis) for different shares of electricity generated by renewables (the x-axis). We assume that whatever electricity is not being generated by renewables is being generated by nuclear.

We map out three different scenarios:

- *“2019 Baseline”* – This resembles the current (2019) make-up of energy demand and electricity mix: 1,800 PJ of annual energy demand, with 20% being met by electricity. In other words, every combination of nuclear and renewables supplies 360 PJ of energy per annum.
- *“2030 Target”* – This represents the Czech Republic’s official target for 2030 that projects 1,600 PJ per annum and a 25% rate of electrification. Renewable and nuclear power jointly supply 400 PJ per annum.
- *“Conservative Scenario”* – This represents a more conservative scenario in which energy demand increases to 2,000 PJ per annum as does the electronification to 30%. Renewable and nuclear power jointly supply 600 PJ per annum.

We assume a renewable power mix that is one quarter onshore wind and three quarters land solar. For simplicity, we have not included roof solar, which makes only a small contribution to total power. Furthermore, we are operating in the pessimistic case.

Figure 5.3, presents the results.

The graph demonstrates the spatial trade-offs between nuclear and renewables. **At the extremes, it shows that 100% renewable power requires more than the available space and, as such, is not a realistic scenario for the Czech Republic**.

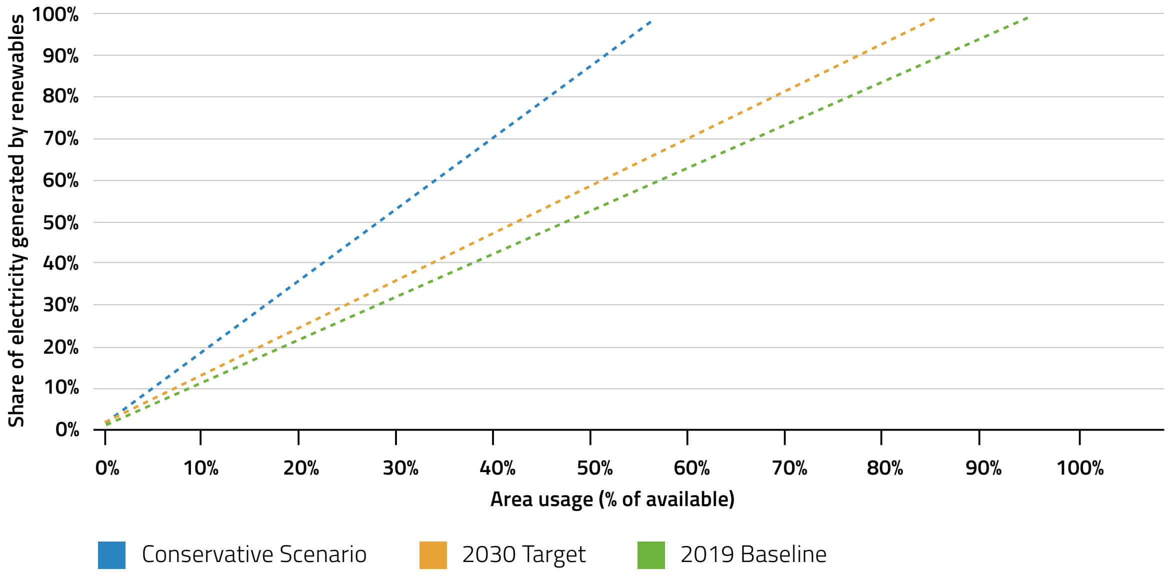

Figure 5.3. Impact of Increasing Share of Renewables on Area Usage

Put differently, the pressure on space and the potential for conflicting demands continue to increase as the share of renewable power in the mix increases, even if policy makers are willing to dedicate very large portions of available space to power generation in order to avoid having to resort to nuclear.

The 2019 Baseline scenario begins to show what increasing shares of renewable power will mean for space utilization. Even at constant levels of demand, relatively modest levels of renewable energy impose serious requirements on land space.

In the 2030 Target scenario, the limits of available space are reached or exceeded even earlier. At 90% renewables, there is not enough land available. These findings highlight the importance of integrating other sources of energy (e.g. nuclear), as relying solely, or to a significant extent, on renewables can lead to issues if by 2030 electricity demand increases by more than projections.

In the Conservative scenario, the pressure on land usage becomes clearer. Hence, if there is some **modest growth in energy demand and electrification increases, renewables would occupy all the available space at just over 50% of the energy mix**. This further emphasizes the potential benefit of having higher density energy technologies represented significantly in the overall mix.

100% Renewables

In this sensitivity analysis, the energy demand (y-axis) and rate of electrification (x-axis) vary, and all of the electricity demand is met by renewables (non-electricity energy demand is met by other energy sources[331]). We assume a renewable power mix of 25% onshore wind and 75% solar. We have used the

Energy Demand (PJ)	10%	15%	20%	25%	30%	40%	60%	75%	100%
	% of Energy Demand Supplied by Renewables								
1,000	29.0%	43.5%	58.0%	72.5%	87.0%	116.0%	174.1%	217.6%	290.1%
1,200	34.8%	52.2%	69.6%	87.0%	104.4%	139.3%	208.9%	261.1%	348.1%
1,400	40.6%	60.9%	81.2%	101.5%	121.8%	162.5%	243.7%	304.6%	406.2%
1,600	46.4%	69.6%	92.8%	116.0%	139.3%	185.7%	278.5%	348.1%	464.2%
1,800	52.2%	78.3%	104.4%	130.5%	156.7%	208.9%	313.3%	391.6%	522.2%
2,000	58.0%	87.0%	116.0%	145.1%	174.1%	232.1%	348.1%	435.2%	580.2%
2,200	63.8%	95.7%	127.6%	159.6%	191.5%	255.3%	382.9%	478.7%	638.2%
2,400	69.6%	104.4%	139.3%	174.1%	208.9%	278.5%	417.8%	522.2%	696.3%
2,600	75.4%	113.1%	150.9%	188.6%	226.3%	301.7%	452.6%	565.7%	754.3%
2,800	81.2%	121.8%	162.5%	203.1%	243.7%	324.9%	487.4%	609.2%	812.3%
3,000	87.0%	130.5%	174.1%	217.6%	261.1%	348.1%	522.2%	652.7%	870.3%

Table 5.9. Sensitivity Table of Area Occupied by Renewable Power As a Function of Energy Demand and Share Supplied by Renewables

% of Available Land Occupied

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[331] For the purposes of this model, if not the full 100% of energy is supplied by renewable power, the remainder is supplied by other energy sources. The model focuses solely on the space impact of renewable power and does not consider the impact on space usage of other energy sources.

In this scenario, if only 30% of the power is generated by renewables, all available land is occupied with wind and solar at a power demand of 1,000 PJ.

low end of the range for both the capacity factor and the required land for installation, i.e. the “pessimistic” case. Table 5.10., presents the results for the land area required.

The black dividing line running through these tables indicates where the available space is exceeded (i.e. percentages of more than 100% in the lower right area under the line colored yellow/red). As these tables show, ***in this scenario, if only 30% of the power is generated by renewables, all available land is occupied with wind and solar at a power demand of 1,000 PJ***.

75% Nuclear / 25% Renewables

In this scenario, 75% of the electricity demand is met by nuclear power, 6.3% by onshore wind and 18.7% by solar on land; the other assumptions for the 100% renewable case above apply here too. Table 5.9. presents the results.

As the numbers demonstrate, **the addition of nuclear has greatly reduced the total demand for land and space**. In this scenario, all available land is occupied by renewable power (and, to an insignificant degree also by nuclear power), when the 75/25 nuclear/ renewable power mix delivers 75% of the total energy demand of 1,800 PJ per annum, or 100% of the total energy demand of 1,400 PJ per annum.

	% of Energy Demand Supplied by Renewables & Nuclear								
Energy Demand (PJ)	10%	15%	20%	25%	30%	40%	60%	75%	100%
1,000	7.4%	11.2%	14.9%	18.6%	22.3%	29.8%	44.7%	55.9%	74.5%
1,200	8.9%	13.4%	17.9%	22.3%	26.8%	35.7%	53.6%	67.0%	89.4%
1,400	10.4%	15.6%	20.9%	26.1%	31.3%	41.7%	62.6%	78.2%	104.3%
1,600	11.9%	17.9%	23.8%	29.8%	35.7%	47.7%	71.5%	89.4%	119.2%
1,800	13.4%	20.1%	26.8%	33.5%	40.2%	53.6%	80.4%	100.5%	134.1%
2,000	14.9%	22.3%	29.8%	37.2%	44.7%	59.6%	89.4%	111.7%	149.0%
2,200	16.4%	24.6%	32.8%	41.0%	49.2%	65.5%	98.3%	122.9%	163.9%
2,400	17.9%	26.8%	35.7%	44.7%	53.6%	71.5%	107.2%	134.1%	178.7%
2,600	19.4%	29.0%	38.7%	48.4%	58.1%	77.5%	116.2%	145.2%	193.6%
2,800	20.9%	31.3%	41.7%	52.1%	62.6%	83.4%	125.1%	156.4%	208.5%
3,000	22.3%	33.5%	44.7%	55.9%	67.0%	89.4%	134.1%	167.6%	223.4%

Table 5.10. Sensitivity Table of Area Occupied by Renewable and Nuclear Power As a Function of Energy Demand and Increasing Electrification Share

% of Available Land Occupied

100% Nuclear

In this scenario, all of the electricity demand is met by nuclear power.[332] Table 5.11., presents the results.

Thus, even if the power demand is high, nuclear power has only a marginal effect on land use. **Even if total energy demand in the Czech Republic were 3,000 PJ and 100% of that were supplied by nuclear, less than 8% of the available land would have to be used**. This implies that more than 92% of the available land would be available for other uses. **Compared to renewable power, nuclear power thus has such a low space impact that even in extreme situations, it presents very little potential for space usage conflicts**.

iv. Conclusions and Discussion

The model output confirms that **the spatial requirements of wind/solar are such that these technologies cannot be the main sources of power in the Czech Republic**. While wind/solar would use up all available space quickly and still provide power output that may be insufficient to meet the demand, nuclear power would have much smaller spatial impacts and provide much more power. Indeed, the results of our modelling demonstrate also that the Czech government's plans for the electricity sector, with a **modest role for wind/solar and a significant role for nuclear power, are sensible from a spatial perspective**.

There are historical, cultural, and structural reasons that can explain why nuclear energy is a cornerstone of contemporary Czech energy policy.[333] The issue of nuclear waste is handled exclusively by a dedicated agency, the Radioactive Waste Repository Agency, which negotiates geological repositories with municipalities.[334] A state-controlled entity, CEZ Group,

	% of Energy Demand Supplied by Nuclear								
Energy Demand (PJ)	**10%**	**15%**	**20%**	**25%**	**30%**	**40%**	**60%**	**75%**	**100%**
1,000	0.3%	0.4%	0.5%	0.7%	0.8%	1.0%	1.6%	2.0%	2.6%
1,200	0.3%	0.5%	0.6%	0.8%	0.9%	1.2%	1.9%	2.3%	3.1%
1,400	0.4%	0.5%	0.7%	0.9%	1.1%	1.5%	2.2%	2.7%	3.6%
1,600	0.4%	0.6%	0.8%	1.0%	1.2%	1.7%	2.5%	3.1%	4.2%
1,800	0.5%	0.7%	0.9%	1.2%	1.4%	1.9%	2.8%	3.5%	4.7%
2,000	0.5%	0.8%	1.0%	1.3%	1.6%	2.1%	3.1%	3.9%	5.2%
2,200	0.6%	0.9%	1.1%	1.4%	1.7%	2.3%	3.4%	4.3%	5.7%
2,400	0.6%	0.9%	1.2%	1.6%	1.9%	2.5%	3.7%	4.7%	6.2%
2,600	0.7%	1.0%	1.4%	1.7%	2.0%	2.7%	4.1%	5.1%	6.8%
2,800	0.7%	1.1%	1.5%	1.8%	2.2%	2.9%	4.4%	5.5%	7.3%
3,000	0.8%	1.2%	1.6%	2.0%	2.3%	3.1%	4.7%	5.9%	7.8%

Table 5.11. Sensitivity Table of Area Required by Nuclear Power As a Function of Energy Demand and Share Supplied by Nuclear

% of Available Land Occupied

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[332] As for 100% renewable, for the purposes of this model, if not the full 100% of energy is supplied by nuclear power, the remainder is supplied by other energy sources. The model focuses solely on the space impact of nuclear power and does not consider the impact on space usage of other energy sources.

[333] Osička, Jan ; Černoch, Filip, Anatomy of a black sheep: The roots of the Czech Republic's pro-nuclear energy policy, Energy Research & Social Science, 2017-05, Vol.27, pp. 9-13.

[334] Id, at 11.

The model output confirms that the spatial requirements of wind/solar are such that these technologies cannot be the main sources of power in the Czech Republic. The Czech government's plans for the electricity sector, with a modest role for wind/solar and a significant role for nuclear power, are sensible from a spatial perspective.

operates 75% of the Czech generation capacity, including the nuclear plants.[335] These and other cultural and structural factors have resulted in a **pro-nuclear culture that can be effectively translated into pro-nuclear policies**.[336]

There also seems to a **skeptical attitude toward wind/solar** and a strong awareness of the **limitations of renewable energy**, including, but not limited to, the spatial impacts, which may help to explain why there is low tolerance for the spatial impacts of wind and solar energy:

- The use of agricultural land for wind and solar farms has been described as **"not right," but only done for the money**; the "discrepancy between attitude and behaviour toward renewable energy seems to be characteristic for the entire Czech population."[337]
- Further, a paper authored by the chairman of the Energy Committee and a leading energy consultant describes the challenges arising from the increase in renewable energy sources, in particular solar, in the Czech Republic – "[h]igh levels of electricity generation from renewable energy sources ... during favorable weather conditions ... causes loop flows and overloading of transmission systems .. considerably affects both the distribution system and the transmission system of the Czech Republic." According to these authors, "[o]peration of the Czech power system is negatively influenced and project development of the power system needs to be repeatedly modified and updated." They conclude that "[s]teeply raising development of subsidized renewable energy sources in Europe and in the Czech Republic brings about **many challenges and risks, technical as well as economic and social**."[338]

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[335] Id, at 12.

[336] Cf. Frantál, Bohumil ; Malý, Jiří, Close or renew? Factors affecting local community support for rebuilding nuclear power plants in the Czech Republic, Energy policy, 2017-05, Vol.104, pp. 134-143 ("it seems that the education of the public and awareness of nuclear power plants as a clean, safe and landscape compatible system of energy production are more important for increasing acceptance of rebuilding projects than spatial distribution of economic benefits to local communities"). Cf. Rečka, Lukáš ; Ščasný, Milan, Brown coal and nuclear energy deployment: Effects on fuel-mix, carbon targets, and external costs in the Czech Republic up to 2050, Fuel (Guildford), 2018, Vol.216, pp. 494-502.

[337] Frantál, Bohumil ; Prousek, Adam, It's not right, but we do it. Exploring why and how Czech farmers become renewable energy producers. Biomass & Bioenergy, 2016-04, Vol.87, pp. 26-34 (reporting Czech farmers as saying "it is not right to use arable land for energy production ... but it brings money to keep our farming business running").

[338] Vrba, Miroslav ; Špaček, Zdeněk ; Jež, Jiří ; Ptáček, Jiří, Integration of Electricity from Renewable Energy Sources — The Czech Story, Energy & Environment, 2015-01, Vol.26 (1-2), pp. 157-166

- It has also been argued that in the Czech Republic renewable energy is being viewed as "**forced upon the country by the EU.**"[339]

- The necessity of subsidies for renewable energy has also raised questions in the Czech Republic, with one group of scholars arguing that **renewable subsidies should be abolished**.[340]

Given these factors and the spatial requirements of renewable energy demonstrated through our modeling, the Czech Republic's energy preferences become understandable, and may provide insights into understanding the current situation in The Netherlands.

c. The Netherlands

i. Policy Framework

The Dutch NECP provides for a package of measures aimed at a CO_2 reduction target of 49% by 2030, compared to 1990.[341] Pursuant to the Climate Agreement[342] and Climate Law, The Netherlands pursues a climate-neutral society and a **reliable, affordable, secure and low CO_2 energy supply** by 2050.

Based on this emission reduction of 49% by 2030, The Netherlands proposes contributions to renewable energy and energy savings of respectively "at least 27% and a maximum of 1,950 petajoules in primary energy consumption."[343]

Renewable Energy

Although The Netherlands intends to achieve a 27% renewable energy share by 2030, there is some uncertainty around its ability to deliver.[344] As its NECP notes, "[d]espite the positive attitude towards increased sustainability, in certain parts of the Netherlands there is **opposition to the emergence of projects including infrastructure, solar farms and wind farms**." The reason for this opposition is that "local residents consider that these types of projects **encroach on their living environment**." Consequently, "the spatial integration of the climate and energy transition is a difficult one."[345] As we will see below, there indeed is a conflict between the government's ambitions and the physical reality of The Netherlands.

To provide a framework for managing the issues around the deployment of wind and solar on a large scale, the Dutch government has adopted assessment principles and concepts for "spatial elaboration of the climate and energy transition."[346] To avoid, as much as possible, problems with local residents, the Dutch government has a strong preference for offshore wind energy. Where feasible, energy-intensive industry will be concentrated at the sites where the wind power comes ashore[347].

Another instrument that the Dutch government uses to implement its strategy is a "multi-annual programmatic national approach with nationwide

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[339] Kratochvíl, Petr ; Mišík, Matúš, Bad external actors and good nuclear energy: Media discourse on energy supplies in the Czech Republic and Slovakia, Energy policy, 2020-01, Vol.136, p. 111058.

[340] Maroušek, Josef ; Hašková, Simona ; Zeman, Robert ; Váchal, Jan ; Vaníčková, Radka, Assessing the implications of EU subsidy policy on renewable energy in Czech Republic, Clean Technologies and Environmental Policy, 2015-02, Vol.17 (2), pp. 549-554.

[341] Ministry of Economic Affairs and Climate Policy, Integrated National Energy and Climate Plan 2021-2030, November 2019, available at https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en ("Dutch NECP"), p. 5.

[342] The Climate Agreement ("Klimaatakkoord") sets forth a series of agreements on the measures required to achieve a 49% reduction in greenhouse gas emissions by 2030. It has been agreed by stakeholders in The Netherlands.

[343] Dutch NECP, p. 8.

[344] Dutch NECP, p. 9.

[345] Dutch NECP, p. 11.

[346] Rijksoverheid, Nationale Omgevingsvisie, available at https://www.denationaleomgevingsvisie.nl/default.aspx

[347] Dutch NECP, p. 13.

Although The Netherlands intends to achieve a 27% renewable energy share by 2030, there is some uncertainty around its ability to deliver. As its NECP notes, "despite the positive attitude towards increased sustainability, in certain parts of the Netherlands there is opposition to the emergence of projects including infrastructure, solar farms and wind farms."

integral **Regional Energy Strategies (RES)**." The idea behind the RES program is that the region is "the right level of scale for linking the energy transition challenge with other challenges in the physical environment, and thus comparatively weighing up the various interests," including the spatial requirements.[348]

As a result of the energy transition, the NECP observes that "**electricity generation will be more dependent on weather conditions.**" To ensure supply security with a power energy mix "largely consisting of wind and solar power," **more and stronger flexibility and controllable power are required**. This power should be both decarbonized and provided via the market.[349] The NECP does not discuss the cost implications thereof.

To promote renewable energy, The Netherlands put into the place 'The Sustainable Energy Production Incentive Scheme' (called 'SDE+').[350] The SDE+ is currently the most important instrument for stimulating the generation of renewable energy. This **subsidy instrument** provides "**multi-annual security for investors**."[351] An expanded subsidy program (SDE++) will also subsidize the deployment of large-scale CO_2 reducing techniques, but the government expects "sufficient grant resources will be available to achieve the renewable energy targets." SDE++ subsidies will be made available for renewable energy projects up to 2025; after 2025, the Dutch government hopes that renewable electricity can do without subsidies.[352] The Renewable Energy Scheme (the "HER") is aimed at achieving the 2030 energy targets in a more cost-effective manner through innovation.[353]

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[348] "The RES offers a new instrument in which municipalities, provinces and water boards work together at the regional level and assess renewable electricity generation, the heat transition in the built-up environment and the related storage and infrastructure needed. They do this together with grid operators, businesses and social parties." Dutch NECP, p. 14.

[349] Dutch NECP, p. 30.

[350] Dutch NECP, p. 140.

[351] Dutch NECP, p. 57. The SDE+ has been expanded (SDE++) to make other CO_2 reducing techniques eligible for subsidy. The new scheme is being discussed in detail with the European Commission (DG Competition).

[352] Dutch NECP, p. 53.

[353] Dutch NECP, p. 57 ("Renewable energy projects should lead to renewable energy generation by 2030 and to savings on future expenditure on grants under the SDE+ scheme. These savings must be greater than the subsidy that is requested for the project.")

Nuclear energy is not entirely ruled out. As the NECP states, a mix of different sources of flexibility is required, including increasingly decarbonized adjustable capacity. The options include CO_2-free hydrogen, renewable sources such as biomass and green gas, nuclear power, and the use of fossil sources with carbon capture.

To finance the SDE, The Netherlands levies a surcharge for sustainable energy under the "**Surcharge for Sustainable Energy Act**" ("ODE"). The ODE is levied in addition to the energy tax; it is not an earmarked levy, however, but an estimate of the SDE's costs. As the SDE budgets go up from year to year, the surcharge goes up. On 1 January 2020, the ODE was charged one third to households and two thirds to industry.[354]

Through VAT reimbursement and a "**net-metering scheme**," which results in exemptions from charges and taxes that would otherwise apply, The Netherlands promotes solar power self-consumption.[355] The net-metering scheme will gradually be phased out from 2023 to 2030. Sustainability requirements for homes also provide incentives for the purchase of solar panels and the self-consumption of solar power. Further, various subsidies and credit facilities are used to promote renewable self-consumption. A tax incentive scheme stimulates regional "energy cooperatives."

Nuclear Power

The Netherlands has only one nuclear power plant at Borssele. This plant is due to close in 2033.[356] Nuclear energy, however, is not entirely ruled out. As the NECP states, a mix of different sources of flexibility is required, including increasingly decarbonized adjustable capacity. The options include CO_2-free hydrogen, renewable sources such as biomass and green gas, nuclear power, and the use of fossil sources with carbon capture.

Thus, **nuclear power** remains **one of the options** for the future energy mix. According to the NECP, "[a] number of studies reveal that for 2050, **nuclear power could be a cost-effective option**."[357] However, given the delays involved, the NECP does not regard additional nuclear power plants before 2030 likely. Research on thorium reactors, it observes, is still in an early phase, and market introduction may still take a couple of decades.

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[354] Dutch NECP, p. 74.

[355] Dutch NECP, p. 58.

[356] Dutch NECP, p. 109. "Without new investments, the closure of the nuclear power plant in Borssele in 2033 will bring an end to the contribution of nuclear energy to the energy mix." Dutch NECP, p. 9.

[357] Dutch NECP, p. 45.

Although these studies do not treat nuclear power on equal footing with renewables and are silent on the costs of the policy options, 'Netbeheer Nederland' (representing the companies managing the power network) states that the network managers "in the next phase, will ask for guiding policy."

Planning

Pursuant to the 'Klimaatakkoord',[358] a study has been conducted by Berenschot/Kalavasta on 'climate neutral scenarios 2050'[359] (the "CNS Study"). A companion study examined the land/space impacts of the climate neutral scenarios[360] (the "Space Impact Study"). Since the CNS Study did not consider nuclear power at all, at the request of the Dutch Ministry of Economic Affairs and Climate, a separate study was done on the 'system effects of nuclear power plants in climate neutral scenarios 2050'[361] (the "Nuclear Study"). Recently, the Ministry of Economic Affairs and Climate Policy also had a study done on the possible role of nuclear energy in the Dutch energy mix in the future.[362]

For purposes of this report, the Space Impact Study and the Nuclear Study are particularly relevant. The CNS Study provides the background, however, and the Space Impact Study builds on this report to look specifically at the consequences for the use of land in The Netherlands. In many ways, the Nuclear Study is a different kind of study. While the CNS Study and **Space Impact Study do not discuss costs, the Nuclear focuses mainly on cost**. Because the Space Impact report builds on the scenarios of the CNS Study, it does not discuss the space impact of nuclear power; nor does the Nuclear Study discuss the space impact of nuclear power. As a result, it is hard to place nuclear power in the context of the scenarios analyzed by the consultants.

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[358] Klimaatakkoord, 2019, available at https://www.klimaatakkoord.nl/

[359] Berenschot/Kalavasta, Klimaatneutrale energiescenario's 2050, Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, maart 2020, available at https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2020Z06737&did=2020D14346

[360] Generation Energy, Ruimtelijke uitwerking Energiescenarios, maart 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/31/ruimtelijke-uitwerking-energiescenarios

[361] Kalavasta/Berenschot, Systeemeffecten van nucleaire centrales in Klimaatneutrale Energeiscenarios 2050, 9 maart 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-in-klimaatneutrale-energiescenarios-2050 For the related data sheets in English, see https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-in-klimaatneutrale-energiescenarios-2050

[362] ENCO, Possible role of nuclear energy in the Dutch energy mix in the future, Final Report, 1 Sep. 2020, ENCO-FR-(20)-13, available at https://www.laka.org/docu/catalogue/publication/1.01.0.20/23_possible-role-of-nuclear-in-the-dutch-energy-mix-i

Although these studies do **not treat nuclear power on equal footing** with renewables and are **silent on the costs of the policy options**, in a letter to the Minister of Economic Affairs and Climate, 'Netbeheer Nederland' (representing the companies managing the power network) states that the network managers "in the next phase, will ask for guiding policy."[363] The question is whether the studies conducted so far offer a sound basis for making the important policy decisions that are to be made.

Much of the same data used in these studies has been used for this study, except where we indicate specifically that we use different data; in those cases, we explain our decision to use other data. In connection with developing our own models, we conducted a review of the CNS Study and the Space Impact Study (and, as noted below, the Nuclear Study). These reviews are attached to this report as Annexes IV, V and VI, respectively.

ii. Model Inputs

Contrary to the Czech Republic, The Netherlands can not only build onshore wind farms on land, solar on land, and solar on roof, but also onshore wind on internal waters and offshore wind, greatly increasing the options available to the government.

Below, we provide the minimum and maximum values we used for each of the inputs into the model for The Netherlands. We contextualize the inputs by referencing the CNS Study prepared by Berenschot/Kalavasta (hereafter, the "CNS Study"). For the **power density** inputs, our ranges comprise the values from the CNS Study, which is why these are not separately discussed. As referenced earlier, further details can be found in Annex I attached to this report.

Technology	Min.	Max.	CNS Study
Onshore Wind	20.0%	25.0%	34.2% (3,000 hours)
Offshore Wind	30.0%	45.0%	51.4% (4,500 hours)
Solar (roof & land)	8.0%	9.5%	9.9% (867 hours)
Nuclear	85.0%	93.0%	n/a

Table 5.12. Capacity Factor Model Inputs for The Netherland

Technology	Min.	Max.
Onshore Wind Land	4	9
Onshore Wind Water	6	8
Offshore Wind	6	10
Solar Roof	160	195
Solar Land	35	88
Nuclear	250	1,541

Table 5.13. Power Density Model Inputs for The Netherlands

With respect to the available area, our approach has been to use the available area after considering "**hard restrictions**" as defined in the Space Impact Study. The reason is that the areas currently permitted for a particular use are available without amendment to the laws and policies of The Netherlands. The theoretically available area used in the CNS study is a hypothetical number that is less useful to energy policy making, because utilization of this theoretically available area would require amendments to zoning laws and policies and the elimination of conflicting uses of such space. Even authorized land use changes to permit power generation require political decisions, because they change the living environment and detract from the land available for other uses, such as residential. Land use changes present political choices that should be clearly articulated for policy makers. To assume that additional land could be

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[363] Netbeheer Nederland, Integrale Infrastructuurverkenning 2030-2050, BR-2020-1720, 2 april 2020, available at https://www.rijksoverheid.nl/documenten/brieven/2020/04/02/aanbieding-integrale-infrastructuurverkenning-2030-2050

Category	Total (sq. km)	Available after restrictions (sq. km)	% of total	Technologies Considered
Land	37,390	21,230	57%	Wind, Solar, Nuclear
Waters	7,872	700	9%	Wind
Roof	1,250	286	23%	Solar
North Sea	57,800	18,000	31%	Wind

Table 5.14. Areas available in The Netherlands for power generation

made available for renewable energy projects is also inconsistent with the policy articulated in the Dutch government's 'National Vision on Land Use,' which states explicitly that **various demands such as housing and the circular economy, require more space than available**.[364]

Unlike the CNS Study by Berenschot,[365] our model regards energy demand as an exogenous variable, given that it is extremely difficult to predict energy demand 30 years from now and that energy policy choices at one point in time (as in the ETM model) cannot be used to accurately predict energy demand. This is so **because energy demand is a function of many variables**, such as general economic development and welfare, industrial mix, innovation, etc. This is why the sensitivity analysis of the model accounts for broad ranges of energy demand and electricity production.

In addition to total energy demand, the percentage of energy provided by electricity is a critical factor. This is the degree of '**electrification**' of the energy demand. The general thinking, as reflected in the CNS Study, is that the degree of electrification of the energy demand is bound to increase over the next several decades, as activities such as heating and transport increasingly move away from fossil fuel and switch to power or batteries. We believe that, like total energy demand, the degree of electrification in 2050 is hard to predict and necessitates a wide range.

Our sensitivity analysis takes into account primary energy demand in the range of 1,500 PJ to 4,000 PJ per annum, with electrification rates of 10% to 100%. Ultimately, what determines the amount of nuclear and renewables capacity necessary is the electricity demand. To simplify the analysis, we make the assumption that nuclear and renewables (wind, solar) are the only sources generating electricity.[366]

iii. Model Outputs

The **model outputs** for The Netherlands follow the pattern of the model outputs for the Czech Republic, as follows:

1. Comparison of the various technologies to establish the space trade-offs involved in choosing between technologies
2. Spatial restraints to assess maximum power capacity of The Netherlands for the power technologies concerned

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[364] "In Nederland staan we voor grote opgaven. De bouw van 1 miljoen nieuwe woningen, duurzaam energie opwekken, klimaatverandering en de overgang naar een circulaire economie vragen veel ruimte. Meer ruimte dan beschikbaar is in Nederland. We moeten keuzes maken zodat Nederland ook voor toekomstige generaties een veilig, gezond en welvarend land kan blijven." Nationale Omgevingsvisie, available at https://www.denationaleomgevingsvisie.nl/default.aspx

[365] The CNS Study relies on the ETM model, which treats energy demand as an endogenous variable that is determined by a series of policy choices made by planners (i.e. model users).

[366] Thus, we exclude other potential power sources, such as H_2, gas, or import. The share of these other sources in the power mix in 2050 in the CNS Study varies from just over 20% to 40%.

3. Impact of increasing share of renewables on land and sea usage
4. Sensitivity analysis of a 100% renewables scenario
5. Sensitivity analysis of a 50% / 50% nuclear and renewables scenario
6. Sensitivity analysis of a 100% nuclear scenario

Comparing Technologies

As a first exploratory step, we compare the technologies by imposing the same energy demand requirements on each. In our first scenario, we require that **each technology meet 100% of the electricity demand**. In this scenario, total energy demand supplied by electricity is 800 PJ per annum, which represents 40% of the total energy demand of 2,000 PJ per annum, somewhere in the middle of the Berenschot ranges and consistent with our ranges as stated in Annex I attached to this report. The outcomes are presented in Table 5.15.

Based on those figures, if solar roof installations must produce 800 PJ of electricity annually, it would require at least 479% of the available roof space. Thus, at this level of demand, solar roof exceeds the available roof space. More realistically, **if the full demand is met through onshore wind on land, at least 52% and up to 149% of the available area is required**. On the other hand, if nuclear is to meet 800 PJ of electricity demand, it would require at most **120 square km** of land. This scenario, of course, is not realistic, because it is unlikely that policy makers would want only one power technology to supply all power, but it is useful to illustrate the relative land/space demand.

The absolute and relative space demands can be more realistically illustrated by requiring that **each technology supply an equal share of the demand**. Specifically, if each of the six technologies is to generate 16.67% of the annual 800 PJ of electricity demand, the areas required are set forth in Table 5.16.

Thus, for onshore wind on water and solar on roof, the scenario whereby all the available space is exceeded is within our reasonable range of possible outcomes.

Table 5.17., summarizes the impact on the total land, water, roof, and sea usage for this scenario of equal share.

As the tables show, **a perfectly equal power mix implies that the space demand of onshore water and roof space could exceed the available space**. Thus, this mix might not be feasible. However, this exercise allows us to get a better feel for the impact of each technology on their spatial environment.

In the CNS Study, in the scenario with the highest output of wind and solar, the “Nationale sturing,” 15% is generated by solar on roof, 17% by solar on land, about

	Area Required (km^2)			Area Required (% of Available)		
Technology	**Pessimistic**	**Average**	**Optimistic**	**Pessimistic**	**Average**	**Optimistic**
Onshore Wind Land	31,710	16,987	10,941	149%	80%	52%
Onshore Wind Water	21,140	16,107	12,684	3020%	2301%	1812%
Offshore Wind	14,093	8,456	5,637	78%	47%	31%
Solar Roof	1,982	1,633	1,369	693%	571%	479%
Solar Land	8,983	4,722	3,052	42%	22%	14%
Nuclear	119	32	18	1%	0%	0%

Table 5.15. Area Required At Full Demand Met By Specific Power Technology

	Area Required (km^2)			Area Required (% of Available)		
Technology	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
Onshore Wind Land	5,285	2,831	1,824	25%	13%	9%
Onshore Wind Water	3,523	2,684	2,114	503%	383%	302%
Offshore Wind	2,349	1,409	940	13%	8%	5%
Solar Roof	330	272	228	115%	95%	80%
Solar Land	1,497	787	509	7%	4%	2%
Nuclear	20	5	3	0%	0%	0%

Table 5.16. Area Required By Each Technology If Each Produces Equal Share of Total Electricity Demand

	Area Required (km^2)			Area Required (% of Available)		
Technology	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
Onshore Land	6,802	3,623	2,335	32%	17%	11%
Onshore Water	3,523	2,684	2,114	503%	383%	302%
Sea	2,349	1,409	940	13%	8%	5%
Roof	330	272	228	115%	95%	80%

Table 5.17. Impact on Space If Each Technology Produces Equal Share of Total Electricity Demand

8.5% by onshore wind, and 32% by offshore wind. If we put this in our model, the space demand would be as set forth in Table 5.18.

In this scenario, renewables generate 580 PJ of energy per annum. While this scenario is relatively conservative in terms of its final energy demand, **already a quarter of the available North Sea is covered in wind turbines, and a fifth of the available land**. Furthermore, **solar on roof might already exceed the available space**.

	Area Required (km^2)			Area Required (% of Available)		
Technology	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
Onshore Wind Land	2,695	1,444	930	13%	7%	4%
Onshore Wind Water	0	0	0	0%	0%	0%
Offshore Wind	4,510	2,706	1,804	25%	15%	10%
Solar Roof	297	245	205	104%	86%	72%
Solar Land	1,527	803	519	7%	4%	2%
Nuclear	0	0	0	0%	0%	0%

Table 5.18. Area Required By Each Technology In Berenschot Scenario “Nationale Sturing”

As the table shows, a perfectly equal power mix implies that the space demand of onshore water and roof space could exceed the available space. Thus, this mix might not be feasible.

Spatial Restraints and Power Produced

A scenario that takes restraints into account is probably more relevant to policy makers who by necessity operate under restraints. Under this kind of scenario, policy makers, confronted with conflicting demands on land and space, ex- or implicitly set limits on any land or space demand by an activity, be it residential, industrial, power generation, agriculture, fishery, recreation, nature protection, landscape, horizon and silence protection, transportation or yet another demand.

In the scenario that is explored here, the model operates under the following restraints: (i) **no more than 50% of any available space** may be used for power generation, and (ii) priority should be given to the various technologies in the following hierarchical order, which is based on **space efficiency** relative to power output, with the more efficient ranked higher:

- offshore wind (sea, few competing uses)
- solar roof (few competing uses)
- solar land (many competing uses)
- onshore wind land (many competing uses)
- onshore wind water (many competing uses)

In this scenario, nuclear is not regarded as an option, and is added only for purposes of comparison. Furthermore, we are operating in the pessimistic case.

The hierarchy demands that the higher ranked technology be exhausted first up to the 50% space limit before the next technology is added. We first explore how much power is produced if all of these technologies, except nuclear, are fully utilized up to maximum limit; we then add nuclear up to 50% of the space to compare with renewable. Table 5.19. presents the results.

Technology	Land	Water	Sea	Roof	Electricity Production (PJ p.a.)
Offshore Wind	-	-	50%		510
Solar Roof	-	-	-	50%	58
Solar Land	50%	-	-	-	950
Onshore Wind (Land)	n/a (full)	-	-	-	0
Onshore Wind (Water)	-	50%	-	-	13
TOTAL RENEWABLE	50%	50%	50%	50%	**1,531**
Nuclear (as alternative)	50%				**71,800**

Table 5.19. Area Required If Restraints Are Put in Place (no more than 50% of space, hierarchical order for technology)

Technology	Land	Water	Sea	Roof	Electricity Production (PJ p.a.)
Offshore Wind	-	-	20%	-	204
Solar Roof	-	-	-	20%	23
Solar Land	20%	-	-	-	380
Onshore Wind (Land)	n/a (full)	-	-	-	0
Onshore Wind (Water)	-	20%	-	-	5
TOTAL RENEWABLE	**20%**	**20%**	**20%**	**20%**	**612**
Nuclear (as alternative)	20%				28,720

Table 5.20.. Area Required If Restraints Are Put in Place (no more than 20% of space, hierarchical order)

Thus, the expected electricity production if we use 50% of the available space for renewable power in this scenario would be about 1,500 PJ per annum. For context, The Netherlands has had an energy demand of over 3,000 PJ for the last 20 years. There is no scenario in the CNS Study where renewables are tasked to generate this much energy. However, Berenschot assumes that in its most ambitious scenario almost half of the available energy demand is met by electricity from renewables. Hence, this scenario would mean that if overall energy demand in the Netherlands stays flat at about 3,000 PJ, but we ensure that **renewables provide about half of it, we would hit the area usage restraint of 50%**.

A maximum space utilization of 50% for power generation still is an enormous portion of available space allocated to power generation. Given other competing uses of space (residential use, recreation, industrial use, agriculture, fishery, nature and fauna protection, etc.), a maximum percentage that is politically probably more realistic and feasible is 20%. The model now determines how much power is generated by renewable power under this constraint, and then compares to nuclear. Table 5.20., presents the results.

With total power generated at 612 PJ per annum, **power production would be insufficient** to meet the power demand in our middle range scenario of 2,750 PJ per annum and 30% electrification, which results in a power demand of 825 PJ per annum. Under these conditions, there would not be enough power to meet the power demand in Berenschot's lowest demand scenario (lowest energy demand of 1,600 PJ per annum, and 40% electrification, resulting in power demand of 700 PJ per annum.

With total power generated at 612 PJ per annum, power production would be insufficient to meet the power demand in our middle range scenario of 2,750 PJ per annum and 30% electrification, which results in a power demand of 825 PJ per annum.

Space Impact of Increasing Share of Renewables
We now proceed to explore the space impact of renewable power more systematically. To illustrate the impact of increasing the share of renewables on area usage, we plot the percentage (%) of available land and sea utilized for energy (the y-axis) for different shares of electricity generated by renewables (the x-axis). We assume that whatever electricity is not being generated by renewables is being generated by nuclear.

We map out three different scenarios:

- ***"2019 Baseline"*** – This resembles the current (2019) make-up of energy demand and electricity mix: 3,000 PJ of annual energy demand, with 15% being met by electricity. In other words, every combination of nuclear and renewables supplies 450 PJ of energy per annum.
- ***"2050 H/H"*** – This represents an extreme scenario that projects 4,000 PJ per annum and a 50% rate of electrification (high/high). Renewable and nuclear power jointly supply 2,000 PJ per annum.
- ***"2050 Berenschot"*** – This resembles Berenschot's "Regionale sturing" scenario from the CNS Study, with energy demand dropping to 1,750 PJ per annum and 45% of that being met with electricity. In other words, every combination of nuclear and renewables supplies roughly 790 PJ per annum. This, in combination with the "Nationale sturing" scenario, are the most demanding Berenschot scenarios when it comes to renewables power.

We assume a renewable power mix that is one part onshore wind, four parts offshore wind, and three parts land solar. This is very roughly in-line with the Berenschot electricity make-up from the Space Impact Study.[367] For simplicity, we have not included roof solar and onshore wind on water, which make only small contributions to total power in the Berenschot scenario.

Figure 5.4., presents the results.

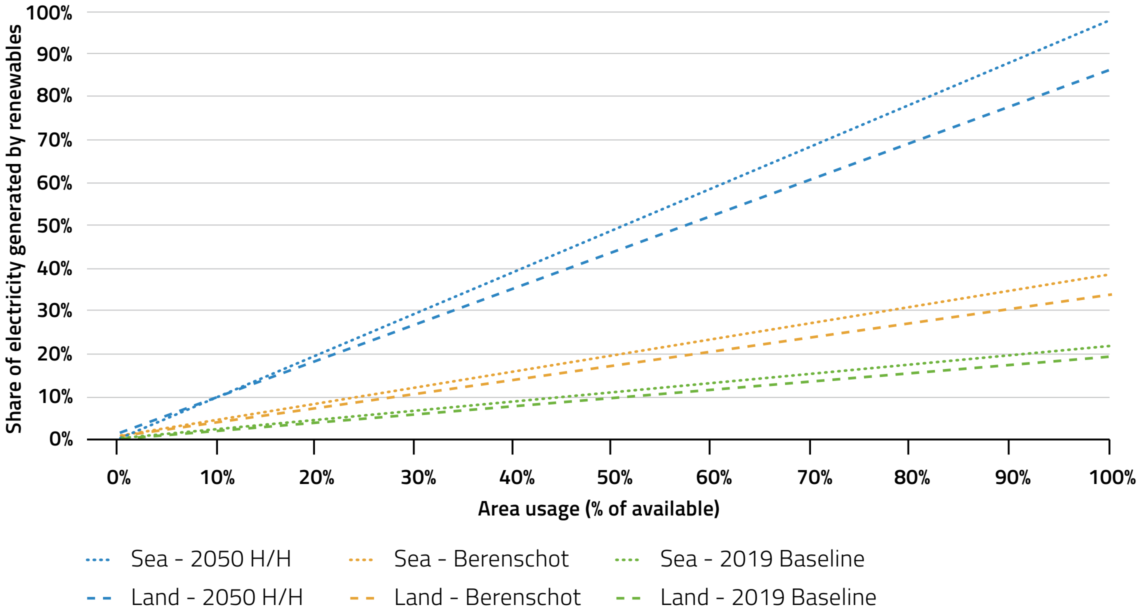

Figure 5.4. Impact of Increasing Share of Renewables on Area Usage

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[367] Space Impact Study, p. 13. The Space Impact focuses on what Berenschot calls the 'European Governance' scenario.

At a low level of power demand, 100% renewable power imposes serious requirements on land and sea space, at 34% and 39%, respectively; these ratios may exceed the amount of space policy makers are willing to allocate to power generation.

The graph demonstrates the spatial trade-offs between nuclear and renewables. At the extremes, it shows that **100% renewable power requires substantial portions of the available space -- from approximately 19% up to 86% of available land, and from 22% to 98% of available sea**. Put differently, the pressure on space and the potential for conflicting demands continue to increase as the share of renewable power in the mix increases, even if policy makers are willing to dedicate very large portions of available space to power generation in order to avoid having to resort to renewable.

The 2050 Berenschot scenario begins to show what increasing shares of renewable power will mean for space utilization. **At a low level of power demand, 100% renewable power imposes serious requirements on land and sea space, at 34% and 39%, respectively; these ratios may exceed the amount of space policy makers are willing to allocate to power generation**.

In the 2050 H/H scenario, the limits of available space are reached or exceeded. At 100% renewables, 98% of the available sea is utilized and 86% of the available land. These findings highlight the importance of potentially integrating other sources of energy (e.g. nuclear), as relying solely, or to a significant extent, on renewables can lead to issues if by 2050 electricity demand increases by more than the CNS Study is willing to assume.

In the 2019 Baseline scenario, based on 2019 data from the CBS,[368] of the roughly 3,000 PJ in total energy demand, about 232 PJ came from renewables, just below 8%. This suggests that **if policies were to move towards 100% renewables, we would need to increase the area currently covered by renewable energy sources by a factor of 12, both on sea and on land**; in other words, the same surface of land and sea allocated to renewable power up to and including 2019, would have to be allocated 11 more times up to 2050 to provide sufficient space for renewable power.

100% Renewables

In this sensitivity analysis, the energy demand (y-axis) and rate of electrification (x-axis) vary, and all of the electricity demand is met by renewables (non-electricity energy demand is met by other energy sources[369]). We assume a renewable power mix of 30% onshore wind, 40% offshore wind, and 30% solar (thus, 60% is generated onshore, 40% is generated offshore).

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[368] CBS Statline website, link: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82610NED/table?ts=1595021228421

[369] For the purposes of this model, if not the full 100% of energy is supplied by renewable power, the remainder is supplied by other energy sources. The model focuses solely on the space impact of renewable power and does not consider the impact on space usage of other energy sources.

We have used the low end of the range for both the capacity factor and the required land for installation, i.e. the "pessimistic" case. Table 5.21., presents the results for both land area required and sea area required.

The black dividing line running through these tables indicates where the available space is exceeded (i.e. percentages of more than 100% in the lower right area under the line colored yellow/red). As these tables show, in this scenario, **if only half of the power is generated by renewables, all available land is occupied with wind and solar at a power demand of 3,000 PJ. The available North Sea space is exhausted if renewable supplies 75% of the power and the demand is 3,500 PJ**.

50% Nuclear / 50% Renewables

Energy Demand (PJ)	% of Energy Demand Supplied by Renewables								
	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	10.8%	16.2%	27.0%	37.7%	48.5%	53.9%	59.3%	80.9%	107.8%
1,750	12.6%	18.9%	31.4%	44.0%	56.6%	62.9%	69.2%	94.3%	125.8%
2,000	14.4%	21.6%	35.9%	50.3%	64.7%	71.9%	79.1%	107.8%	143.8%
2,250	16.2%	24.3%	40.4%	56.6%	72.8%	80.9%	88.9%	121.3%	161.7%
2,500	18.0%	27.0%	44.9%	62.9%	80.9%	89.8%	98.8%	134.8%	179.7%
2,750	19.8%	29.6%	49.4%	69.2%	88.9%	98.8%	108.7%	148.2%	197.7%
3,000	21.6%	32.3%	53.9%	75.5%	97.0%	107.8%	118.6%	161.7%	215.6%
3,250	23.4%	35.0%	58.4%	81.8%	105.1%	116.8%	128.5%	175.2%	233.6%
3,500	25.2%	37.7%	62.9%	88.1%	113.2%	125.8%	138.4%	188.7%	251.6%
3,750	27.0%	40.4%	67.4%	94.3%	121.3%	134.8%	148.2%	202.2%	269.5%
4,000	28.8%	43.1%	71.9%	100.6%	129.4%	143.8%	158.1%	215.6%	287.5%

% of Available Land Occupied

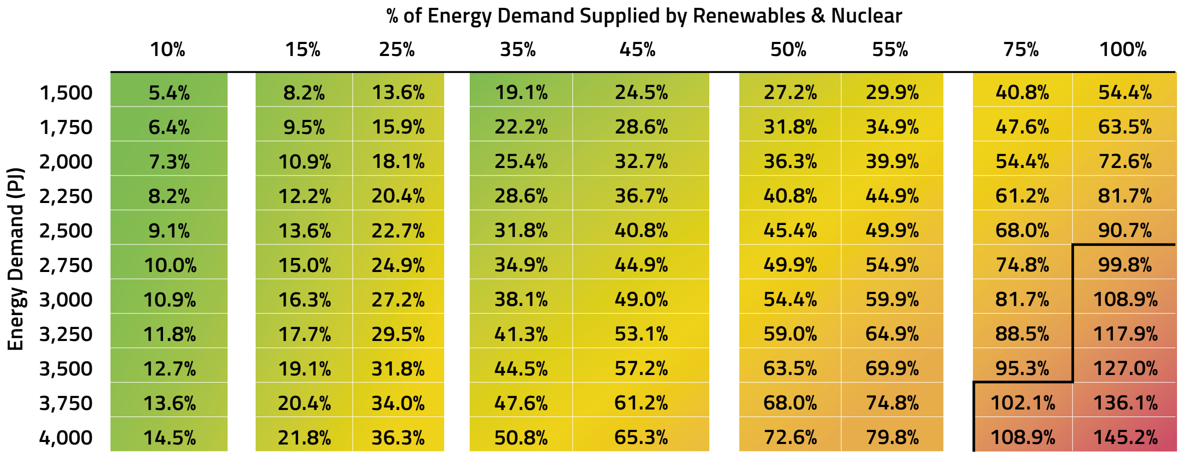
Energy Demand (PJ)	% of Energy Demand Supplied by Renewables								
	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	6%	9%	15%	21%	26%	29%	32%	44%	59%
1,750	7%	10%	17%	24%	31%	34%	38%	51%	69%
2,000	8%	12%	20%	27%	35%	39%	43%	59%	78%
2,250	9%	13%	22%	31%	40%	44%	48%	66%	88%
2,500	10%	15%	24%	34%	44%	49%	54%	73%	98%
2,750	11%	16%	27%	38%	48%	54%	59%	81%	108%
3,000	12%	18%	29%	41%	53%	59%	65%	88%	117%
3,250	13%	19%	32%	45%	57%	64%	70%	95%	127%
3,500	14%	21%	34%	48%	62%	69%	75%	103%	137%
3,750	15%	22%	37%	51%	66%	73%	81%	110%	147%
4,000	16%	23%	39%	55%	70%	78%	86%	117%	157%

% of Available Sea Occupied

Table 5.21. Sensitivity Table of Area Occupied by Renewable Power As a Function of Energy Demand and Share Supplied by Renewables

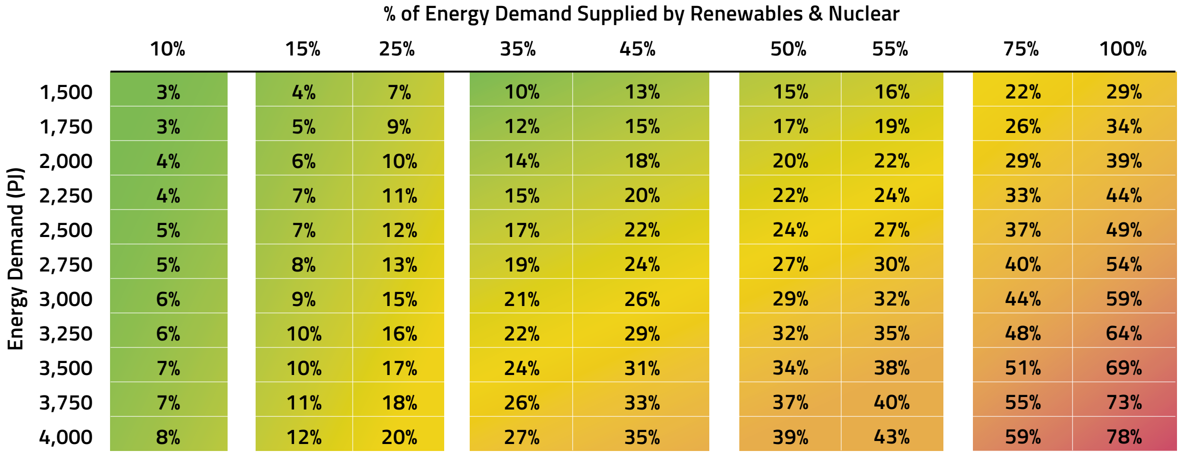
In this scenario, half of the electricity demand is met by nuclear power, 15% by onshore wind, 20% by offshore wind, and 15% by solar on land; the other assumptions as for the 100% renewable case above apply here too. Table 5.22., presents the results.

As the numbers demonstrate, **the addition of nuclear has greatly reduced the total demand for land and space**. In this scenario, **all available land is occupied by renewable power** (and, to an insignificant degree also by nuclear power), when the 50/50 nuclear/ renewable power mix delivers 75% of the total energy demand of 3,750 PJ per annum, or 100% of the total energy demand of 2,750 PJ per annum.



Energy Demand (PJ)	% of Energy Demand Supplied by Renewables & Nuclear								
	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	5.4%	8.2%	13.6%	19.1%	24.5%	27.2%	29.9%	40.8%	54.4%
1,750	6.4%	9.5%	15.9%	22.2%	28.6%	31.8%	34.9%	47.6%	63.5%
2,000	7.3%	10.9%	18.1%	25.4%	32.7%	36.3%	39.9%	54.4%	72.6%
2,250	8.2%	12.2%	20.4%	28.6%	36.7%	40.8%	44.9%	61.2%	81.7%
2,500	9.1%	13.6%	22.7%	31.8%	40.8%	45.4%	49.9%	68.0%	90.7%
2,750	10.0%	15.0%	24.9%	34.9%	44.9%	49.9%	54.9%	74.8%	99.8%
3,000	10.9%	16.3%	27.2%	38.1%	49.0%	54.4%	59.9%	81.7%	108.9%
3,250	11.8%	17.7%	29.5%	41.3%	53.1%	59.0%	64.9%	88.5%	117.9%
3,500	12.7%	19.1%	31.8%	44.5%	57.2%	63.5%	69.9%	95.3%	127.0%
3,750	13.6%	20.4%	34.0%	47.6%	61.2%	68.0%	74.8%	102.1%	136.1%
4,000	14.5%	21.8%	36.3%	50.8%	65.3%	72.6%	79.8%	108.9%	145.2%

% of Available Land Occupied



Energy Demand (PJ)	% of Energy Demand Supplied by Renewables & Nuclear								
	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	3%	4%	7%	10%	13%	15%	16%	22%	29%
1,750	3%	5%	9%	12%	15%	17%	19%	26%	34%
2,000	4%	6%	10%	14%	18%	20%	22%	29%	39%
2,250	4%	7%	11%	15%	20%	22%	24%	33%	44%
2,500	5%	7%	12%	17%	22%	24%	27%	37%	49%
2,750	5%	8%	13%	19%	24%	27%	30%	40%	54%
3,000	6%	9%	15%	21%	26%	29%	32%	44%	59%
3,250	6%	10%	16%	22%	29%	32%	35%	48%	64%
3,500	7%	10%	17%	24%	31%	34%	38%	51%	69%
3,750	7%	11%	18%	26%	33%	37%	40%	55%	73%
4,000	8%	12%	20%	27%	35%	39%	43%	59%	78%

% of Available Sea Occupied

Table 5.22. Sensitivity Table of Area Occupied by Renewable and Nuclear Power As a Function of Energy Demand and Increasing Electrification Share

	% of Energy Demand Supplied by Nuclear								
Energy Demand (PJ)	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	0.1%	0.2%	0.3%	0.4%	0.5%	0.5%	0.6%	0.8%	1.1%
1,750	0.1%	0.2%	0.3%	0.4%	0.6%	0.6%	0.7%	0.9%	1.2%
2,000	0.1%	0.2%	0.4%	0.5%	0.6%	0.7%	0.8%	1.1%	1.4%
2,250	0.2%	0.2%	0.4%	0.6%	0.7%	0.8%	0.9%	1.2%	1.6%
2,500	0.2%	0.3%	0.4%	0.6%	0.8%	0.9%	1.0%	1.3%	1.8%
2,750	0.2%	0.3%	0.5%	0.7%	0.9%	1.0%	1.1%	1.4%	1.9%
3,000	0.2%	0.3%	0.5%	0.7%	0.9%	1.1%	1.2%	1.6%	2.1%
3,250	0.2%	0.3%	0.6%	0.8%	1.0%	1.1%	1.3%	1.7%	2.3%
3,500	0.2%	0.4%	0.6%	0.9%	1.1%	1.2%	1.4%	1.8%	2.5%
3,750	0.3%	0.4%	0.7%	0.9%	1.2%	1.3%	1.4%	2.0%	2.6%
4,000	0.3%	0.4%	0.7%	1.0%	1.3%	1.4%	1.5%	2.1%	2.8%

Table 5.23. Sensitivity Table of Area Required by Nuclear Power As a Function of Energy Demand and Share Supplied by Nuclear

% of Available Land Occupied

100% Nuclear

In this scenario, all of the electricity demand is met by nuclear power.[370] Table 5.23., presents the results.

Thus, even if the power demand is high, **nuclear power has only a marginal effect on land use, and no effect on sea use**. Even if total energy demand in the Netherlands were 4,000 PJ and 100% of that were supplied by nuclear, **less than 3% of the available land** would have to be used, and no sea would be affected. This implies that 97% of the available land and 100% of the sea would be available for other uses.

Compared to renewable power, nuclear power thus has such a low space impact that even in extreme situations, it presents very little potential for space usage conflicts.

iv. Conclusions and Discussion

Thus, if electricity in The Netherlands is solely or chiefly provided by wind turbines and solar panels, these renewable energy technologies will take up very significant portions of the available land. This is due to the **low power density of wind and solar**, which is **150 to 500 times lower** than the power density of nuclear power, on average.

Compared to renewable power, nuclear power thus has such a low space impact that even in extreme situations, it presents very little potential for space usage conflicts.

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[370] As for 100% renewable, for the purposes of this model, if not the full 100% of energy is supplied by nuclear power, the remainder is supplied by other energy sources. The model focuses solely on the space impact of nuclear power and does not consider the impact on space usage of other energy sources.

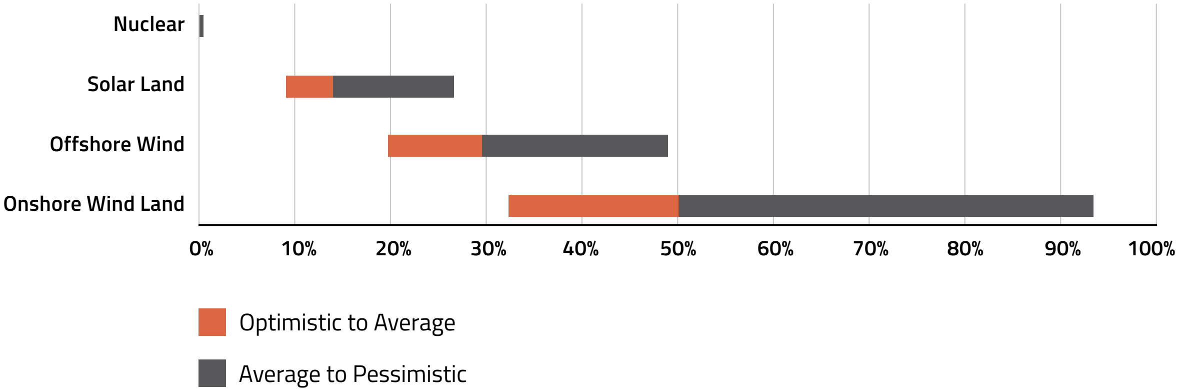

Figure 5.5. The Netherlands - Area Required if Each Source Provides 500 PJ in Energy Annually

Depending on variables such as electricity demand and capacity factors, in realistic scenarios, there is **not enough land to meet all power demand** if The Netherlands were to rely solely or predominantly on wind and solar power. Table 5.24., shows the percentage of available land occupied in a 100% renewables scenario as a function of electricity demand and degree of electrification.

In any event, and in any plausible scenario, **the spatial impact of high penetration of wind and solar** in the electricity system will be **very substantial** and increase as a function of the percentage of wind and solar in the power mix. In The Netherlands, **offshore wind may alleviate the pressure on land somewhat**, but creates its own issues in terms of marine impacts, costs, etc. (see further Part 3 and Annex IX attached to this report).

As the penetration of wind and solar increases, **competing land uses, landscape protection, and nature protection** will increasingly come under pressure, resulting in land price increases and deterioration of the living environment.

	% of Energy Demand Supplied by Renewables								
Energy Demand (PJ)	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	10.8%	16.2%	27.0%	37.7%	48.5%	53.9%	59.3%	80.9%	107.8%
1,750	12.6%	18.9%	31.4%	44.0%	56.6%	62.9%	69.2%	94.3%	125.8%
2,000	14.4%	21.6%	35.9%	50.3%	64.7%	71.9%	79.1%	107.8%	143.8%
2,250	16.2%	24.3%	40.4%	56.6%	72.8%	80.9%	88.9%	121.3%	161.7%
2,500	18.0%	27.0%	44.9%	62.9%	80.9%	89.8%	98.8%	134.8%	179.7%
2,750	19.8%	29.6%	49.4%	69.2%	88.9%	98.8%	108.7%	148.2%	197.7%
3,000	21.6%	32.3%	53.9%	75.5%	97.0%	107.8%	118.6%	161.7%	215.6%
3,250	23.4%	35.0%	58.4%	81.8%	105.1%	116.8%	128.5%	175.2%	233.6%
3,500	25.2%	37.7%	62.9%	88.1%	113.2%	125.8%	138.4%	188.7%	251.6%
3,750	27.0%	40.4%	67.4%	94.3%	121.3%	134.8%	148.2%	202.2%	269.5%
4,000	28.8%	43.1%	71.9%	100.6%	129.4%	143.8%	158.1%	215.6%	287.5%

Table 5.24. The Netherlands - % of Available Land Occupied in 100% Renewables Scenario

As the penetration of wind and solar increases, competing land uses, landscape protection, and nature protection will increasingly come under pressure, resulting in land price increases and deterioration of the living environment.

If electricity in The Netherlands is solely or chiefly provided by nuclear power, **nuclear power plants will take up only a minute fraction of the land and space necessary for wind and solar**. This is due to the very high power density of nuclear, which is **at least 150 to 500 times higher** than the power density of wind and solar.

Nuclear power plants offer **additional spatial advantages** over renewables thanks to the following two features:

- Nuclear power plants can be sited at the same sites where fossil fuel-fired power plants are located, and require approximately the same area as such plants, which implies **savings on infrastructure** to connect to the network.
- These features **greatly reduce pressures on land availability, landscape protection** and nature protection, which is a significant advantage, in particular when competition for land increases.

The findings in this part can be explained by one simple fact -- compared to wind and solar, **nuclear power produces approx. 500 and 150 times more electricity per square kilometer**. We call this **power density**. Table 5.25., provides relative power densities for the power generation technologies studied here.

Thus, per km^2 nuclear energy generates **over 500 times** more energy than onshore wind, and **over 260 times** more energy than offshore wind. From the perspective of land and space utilization, these differences are very significant.

Note that these estimates are ***lower than other estimates we found in the literature***, some of which were dated (although the effect of innovation in renewables on spatial requirements is limited). For instance, one author reports a ratio of spatial requirements for nuclear relative to solar of 1:1,000, i.e. solar requires 1,000 times more land than nuclear to produce the same amount of energy.[371] This author also reports other data showing that the land use ratio for nuclear/solar is 1:160, and for

	Average GWh / km^2	Indexed to Nuclear (i.e. nuclear produces x times more electricity per km^2)
Onshore Wind Land	13	534
Onshore Wind Water	14	506
Offshore Wind	26	266
Solar Roof	136	51
Solar Land	47	148
Nuclear	6,982	--

Table 5.25. Power Density

[371] Kelly, Michael, Energy Utopias and Engineering Reality, The Global Warming Policy Foundation 2019 Annual Lecture, London, 11 November 2019, p. 14.

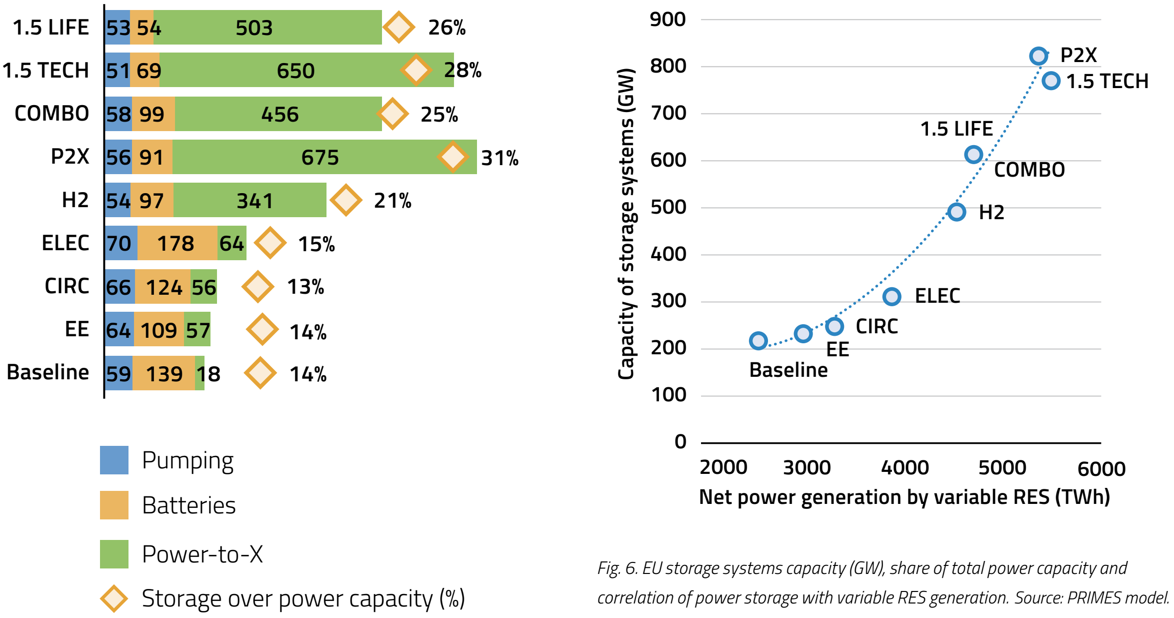

Fig. 6. EU storage systems capacity (GW), share of total power capacity and correlation of power storage with variable RES generation. Source: PRIMES model.

Figure 5.6.. Exponential Increase of Storage Capacity Due to Intermittent Renewable Energy

Source: Capros P, Zazias G, Evangelopoulou S, Kannavou M, Fotiou T, Siskos P, De Vita A, Sakellaris K. Energy-system modelling of the EU strategy towards climate-neutrality. Energy Policy, Vol. 134 (2019), p. 110960

nuclear/wind 1:4,000. Thus, if anything, our findings are conservative, and in reality the difference may be larger.

The power density numbers set forth in Table 5.25., **do not include the additional land and space demand imposed by renewable energy**, which increases exponentially as renewable energy expands and makes up a larger share of the power mix (see Figure 5.5, and further Part 7 of this report).[372] This additional land is required for the additional infrastructure necessary for the integration of renewable energy into the electricity system, such as energy storage and conversion facilities.

d. Further Reflections

Spatial requirements and spatial planning has been recognized relatively recently as a key issue for a successful energy transition. As Stoeglehner et al. note,

"In policy making, research, and development, much attention has been paid to the technological aspects of the energy turn, which allows us now to choose between a wide range of options for energy saving and the generation of renewable energy, with some technological issues such as energy storage still partly unsolved. Yet, implementing the energy turn does not only mean to deal with technologies. A complex fabric of issues influences

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[372] See, e.g., Capros P, Zazias G, Evangelopoulou S, Kannavou M, Fotiou T, Siskos P, De Vita A, Sakellaris K. Energy-system modelling of the EU strategy towards climate-neutrality. Energy Policy, Vol. 134 (2019), p. 110960 ("Developing a power system with a high share of variable RES requires the development of storage technologies, demand response, mesh grids and an efficient multi-country integrated system and market, to share the resources that would enable the cost-effective balancing of variable RES generation. Large-scale storage of electricity with versatile features and seasonal cycles such as large-scale batteries, power-to-H_2 for chemical storage and compressed air electricity storage, depends on the technology readiness levels (TRL) of those technologies that currently remain at a demonstration stage. Without the synergy between chemical storage and the production of hydrogen and synthetic fuels, the huge increase of the power system size, projected in the climate-neutral scenarios, would have been unmanageable. The non-linear increase of storage as a function of the volume of total generation can be depicted in the right-hand side chart shown in Fig. 6." – Figure 6 is reproduced as Graph 5.4, below.)

possibilities and options to proceed toward the energy turn, which are, inter alia, ***the base values of society, the interplay of different policies with relevance for energy policy (e.g., economic policies, agricultural policies, fiscal policies, environmental policies), the availability of technologies, regional and local resource potentials, demographic development of societies, individual lifestyles, economic practices as well as the physical and planned spatial development.*** *… The list can be further expanded and deepened with the issues of educational backgrounds and awareness of populations which have a direct effect on the base values of societies, or societies' and decision makers' capacity to learn about alternative options to reach the energy turn, adding to the complexity of the problem at hand."*[373] *(emphasis supplied).*

From the perspective of proponents of a fully renewable energy system, the issue of spatial requirements is a management issue, a barrier that needs to be overcome. From a broader more inclusive perspective, however, spatial requirements present conflicts between incompatible land and space uses. These conflicts are typically phrased in terms of competition for land and space:

"Competition for land is increasing as demand for multiple land uses and ecosystem services rises. Food security issues, renewable energy and emerging carbon markets are creating pressures for the conversion of agricultural land to other uses such as reforestation and biofuels. At the same time, there is a ***growing demand for land in connection with urbanization and recreation, mining, food production, and biodiversity conservation****. Managing the increasing competition between these services, and balancing different stakeholders' interests,* ***requires efficient allocation of land resources****."*[374] *(emphasis supplied).*

This ***efficiency requirement of land and space use planning has not been incorporated into the energy policy making***, which has proceeded on the basis that the renewable energy revolution is absolutely necessary and land and space use therefore is just a technical issue to be resolved as it presents itself. With wind and solar parks demanding ever growing plots of land and space, it has become clear that this position is untenable, and that ***efficient allocation of land resources*** is critical. In this vein, the energy transition has been criticized for its "geographical naivety" and its failure to explain "how different spatial contexts matter, treating places either as homogeneous actors of transition or merely as the locations where transitions happen."[375]

The enormous spatial requirements of wind and solar energy is neither a novel nor a surprising finding. In 2009, research on the spatial requirements of the ***wind turbines that would be necessary to generate electricity to produce hydrogen to power hydrogen-cell vehicles for transport in the United Kingdom***, found that this switch, for transport alone, would require an amount of land, either off-shore or on-shore, equal to ***15% of the UK's space***, i.e. wind turbines would have to cover ***an area twice the size of Wales***.[376] Given that transport constituted one third of the entire energy use, wind turbines would require ***45% of the UK's space***. Calculations for wave, biofuel and solar showed that this problem is a general one. Although the efficiency of wind turbines may have increased since then, the efficiency of wind has not, and the spatial requirements today are still enormous, as we have seen in this study.

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[373] See, e.g., Stoeglehner, Gernot, Michael Narodoslawsky, Susanna Erker, Georg Neugebauer, Integrated spatial and energy planning: supporting climate protection and the energy turn with means of spatial planning, Springer, 2016.

[374] Metternicht, Graciela, Land Use and Spatial Planning: Enabling Sustainable Management of Land Resources. 1st Ed. 2018. ed. Cham, Switzerland: Springer, 2018.

[375] Gailing L. The Spatiality of Germany's Energy Transition: Spatial Aspects of a Reconfiguration of an Energy System. In: Gawel E., Strunz S., Lehmann P., Purkus A. (eds) The European Dimension of Germany's Energy Transition. Springer, 2019, pp. 467-476.

[376] Oswald, James I., Oswald, Andrew J., Ashraf-Ball, Hezlin, Hydrogen Transport and the Spatial Requirements of Renewable Energy, Working Paper. Coventry: University of Warwick, Department of Economics. Warwick economic research papers (No.903), 2009.

> " There is a growing demand for land in connection with urbanization and recreation, mining, food production, and biodiversity conservation. Managing the increasing competition between these services, and balancing different stakeholders' interests, requires efficient allocation of land resources. "

As discussed, the concept of ***power density*** explains the large differences in spatial requirements between renewable energy and nuclear energy. Other concepts that make the enormity of these differences understandable are ***energy densities of 'fuels'*** (including wind) and ***energy return on investment (EROI)***.

Energy density

The energy density of fossil fuels is over a million times greater than hydro gravity energy density, and ***nuclear fuel is a million times more dense than fossil fuel***.[377] The net average energy density per square meter for wind is much lower than hydro; all renewables are within a factor of approximately 20 of each other. As Table 5.26., shows, this results in ***energy density ratios for nuclear/renewable that are extremely large***.

Fuel type	Energy density MJ/kg
Wind	0.00006
Battery	0.001
Hydro	0.72
TNT	4.6
Wood	5.0
Petrol	50
Hydrogen	143
Nuclear fission	88250000
Nuclear fusion	645000000

Table 5.26 Energy Densities of Different Fuels

From: Kelly, Michael, Lessons from technology development for energy and sustainability, MRS Energy and Sustainability 2016, Vol. 3, pp. 2-13

Energy Return on Investment

The concept of EROI is a measure of the ***energy efficiency of a power generation facility*** – it is the useful energy produced by a particular power plant divided by the energy needed to build, operate, maintain and decommission the plant, in short, energy retuned on energy invested.[378] EROI raises issues of system boundaries (what is included and what is excluded),

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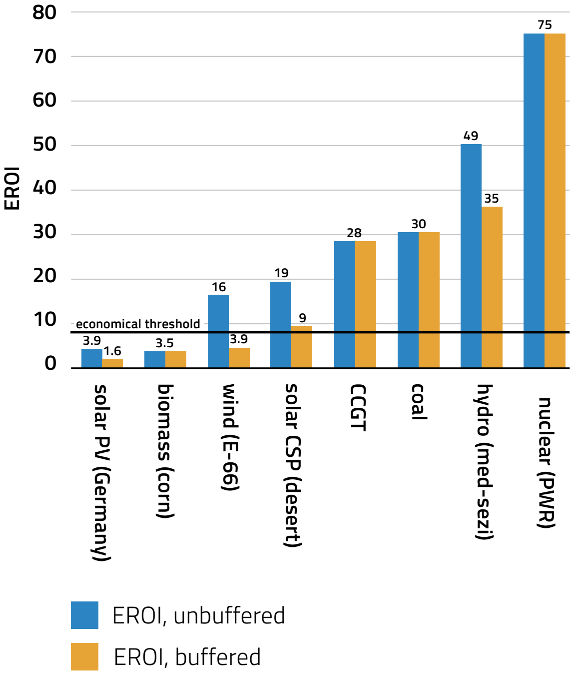
[377] Kelly, Michael, Lessons from technology development for energy and sustainability, MRS Energy and Sustainability 2016, Vol. 3, pp. 2-13.

[378] Weissbach, D ; Herrmann, F ; Ruprecht, G ; Huke, A ; Czerski, K ; Gottlieb, S ; Hussein, A, Energy intensities, EROI (energy returned on invested), for electric energy sources, Energy 2013, vol. 52, pp. 210-221. For an application of this concept to solar panels, see Raugei, Marco, Pere Fullana-i-Palmer, Vasilis Fthenakis, The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel lifecycles, Energy Policy vol. 45, 2012, pp. 576–582. For comments on the article by Weissbach et al., see Raugei, Marco, Comments on "Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants" Making clear of quite some confusion, Energy Policy, vol. 45, 2012, pp. 576–582. For the authors' reply, see Weissbach, D ; Herrmann, F ; Ruprecht, G ; Huke, A ; Czerski, K ; Gottlieb, S ; Hussein, A, Reply on "Comments on 'Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants' -- Making clear of quite some confusion", Energy, vol. 68, 2014, pp. 1004 -1006. For a rebuttal, see Raugei, Marco, Pere Fullana-i-Palmer, Vasilis Fthenakis, Rebuttal: "Comments on 'Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants' -- Making clear of quite some confusion", Energy, vol. 82, 2015, pp. 1088-1091.

and, thus, to understand EROIs, one needs to know how the boundaries were drawn.[379]

Having said that, EROIs can be useful tools to compare the relative energy balance of power generation facilities. In one study, the EROI has been evaluated for typical power plants representing wind energy, photovoltaics, and nuclear power, among others, based on the strict "exergy concept" (defined, in the context of transformation of primary energy, as the usable work inside a system with borders to, most frequently, the surrounding) with no "primary energy weighting".[380] The results of this study show that ***nuclear energy is at least one order of magnitude more effective than photovoltaics and wind power***. Figure 5.7. shows the relative EROIs. As the authors explain, the economic threshold shown in this table is based on "the current production cost ratio electricity/thermal energy of w = 3."[381]

EROIs can also be used to compare power generation technologies over time or using different system boundaries. For instance, if some integration or system-related energy cost are added in, the outcomes may change dramatically, because "***any substantial penetration of intermittent energy into the grid will probably be very energy costly to accommodate to.***"[382]



From: Weissbach, D ; Herrmann, F ; Ruprecht, G ; Huke, A ; Czerski, K ; Gottlieb, S ; Hussein, A, Energy intensities, EROI (energy returned on invested), for electric energy sources, Energy 2013, vol. 52, pp. 210-221.

Figure 5.7.. EROIs for power generation technologies with economic threshold

From: Weissbach, D ; Herrmann, F ; Ruprecht, G ; Huke, A ; Czerski, K ; Gottlieb, S ; Hussein, A, Energy intensities, EROI (energy returned on invested), for electric energy sources, Energy 2013, vol. 52, pp. 210-221.

The results of this study show that nuclear energy is at least one order of magnitude more effective than photovoltaics and wind power.

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[379] Hall, Charles A.S., Energy Return on Investment: A Unifying Principle for Biology, Economics, and Sustainability, Lecture Notes in Energy, Vol. 36, Springer, 2016.

[380] "Pump storage systems, needed for solar and wind energy, have been included in the EROI so that the efficiency can be compared with an "unbuffered" scenario." Weissbach, D ; Herrmann, F ; Ruprecht, G ; Huke, A ; Czerski, K ; Gottlieb, S ; Hussein, A, Energy intensities, EROI (energy returned on invested), for electric energy sources, Energy 2013, vol. 52, pp. 210-221.

[381] Id., p. 219. "The weighting factor w is expected to decrease with time, approaching 1 or even lower."

[382] Hall, Charles A.S., Energy Return on Investment: A Unifying Principle for Biology, Economics, and Sustainability, Lecture Notes in Energy, Vol. 36, Springer, 2016, p. 137.

Despite the dramatic change in land and space use for power generation, this issue still seems to escape the attention of policy makers in centralized bureaucracies. It is time land and space use is placed front and center in climate and energy policy making.

A 2014 study found that adding a relatively small amount of storage to solar PV systems would quickly put them into energy deficit.[383] Another study found that batteries doubled the energy cost of rooftop solar systems.[384] There is no reason for not including types of costs in EROI assessments of renewables. For our purposes, we note merely that the EROI, directly or indirectly, affects spatial requirements of power generation.

A first attempt at estimating ***future EROIs in a decarbonized electricity system***, a 2019 study suggested that there is reason for concern if the share of renewables continues to grow. According to this author, global EROI of electricity is predicted to go down from 12.2 in 2010 to 5.8 in a 100% renewable scenario.[385] Although the EROI of renewables is expected to remain well above 1, renewable electricity appears not to be as energetically efficient as previously thought. Moreover, due to the ***inverse relationship between EROIs and energy prices***, a declining EROI could mean ***higher energy prices***, and risk of recession.[386] A declining EROI may also imply even more onerous spatial requirements, and, of course, higher costs, which is the topic of the next part.

Final observations

To conclude this part, a few final observations are in order. The ***renewable energy revolution places very substantial spatial demands on society and the economy***. EU policy makers appear to have given little thought to the spatial demands of renewable energy generation. In an energy system dominated by fossil fuels or nuclear energy, the spatial demands related to the supply of energy are relatively unimportant, as they impose comparatively minute land and spatial requirements.[387] This has now changed dramatically.

Despite this change, ***the issue of land and space use still seems to escape the attention of policy makers in centralized bureaucracies***. It is time land and space use is placed front and center in climate and energy policy making.

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[383] Carbajalis Dale, M., M. Raugei, C.J. Barnhart, and V. Fthenakis. 2015. Energy return on investment (EROI) of solar PV: an attempt at reconciliation. Proceedings of the IEEE. doi:10. 1109/JPROC.2015.2438471.

[384] Palmer, G., Household solar photovoltaics: supplier of marginal abatement, or primary source of low-emission power?, Sustainability 5(4), 2013, pp. 1406–1442. Cf. Diesendorf, M., T. Wiedmann, Implications of Trends in Energy Return on Energy Invested (EROI) for Transitioning to Renewable Electricity, Ecological Economics ,176, 2020, 106726.

[385] Fabre, Adrien, Evolution of EROIs of electricity until 2050: Estimation and implications on prices, Ecological Economics, 164, 2019, 106351.

[386] Id., p. 8. The author emphasizes that the choice as to whether or not to pursue a renewable transition should not be reduced to considerations of EROIs only, as negative externalities of the options should be taken into account.

[387] Oswald, James I., Oswald, Andrew J., Ashraf-Ball, Hezlin, Hydrogen Transport and the Spatial Requirements of Renewable Energy, Working Paper. Coventry: University of Warwick, Department of Economics. Warwick economic research papers (No.903), 2009.

6

Cost of Wind/Solar and Nuclear Energy

Cost of Wind/Solar and Nuclear Energy

In this section, the cost of wind/solar and nuclear power is estimated. To this end, we have developed a fairly standard model to estimate the levelized cost of electricity (LCOE). However, as discussed further below, we made an improvement to the standard way of computing LCOE in relation to the discounting of power generated.

We use ***the model we developed for estimating the LCOE for wind/solar and nuclear*** in both the Czech Republic and The Netherlands. Of course, input data for the two countries differ, and, thus, model outputs differ too. For each country, we discuss the input data, and explain how the data were obtained.

In the case of The Netherlands, as noted above, studies have been conducted for the network operators and the Ministry of Economic Affairs and Climate, including a study on the cost of nuclear power, relative to the cost of renewable energy (the "Nuclear Study").[388] This study was intended to supplement other studies on climate neutral scenarios and space use, although the Nuclear Study is more limited and does not analyze the land use requirements associated with nuclear power. In Annex VI attached to this report, we provide comments on the Nuclear Study. No such study is available for the Czech Republic. The Czech Republic did prepare an extensive National Climate and Energy Plan, however.[389]

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[388] Kalavasta/Berenschot. Systeemeffecten van nucleaire centrales in Klimaatneutrale energiescenario's 2050. 9 maart 2020, available at https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2020Z06737&did=2020D14346 ; Kalavasta/Berenschot. Systeemeffecten van nucleaire centrales in Klimaatneutrale Energiescenario's 2050 – Datasheets, 9 maart 2020, available at https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2020Z06737&did=2020D14346. An Excel spreadsheet has also been made available. (Jointly, the "Nuclear Study").

[389] Czech Republic, National Energy and Climate Plan 20121-20130, Nov. 2019, available at: https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en (the "Czech NECP").

a. Model Introduction and Mechanics

i. Introduction

The model we developed generates ***cost estimates (in €/MWh) for electricity generated from renewable (wind and solar) and nuclear power sources***. Importantly, the model allows users to scale certain inputs to test the output for sensitivity to assumptions.

The model does not take into account integration- and system-related costs. At several points, these integration- and system-related costs are discussed qualitatively; a fuller discussion of such costs is included in Part 7 of this report.

Our model is similar to the model used by Kalavasta and Berenschot in the Nuclear Study with respect to the formula and methodology.[390] There are important differences, however, with respect to some of the calculations, and some of the inputs. In Annex VI, we note these differences, and provide explanations for the divergence. In the interest of transparency, we present our model and all data in such detail that the reader has all ***information necessary to reproduce the results*** we obtained. This way, all of the outcomes can be verified by any interested party.

We run our model for both the Czech Republic and The Netherlands. As with the model for space requirements, the formulas and methodologies for both countries are the same, but, of course, the inputs and outputs differ. To provide an accurate picture of the influence of input values, we conduct sensitivity analysis on key parameters. In the discussion of the model outputs, we identify the main drivers so that specific attention can be paid to these inputs.

ii. Model Mechanics

The model incorporates the following electricity technologies: onshore and offshore wind, commercial solar, and nuclear. The ***present value cost of electricity*** is calculated by dividing the discounted sum of all costs by the discounted sum of all electricity produced. The costs included in the model are those costs incurred during design and construction as well as operation and end-of-life of the power generation facilities included in our model. Of course, electricity is only produced during the operational period, and, thus, we assume that revenues only accrue during the operational period.

By default, the ***energy produced is not discounted*** (i.e. discount rate of 0%), although the option to discount exists for the user, and we run several scenarios with discounting of electricity production. The justification for not discounting the electricity produced is provided in this part and Annex II of this report. In short, from a ***planning perspective (as opposed to an investment and trading perspective)***, the present value of future electricity is not relevant, because the task of the planner is to ensure that electricity is available at defined points in the future.

Most levelized cost of electricity (LCOE) calculations discount the energy produced to account for the fact that different technologies have different lifetimes and different energy production schedules. For example, a nuclear plant can only start producing seven years into the future due to its long construction time, while a solar installation can start producing electricity much sooner. On the other hand, a nuclear plant will still be producing electricity in 20 years, whereas the solar installation will have been decommissioned by then. We argue that discounting the energy produced is not a proper method to solve for this issue – it implicitly

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[390] For further discussion, see also Annexes II, IV and VI attached to this report.

To account for time differences of power generated by various technologies, we employ a synchronized lifetime analysis, which equalizes the amount of electricity produced over a given (fixed) number of years and then compares the absolute costs of the different electricity generation technologies producing that amount of electricity.

assumes that energy produced 20 years from now is worth less than a similar unit of electricity produced next year solely based on its present market value. The unit of electricity produced in 20 years is deemed of lesser value because the effect of the discount factor over 20 years is greater, causing the same unit of electricity to be discounted much more, decreasing its present value.

A ***policy maker is not an energy trader***, however. A policy maker is interested to the same extent in ensuring that a certain amount of electricity is produced in year 20, as in year 1, and a unit of electricity produced in year 20 is not necessarily worth less than the same unit produced in year 1. We do recognize, however, that there is a ***time difference between the two units of electricity***. To account for such differences, we employ a ***synchronized lifetime analysis***, which equalizes the amount of electricity produced over a given (fixed) number of years and then compares the absolute costs of the different electricity generation technologies producing that amount of electricity. The number of years is chosen so that it coincides with the shortest period of time in which the lifespans of the power generation technologies can be synchronized as integers (i.e. whole numbers, instead of pro rating to address an incomplete lifespan). We return to this methodology, below.

The model cost estimates represent somewhat simplified cost structures that might not take into account all costs, nor potential externalities. For example, some historic data for renewable power plants did not disaggregate variable and fixed maintenance and operating costs, which are thus reported as one figure. Externalities are ignored completely.

Our model allows the user to make a choice regarding the costs that are used: ***realized or expected costs*** in 2050. For most technologies, expected 2050 costs are substantially lower as significant cost savings are expected over the next three decades. Whether such efficiencies will actually be realized is uncertain, and ***optimism bias may affect these projections***. For near-term policy choices, ***realized costs are likely to be more reliable*** and relevant, given they reflect the costs of technologies that have recently been operated and, thus, are proven costs. Using realized costs also avoids the ***potential bias*** associated with choosing between subjective estimates of possible future efficiencies associated with various power generation technologies; whether any expert is optimistic or pessimistic about future efficiency gains is, at least in part, a function of the expert's own knowledge of and belief in the

Realized costs are likely to be more reliable and relevant, given they reflect the costs of technologies that have recently been operated and, thus, are proven costs. Using realized costs also avoids the potential bias associated with choosing between subjective estimates of possible future efficiencies associated with various power generation technologies.

technologies concerned.[391] Nevertheless, we also use expected costs for purposes of comparison.

The data and assumptions underlying the inputs for each of the technologies are discussed in more detail in Annex II attached to this report. In this part, we note the main assumptions for inputs into the model, as well as the most important model outputs. For further discussion of the inputs and outputs, we refer the reader to Annex II.

b. Czech Republic

We now proceed to run the model for the Czech Republic. Below, we first describe the data inputs and sources we used for each of the power generating technologies, and then proceed to present the model outcomes. Note that we will not estimate costs for offshore wind, given that the Czech Republic has no access to offshore waters.

Most of the realized cost inputs are based on ***data provided by the Ministry of Industry and Trade*** of the Czech Republic. These data are also partially reflected in an English language public report.[392] The government-provided data is originally in Czech koruna, but has been scaled to the EUR at an exchange rate of 25 CZK per EUR. This has been well within the average range of the last ten years.

For the expected costs, we rely on a report commissioned by the European Commission for both the Czech Republic and The Netherlands.[393] This triangulates literature cost estimates, industry stakeholder expectations, and expert input. In the absence of reliable realized data, we believe that ***these estimates are more robust*** than those in any one study, given that they are based on input from multiple credible sources, eliminating the distorting effect of outliers. These cost estimates were presented to the European Commission and published with the

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[391] On optimism bias, see Hughes, Gordon, WIND POWER ECONOMICS: RHETORIC & REALITY, Volume II -- The Performance of Wind Power in Denmark, Renewable Energy Foundation, Stratford-sub-Castle, 2020. ("Optimism bias in claims about the cost and performance of infrastructure and other projects has been endemic for millennia.")

[392] OTE, Expected Electricity and Gas Balance Report, 2019, link: https://www.ote-cr.cz/en/about-ote/files-annual-reports/expected_balance_report_2019.pdf

[393] Asset, Technology pathways in decarbonization scenarios, Advanced System Studies for Energy Transition, July 2018, available at https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

expressed intent to be used in modeling exercises exploring the decarbonization of Europe.

i. Data Inputs & Sources

The model takes numerous inputs and for every input, assumptions are required. We look at each category of inputs, in turn, to explain the default assumptions used in the model.

Technical Parameters

Table 6.1., lists the assumptions for the technical parameters for each technology. A discussion of the assumptions follows the table.

- The size of the power units, i.e. the ***capacity***, is as reported by the Czech Ministry of Industry and Trade. For purposes of the model, capacity as such is not directly relevant, since all costs scale linearly with capacity. In other words, given that the ultimate output is cost per unit of electricity produced, the capacity of the power plants has no bearing on the output. If system costs had been taken into account, not all costs would scale linearly with capacity. Some costs might increase non-linearly (for example, network balancing cost in systems with high penetration of renewable power), other costs might decrease with economies of scale (e.g. the cost of nuclear waste disposal and decommissioning), and yet other system costs could be avoided (e.g., if multiple wind turbines were built on the same plot of land). Hence, this assumption would become more impactful if system costs are taken into account.
- For the ***full load hours***, we utilized the ***capacity factors*** we calculated in Model 1; we refer to Annex II attached to this report for sources and a broader discussion of the capacity factors and the resulting full load hours. From the Space Model, we take the maxima of the ranges, so our values represent optimistic full load hours. Note that solar has more full load hours in the Czech Republic than in The Netherlands, which should ultimately be beneficial for the relative cost of solar compared to other technologies in the Czech Republic.

Cost Parameters

Table 6.2., lists the assumptions for the cost parameters for each technology. A discussion of the assumptions follows the table. For some of the inputs, there are various options that the user can specify; we denote these in the table as follows: (1) refers to realized costs and (2) refers to expected 2050 costs.

- In terms of ***capital costs***,
  - The model gives the user two options: ***either realized capital costs or projected capital costs*** in 2050, for all technologies (i.e. no discrimination is allowed, and the user cannot use realized costs for one and expected cost for another in the same calculation).

	Units	Nuclear	Solar	Onshore Wind
Capacity per unit	MWe	1,200	0.005	1
Full load hours	Hours per annum	8,147	1,226	2,190

Table 6.1. Technical Parameters by Technology

	Units	Nuclear	Solar	Onshore Wind
Capital costs	€ / kWe	(1) 7,000 (2) 4,700	(1) 1,000 (2) 454	(1) 1,280 (2) 943
WACC (for costs)	% per annum	4.2%	4.2%	4.2%
Discount rate (for energy production)	% per annum	0%	0%	0%
Fixed maintenance and operation costs	€ / MWe per annum	(1) n/a (2) 105,000	(1) n/a (2) 9,200	(1) n/a (2) 12,000
Variable maintenance and operation costs	€ / MWh	(1) 8.28 (2) 7.80	(1) 0.04 (2) n/a	(1) 0.20 (2) 0.18
Fuel costs	€ / MWh	4.36	n/a	n/a
Waste processing and storage costs	€ / MWh	n/a	n/a	n/a
Decommissioning	% of capital cost[394]	8,172	5%	5%

Table 6.2. Cost Parameters by Technology

  - For realized capital costs, these figures were provided by the Ministry of Industry and Trade. We opted for the low end of the estimates. For renewables, they were in-line with estimates for The Netherlands. For nuclear, they are slightly higher.
  - For projected capital costs in 2050, we rely on the European Commission report referenced above.[395]

- For the ***WACC***, the default is a ***uniform WACC of 4.3%***. We explain in more detail below how we arrived at this figure. For other outputs, we also apply a 0% rate, as is requested in the questionnaire.

- With respect to the ***discount rate*** for electricity produced: The default is ***not to discount electricity*** produced (i.e. a discount rate of 0%).

- For ***fixed maintenance and operating costs, fuel costs, and waste processing and storage costs***, the Ministry of Industry and Trade has collapsed these into one variable cost figure that is reported for each technology. While this might not give as much detail about the different cost components, it provides for easier comparisons between technologies given that it encompasses both cost categories at issue. We do not allow the user to use projected operating costs in this case given that all the costs figures are collapsed into one assumption.

- With respect to ***decommissioning costs***, for nuclear power plants, we have relied on data provided by the Ministry of Industry and Trade. The data estimates the decommissioning costs for two existing nuclear power plants in the Czech Republic: Dukovany and Temelin. Based on those data, we calculated an annual figure per MWe for nuclear power plants. For renewables, we use the same input as we did for The Netherlands.

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[394] For nuclear, the units are €/MWe/year.

[395] Asset, Technology pathways in decarbonization scenarios, Advanced System Studies for Energy Transition, July 2018, available at https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

	Units	Nuclear	Solar	Onshore Wind
Construction time	Years	8	1	1
Technical lifetime	Years	60	20	20

Table 6.3. Other Parameters by Technology

Other Parameters

Table 6.3., lists the assumptions for the other parameters for each technology. A discussion of the assumptions follows the table.

- The assumptions around construction time and technical lifetimes are as reported by the Ministry of Industry and Trade. We note that the construction time for nuclear is longer than for The Netherlands, and the lifetime of the solar and wind power plants is lower.

External Parameters

Table 6.4., lists the assumptions for the external parameters.

	Units	Value
Exchange Rate	CZK per EUR	25

Table 6.4. External Parameters

- This exchange rate is as reported by the Ministry of Industry and Trade. The exchange rate has, for the last ten years, hovered between 24 and 28, with long stretches of time around 25. Hence, we believe that this is a reasonable exchange rate to employ consistently.

ii. Cost of Capital Assumptions

Our general approach to the cost of capital assumption is exactly the same as for The Netherlands.

Estimating WACC

For simplicity, we can delineate the WACC into three components:

WACC = risk free rate + government risk premium + project risk premiun

The ***government risk premium*** is driven by the (i) ***policy and regulatory uncertainty***, and (ii) ***commercial uncertainty***, insofar as it is caused by factors directly controlled by the government. The project risk premium is driven by (i) technology, (ii) operational, and (iii) ***external risks*** that are inherent to energy projects. We discuss each of these in much more detail in Annex II of this report. In this case, we are assuming that the premia reflect a typical debt and equity financing structure. The capital structure from which the underlying data is drawn is unknown, although they typically follow a 10-30% equity and 70-90% debt financing structure.

As a reference point, we regard the rate at which the Czech Republic government borrows money as a risk-free rate. As of September 2020, the Czech Republic government can borrow for 20 years at a nominal rate of approximately 1.3%.

For the government risk premium, we employ the same methodology as we do for The Netherlands. If we want to evaluate these energy technologies on a ***level playing field***, the government policy risk premium should be zero. If a specific government policy is taken into account in WACC calculations, estimates might reflect a policy ***status quo bias*** and not be representative of the true costs should the government change its policy regime.

The project risk premium is the same as it is for The Netherlands, given that there is no inherent cause for

The government policy risk premium should be zero, if we want to evaluate energy technologies on a level playing field. If a specific government policy is taken into account in WACC calculations, estimates might reflect a policy status quo bias and not be representative of the true costs should the government change its policy regime.

energy projects to be riskier in the Czech Republic than in The Netherlands - in other words, these projects carry similar amounts of risk. The estimates are based on a literature review, as we discuss in more detail in Annex II of this report. Our review of the existing literature reveals that in an ideal government policy climate, where the risk premium for government policy is practically zero, WACCs for renewable projects could be as low as 2.5%. Given the mix of energy technologies, we assume a uniform 5% after-tax, nominal WACC for all renewables, roughly in-line with the latest estimates.

The Czech National Bank also has an ***inflation target of 2%***, similar to the European Central Bank.

On the basis of this methodology, our model for the Czech Republic uses ***a 4.2% uniform, real, after-tax WACC for all renewables***. We arrive at this WACC through the calculations shown in Table 6.5.

WACC	
Risk-free rate	~ 1.3%
Government policy premium	~ 0.0%
Energy project premium	~ 5.0%
RENEWABLE NOMINAL WACC	**~ 6.3%**
RENEWABLE REAL WACC	**~ 4.2%**

Table 6.5. Calculation of Real, After-Tax WACC for Renewables in the Czech Republic

We use the Fisher equation to calculate the real WACC based on the nominal WACC and expected inflation rate.

With respect to nuclear, the Czech Republic recently issued a ***2% loan for a nuclear energy project***. We assumed an additional 3% for the equity financing. Hence, from an investor standpoint, the energy risk premium was about 5%, but needs to be added to the risk-free rate to calculate the approximate nominal WACC, which is then transformed to a ***real, after-tax WACC of 4.2% for nuclear***. Table 6.6., sets forth the calculation.

WACC	
Risk-free rate	~ 1.3%
Government risk premium	~ 0.0%
Energy risk premium	~ 5.0%
NUCLEAR NOMINAL WACC	**~ 6.3%**
NUCLEAR REAL WACC	**~ 4.2%**

Table 6.6. Calculation of Real, After-Tax WACC for Nuclear in the Czech Republic

For further discussion, refer to section c, below, on The Netherlands.

WACC Estimate
As a default, the model uses a **4.2% uniform policy-neutral WACC for both renewables and nuclear**. We believe that this reflects a reasonable estimate of the project risks and a cost of capital that can be achieved in a policy regime that is neutral (or friendly) towards these energy source technologies. Choosing a WACC reflective of a 0% government policy premium offers the best methodology for rationally evaluating the alternatives to meeting the country's energy needs.

iii. Model Outcomes & Sensitivity Analysis

We present several model outputs, in the following order:

1. *Synchronized lifetime analysis*: This involves a comparison of (1) the total cost of a nuclear plant over its entire useful life to (2) the total costs of consecutive renewable power installations over the same period of time that produce the same electricity output, using no discounting and WACCs of 0% and 4.2%.

2. *Comparison of technologies*: Here, we assess the impact of discounting and of using realized vs. expected costs.

We have not included the sensitivity analysis here, but refer the reader to Annex II of this report.

Our decision to ***not discount the electricity produced*** means that we need to account for the fact that the electricity produced by different technologies is produced at ***different times*** in the future through a method other than discounting. After all, an analysis that does not distinguish between one unit of electricity produced in 10 years and the same unit of electricity generated next year, needs another method to reflect this relevant distinction.

In a ***no-discount approach*** that does nothing to address the timing of electricity production, the issue arises that a higher WACC only decreases the costs, while the total electricity produced over varying productive lifetimes remains the same, which distorts the economic picture and the comparison. This is true even if a realistic WACC is used. When using a realistic WACC, however, a ***no-discount approach may still be preferred over the electricity discount approach***. We believe the model output generated by us using the no-discount approach provides a valuable tool to compare power generation technologies for purposes of policy making and planning, as opposed to energy investing, for the reasons explained above. For purposes of this study, the no-discount approach is to be preferred also because, where ***intermittent renewable energy*** is compared to a constant supply of nuclear energy, intermittency presents timing issues with respect to electricity generation that are ***more salient to financial and economic analysis*** than the timing issues associated with nuclear energy generation; renewable energy generation's ***intermittency-related timing problems*** directly (and significantly) affect the ***economic value of the electricity produced***.[396] In any event, to reflect the timing issue, we favor the synchronized lifetime analysis described below, because it completely removes the issue of discounting electricity produced, although it does not address the economic valuation issues associated with the intermittency of renewable electricity generation.

The intermittency of renewable energy generation directly (and significantly) affects the economic value of the electricity produced.

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[396] Thus, nuclear energy and renewable energy are like apples and oranges; not the same product. Cf. Hughes, Gordon, WIND POWER ECONOMICS: RHETORIC & REALITY, Volume I -- Wind Power Costs in the United Kingdom, Renewable Energy Foundation, Stratford-sub-Castle, 2020.

To accommodate renewable energy, our model ignores the problem of intermittency of renewable energy, which implies that in our model the output of renewable power plants is not deemed worth less than the output of nuclear power plants. Our model does not address the economic valuation issues associated with renewable power's intermittency.

Synchronized Lifetime Analysis
Some of the main issues with comparing different electricity generating technologies are the varying lead times, varying lifetimes, and power output varying in time. By applying a chosen discount rate or WACC,[397] we could arrive at a EUR/MWh cost figure. This is not the most suitable and appropriate method for purposes of energy system planning, however.

In standard LCOE calculations, non-intermittent nuclear energy is discounted more heavily than intermittent renewable energy, even though the economic value of intermittent energy is lower. Our method avoids this practice, but does not discount intermittent renewable electricity to account for its lesser economic value. While calculating a EUR/MWh cost figure is useful, it should not lead to the result that the cost of electricity generated by nuclear is much more sensitive to the WACC than the cost of electricity generated by offshore wind turbines, for example, as electricity is deemed to be fungible and fed into one and the same network. To make the comparison more robust and more suitable and appropriate for planning and policy-making, we developed a ***synchronized lifetime analysis***, which is composed of the following elements:

- The synchronized lifetime analysis' starting point is that a certain level of annual electricity production over a defined period of time is required.

- Based on this power output and timing requirement, it examines the costs of various energy sources to meet that requirement.
- To do so, it requires that **various technologies produce the chosen level of power over the chosen time period**, and subsequently the cost of producing that output over that time period is computed; to accommodate renewable energy, however, we here ***ignore the problem of intermittency***, which implies that in our model the output of renewable power plants is not deemed worth less than the output of nuclear power plants, although the discrepancy between the production of renewable power and power demand suggests that its economic value is less.

- This method provides relative cost estimates that are not sensitive to changes in the discount rate for electricity, although it does not address the economic valuation issues associated with renewable power's intermittency.

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[397] An additional complication is that the discount rate applicable to capital does not necessarily have to be the same as the discount rate applicable to electricity. In the relevant literature, however, it typically is, although logically the discount rate for intermittent, stochastic electricity should be higher than the discount rate for constant output electricity.

In the synchronized lifetime analysis for the Czech Republic, we assume an electricity production requirement of just under 10mn MWh per annum, which is equal to the output of a 1,200-MW nuclear power plant.

In the synchronized lifetime analysis for the Czech Republic, we assume an electricity production requirement of just under 10mn MWh per annum, which is equal to the output of a 1,200-MW nuclear power plant. The required time period during which this production level is to be sustained is ***60 years***,

which is the time period necessary to synchronize and equalize the consecutive lifetimes of nuclear plants and renewable power facilities, such that at the end of the 60-year period, all energy sources have met the ends of their respective useful lives.

The required output level of 10mn MWh is equivalent to the production of 4,464 onshore wind turbines and 1,594,286 solar panels. The analysis also accounts for the differences in lead times/construction periods, but, as noted above, is unable to account for the intermittency of renewable energy.

Table 6.7., sets forth the results of this analysis. We use a ***0% WACC for all technologies*** and a ***4.2% WACC for comparison***. For each technology, the ***total costs*** of meeting the electricity requirements for 60 years are provided.

Note that the amounts are expressed as billions, i.e. 10^9.

Figure 6.1, shows these results graphically.

The synchronized lifetime analysis reveals that ***nuclear power is roughly on-par with renewables at both 0% and 4.2%, although at 4.2%***, onshore wind costs less (if the value of the output of wind and nuclear is deemed equal, which is economically not so). This result is ***independent of the level of power output required.*** It is also independent of the time period over which the analysis is conducted, assuming the lifetime of the technology is exhausted.

Note, however, that these LCOE cost estimates do ***not present a complete, accurate picture of total costs***, since they ignore the reduced economic value of stochastic renewable electricity generation, and only take into account the cost of generating the electricity, not the spatial requirements and the broader system-related costs; once these are factored into the analysis, the results change dramatically (see for further discussion Part 7 of this report).

	Nuclear	**Solar**	**Onshore Wind**
Present Value of Costs at 0% WACC	€18bn	€25bn	€18bn
Relative to nuclear	*1.0x*	*1.4x*	*1.0x*
Present Value of Costs at 4.2% WACC	€9bn	€9bn	€7bn
Relative to nuclear	*1.0x*	*1.0x*	*0.7x*

Table 6.7. Synchronized Lifetime Analysis

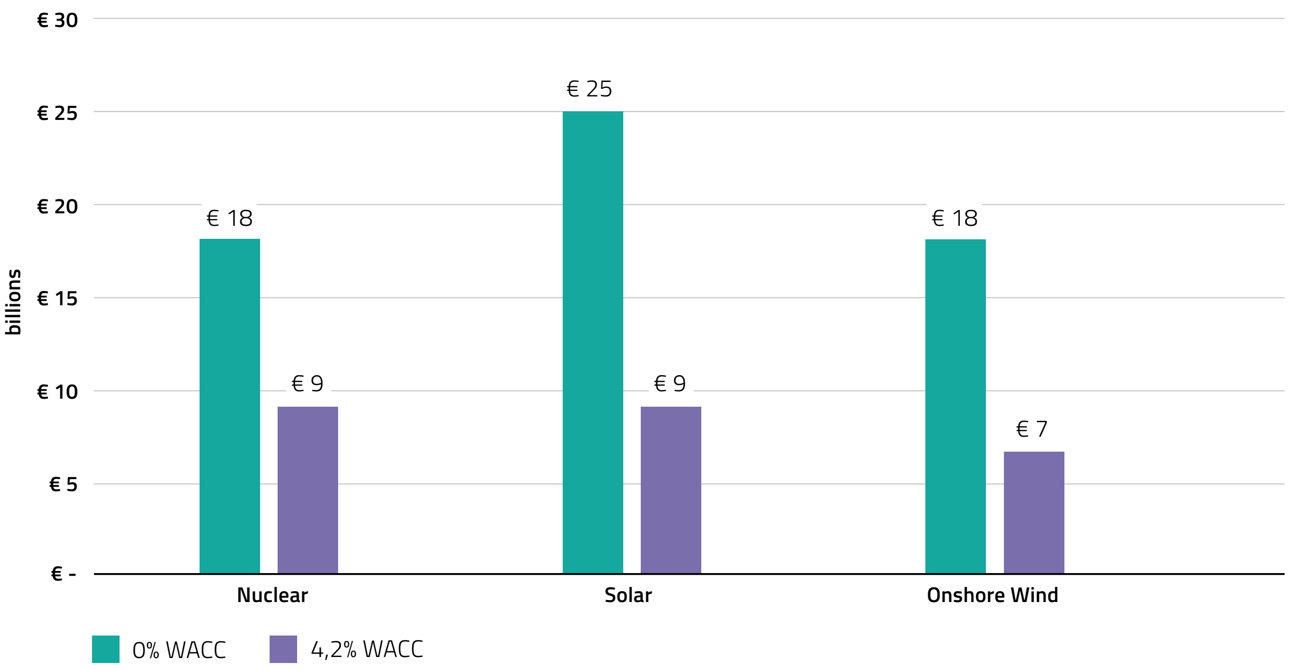

Figure 6.1. Synchronized Lifetime Analysis

The synchronized lifetime analysis reveals that nuclear power is roughly on-par with renewables at both 0% and 4.2%, independent of the level of power output required and of the time period over which the analysis is conducted, assuming the lifetime of the technology is exhausted.

Comparing Technologies
We present the cost of electricity (EUR/MWh) for various iterations of discount rates and cost structures. Table 6.8., gives the various WACC's, energy discount rates, and capital costs used in the various scenarios.

In Figure 6.2., we show the resulting electricity costs for each of these scenarios.
For renewables, ***significant drivers*** of the different cost estimates across the scenarios are the ***capital costs***. Because the realized figures are much higher than expected values, which factor in substantial cost savings over the next 30 years, especially for renewables, electricity costs can decrease by almost 50% depending on the type of technology. This means that for all renewables to be at least somewhat competitive with nuclear energy, ***significant capital cost decreases need to materialize*** and nuclear power

	Nuclear WACC	Renewables WACC	Energy Discount Rate	Capltal & Fixed O&M Costs
Scenario 1	4.2%	4.2%	0.0%	Realized
Scenario 2	4.2%	4.2%	0.0%	Expected
Scenario 3	7.0%	4.2%	0.0%	Realized
Scenario 4	7.0%	4.2%	3.0%	Realized
Scenario 5	7.0%	4.2%	3.0%	Expected

Table 6.8. Scenario Assumptions for Cost of Electricity (EUR/MWh)

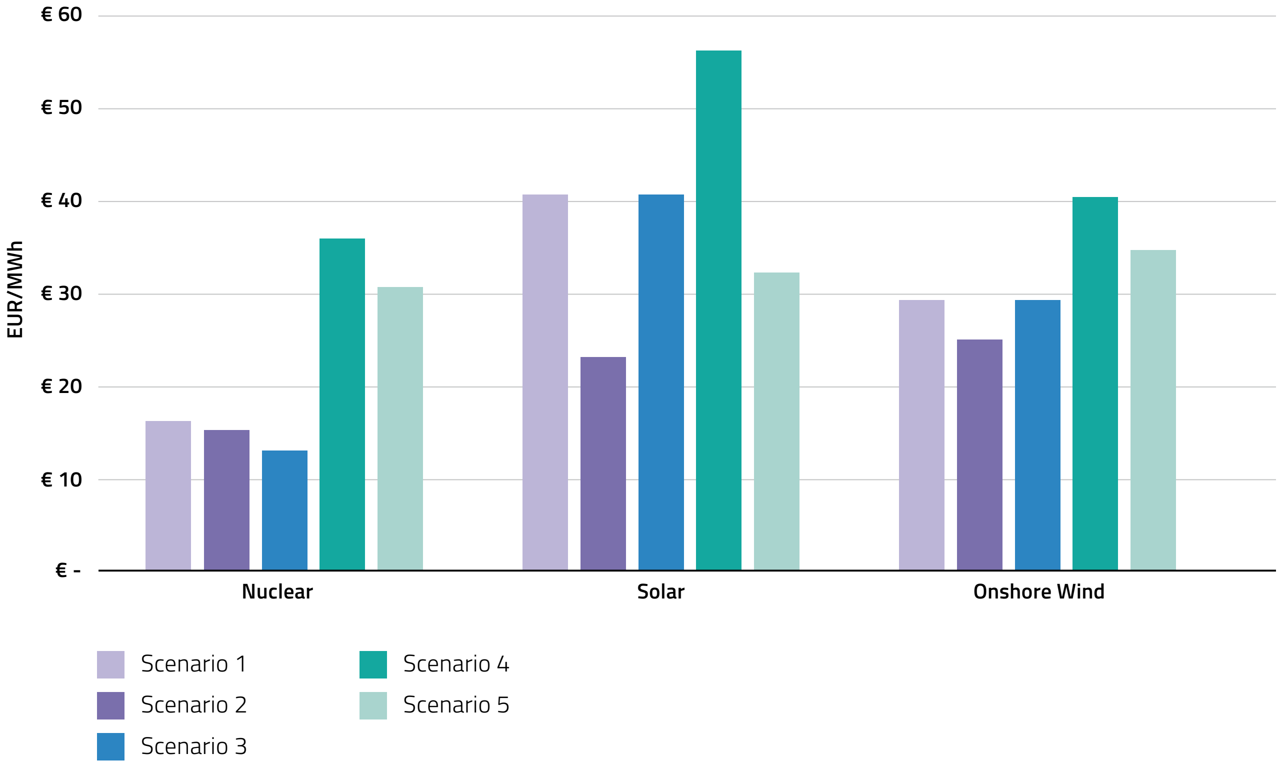

Figure 6.2. Comparison of Electricity Costs (EUR/MWh) for Various Scenarios

should not realize any significant cost reductions; if such substantial decreases (and corresponding absence of reductions) do not materialize, ***renewables remain uncompetitive***.

We also observe a relatively ***muted impact of the WACC***. Between scenarios 1 and 3, the only difference is the WACC for nuclear, which is 7% in scenario 3 compared to 4.2% in scenario 1. The cost of nuclear electricity decreases from €16.23 in scenario 1 to €13.14 in scenario 3, with nuclear essentially maintaining its significant cost advantage over wind and solar.

In ***no scenario is nuclear more expensive than either of the renewable options***. Scenario 5 resembles the methodology most often used in the literature covering the topic, where energy is discounted, nuclear is discounted at a higher rate than renewables, and significant cost decreases are modeled in for renewables; even in this scenario, nuclear remains competitive.

C. The Netherlands

In this section, we run the model for The Netherlands. Below, we first describe the data inputs and sources we used for each of the power generating technologies, and then proceed to present the model outcomes.

i. Data Inputs & Sources

As laid out in Table 6.1., the model takes numerous inputs and for every input, assumptions are required. We look at each category of inputs, in turn, to explain the default assumptions used in the model, as well as the rationale for these assumptions.
As we did for the Space Model, we compare the assumptions of this model directly to those used in the Nuclear Study done for the Dutch government.[398]

Technical Parameters
Table 6.8., lists the assumptions for the technical parameters for each technology. We list the assumptions from the Nuclear Study in italics and parentheses for reference. A discussion of the assumptions follows the table.

- The size of the power units, i.e. the ***capacity***, is the same as in the Nuclear Study and corresponds to the assumptions listed in the European scenario in the study. For purposes of the model, capacity as such is not directly relevant, as all costs scale linearly with capacity.

- For the ***full load hours***, we utilized the capacity factors we calculated in the Space Model; we refer to Annex II of this report for sources and a broader discussion of the capacity factors and the resulting full load hours. From the Space Model, we take the maxima of the ranges, so our values represent optimistic full load hours. The Nuclear Study has lower full load hours for nuclear, and higher for renewables than our model. Hence, it would overestimate the costs of nuclear relative to renewables because a significant portion of the costs are fixed and thus with lower production for nuclear relative to renewables, the relative costs will be higher.

	Units	Nuclear	Solar	Onshore Wind	Offshore Wind
Capacity per unit	MWe	1,600 *(1,600)*	20 *(20)*	3 *(3)*	3 *(3)*
Full load hours	Hours per annum	8,147 *(7,800)*	832 *(895)*	2,190 *(3,000)*	3,942 *(4,500)*

Table 6.9. Technical Parameters by Technology

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[398] Kalavasta/Berenschot. Systeemeffecten van nucleaire centrales in Klimaatneutrale energiescenario's 2050. 9 maart 2020, available at https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2020Z06737&did=2020D14346 ; Kalavasta/Berenschot. Systeemeffecten van nucleaire centrales in Klimaatneutrale Energiescenario's 2050 – Datasheets, 9 maart 2020, available at https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2020Z06737&did=2020D14346
An Excel spreadsheet has also been made available. (Jointly, the "Nuclear Study").

In this section, we run the model for The Netherlands. Below, we first describe the data inputs and sources we used for each of the power generating technologies, and then proceed to present the model outcomes.

Cost Parameters

Table 6.10., lists the assumptions for the cost parameters for each technology. We list the assumptions made by the authors of the Nuclear Study in italics and parentheses for reference at the bottom end of each field. A discussion of the assumptions follows the table. For some of the inputs, there are various options that the user can specify; we denote these in the table accordingly.

Realized cost estimates, denoted by (1) in table 6.10, are based on ***historical 2018 or 2019 data*** for representative countries (e.g., OECD countries, other European countries). In cases where data was available for multiple countries, we have used averages for countries neighboring The Netherlands. In some cases, where data was sparse, we have included other representative OECD countries, such as the U.S. In one case, there was data specifically for The Netherlands. In Annex II of this report, we discuss in more detail the sources for these estimates. We have aimed to be consistent in our use of sources for different categories of costs. For example, we use the same source for both capital and O&M costs.

	Units	Nuclear	Solar	Onshore Wind	Offshore Wind
Capital costs	€ / kWe	(1) 5,451 (2) 4,700 (5,135)	(1) 1,039 (2) 454 (278)	(1) 1,681 (2) 943 (711)	(1) 3,447 (2) 1,891 (1,000)
WACC (for costs)	% per annum	3.0% (7.0%)	3.0% (4.3%)	3.0% (4.3%)	3.0% (4.3%)
Discount rate (for energy production)	% per annum	0% (7.0%)	0% (4.3%)	0% (4.3%)	0% (4.3%)
Fixed maintenance and operation costs	€ / MWe per annum	(1) 105,900 (2) 105,000 (89,000)	(1) 16,287 (2) 9,200 (4,170)	(1) 32,337 (2) 12,000 (17,775)	(1) 88,555 (2) 28,000 (32,000)
Variable maintenance and operation costs	€ / MWh	(1)2.1 (2)7.8 (7.4)	(1) n/a (2) n/a (n/a)	(1) n/a (2)0.18 (n/a)	(1) n/a (2)0.39 (n/a)
Fuel costs	€ / MWh	5.50 (6.27)	n/a	n/a	n/a
Waste processing and storage costs	€ / MWh	2.07 (2.07)	n/a	n/a	n/a
Decommissioning	% of capital cost	12.5% (15%)	5% (5%)	5% (5%)	5% (5%)

Table 6.10. Cost Parameters by Technology

We provide more context for the cost inputs used in our model relative to the Nuclear Study, below:

- In terms of ***capital*** costs, the Nuclear Study is inconsistent in its treatment of 2050 cost, since it uses a 2015 realized figure for nuclear, and adjusts it for some learning effect,[399] but a projected capital cost for renewables that is based on hypothetical cost reductions. The hypothetical costs for renewables are based on a global estimate, which incorporates ***countries that have structurally lower costs*** such as India and China, as a more recent IRENA study points out.[400] This distorts the numbers in favor of renewable energy.

- Furthermore, the Nuclear Study, without explanation, uses an ***arbitrary exchange rate*** different from the one used elsewhere in the Nuclear Study; elsewhere; while specifically for nuclear a 0.89 EUR/USD rate is used, for the capital costs of renewables the rate used is 0.86 EUR/USD.

- Because the Nuclear Study incorporates these estimates into a broader system model, they have ***removed a portion of the offshore wind capital costs earmarked for grid connection***; an assumption is made regarding the size of that portion. IRENA, the source for the figures in the Nuclear Study, is clear, however, that these costs are for "connection to the local distribution […] network".[401]
    - For the realized capital costs for renewables, we sourced 2018 figures from an IRENA study.[402] We used the data that are most representative for The Netherlands. For nuclear, in the absence of more representative data, we rely on the NREL's 2020 Annual Technology Baseline;[403] although this data originates from the United States, we believe the estimate to be reasonable. Further review has confirmed this. For example, the figure from the U.S. data is a bit higher than that from a recent French study prepared by their nuclear energy agency.[404] The realized cost figure used in our model is also slightly higher than the one used in the Nuclear Study.
    - For projected capital costs in 2050, we rely on the above-referenced report for the European Commission.[405]

- For the ***WACC***, the default is a ***uniform WACC of 3%***. This is in-line with the Nuclear Study's public WACC. For other outputs, we also apply a 0% rate, as is requested in the questionnaire.

- The Nuclear Study takes the same approach to the ***discount rate*** for electricity produced as it does for the WACC. Our model allows the user to specify whether energy should be discounted and, if so, at what rate. As discussed above, the default is not to discount electricity produced (i.e. discount rate of 0%).

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[399] The EU estimates that in the case of nuclear learning effects can reduce cost by 27%. European Commission, STAFF WORKING DOCUMENT Accompanying the Communication from the Commission: Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty for the opinion of the European Economic and Social Committee, Brussels, 4.4.2016, SWD(2016) 102 final, available at https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v10.pdf

[400] International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi, 2020.

[401] International Renewable Energy Agency (IRENA). Future of wind. Deployment, investment, technology, grid integration and socio-economic aspects. October 2019, p. 47 (see footnote), available at https://www.irena.org/publications/2019/Oct/Future-of-wind

[402] International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi, 2020.

[403] National Renewable Energy laboratory (NREL). Annual Technology Baseline 2020. Available at https://www.nrel.gov/docs/fy20osti/76814.pdf

[404] Berthélemy, M. et al. (2018), "French Nuclear Power in the European Energy System", p. 31, SFEN, Paris.

[405] Asset, Technology pathways in decarbonization scenarios, Advanced System Studies for Energy Transition, July 2018, available at https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

- For ***fixed maintenance and operating costs***, the Nuclear Study uses a 2015 realized cost figure for nuclear from the NEA report,[406] and relies on projected costs (as a percentage of capital costs) for renewables. For these projected costs, the Nuclear Study relies on a 2018 Agora-commissioned report,[407] which in turn cites another report by the IEA,[408] for which we ultimately could not find any reliable source or data. Hence, the fixed maintenance and operating costs the ***Nuclear Study uses for renewables are unverifiable***. In general, selecting different sources for different parts of the cost structure is ***not best practice*** given the variations in underlying methods and assumptions employed by each source. We therefore believe the estimates in the Nuclear Study might not be realistic.

    - Our model provides the user with two options: use realized costs in 2018 or expected costs in 2050.
    - The realized costs for nuclear are sourced from the NREL report,[409] while for renewables we rely on the same IRENA study as we did for capital costs.[410]
    - For expected costs, we rely again on the European Commission report for all technologies.[411]

- For ***variable maintenance and operating costs***,[412] the Nuclear Study uses a 2018 value with an exchange rate of 0.89 EUR per USD, but from an ***entirely different source*** (an MIT report[413]) than for any of the other costs. It is unclear why the Nuclear Study switches to this MIT report in this specific context only. The Nuclear Study only specifies variable cost estimates for nuclear.

    - To ensure ***consistency***, our model uses the same sources as for the fixed M&O costs for realized cost estimates. Note that for renewables, historic data incorporates both fixed and variable into one figure so there is no separate variable component. For nuclear, however, the NREL specifies a variable component. The NREL report's variable cost estimate is significantly lower than that of the MIT study cited by the Nuclear Study.
    - For expected cost estimates, we rely again on the European Commission report for all technologies.[414] This report provides variable cost estimates for renewables.

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[406] OECD, Nuclear Energy Agency (2019), The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables. OECD Publishing, Paris, 2019.

[407] Frontier-Economics, The Future Cost of Electricity-Based Synthetic Fuels. 2018, available at https://www.frontier-economics.com/uk/en/home

[408] International Energy Agency. World Energy Outlook 2016. (2016), available at https://www.iea.org/reports/world-energy-outlook-2016

[409] National Renewable Energy laboratory (NREL). Annual Technology Baseline 2020. Available at https://www.nrel.gov/docs/fy20osti/76814.pdf

[410] International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi, 2020.

[411] Asset, Technology pathways in decarbonization scenarios, Advanced System Studies for Energy Transition, July 2018, available at https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

[412] Hughes warns that the maintenance and operating cost of offshore wind turbines may increase exponentially with age, possibly resulting in decommissioning after subsidy programs expire. Hughes, Gordon, WIND POWER ECONOMICS: RHETORIC & REALITY, Volume I -- Wind Power Costs in the United Kingdom, Renewable Energy Foundation, Stratford-sub-Castle, 2020.

[413] Massachusetts Institute of Technology. Energy Initiative. The Future of Nuclear Energy in a Carbon-Constrained World, 2018. Available at http://energy.mit.edu/research/future-nuclearenergy-carbon-contstrained-world

[414] Asset, Technology pathways in decarbonization scenarios, Advanced System Studies for Energy Transition, July 2018, available at https://ec.europa.eu/energy/sites/ener/files/documents/2018_06_27_technology_pathways_-_finalreportmain2.pdf

- For ***fuel costs***, this input is only relevant for nuclear power. Projecting future fuel costs (i.e. uranium) is a highly speculative exercise, as is the case with any commodity where prices depend heavily on demand. The uranium price used in the Nuclear Study ($135/kg) is derived from two sources, the World Nuclear Association[415] and the International Atomic Energy Agency.[416] The primary driver of the Nuclear Study's high assumed uranium price is the 20-year old (sic!) IAEA study. Since then, the literature has taken a generally less pessimistic view. A 2018 MIT study states that there are enough sources so as not to present an obstacle to demand growth.[417] Indeed, since the IAEA study was published in 2001, uranium prices increased to their peak in 2008 of $125-150/kg, before coming back to more moderate levels of around the $100/kg. Prices have remained steady at that level for half a decade (2010-2015). In the 'Economics of Nuclear Power,' the World Nuclear Organization uses a uranium price of $68/kg for its cost estimate;[418] the Nuclear Study also references this website for other purposes, so apparently it is regarded by Kalavasta and Berenschot as a reliable source (but, for unexplained reasons, not for this purpose). In conclusion, it appears the ***Nuclear Study relies on outdated beliefs*** about the ***uranium price***. Our model uses $100/kg instead, which is below the peak prices reported above, but higher than the optimistic price used by the World Nuclear Organization. The 2015 Nuclear Energy Agency study on the projected costs of generating electricity also uses this figure.[419] This results in fuel costs of € 5.50/MWh.

- With respect to ***waste management costs***, note that this input applies also only to nuclear (although wind and solar also generate waste at end of life, but this cost is not yet generally recognized). These costs include processing and storage. The Nuclear Study relies on the above-referenced 2015 Nuclear Energy Agency study. Other sources, such as the MIT study, the World Nuclear Organization's website on the Economics of Nuclear Power, and the more recent NEA report do not specifically split out waste management costs. It appears this is typically not done because these costs are included in other costs. Our model also uses the 2015 NEA study and applies the same waste management cost as the Nuclear Study.

- For ***decommissioning costs***, the Nuclear Study relies on the 2015 NEA study and expresses decommissioning costs as a percentage of the capital costs. Other sources for nuclear broadly agree, with the World Nuclear Association stating that decommissioning costs are 9-15% of the initial capital costs. Hence, the figure used in the Nuclear Study is on the high end of the range, but still reasonable. Given the lack of other sources that specifically provide decommissioning costs for all technologies, our model also uses 5% for renewables, and 12.5% for nuclear to better represent the range of possible values. We have not taken into account any efficiency gains (economies of scale) associated with large scale decommissioning and nuclear waste disposal.

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[415] World Nuclear Association. Economics of Nuclear Power, 2020, available at https://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx.

[416] International Atomic Energy Agency. Analysis of Uranium Supply to 2050. Available at https://ww.iaea.org/publications/6115/analysis-of-uranium--supply-to-2050

[417] Massachusetts Institute of Technology. Energy Initiative. The Future of Nuclear Energy in a Carbon-Constrained World, 2018, p. 180. Available at http://energy.mit.edu/research/future-nuclearenergy-carbon-contstrained-world

[418] World Nuclear Association. Economics of Nuclear Power, 2020, available at https://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx.

[419] Nuclear Energy Agency. Projected Costs of Generating Electricity. Nuclear Energy Agency, 2015, available at https://www.oecd-nea.org/jcms/39492_Media/projected-costs-of-generating-electricity-2015-edition-cover

	Units	Nuclear	Solar	Onshore Wind	Offshore Wind
Construction time	Years	7 *(7)*	0.5 *(0.5)*	1 *(1)*	1.5 *(1.5)*
Technical lifetime	Years	60 *(60)*	25 *(25)*	25 *(25)*	25 *(25)*

Table 6.11. Other Parameters by Technology

Other Parameters

Table 6.11., lists the assumptions for the other parameters for each technology. We list the assumptions from the Nuclear Study in italics and parentheses for reference. A discussion of the assumptions follows the table.

- The assumptions around construction time and technical lifetimes in the Nuclear Study were based on assumptions imposed by the European scenario the study was trying to mimic. We have made no changes to these assumptions.

External Parameters

Table 6.12., lists the assumptions for the external parameters.

	Units	Value
Exchange Rate	EUR per USD	0.89

Table 6.12. External Parameters

- This exchange rate is based on the average from January 2015 through January 2020. As long as the exchange rate is uniformly applied, the interpretation of the model output should not change. The Nuclear Study also uses this exchange rate for most of its calculations (but not all, as noted above).

ii. Cost of Capital Assumptions

Estimating WACC

As we did for the Czech Republic, we break down the WACC into three constituent components:

WACC = risk free rate + government risk premium + project risk premiun

As a reference point, we regard the rate at which the Dutch government borrows money as a risk-free rate. As of September 2020, the Dutch government can borrow for 30 years at very modest negative rates in nominal terms, meaning investors are willing to pay the Dutch government for borrowing from them. This is currently the case for most governments in Western and Northern Europe. The ***nominal risk-free rate is roughly 0%***.

The ***project risk premium*** is exactly the same as for the Czech Republic given that there is no inherent reason as to why these energy projects would carry different risks in these two European Union countries.

The European Central Bank targets 2% inflation,[420] leading to a ***real WACC for renewables of roughly 3%***, as Table 6.13., shows.

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[420] See ECB, https://www.ecb.europa.eu/mopo/html/index.en.html for more information on the ECB’s inflation target.

Risk-free rate	~ 0%
Government policy premium	~ 0%
Energy project premium	~ 5%
RENEWABLE NOMINALWACC	**~ 5%**
RENEWABLE REAL WACC	**~ 3%**

Table 6.13. Calculation of Real, After-Tax WACC for Renewables in The Netherlands

Risk-free rate	~ 0%
Government risk premium	~ 0%
Energy risk premium	~ 5%
NUCLEAR NOMINAL WACC	**~ 5%**
NUCLEAR REAL WACC	**~ 3%**

Table 6.14. Calculation of Real, After-Tax WACC for Renewables in The Netherlands

For nuclear, the data is even less reliable given that there are very few countries in the European Union that have fostered positive policy regimes for nuclear energy, where the WACC would truly reflect the energy project risks, as opposed to government policy risks. One country in the European Union that might be amongst those least hostile towards nuclear is the Czech Republic (but, again, the data is very limited). The Czech government recently offered a loan for the expansion of a nuclear power plant at an interest rate of 2%.[421] The project financing was 70% debt to 30% equity.

Of course, this was a government loan, not a market-based loan, but it offers a glimpse of how low the energy risk premium for nuclear power plants can be.[422] We believe that the low Czech interest rate of 2% could be regarded as representative for the rate in The Netherlands under a technology-neutral energy policy. We assume that roughly another 3% points are added to the WACC due to the equity financing piece, which translates to a cost of equity of 10%. A cost of equity of 10% in nominal terms is exactly what the NREL estimates for nuclear projects in their latest technology baseline.[423] We again adjust for 2% inflation to arrive at a **real WACC** of 3%, as Table 6.13., shows.

In real terms, the ***WACC of 3%*** is close to the estimate of the NREL.

WACC Estimate

As a default, the model uses a 3% uniform policy-neutral, after-tax, real WACC for both renewables and nuclear. We believe this reflects a reasonable estimate of the project risks and reflects a cost of capital that can be achieved in a policy regime that is neutral (or friendly) towards these energy source technologies. Choosing a WACC reflective of a 0% government policy premium offers the best methodology for rationally evaluating the alternatives to meeting the country's energy needs.

iii. Model Outcomes & Sensitivity Analysis

In this section, we present several model outputs, in the following order:

1. ***Synchronized lifetime analysis***: This involves a comparison of (1) the total cost of a nuclear plant over its entire useful life to (2) the total costs of consecutive renewable power installations over the same period of time that produce the same electricity output, using no discounting of power output and WACCs of 0% and 3%.

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[421] "Czech Republic and CEZ sign nuclear power plant expansion agreement" by PowerTechnology, 2020, link: https://www.power-technology.com/news/czech-republic-cez-sign-agreement-dukovany-nuclear-power-plant-expansion/

[422] There is plenty of evidence that the technological, operational, and other external risks for nuclear are very low. See, for instance, a post by the World Nuclear Association that outlines the safety record of nuclear energy globally: WNA, https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx With the newer nuclear technologies, such as the molten salt reactor, some risks might be different, as is the case for offshore wind turbines.

[423] National Renewable Energy laboratory (NREL). Annual Technology Baseline 2020. Available at https://www.nrel.gov/docs/fy20osti/76814.pdf

Synchronized lifetime analysis involves a comparison of (1) the total cost of a nuclear plant over its entire useful life to (2) the total costs of consecutive renewable power installations over the same period of time that produce the same electricity output, using no discounting of power output and WACCs of 0% and 3%.

2. ***Comparison of technologies***: We assess the impact of discounting and of using realized vs. expected costs.

Synchronized Lifetime Analysis
We have introduced the basics and rationale of the synchronized lifetime analysis above. The synchronized lifetime analysis has slightly different parameters for The Netherlands, primarily due to the different technical lifetimes of their solar and wind technologies.

In the synchronized lifetime analysis, we assume an electricity production requirement of just over 13mn MWh per annum, which is equal to the output of a 1,600-MW nuclear power plant. The required time period during which this production level is to be sustained is ***300 years,*** which is the shortest time period necessary to synchronize and equalize the consecutive lifetimes of nuclear plants and renewable power facilities, such that at the end of this period, all energy sources have met the ends of their respective useful lives.

The required output level of 13mn MWh is equivalent to the production of 1,984 onshore wind turbines, 1,103 offshore wind turbines, and 784 solar farms. The analysis also accounts for the differences in lead times/construction periods.

Table 6.14., provides the results of this analysis. We use a ***0% WACC*** for all technologies and a ***3% WACC*** for comparison. For each technology, the total costs of meeting the electricity requirements for 300 years are provided.

Note that the amounts are expressed as billions, i.e. 10^9. Figure 6.3., shows these results graphically.

The synchronized lifetime analysis reveals that ***nuclear power is a much more cost-efficient solution*** to meet chosen levels of electricity production over a given period of time. Even at a WACC of 3%, nuclear provides a given level of electricity at about half the cost of solar.

	Nuclear	Solar	Onshore Wind	Offshore Wind
Present Value of Costs at 0% WACC	€138bn	€282bn	€184bn	€232bn
Relative to nuclear	*1.0x*	*2.0x*	*1.3x*	*1.7x*
Present Value of Costs at 3% WACC	€17bn	€33bn	€21bn	€26bn
Relative to nuclear	*1.0x*	*1.9x*	*1.2x*	*1.5x*

Table 6.15. Synchronized Lifetime Analysis

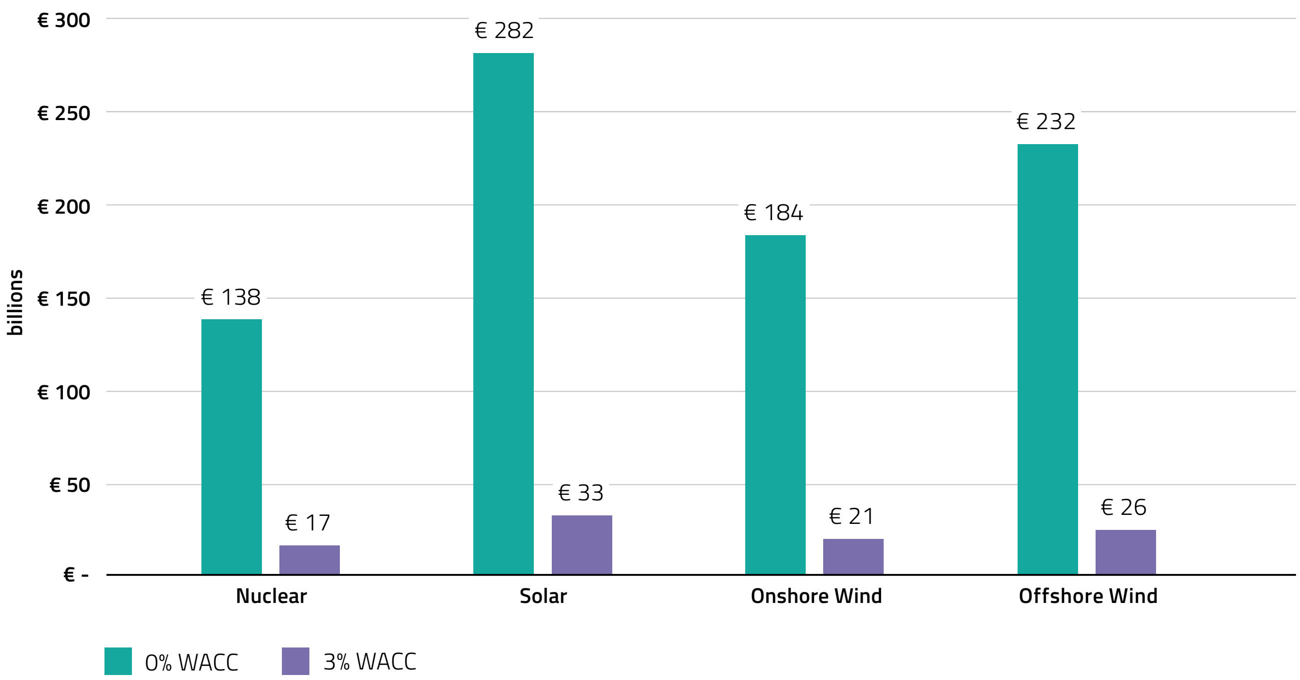

Figure 6.3. Synchronized Lifetime Analysis

The cost advantage of nuclear decreases, however, as the WACC increases. This is due to the fact that nuclear has a larger share of its costs early in the time period. At a WACC of 6.7%, nuclear and onshore wind cost roughly the same. This result is independent of the level of power output required. It is also independent of the time period over which the analysis is conducted, assuming the lifetime of the technology is exhausted. The only reason as to why we applied a long period of 300 years is that it avoids having to pro rate for a technology that has not yet reached end of life, which requires allocation and might introduce distortions.

Comparing Technologies

We present the ***cost of electricity (EUR/MWh)*** for various iterations of discount rates and cost structures, as well as a comparison to the results of the Nuclear Study. Table 6.16., gives the various WACC's, energy discount rates, and capital and fixed O&M costs used in the various scenarios.

The synchronized lifetime analysis reveals that nuclear power is a much more cost-efficient solution to meet chosen levels of electricity production over a given period of time. Even at a WACC of 3%, nuclear provides a given level of electricity at about half the cost of solar.

	Nuclear WACC	Renewables WACC	Energy Discount Rate	Capltal & Fixed O&M Costs
Scenario 1	3.0%	3.0%	0.0%	Realized
Scenario 2	3.0%	3.0%	0.0%	Expected
Scenario 3	7.0%	4.3%	0.0%	Realized
Scenario 4	7.0%	4.3%	3.0%	Realized
Scenario 5	7.0%	4.3%	3.0%	Expected

Table 6.16. Cost of Electricity (EUR/MWh) for Varying Discount Rates and Cost Assumptions

The scenario that most closely resembles the values from the Nuclear Study is scenario 5.

In Figure 6.4., we also include two different LCOE figures from the Nuclear Study, the difference being whether a uniform 3% discount rate is used (2) or not (1).

For ***renewables*** in particular, ***significant drivers*** of the different values across the scenarios are the ***capital costs*** and ***fixed O&M costs***. Because the realized figures lie so much higher than expected values, which factor in substantial cost savings over the next 30 years, electricity costs can decrease by 50% or more for renewables if these cost savings materialize; we

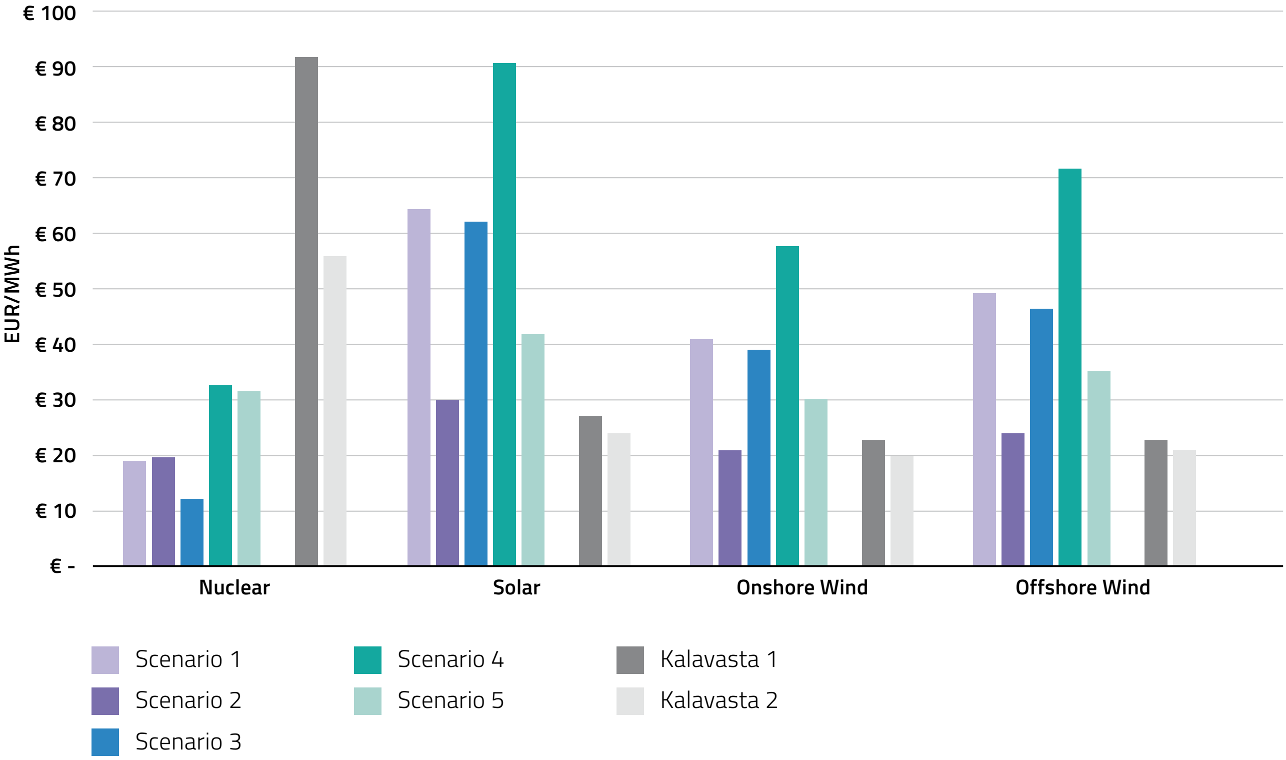

Figure 6.4. Comparison of Electricity Costs (EUR/MWh) for Various Scenarios

have not attempted to assess whether any such expectations are realistic and plausible. If these expectations materialize, it would put renewables at roughly equal footing as nuclear (around the 20 EUR per MWh). At realized costs, nuclear is substantially less costly. Presumably, this means that, for the foreseeable future, electricity generated through nuclear would be cheaper than renewables.

In other words, for renewables to be at least somewhat competitive with nuclear, significant capital and O&M cost decreases need to materialize and nuclear power should not realize any significant cost reductions.
If such substantial decreases for renewables and absence of reductions for nuclear do not materialize, renewables remain uncompetitive.

For offshore wind, we note that the capital costs in the model include a connection to the distribution grid, which the Nuclear Study has removed. To be clear, this does not include actual grid costs, but solely the cables from the wind turbines to a point where grid connection is made available. There will be additional costs to expand the grid into the sea to allow offshore wind parks to connect.

These costs do not yet include any system-related costs, which, as discussed in Part 7 of this report, would widen the cost differential between nuclear and renewables.

d. Conclusions and Discussion

Based on synchronized lifetime analysis, ***nuclear energy is extremely competitive*** from a cost perspective relative to renewable options. These results hold both at market-based WACCs as well as zero interest WACCs. These estimates are based on realized costs and reflect the current cost competitive cost position of nuclear:

- In the Czech Republic, nuclear is at cost parity with onshore wind and less costly than solar at a 0% WACC. Solar and nuclear are at parity at a 4.2% WACC, while onshore wind is slightly less costly than both nuclear and solar in that case (without discounting for the lesser value of renewable electricity due to intermittency).

- In The Netherlands, nuclear is in fact extremely competitive and at both the 0% and market-based WACC, the second-cheapest alternatives are still, respectively, 1.3 and 1.2 times as expensive as the nuclear option.

The Czech Republic

	Nuclear	Solar	Onshore Wind
Present Value of Costs at 0% WACC	€18bn	€25bn	€18bn
Relative to nuclear	*1.0x*	*1.4x*	*1.0x*
Present Value of Costs at 4.2% WACC	€9bn	€9bn	€7bn
Relative to nuclear	*1.0x*	*1.0x*	*0.7x*

Table 6.17.

The Netherlands

	Nuclear	Solar	Onshore Wind	Offshore Wind
Present Value of Costs at 0% WACC	€138bn	€282bn	€184bn	€232bn
Relative to nuclear	*1.0x*	*2.0x*	*1.3x*	*1.7x*
Present Value of Costs at 3% WACC	€17bn	€33bn	€21bn	€26bn
Relative to nuclear	*1.0x*	*1.9x*	*1.2x*	*1.5x*

Table 6.18.

When comparing the results for the Czech Republic and The Netherlands, which are set side-by-side here, remember that the time period under consideration for the Czech Republic is 60 years, while it is 300 years for The Netherlands. This is why we primarily look at the

In most plausible scenarios nuclear power is at least on par, and in most cases cheaper, than all types of renewable energy (offshore wind, onshore wind, solar). In The Netherlands, the cost advantage of nuclear is clear; in the Czech Republic, these technologies are roughly on par (without discounting for intermittency of renewable energy).

relative cost differences of the various power generation technologies, not necessarily at the absolute costs. While tables 5 .16. and 5.17. only lists the **costs of generating the electricity**, the costs of the electricity system include both the (i) cost of electricity-generation (LCOE), and (ii) the cost of transmission and distribution (integration and system-related cost) (for now, we disregard the broader social costs). Each electricity-generating technology (wind, solar, nuclear) produces **both types of cost**, which, to a significant extent, are a function of (i) the extent to which a technology is deployed in a system (the power mix), and (ii) the pre-existing infrastructure.

The **main drivers of the LCOE for both wind/solar and nuclear** are, roughly in order of importance based on our sensitivity analyses:

i. weighted average cost of capital (WACC)
ii. capacity factor
iii. capital cost
iv. fixed O&M cost

The **WACC is the most influential**, but also the most controversial factor.[424] Based on thorough analysis of this debate, our approach estimates the WACC for policy makers by **separating government risk** (which policy makers control) **from project risk** (which operators control to a great extent).

The main conclusion of the analysis presented here, is startling. Using a **policy-neutral WACC**, we find that **in most plausible scenarios nuclear power is at least on par, and in most cases cheaper, than all types of renewable energy (offshore wind, onshore wind, solar)**. In The Netherlands, the cost advantage of nuclear is clear; in the Czech Republic, these technologies are roughly on par (without discounting for intermittency).

- Only if all or most variables turn out to be in favor of renewable and to the detriment of nuclear, some renewable power might be more cost efficient than nuclear power based on the LCOE.

- Note that this cost comparison is based merely on LCOE and, thus, does not take into account

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[424] As the Dutch Planning Agency for the Environment found, "with its high capital cost and long lifetime, the costs of nuclear energy are very sensitive to all sorts of assumptions." Planbureau voor de Leefomgeving, Kosten Energie- en Klimaattransitie in 2030, Notitie, PBL, 28 maart 2018, p. 27, available at https://www.pbl.nl/sites/default/files/downloads/pbl-2018-kosten-energie-en-klimaattransitie-in-2030-update-2018_3241.pdf

integration and system-related costs, which are much **higher for renewable power** than for nuclear (see further below).[425]

- Likewise, ***spatial requirements*** are not taken into account in this analysis (refer to Part 5 of this report for discussion of spatial requirements). In a ***holistic evaluation*** of competing power generation technologies, in addition to LCOE, integration- and system-related costs, spatial requirements, and externalities are taken into account to make decisions on policies and investments.

- Note, too, that making energy policy decisions on the basis of expected, unrealized cost projections imports potential ***optimism bias*** into the analysis. As discussed above, this risk is significant in the case of renewables, as substantial cost reductions are expected.

- Our findings are **corroborated by the results of other recent studies and analyses**. Below, we review some recent reports that are consistent with the proposition that nuclear power is not more expensive than renewable power in The Netherlands and the Czech Republic. In light of the important role of capital cost, we also review some of the literature on financing of nuclear power.

Other Studies

A recent study conducted for the Netherlands government by ENCO concluded that while the nuclear power's LCOE, using differentiated WACCs for nuclear and renewable power (7 versus 4.3%), is higher than that of renewable power – 72 €/MWh or 40% more than off-shore wind.[426] As we do, ENCO did not discount renewable power based on its intermittency. However, once system costs are added to the equation, nuclear power's LCOE is lower – 74 €/MWh versus 85 €/MWh for offshore wind. Once the WACC is corrected and the same rate (7%) is used for both nuclear and wind, the LCOEs for nuclear and offshore wind are at the same level. ENCO points out that nuclear power facilities are best deployed at **75% capacity in baseload mode, "making the rest of the capacity available to support medium and long term grid needs or to produce green hydrogen."**[427]

The findings by ENCO are consistent with earlier calculations by CE Delft. This study found that the LCOE of nuclear in The Netherlands was about the same as the LCOE of onshore wind; offshore wind was more expensive. These costs, however, did not include integration- and system-related costs. The authors of this study note also that "[o]nce the investment expenditure has been paid off in one way or another and the fixed costs are consequently lower

ENCO points out that nuclear power facilities are best deployed at 75% capacity in baseload mode, "making the rest of the capacity available to support medium and long term grid needs or to produce green hydrogen."

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[425] "The LCOE calculations also do not capture other systemic costs or externalities beyond plant-level CO_2 emissions ... This report does however recognise the importance of the system effects of different technologies, most notably the costs induced into the system by the variability of wind and solar PV at higher penetration rates." IEA/NEA, Projected Costs of Generating Electricity, 2020 Edition, available at https://www.oecd-nea.org/jcms/pl_51110/projected-costs-of-generating-electricity-2020-edition?id=pl_51110&preview=true

[426] ENCO, Possible Role of Nuclear in the Dutch Energy Mix, Final Report, 1 Sep. 2020, ENCO-FR-(20)-13.

[427] Id., p. 57.

(or perhaps part-covered by a party other than the utility), a nuclear power station is of considerable value to a utility as the electricity generated has very low marginal costs and can consequently have a high profit margin per kWh."[428]

Kalavasta, a Dutch consultancy firm that previously conducted studies for Dutch government, responded to the ENCO report; its response has been published on the website of the Dutch Renewable Energy Association.[429] Its response frequently refers to existing policies (SDE++, Klimaatakkoord) to rebut ENCO's findings. Kalavasta thus misses the point that this kind of economic analysis is only useful to policy makers if it does not incorporate policy status quo bias; ***its insistence that nuclear power plants should run at 40% of capacity is idiosyncratic.***[430] Further, Kalavasta insists that ***expected costs, not realized costs***, be used

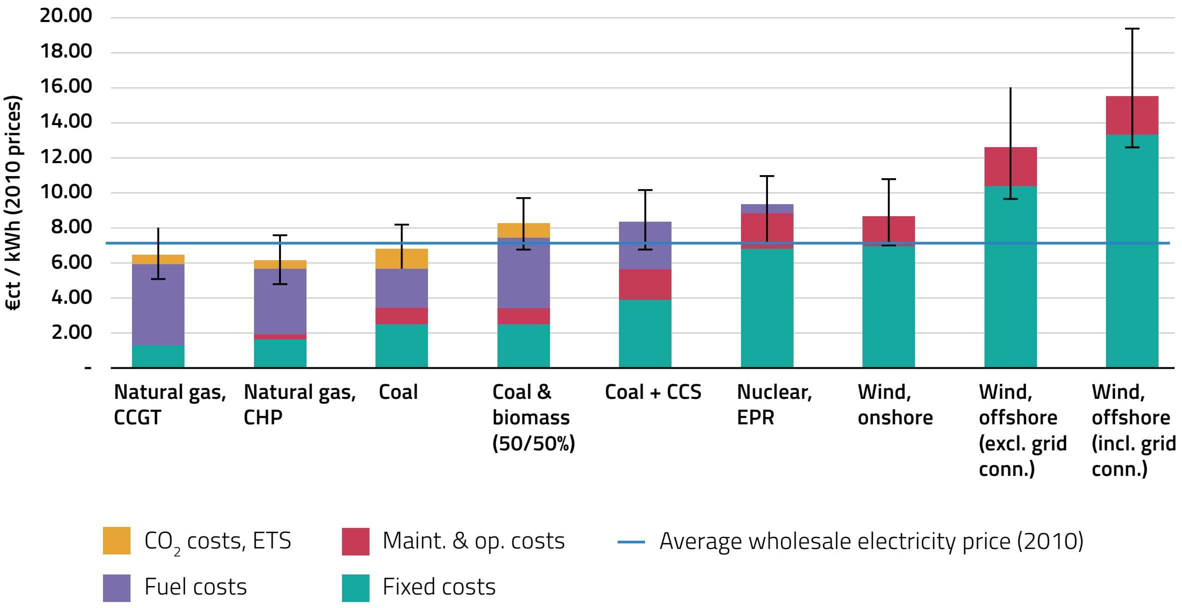

Figure 6.5. Direct costs of electricity generation, investor's perspective in 2011

Levelised costs of electricity generation *From: CE Delft (2011), p. 87*

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[428] Mart Bles, Maarten Afman, Jos Benner, Martijn Blom, Harry Croezen, Frans Rooijers, Benno Schepers, Nuclear energy: The difference between costs and prices, Delft, CE Delft, July 2011, p. 87.

[429] Kalavasta, Vergelijking van twee rapporten over de kosten van nucleaire en zon- & windstroom in het Nederlandse energiesysteem, die Minister Wiebes in april en september 2020 naar de Tweede Kamer heeft gestuurd, 24 september 2020, available at https://www.nvde.nl/nvdeblogs/kalavasta-geeft-objectieve-analyse-van-tekortkomingen-kernenergiestudie-enco/ ("Hoewel een kerncentrale technisch gezien flexibel is, ... is dit bedrijfseconomisch niet aantrekkelijk").

[430] Kalavasta apparently believes that this would be the natural result of market forces; again, they confuse the market with a policy-distorted market or rather their version of such a market. Cf. Planbureau voor de Leefomgeving, Kosten Energie- en Klimaattransitie in 2030, Notitie, PBL, 28 maart 2018, available at https://www.pbl.nl/sites/default/files/downloads/pbl-2018-kosten-energie-en-klimaattransitie-in-2030-update-2018_3241.pdf

Once system costs are added to the equation, nuclear power's LCOE is lower – 74 €/MWh versus 85 €/MWh for offshore wind. Once the WACC is corrected and the same rate (7%) is used for both nuclear and wind, the LCOEs for nuclear and offshore wind are at the same level.

for renewable energy, and appeals to authority to support its wish.[431] As discussed, expected costs are not reliable, and therefore, should not be used if realized cost is available. Finally, Kalavasta criticizes ENCO's approach to determining system-related costs, because, inter alia, it would be too general and not country-specific. As we demonstrate (see Section 7.c of this report), using the Dutch ETM model, which is country-specific, and using the scenarios developed by Kalavasta, ***system-related cost*** can be ***substantially reduced*** by adding a sufficient amount of ***nuclear power*** to the mix.

A 2018 study conducted by FTI and CompassLexecon for Foratom found that further ***nuclear development (high scenario) would mitigate the impact of the low carbon transition on customer cost by 350bn€ (real 2017)*** via lower total generation costs.[432] Anticipated nuclear closure (low scenario), on the other hand, would increase EU customer cost by €315 (real 2017) over 2020-35. This study also found that further nuclear development would ***mitigate network and balancing cost by 160bn€ (real 2017) and 13bn€ (real 2017) by 2050***, respectively.[433]

Another study published in 2018 on the Swedish electricity market found that replacing nuclear power with wind and solar would result in **annual spending on electricity systems five times higher than the then current levels**.[434] The authors of this study concluded that **replacing nuclear power with renewables would be neither economic nor climate-friendly.**

These findings raise an additional issue, which is further briefly discussed in Part 7 of this report. If renewable energy is forced onto the market and replaces other power generation assets before they reach end of life, the cost will further inflate, also knowns as the **'stranded assets' problem**.[435] Given that renewable energy often is intended to replace fully functional

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[431] Id., p. 3 ("De verwachting dat de investeringskosten van zon en wind nog (veel) verder kunnen en zullen dalen wordt algemeen gedeeld.") Cf. Williams, Eric ; Hittinger, Eric ; Carvalho, Rexon ; Williams, Ryan, Wind power costs expected to decrease due to technological progress, Energy Policy, 2017, Vol.106, pp. 427-435.

[432] FTI/CompassLexecon, Pathways to 2050: role of nuclear in a low-carbon Europe, 19 November 2018, presented to Foratom, available at https://www.foratom.org/2018-11-22_FTI-CLEnergy_Pathways2050.pdf

[433] FTI/CompassLexecon, Pathways to 2050: role of nuclear in a low-carbon Europe, 19 November 2018, presented to Foratom, available at https://www.foratom.org/2018-11-22_FTI-CLEnergy_Pathways2050.pdf

[434] Hong, Sanghyun ; Qvist, Staffan ; Brook, Barry W, Economic and environmental costs of replacing nuclear fission with solar and wind energy in Sweden, Energy Policy, 2018-01, Vol.112, pp. 56-66

[435] Löffler, Konstantin ; Burandt, Thorsten ; Hainsch, Karlo ; Oei, Pao-Yu, Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem, Energy Strategy Reviews, 2019, Vol.26, p.100422 (estimating a worst case of € 200 billion stranded assets by 2035).

Firm low-carbon power generation resources, such as nuclear, consistently lower decarbonized electricity system costs, between 10% and 62% in zero-CO_2 cases, and, importantly, batteries and demand flexibility do not substitute for such firm low-carbon resources.

power generation assets, this is a cost that is properly allocated to the introduction of renewable power.

When **decarbonization** is factored into the analysis, the case for nuclear power remains strong. A 2019 NEA study found that, relative to a high share of variable renewable energy, a ***higher nuclear share in the power mix reduces the total cost for the consumer or tax payer***.[436] Likewise, for the US situation, MIT research emphasized that when nuclear power is excluded from the list of available low-carbon technology solutions, the average cost of electricity increases as the carbon constraint becomes more stringent.[437] Specifically, firm low-carbon power generation resources, such as nuclear, consistently lower decarbonized electricity system costs, between 10% and 62% in zero-CO_2 cases, and, importantly, ***batteries and demand flexibility do not substitute for such firm low-carbon resources***.[438]

These studies confirm that high share of wind/solar in the power mix, to the detriment of nuclear energy, impose substantial direct cost on society. Nevertheless, pleas continue to be made to move towards 100% renewable energy.[439] As has been argued in 2013, however, any such transformation would not only be terribly expensive, but also require "a **transition to structures, ways and values that enable … non-affluent lifestyles**."[440]

Financing Nuclear Energy

Financing of nuclear energy projects raises a preliminary question: what is the investment climate for nuclear energy in a particular country? If nuclear energy is not treated in the same way as other decarbonized power generation technologies, obviously, this will affect the availability of financing and the conditions under which it is made available. As discussed above, the high interest rates for nuclear power are a function of both commercial risk and policy, political, government-related risk.

To promote nuclear financing, the World Nuclear Association (WNA) emphasizes that "the confidence provided by clear, long-term governmental commitment to a nuclear power programme remains critical." [441] While in regulated energy markets returns

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[436] NEA, The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables, OECD Publishing, Paris, 2019.

[437] MIT Energy Initiative, The Future of Nuclear Energy in a Carbon-Constrained World, http://energy.mit.edu/research/future-nuclearenergy-carbon-constrained-world

[438] Sepulveda, Nestor A ; Jenkins, Jesse D ; de Sisternes, Fernando J ; Lester, Richard K, The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation, Joule, 2018, Vol.2 (11), pp. 2403-2420.

[439] Hansen, Kenneth ; Mathiesen, Brian Vad ; Skov, Iva Ridjan, Full energy system transition towards 100% renewable energy in Germany in 2050, Renewable & Sustainable Energy Reviews, 2019, Vol. 102, pp. 1-13.

[440] Trainer, Ted, Can Europe run on renewable energy? A negative case, Energy Policy, 2013-12, Vol. 63, pp. 845-850.

[441] World Nuclear Association, Financing Nuclear Energy (updated Oct. 2020), available at https://world-nuclear.org/information-library/economic-aspects/financing-nuclear-energy.aspx

on investment were generally secure, WNA observes, "***deregulation of markets has altered the risk profile related to investing in new capacity because electricity prices are less predictable***." New models are therefore required to facilitate investment. These models include long-term power purchase contracts to reduce revenue risk, and capping investor exposure, for example through loan guarantees.

As WNA notes, financing models can vary broadly from government or public finance to corporate, private finance.[442] Public finance may mean that the ***government makes the financing available to a defined power project***, e.g. as part of the tender conditions. This means that (i) the government uses its credit lines to finance the project, which generally means much lower interest rates, and (ii) the financial risk to investors is substantially reduced. In any event, short of public finance, ***significant risk transfers onto governments or other parties is likely required to make nuclear power projects attractive*** to investors in liberalized markets.[443] Why this so, has much to do with the privileged treatment of renewable energy, and the concept of the 'energy only' market. This subject is discussed further in Part 8.

e. Further Reflections on the WACC and Discount Rate

As we have seen, the WACC is the most important variable in cost assessment of capital-intensive power plants, such as wind turbines and nuclear power plants. The WACC is the compound annual return required by equity and bond investors to make an investment in power plants attractive to them, and reflects, among other things, expected rates of return, perceived risks, and opportunity costs.

As we have seen, in conventional LCOE, **the WACC is also used to discount the energy produced by a plant**. This practice is based on the rationale that the WACC reflects the risk inherent in the power project, and this risk is assumed to also affect the present value of uncertain future output. In relation to the assessment of the power generation technologies considered here (wind/solar and nuclear), this assumption, as discussed, needs to be reconsidered, since **differences WACC between technologies reflects current policies more so than anything inherent to the technologies**. This explains also why the LCOE analyses done for the Dutch government discussed in this part, are pointless - we already know that current policies favor renewable energy.

Arguments Against Discounting Energy

Our argument runs as follows. In determining the present value of future cash flows, including those derived from future sale of electricity produced by power plants, a discount rate, typically equal to the WACC, is used. In the discussion of the WACC above, we made the following three arguments:

- **Because the purpose of a public planner is not to trade energy, discounting energy to present value is not necessarily appropriate**. The planner is interested in having electricity available at a specific moment in time, not in its commercial value today.

- **Discounting energy at differentiated rates, depending on whether it is produced by a renewable power plant or a nuclear power plant, is inappropriate**, because there is no underlying difference in inherent risk independent of current policy preferences. For this reason, where we discount electricity, we apply the same discount rate to alternative power generation technologies.

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[442] Id.

[443] Dominique Finon and Fabien Roques, Financing Arrangements and Industrial Organisation for New Nuclear Build in Electricity Markets, Competition and Regulation in Network Industries, Vol. 9, 2008, No. 2, pp. 147-181.

From an economic perspective, the common practice of disregarding intermittency for purposes of LCOE calculations arbitrarily deflates the LCOE of intermittent electricity and implies that integration- and system-related cost must be considered to obtain a reliable estimate of the true cost of electricity generated by variable renewable power technologies.

- **Discounting electricity can be avoided if the lifetimes and production of alternative power generation technologies are synchronized**. Our preferred method of synchronized lifetime analysis is applied in this part of the report.

- **If discounting is applied, it should be applied also to intermittent power,** because the economic value of this power is less since it is not demand-responsive and requires additional investment in backup facilities, or energy storage or conversion. From an economic perspective, the common practice of disregarding intermittency for purposes of LCOE calculations **arbitrarily deflates the LCOE of intermittent electricity**[444] and implies that integration- and system-related cost must be considered to obtain a reliable estimate of the true cost of electricity generated by variable renewable power technologies.

In this concluding section, we extend our argument by reviewing the issue of discounting of future climate-related damage, and analyzing how insights derived therefrom inform the discussion around discounting energy output. We do not discuss whether it is appropriate to price the climate; this is the issue of **incommensurability** – can and should the priceless be priced?[445]

Climate-related damage and prevention

With respect to the prevention of climate-related damage, there are two key questions: (i) how much damage will climate change cause (and when); and (ii) **how much should we spend now (and over time) to avoid this future damage**[446] (and on what should we spend[447])? None of these questions have certain or simple answers, which complicates policy making.

Focusing on the second question, the question as to how much we should spend on avoiding climate-related damage relates economically to the present value of the damage and, thus, to the choice of discount rate. Climate-related damage, however,

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[444] Because electricity produced by renewable sources receives preferential treatment, this is not necessarily so from a business perspective.

[445] Ackerman, Frank; Lisa Heinzerling, Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection, University of Pennsylvania Law Review, 2002, Vol.150 (5), pp. 1553-1584.

[446] This question relates to the 'social cost of carbon.' Nordhaus, William D., Revisiting the Social Cost of Carbon, Proceedings of the National Academy of Sciences - PNAS 114.7, 2017, pp. 1518-523

[447] The two main categories of spending are mitigation and adaptation.

not only involves **deep uncertainty, long time spans and multiple generations, but also hinges on the aggregate effects of the actions of all countries**. If we are unable to estimate the size of future climate-related damage, and assign a monetary value to it, **how are we to decide how much we should spend on prevention?**[448] While this is a big issue, it is not an issue at the level of the policy choice between alternative decarbonized power generation technologies.

Discounting future climate-related damage

Discounting converts future cash into current cash, and can be thought of as **reversing the effect of compounded interest**.[449] It is **not aimed at accounting for inflation**; in the absence of inflation, it would still be necessary to discount future positive or negative cash flows. While not the only issue,[450] the discount rate has a strong influence on damage assessment and, thus, on the **present value of the net benefit of prevention**.[451]

As the Stern-Nordhaus debate testifies,[452] **discounting future climate-related damages is a heavily debated issue**.[453] The reason for the controversy is that the **choice of discount rate is not an objective, neutral, economic, scientific and technical activity**. Whether or not to discount, and, if so, by how much, is a subjective choice informed by assumptions and values. In economics, discounting is based on **revealed time preferences**[454] and **opportunity cost**[455] - put in simple terms, assuming positive returns on capital, EUR 100 now is deemed worth more than EUR 100 in 10 years (time preference), and EUR 100 now can be invested to generate a higher return than the discount rate

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[448] To solve the problem of applying cost–benefit analysis in the realm of large structural uncertainty, the precautionary principle is sometimes invoked. The "dismal theorem" has been posited to suggest society should be willing to devote all of its resources to protect against future climate change. Weitzman, M.L., On modeling and interpreting the economics of catastrophic climate change, Rev. Econ. Stat., 91 (1), 2009, pp. 1-19. Cf. Horowitz, John, Lange, Andreas, Cost–benefit analysis under uncertainty — A note on Weitzman's dismal theorem, Energy Economics, 2014, Vol.42, pp. 201-203. For a forceful critique, see Nordhaus, W.D., The economics of tail events with an application to climate change, Rev. Environ. Econ. Policy, 5 (2), 2011, pp. 240-257. Cf. Frisch M., Modeling Climate Policies: The Social Cost of Carbon and Uncertainties in Climate Predictions. In: A. Lloyd E., Winsberg E. (eds) Climate Modelling. Palgrave Macmillan, Cham, 2018. (arguing that "the deep uncertainties concerning the climate system and climate damages make the exercise of trying to calculate a well-supported value for the SCC (social cost of carbon) impossible. Moreover, cost-benefit analyses are blind to important moral dimensions of the climate problem. Yet it is an open question to what extent an alternative, precautionary approach can result in specific policy recommendations such as the temperature targets of the Paris agreement.")

[449] Using the interest rate as the discount rate, if damage discounted to present value is less than the cost of prevention, it is more efficient to forego prevention and put the money in the bank. Goulder, Lawrence H., Robert N. Stavins, Discounting: An eye on the future, Nature, 2002, Vol. 419 (6908), pp. 673-674. For a comment, see Caldeira, Ken, What has posterity done for us? It's not the point, Nature, 2002, Vol. 420, p. 605 (arguing that "Discounting provides a well-defined measure relating present and future sums. The problem is that this measure is not particularly useful for problems involving intergenerational transfer.")

[450] Espagne, Etienne, Franck Nadaud, Baptiste Perrissin Fabert, Antonin Pottier, Disentangling the Stern/Nordhaus Controversy: Beyond the Discounting Clash, Working Paper, University of Minnesota, April 2012, available at https://ageconsearch.umn.edu/record/138510/ ("A closer look at the actual drivers of the controversy reveals however that Stern and Nordhaus also disagree on two other parameters: technical progress on abatement costs and the climate sensitivity.")

[451] Cf. Goulder, Lawrence H., Robert N. Stavins, Discounting: An eye on the future, Nature, 2002, Vol. 419 (6908), pp. 673-674.

[452] See Stern, N., The Economics of Climate Change: The Stern Review, Cambridge University Press, 2007. Nordhaus, W.D., A review of the Stern Review on the Economics of Climate Change, Journal of Economic Literature, 55, 2007, pp. 686–702. The classic groundwork is Ramsey, F., A mathematical theory of saving, Economic Journal, 38, 1928, pp. 543–559. Nordhaus argued that Stern arrived at inflated estimates of the cost of global warming due to using a discount rate well below the market rate of return on capital.

[453] Daly, Herman E., Joshua Farley, Ecological Economics: Principles and Applications, Second Edition, Island Press, 2010.

[454] A person's revealed time preference is the degree to which that person prefers present benefits (money today) over future benefits (money in the future), as demonstrated by actual choices made by him.

[455] The opportunity cost of a decision to make a specific investment is the cost of foregoing other opportunities.

applying to EUR 100 in 10 years (opportunity cost).[456] Capital markets provide information about discount rates and opportunity costs of capital in the form of interest rates (bonds, loans) and required or expected returns (equity).

At the level of **individual decisions**, the choice of discount rate and assessment of opportunity cost can be left to each person, who can decide whether to consume, invest or save. Individuals, of course, make different decisions in similar situations.[457] At the level of **policy-making**, however, the choice of discount rate and assessment of opportunity costs require **collective decisions**. As the relevant time spans move in the future, these decisions become **less grounded in 'knowns' and 'known unknowns**' and are increasingly plagued by '**unknown unknowns**,' and **deep uncertainty**.[458]

In the case of public goods[459] such as nature and the climate, there is no relevant markets that give economists reliable clues about time preferences or opportunity costs. To remedy the absence of markets, economists prefer to mimic markets, rather than resort to normative approaches (see further below), and utilize **proxies for markets**, i.e. various methods of **non-market valuation**.[460] Non-market valuation includes methods based on (i) revealed preferences, such as travel cost, and (ii) stated preferences, such as contingent valuation.[461] **Contingent valuation** involves a survey-based approach to nonmarket valuation.[462] This method can generate insights into people's **willingness-to-pay for a resource** (or avoiding a loss thereof) and **willingness-to-accept** loss of a resource, expressed in monetary terms, Non-market valuations have been used to generate estimates of (elements of) the social value of renewable energy[463] as well as nuclear energy.[464] It is disputed, however, whether such methods generate reliable valuations on which policy makers can act.

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[456] Buchanan J.M., Opportunity Cost. In: Eatwell J., Milgate M., Newman P. (editors), The World of Economics, The New Palgrave, Palgrave Macmillan, London, 1991. https://doi.org/10.1007/978-1-349-21315-3_69.

[457] Cf. Croote, Denise E., Baojun Lai, Jingchu Hu, Mark G. Baxter, Alison Montagrin & Daniela Schiller, Delay discounting decisions are linked to temporal distance representations of world events across cultures, Nature: Scientific Reports, 2020, Vol. 10, 12913.

[458] Sunstein, Cass R., Laws of Fear: Beyond the Precautionary Principle, Cambridge University Press, 2005.

[459] A pure public good is a good that is both non-excludable and non-rivalrous, meaning that no one can be excluded from enjoying it and enjoyment by each individual does not subtract from enjoyment by other individuals. Samuelson, Paul A., The Pure Theory of Public Expenditure, Review of Economics and Statistics, 36 (4), 1954, pp. 387–89.

[460] Champ, Patricia A., Kevin J. Boyle, Thomas C. Brown, (editors), A primer on nonmarket valuation, Springer, 2017. Segerson, Kathleen, Valuing Environmental Goods and Services: An Economic Perspective, in: Champ, Patricia A., Kevin J. Boyle, Thomas C. Brown, (editors), A primer on nonmarket valuation, Springer, 2017, pp. 1-25. ("Nonmarket valuation, i.e., valuing environmental goods and services that are not traded in a market, has been increasingly used in a variety of policy and decision-making contexts. This is one (but not the only) way that researchers and practitioners have sought to define and measure the values that individuals assign to environmental goods and services.")

[461] Segerson, Kathleen, Valuing Environmental Goods and Services: An Economic Perspective, in: Champ, Patricia A., Kevin J. Boyle, Thomas C. Brown, (editors), A primer on nonmarket valuation, Springer, 2017, pp. 1-25.

[462] Boyle, Kevin J, Contingent Valuation in Practice, in: Champ, Patricia A., Kevin J. Boyle, Thomas C. Brown, (editors), A primer on nonmarket valuation, Springer, 2017, pp. 83-131 ("A contingent-valuation question carefully describes a stylized market to elicit information on the maximum a person would pay (or accept) for a good or service when market data are not available. While controversial, … , contingent valuation and choice experiments —a close cousin in the stated preference family of valuation methods—are arguably the most commonly used nonmarket valuation methods.")

[463] Bigerna, Simona, Polinori, Paolo, The Economic Valuation of Green Electricity, Springer, 2019. (This research "evaluates the attitude of citizens towards the end use of green energy by investigating the likelihood of acceptance of a new infrastructures related to renewable energy production.")

[464] Jun, Eunju ; Joon Kim, Won ; Hoon Jeong, Yong ; Heung Chang, Soon, Measuring the social value of nuclear energy using contingent valuation methodology, Energy Policy, 2010, Vol. 38 (3), pp. 1470-1476. (This study shows that "the social value of nuclear energy increases approximately 68.5% with the provision of adequate information about nuclear energy to the public. Consequently, we suggest that the social acceptance management in nuclear policy development is important along with nuclear technology innovation.")

In deciding which discount rate to use, economists can adopt a 'descriptive' or 'prescriptive' approach. The descriptive approach assumes that discount rates are to conform to actual political and economic decisions and prices, while the prescriptive approach implies that discount rates should be informed by a moral imperative, such as sustainable development or climate conservation.

Descriptive and prescriptive approaches

Without any reliable data about the wealth and living conditions of people in 2100, how can economists make a decision about the right discount rate? They cannot aggregate individual preferences, as these are unknown to them. Moreover, they need to guess the **preferences of people living in 2100**, not those of people living today. Estimating opportunity costs over such a long period of time and wide range of options is equally hard. Economists generally assume that the gross domestic product will increase over time, but they do not know so for sure. Moreover, the problem of **diminishing marginal utility** comes into play here – if future generations will be richer than we are, they would suffer less utility loss if they pay for damage (prevention) themselves.[465] If the cost of prevention is much smaller than the cost of remediation, the relative utility losses change, of course, and taking prevention measures today may be indicated.

In deciding which discount rate to use, economists can adopt a '**descriptive'** or **'prescriptive'** approach.[466] The descriptive approach assumes that discount rates are to conform to **actual political**[467] **and economic decisions and prices**, while the prescriptive approach implies that discount rates should be informed by a **moral imperative**, such as sustainable development or climate conservation.[468]

Adopting the prescriptive approach, Stern has suggested that the **discount rate applicable to climate-related damage** should be very low – 0.1% to reflect time preference, based on a putative moral mandate[469] **to treat losses to future generations in the same manner** as we treat losses to present generations.[470] In response, Nordhaus has suggested that the relevant discount rate is the **market rate of return on capital**, at the time in the 3 to 5% range.[471] To illustrate the absurd

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[465] Cf. Michl, Thomas R., Discounting Nordhaus, Review of Political Economy, 22:4, 2010, pp. 535-549, DOI: 10.1080/09538259.2010.510316

[466] Baum, Seth D., Description, prescription and the choice of discount rates, Ecological Economics, 2009, Vol.69 (1), pp. 197-205.

[467] It is hard to say what discount rate is implicit in the EU's climate policies.

[468] Nordhaus, William D., Critical Assumptions in the Stern Review on Climate Change, Science, 2007, Vol.317 (5835), pp. 201-202.

[469] Other moral mandates would require that, over a given period of time, a nation should leave to future generations at least as much societal capital as it received from prior generations, or that a society should increase the wellbeing of the poorest. Cf. Nordhaus, W.D., A review of the Stern Review on the Economics of Climate Change, Journal of Economic Literature, 55, 2007, pp. 686–702.

[470] Stern, N., The Economics of Climate Change: The Stern Review, Cambridge University Press, 2007.

[471] Nordhaus, W.D., A review of the Stern Review on the Economics of Climate Change, Journal of Economic Literature, 55, 2007, pp. 686–702.

Insofar as decarbonized outputs of power generation facilities can be viewed as measures to prevent climate-related damages (i.e. public goods), should this electricity be discounted at the same rate at which climate-related damage itself is discounted? If so, the issue then becomes what the discount rate for climate-related damage is. Unfortunately, the EU has not explicitly set any discount rate, and it is nearly impossible to calculate any such rate from its policies.

consequences of a discount rate close to zero, Nordhaus shows that extensive damages after the year 2800 would justify enormous expenditure now.[472] **Public discount rates that decline over time**[473] or rates smaller than the economic discount rate have been proposed to address this issue.

Public aspects of discount rates

As argued in this report, there is something unsatisfactory and inconsistent about **using market-based discount rates for purposes of social planning**, because social planning is predicated on the belief that the relevant decisions should not be left to the market. As Michl puts it, "Nordhaus's belief in choosing preference parameters for the social planner based on observed market rates of return is equivalent to **assigning the preferences of the capitalist agents to the social planner.**"[474] On the other hand, an argument could be made that it is not because part of the problem is corrected by the government, that, therefore, other related decisions, including decisions about the prevention measures, should also be shielded from the forces of the market. This proposition is true, **except if there is no meaningful market left** due to government's interventions.

The bottomline is that the discount rate to be applied in planning decisions is **not a given** for policy makers. The choice of a **discount rate is a value-laden decision, not a technical matter to be decided by experts**.

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[472] "How do damages that average around 1% over the next century turn into 14.4% cuts "now and forever"? The answer is that, with the low interest rate, the relatively small damages in the next two centuries get overwhelmed by the high damages over the centuries and millennia that follow 2200. In fact, if the Stern Review's methodology is used, more than half of the estimated damages "now and forever" occur after 2800." Nordhaus, William D., Critical Assumptions in the Stern Review on Climate Change, Science, 2007, Vol.317 (5835), pp. 201-202.

[473] Arrow, Kenneth J., Maureen L. Cropper, Christian Gollier, Ben Groom, Geoffrey M. Heal, Richard G. Newell, William D. Nordhaus, Robert S. Pindyck, William A. Pizer, Paul R. Portney, Thomas Sterner, Richard S. J. Tol, Martin L. Weitzman, Should Governments Use a Declining Discount Rate in Project Analysis?, Review of Environmental Economics and Policy, Volume 8, Issue 2, Summer 2014, pp. 145–163 (arguing that governments should use a discount rate that declines over time when evaluating the future benefits and costs of public projects, because, if the discount rates that will be applied in the future are uncertain but positively correlated, and if the analyst can assign probabilities to these discount rates, then the result will be a declining schedule of certainty-equivalent discount rates).

[474] Michl, Thomas R., Discounting Nordhaus, Review of Political Economy, 22:4, 2010, pp. 535-549, DOI: 10.1080/09538259.2010.510316.

Deciding the appropriate discount rate for policy purposes involves political and moral debates as much as economic and technical issues. The moral judgments that shape discount rates should be made in **open public debate, rather than hidden as inscrutable parameters in economic models**. In some cases, policies should determine discount rates, not the other way around.

Discount rates for electricity generation facilities and their output

A question arises as to how this analysis applies to infrastructure, such as the electricity system, and its output. Insofar as decarbonized outputs of power generation facilities can be viewed as measures to prevent climate-related damages (i.e. a public good), should this **electricity be discounted at the same rate at which climate-related damage itself is discounted?** The argument in favor of this proposition is that the discount rate used for climate-related damage reflects the value the public attaches to preventing this damage, and, thus, to keep unbiased accounts, prevention measures should be assessed on the same basis. If so, the issue then becomes what the discount rate for climate-related damage is. Unfortunately, the EU has not explicitly set any discount rate, and it is nearly impossible to calculate any such rate from its policies, because it has neither specified the size of climate-related damage, nor the costs of its climate policies (i.e. the prevention measures). Instead, the EU appears to pursue a set of precautionary policies. Precautionary climate policy would be consistent with the finding of a leading economist, who computed that "[o]nly a very low discount rate (0% PRTP[475]) would justify the 20% emission reduction target for 2020,"[476] which is only one element of the EU's climate policy.

Arguably, however, the discount rate applicable to decarbonized electricity should be a market-based (WACC) rate, since there is no reason not to leave this to the market, and leaving it to the market will result in efficient outcomes. This argument would have force, if, in the context of climate policy and the energy transition, the government had only set a target (such as climate neutrality target for the electricity system) and left it to the market to decide how best to achieve that target. As discussed throughout this report, however, that is not quite what the EU has done; rather, the **EU has prescribed renewable energy targets and tweaked the rules of the electricity market,** which have distorted the market, causing WACCs of various power generation technologies to reflect the effects of policies.[477] In addition, the EU does not account for the integration- and system-related cost[478] nor for the externalities of power generation technologies,[479] and does not require that member state governments do so. Consequently, there is a risk that decisions are made based solely on **LCOEs derived from skewed WACCs**. Currently, WACCs for renewable and nuclear energy that typically feature in energy policy making debates reflect a status quo policy bias that renders them unfit for the purpose of making policy decisions, as opposed to private investment decisions. This is **not best practice** in energy policy-making. Energy policy makers need WACCs free of policy bias to make well informed, undistorted decisions.

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[475] PRTP means pure rate of time preference. It represents time preference for utility.

[476] Tol, Richard S.J., A cost–benefit analysis of the EU 20/20/2020 package, Energy Policy, 2012, Vol. 49, pp. 288-295.

[477] See Parts 6 and 8 of this report.

[478] See Part 7 of this report.

[479] See Parts 7 and 8 of this report.

Governments can also take measures to mandate, influence, or otherwise correct the discount rates for investments in power generation technologies. They can do so by, for instance, putting public finance behind power projects. This is neither novel, nor controversial.

If, as in the case of the EU electricity system, **government interventions have such a pervasive influence on WACCs**, it may be preferable for government to also correct distorted rates set by finance markets, either directly or indirectly. These distortions arise from a wide range of policy measures, including selective subsidies, selective regulatory privileges, or selective correction of externalities.[480] Where government decides not to correct externalities, it implicitly applies a 100% discount rate; for instance, **the adverse effect of wind turbines on wildlife (birds, bats, etc.) and nature, is discounted very heavily**.

Government-mandated discount rates

Our argument is not that a low or zero discount rate is always appropriate for public policy-making, nor that a 100% discount rate should never be used. We realize that the use of low or zero discount rates by politicians or other decision-makers can have perverse and catastrophic consequences.[481]

Rather, we suggest that, in appropriate cases and under the right circumstances and conditions, governments, just as they can decide not to leave the pricing of the climate to the market and correct externalities, can also take measures to **mandate, influence, or otherwise correct the discount rates for investments in power generation technologies**. They can do so by, for instance, putting **public finance** behind power projects. This is neither novel, nor controversial. Government is already heavily involved in the financing of electricity infrastructure;[482] it would be a small step to include all power generation technologies in these programs. In Part 8 of this report, we return to this idea where we present our policy recommendations.

A final note: we discuss the controversy around discount rates and WACCs extensively because, as shown above, they play such a significant role in determining the LCOE of power generation facilities. In our analysis, however, we have found a way to avoid having to apply discount rates to energy by applying synchronized lifetime analysis. Even those who disagree with this method, should recognize that **discounting for purposes of planning is one of the decisions that governments (can and should) make**, whether explicitly or implicitly.

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[480] See further Part 8 of this report.

[481] "While this feature of low discounting might appear benign in climate-change policy, we could imagine other areas where the implications could themselves be dangerous. Imagine the preventative war strategies that might be devised with low social discount rates. Countries might start wars today because of the possibility of nuclear proliferation a century ahead; or because of a potential adverse shift in the balance of power two centuries ahead; or because of speculative futuristic technologies three centuries ahead. It is not clear how long the globe could long survive the calculations and machinations of zero-discount rate military powers." Nordhaus, William D., Revisiting the Social Cost of Carbon, Proceedings of the National Academy of Sciences - PNAS 114.7, 2017, pp. 1518-523.

[482] Cf. Energy Technologies Institute, The ETI Nuclear Cost Drivers Project, September 2020.

7

Electricity Generation Technology and System-Related Costs

Electricity Generation Technology and System-Related Costs

In this section, we briefly discuss system-related issues related to electricity generation technologies that were not quantitatively accounted for in the model outputs presented in previous parts of this report. Through this chiefly qualitative discussion, we intend to provide insights into the limits of studies that compare energy technologies purely on an LCOE basis. We also show, however, how the evaluation of such technologies should be extended to include system-related cost.

So far, we focused on relative spatial and cost requirements of electricity generation technologies. This part explains why **electricity generation technologies should be evaluated at the level of the system as a whole**, not solely on the basis of the relative cost of power generation technologies. Electricity is fungible, but only if it is delivered at the right time at the right place; because there is a strong preference for electricity to be consumed when it is produced, electricity that is generated when there is no demand has a lesser economic value, and may even command a negative price,[483] which, in turn, has broader economic consequences.[484]

A **systems-approach is essential** because any electricity generation technology has to be integrated into the electricity system as a whole, which, in turn, serves an economy, including industry, households, and other users. Further, power generation technologies cause **adverse impacts** or **negative externalities**, which are also costs in a broad economic and social sense. The space demand and cost specific to an electricity generation technology (wind, solar, nuclear) do not represent all costs associated with that technology; there are other systems-related costs that are not

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[483] Editor, Welcome to the New Normal: Negative Electricity Prices, The Electricity Journal, Vol. 31, Issue 1, January–February 2018, p. 94.

[484] Barbour, Edward ; Wilson, Grant ; Hall, Peter ; Radcliffe, Jonathan, Can negative electricity prices encourage inefficient electrical energy storage devices?, International journal of environmental studies, 2014-11-02, Vol.71 (6), pp. 862-876. Zhou, Yangfang, "Helen" ; Scheller-Wolf, Alan ; Secomandi, Nicola ; Smith, Stephen, Electricity Trading and Negative Prices: Storage vs. Disposal, Management Science, 2016-03, Vol. 62 (3), pp. 880-898.

A systems-approach is essential because any electricity generation technology has to be integrated into the electricity system as a whole, which, in turn, serves an economy, including industry, households, and other users. Further, power generation technologies cause adverse impacts or negative externalities, which are also costs in a broad economic and social sense.

reflected in the technology-specific costs. In this part, we provide an overview of such system-related costs associated with the electricity generation technologies discussed here.

In addition, we present **relevant quantitative analysis for The Netherlands** (not for the Czech Republic[485]) that demonstrates the importance of a system-approach when evaluating power generation technologies. This analysis is both surprising and relevant to policy-making. We also suggest which additional considerations are relevant to policymaking in this area. After all, in an evaluation of power generation technologies based on cost/benefit analysis, land/space demand, generation costs, system-related costs, and other impacts are all relevant.

a. Renewable Power's Implications

The EU's policy **preference for renewable energy (electricity)** presents a series of issues and challenges. As an overall requirement, energy policy should ensure that the power supply and delivery meet the demand for power. There should be a match in terms of timing, location, and quantity. In other words, power should be delivered when it is needed, where it is needed, and in the quantity needed. To the extent there is mismatch between delivery and demand with respect to any of these three parameters, **system adaptations are required to correct the mismatch. Such system adaptations do not come free of charge**: they require investments in physical infrastructure and additional management processes. Even with these investments, system adaptations, such as transmission lines to remote areas that transport electricity over long distances or conversion of power into hydrogen, may

Wind and solar power differ from conventional power sources in that they are:

1. diluted
2. intermittent
3. statistically dependent
4. remote

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[485] For The Netherlands, a model is available that enabled us to estimate system-related cost. For the Czech Republic, no such model is publicly available, as far as we know.

cause power losses,[486] impose further costs, and take up space; these costs should be weighed against their benefits, because they inevitably result in lower net benefits.

Relative to other decarbonized power generation technology, renewable energy's main advantage is that the 'fuel' (wind, sun) it uses is costless. In operation, renewable energy does not emit carbon dioxide, **but the extent to which renewable energy also reduces CO_2 emissions on a life cycle, systems basis is an open question**; much depends on the system boundaries and the assumptions made – mining, transport, manufacturing, and services associated with renewable energy may cause significant emissions and other impacts that may outweigh some of the CO_2 reducing effects of renewable energy.[487]

Unlike convention power production, renewable power has four major disadvantages:

1. **Wind and solar are *diluted*** – This raises the issue of *low power density*,[488] which works to increase the size of area required to produce a given amount of electricity and increases the cost per unit of electricity generated.

2. **Wind and solar are *intermittent*** – This is the issue of *variability*. The supply of renewable energy is weather-, season-dependent, and day/night-dependent, as well as, to a significant extent stochastic, i.e. random. Importantly, renewable power generation does not follow power demand (i.e. is non-demand-responsive), but instead is entirely dependent on factors that are largely outside of the system's control and, to a significant extent, can be unpredictable.[489]

3. **Wind and solar power generation are *statistically dependent*** – Note that this is not the same as intermittent. Statistical dependence refers to the phenomenon that there is a positive correlation between the chance that one wind turbine produces electricity and the chance that another wind turbine produces at the same time. This tendency of renewable energy to produce too little or too much electricity implies that it is unresponsive to demand in two directions, which aggravates the need for back-up power facilities and storage and conversion infrastructure. Statistical dependence prevents the effective operation of the 'law of the large numbers,' presents problems for balancing the power system, and increases system cost.[490] Through diversification (e.g., wind versus solar, various locations, large networks) and aggregation, renewable energy's statistical dependence can be reduced,[491] but not eliminated.

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[486] "Collection and transmission losses represent the cumulative energy losses that occur in the power cables due to the resistive heating." Aldersey-Williams J, Broadbent ID, Strachan PA. Better estimates of LCOE from audited accounts – A new methodology with examples from the United Kingdom offshore wind and CCGT. Energy Policy, Vol. 128 (2019), pp. 25 – 35.

[487] For mining impacts, see, for instance, Sonter LJ, Dade MC, Watson JEM, Valenta RK. Renewable energy production will exacerbate mining threats to biodiversity. Nature Communications, Vol. 11 (1) September 2020, pp. 4174-4174.

[488] Vaclav Smil defines 'power density' as 'W/m2 of horizontal area of land or water surface rather than per unit of the working surface of a converter. Perhaps the greatest advantage of this parameter is that it can be used to evaluate and to compare an enormous variety of energy fluxes ranging from natural flows and exploitation rates of all energy sources (be they fossil or renewable) to all forms of energy conversions (be it the burning of fossil fuels or water- or winddriven electricity generation)." Vaclav Smil, Power Density Primer: Understanding the Spatial Dimension of the Unfolding Transition to Renewable Electricity Generation (Part I – Definitions) May 8, 2010, available at http://vaclavsmil.com/wp-content/uploads/docs/smil-article-power-density-primer.pdf

[489] See Ren, Guorui ; Wan, Jie ; Liu, Jinfu ; Yu, Daren ; Söder, Lennart, Analysis of wind power intermittency based on historical wind power data, Energy (Oxford), 2018, Vol.150, p.482-492 ("As wind power provides an increasingly larger share of electricity supply, the challenges caused by wind power intermittency have become more and more prominent. A better understanding of wind power intermittency would contribute to mitigate it effectively.")

[490] Hughes, Gordon, WIND POWER ECONOMICS: RHETORIC & REALITY, Volume I -- Wind Power Costs in the United Kingdom, Renewable Energy Foundation, Stratford-sub-Castle, 2020. Hughes, Gordon, WIND POWER ECONOMICS: RHETORIC & REALITY, Volume II -- The Performance of Wind Power in Denmark, Renewable Energy Foundation, Stratford-sub-Castle, 2020.

[491] Cf. Mousavi Agah, S. Mohammad, Flynn, Damian, Impact of modelling non-normality and stochastic dependence of variables on operating reserve determination of power systems with high penetration of wind power, International journal of electrical power & energy systems, 2018-04, Vol.97, pp. 146-154.

4. **Wind and solar may be *remote* from the place of demand** – Where wind farms and solar parks are located in areas where land/space is cheap, plentiful, and do not create a nuisance (e.g. in the countryside or at sea),[492] they are also far away from the place where most of their power is needed (e.g. the main metropolitan centers).[493] Remoteness means **more infrastructure** needs to be built to transmit the electricity to the end user. This not only requires **additional space and land** and **larger capital expenditures**,[494] but also leads to more space demand and electricity **loss in transmission**.[495] The loss rate of electricity depends on multiple factors, including the voltage of the transmission lines, and increases with the distance the electricity needs to be transmitted.[496]

Thus, the intrinsic properties and erratic nature of renewable power result in mismatches in time and space, and consequently present technical challenges and impose additional costs. Because renewable power is generated at a (1) time, (2) place, and (3) in quantities that does not match demand and use, the **electricity system has to be adapted** to remedy these deficiencies.

Viewed from a different perspective, the purpose of the electricity system itself is put into question. A conventional power system is aimed at providing power when it is needed, and answers the question:

- ***How should the system be designed and operated so that it can supply power as needed?***

The disadvantages of wind and solar power generation technologies result in additional cost for the electricity system that are not necessarily accounted for as such.

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[492] For an attempt to map the land and space that is technically available for wind farm development, see Peter Enevoldsena,, Finn-Hendrik Permien, In es Bakhtaoui, Anna-Katharina von Krauland, Mark Z. Jacobson, George Xydis, Benjamin K. Sovacool, Scott V. Valentine, Daniel Luecht, Gregory Oxley, How much wind power potential does Europe have? Examining European wind power potential with an enhanced socio-technical atlas, Energy Policy 132 (2019) 1092–1100.

[493] "As planners consider scaling up VRE generation, the inherent variability of wind and solar resources complicates evaluations of whether a system with significant VRE has adequate supply to meet long-term electricity demand. Scaling up VRE generation requires grid expansion and upgrades so that power systems can access high-quality solar and wind resources, which are often remote from existing transmission networks." J. Katz and J. Cochran, National Renewable Energy Laboratory., INTEGRATING VARIABLE RENEWABLE ENERGY INTO THE GRID: KEY ISSUES, May 2015, available at www.greeningthegrid.org

[494] In relation to wind power in the UK, Aris notes: "Claims that there is always somewhere in the UK where the wind is blowing are correct, but only sufficient to generate 2 % or less of full wind fleet output. The power output mode is approximately 800 MW, 8 % of nameplate capacity. The probability that the wind fleet will produce full output is vanishingly small." Capell Aris, Wind Power Reassessed: A review of UK wind resource for electricity generation, Adam Smith Institute/The Scientific Alliance, UK, 2014, available at https://www.wind-watch.org/documents/wind-power-reassessed-a-review-of-the-uk-wind-resource-for-electricity-generation/

[495] "Overall, in 2015 we note a range of between 0.89% and 2.77% in power losses at transmission level as a proportion of total energy injected across the surveyed countries. In comparison, the total losses (transmission and distribution) for the same year range between 2.24% and 10.44% across Europe." Council of European Energy Regulators, CEER Report on Power Losses, Ref: C17-EQS-80-03, 18 October 2017, p. 7.

[496] Sadovskaia, Kristina, Bogdanov, Dmitrii, Honkapuro, Samuli, Breyer, Christian, Power transmission and distribution losses – A model based on available empirical data and future trends for all countries globally, International journal of electrical power & energy systems, 2019, Vol.107, pp. 98-109.

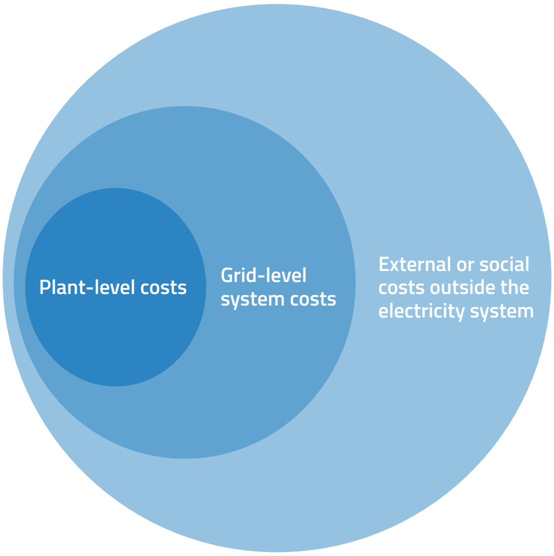
Renewable power, however, challenges society and asks a different question:

- ***How can the system be adapted so that power is used when it is generated?***

The rephrasing of the objective has broad implications for citizens and the economy that are not well understood. From this perspective, the question is not only **how the power infrastructure should be redesigned and operated differently** to accommodate renewable power, but also:

- ***How should power consumers adapt their behavior so that they demand power when it is available?***[497]

In this way, consumer behavior becomes part of the equation to make renewable power work; consumption should adjust to production, not the other way around. It is important that policy makers understand the implications of this **proposed shift in mission of the power system**. The shift explains why during peak renewable generation in Germany, with its high electricity prices,[498] consumers get paid to use electricity,[499] and why many countries charge consumers higher prices during peak demand.[500] Of course, other countries have chosen so far to only tackle the supply side; the UK pays wind turbine operators not to generate power during peak demand,[501] and in The Netherlands conventional power plants scale back when the wind is blowing and the sun is shining, unless it is cheaper to overproduce.[502]



Source: NEA, 2012b.

Figure 7.1. Different cost categories composing the full costs of electricity provision

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[497] Of course, this effect can be mitigated by power storage and conversion, and reliance on non-variable, reliable power generation technologies.

[498] Ellen Thalman & Benjamin Wehrmann, What German households pay for power, Clean Energy Wire, 24 Jan 2020, available at https://www.cleanenergywire.org/factsheets/what-german-households-pay-power ("While wholesale electricity prices on average have been in decline in recent years, surcharges, taxes, and grid fees raise the bill for Germany's private households and small businesses.") Cf. Sören Amelang, Industry power prices in Germany: Extremely high – and low, Clean Energy Wire, 4 Dec 2019, available at https://www.cleanenergywire.org/industrial-power-prices-and-energiewende

[499] Jeremy Berke, Germany paid people to use electricity over the holidays because its grid is so clean -- Power prices went negative in Germany on Christmas - and the phenomenon is less rare than you may think, The Independent, Thursday 04 January 2018, available at https://www.independent.co.uk/environment/germany-power-grid-pays-customers-christmas-sustainability-renewable-energy-a8141431.html

[500] Nina Verhaeghe, Vanaf 2022 wordt onze elektriciteitsfactuur anders berekend: wie stroompiek veroorzaakt, zal meer betalen, VRT NWS, 15 aug 2020, available at https://www.vrt.be/vrtnws/nl/2020/08/15/stroompiek-veroorzaken-meer-betalen/

[501] Edwin Malnick, Wind farms paid up to £3 million per day to switch off turbines, Telegraph, 19 Jan 2020, available at https://www.telegraph.co.uk/politics/2020/01/19/wind-farms-paid-3-million-per-day-switch-turbines/

[502] Hester van Santen, Waarom 'bijna gratis stroom' niet per se goed nieuws is -- Stroom was zondag ineens heel goedkoop. In buurlanden kregen afnemers zelfs geld toe om elektriciteit af te nemen. Hoe zit dat?, nrc.nl, 20 maart 2019, available at https://www.nrc.nl/nieuws/2019/03/20/waarom-bijna-gratis-stroom-niet-per-se-goed-nieuws-is-a3954003

In terms of **system-related costs**, below, we discuss two cost categories: **integration cost** and **other system-related costs**. Both of these types of costs can be substantial, and policy makers should be aware of them before making decisions on future energy investments. Below, we first discuss integration cost and then turn to other system-related cost. How these cost categories relate is depicted in the figure.

b. Integration costs

As the International Energy Agency explains, the inherent challenges associated with renewable power for the power system as a whole increase with a growing share of renewable power, and are the main drivers of power system transformation.[503] With increased penetration of variable renewable energy, there will be a stronger influence on both the necessary investment and system management.[504]

Integration cost comprises the following **four cost categories**:[505]

1. ***Balancing costs*:** Balancing costs arise due to the intermittency (variability) and uncertain supply of renewable power.[506] The increased short-term variability and uncertainty of net load from renewable power result in additional operational costs to ***provide for and use additional reserves*** against forecast errors and to ensure increased ramping and cycling of conventional power plants.[507] As one team of authors put it, due to "day-ahead forecast errors" and short-term variability, additional "intra-day adjustments of dispatchable power plants" and "operating reserves that respond within minutes to seconds" are required.[508]

2. ***Grid costs*:** Grid infrastructure costs include (1) investments in **connections for distant power generation facilities**, reinforcements of the transmission grid, and additional interconnections; and (2) increased costs of ***congestion management*** (e.g. re-dispatch of power plants).[509]

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[503] "The impact of, and issues associated with, VRE depend largely on its level of deployment and the context of the power system, such as the size of the system, operational and market design, regulation and fundamentals of supply and demand." International Energy Agency , IEA, System integration of renewables -- Decarbonising while meeting growing demand, available at https://www.iea.org/topics/system-integration-of-renewables

[504] Cf. Sharma, Tarun, Balachandra, P, Will the integration of renewable energy enable sustainable transition of Indian electricity system? Energy Strategy Reviews, 2018-08, Vol.21, p.137-148 ("Although the dimensions of transition vary from one electricity system to another, there is concurrence in terms of need for and the subsequent issues related to renewable energy integration.")

[505] Falko Ueckerdt, Lion Hirth, Gunnar Luderer, Ottmar Edenhofer, System LCOE: What are the costs of variable renewables?, Energy 63 (2013) 61-75.

[506] European Wind Energy Association, BALANCING RESPONSIBILITY AND COSTS of wind power plants, September 2015 (Maps updated on February 2016), available at https://www.ewea.org/fileadmin/files/library/publications/position-papers/EWEA-position-paper-balancing-responsibility-and-costs.pdf ("wind integration studies suggest that in the EU, increases in balancing costs due to wind variability and uncertainty amounts to approximately 1–4.5 €/MWh for wind energy penetrations of up to 20% of energy demand") Cf. Darwall, Rupert, Suckered by Big Wind in the UK, RealClear Energy, October 29, 2020, available at https://www.realclearenergy.org/articles/2020/10/29/suckered_by_big_wind_in_the_uk_582362.html

[507] "System operations will have to reflect variable renewable power, additional investments in flexibility; structural surpluses of VRE generation leading to curtailment; and structural imbalances in energy supply at seasonal and inter-year periods requiring sector coupling." International Energy Agency , IEA, System integration of renewables -- Decarbonising while meeting growing demand, https://www.iea.org/topics/system-integration-of-renewables

[508] Holttinen H, Milligan M, Ela E, Menemenlis N, Dobschinski J, Rawn B, et al., Methodologies to determine operating reserves due to increased wind power. IEEE Trans Sustain Energy Oct. 2012;3(4):713-723.

[509] "Significant localized growth in PV can raise concerns such as voltage violations and reverse power flow in low-voltage distribution systems. ... Accessing sources of operational flexibility becomes increasingly important in systems with significant grid-connected solar and wind energy." J. Katz and J. Cochran, National Renewable Energy Laboratory., INTEGRATING VARIABLE RENEWABLE ENERGY INTO THE GRID: KEY ISSUES, May 2015, available at www.greeningthegrid.org

3. ***Adequacy (or capacity) costs*:** These costs arise from the fact that often only partial (and unknown) output from renewable power is available at times of peak demand (or any demand for that matter); renewable power is ***erratic***. Consequently, other plants or facilities are required to compensate for this variability and to ensure sufficient generating capacity to meet demand.[510] In other words, adequacy costs arise from the ***low "capacity credit"*** of variable renewable electricity. Renewable power, as discussed before, requires backup capacity in the form of conventional power plants, other dispatchable renewable capacity or storage or conversion capacity.[511] The costs of this backup capacity are directly attributable to the renewable electricity generation.

4. ***Profile costs*:** Profile costs are indirect costs, and, as such, are typically not accounted for in integration costs. Nevertheless, they are incurred by the system and should be considered in the economic analysis before investment decisions are made.

Because renewable electricity requires ***backup capacity***, and the backup capacity is only dispatched periodically to fill in demand where renewable electricity cannot do so, the lifetime electricity generation of the ***backup capacity becomes more expensive*** – the fixed costs of the backup power plant are spread out over less electricity, leading each unit of electricity to become relatively more expensive. [512] The same goes for the renewable power plant itself, albeit in the opposite direction. Because renewable power plants can generate more electricity than required from the system, some of the electricity generated by renewables will have to be discarded (either the electricity is leaked from the system or the renewable power plant is shut down while the oversupply lasts). This effectively **decreases the capacity factor of the renewable power plant**, again **increasing the per unit of electricity costs.**[513] As such, profile costs are the indirect costs renewables impose on the system that lead to an increase in the average cost of electricity. These costs can be substantial.[514]

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[510] Matsuo et al. found that there is "considerable value" in "firm capacities, such as thermal and nuclear power generation, under a high share of VRE (variable renewable energy)." Yuhji Matsuo, Seiya Endo, Yu Nagatomi, Yoshiaki, Shibata, Ryoichi Komiyama, Yasumasa Fujii, Investigating the economics of the power sector under high penetration of variable renewable energies, Applied Energy, Volume 267, 1 June 2020, 113956.

[511] Electricity that is not immediately used can be stored and converted (and converted back into power, if needed). Electricity storage technologies are based on conversion into mechanical, chemical, electrical, electrochemical, and thermal energy. Pumped storage, battery storage, and hydrogen production (for use as fuel) are some of these technologies. However, power storage facilities are expensive and involve energy losses. For further discussion, see Federale Overheidsdienst Economie, K.M.O., Middenstand en Energie, Studie inzake de mogelijkheden tot opslag van elektriciteit die in België kunnen worden aangewend op de korte, middellange en lange termijn teneinde bij te dragen tot de bevoorradingszekerheid van elektriciteit, Brussel, 2015.

[512] Sharma, Tarun, Balachandra, P, Model based approach for planning dynamic integration of renewable energy in a transitioning electricity system, International Journal of Electrical Power and Energy Systems, 2019-02, Vol.105, p.642-659. ("[T]here is a consistent increase in the share of renewable energy-based electricity systems which has caused emergence of several new challenges. The challenges have emerged both with respect to planning and management of the transitioning electricity systems. These new challenges are because of shift away from supply-chain influenced conventional energy resource supply to nature influenced dynamic renewable energy resource supply; shift from conventional firm power to renewable intermittent power; operational complexities due to frequent and steeper ramps; and need for matching dynamic demand for power. … We find that this increased penetration of renewable energy … creates substantial capacity redundancy leading to lower capacity utilization of the overall system.")

[513] Cf. Gabriel Bachner, Karl W.Steininger, KeithWilliges, AndreasTuerk, The economy-wide effects of large-scale renewable electricity expansion in Europe: The role of integration costs, Renewable Energy, Volume 134, April 2019, pp. 1369-1380 (finding that "integration costs [of wind and solar] at high penetration rates can result in negative welfare effects," in particular in the region of Northern Europe and Austria).

[514] Hughes estimates that only the balancing cost associated with wind power output likely falls somewhere between £11 per MWh and £31 per MWh, resulting in 50% of all wind output in a year having a net value of less than £13 per MWh and 20% of all output having a negative net value. The breakeven cost of producing wind output with a net value of less than £13 per MWh is between £91 and £152 per MWh. Hughes, Gordon, Wind Power Economics – Rhetoric and Reality, Renewable Energy Foundation, 4th November 2020, available at https://ref.org.uk/ref-blog/364-wind-power-economics-webinar

> At “wind shares above 20%, marginal integration costs can be in the same range as generation costs if integration options like storage or long-distance transmission are not deployed.”

It is important to note that the integration costs are significant, but are ***not considered in standard LCOE (levelized cost of electricity) studies,*** such as the Nuclear Study by Generation Energy, although the Nuclear Study attempts to address this deficiency by running a limited nuclear scenario in a system model.[515] Put differently, LCOE is only part of the total cost picture; as discussed above, **integration into the existing electricity system** (including, but not limited to the transport and distribution delivery system) is a **substantial cost component.** The LCOE, defined as the lifetime costs of energy generating technologies divided by the amount of energy produced, considers **only generation-related cost,** such as initial investments, operation costs and fuel costs during the facility’s lifetime. To arrive at the total cost, to the LCOE the **integration cost must be added**. The point is not just that renewables (wind/solar) impose more integration cost than nuclear and conventional power; more importantly, integration cost is not only **technology-specific** but also directly **related to the penetration rate of renewable energy.** The three figures (7.2. and 7.3.) demonstrate that at high penetration levels the **integration cost of renewable energy can be as high as the generation cost.**

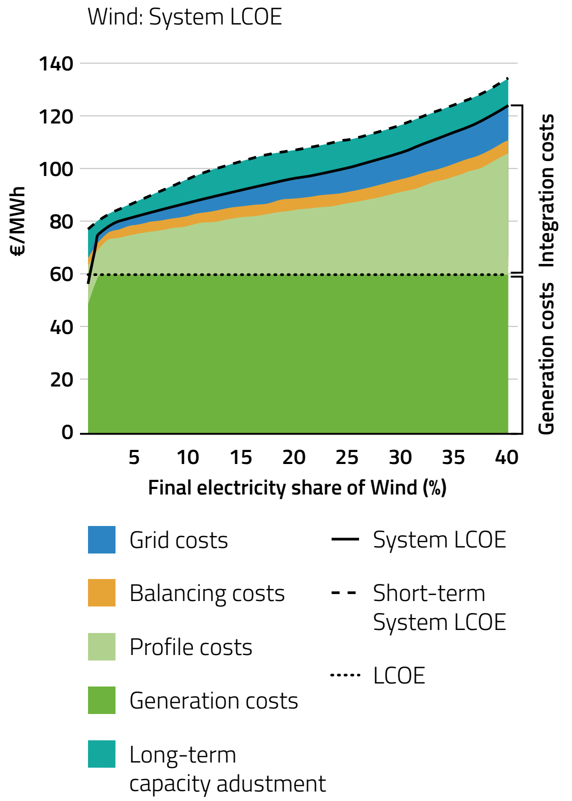

Figure 7.2. System LCOE for increasing shares of wind representing typical thermal power systems in Europe. Integration costs rise up to the order of magnitude of generation costs. Integration costs can thus become an economic barrier to large deployment of VRE. *From: Falko Ueckerdt, Lion Hirth, Gunnar Luderer, Ottmar Edenhofer, System LCOE: What are the costs of variable renewables?, Energy 63 (2013) 61-75.*

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[515] The UK government recently began to use ‘enhanced LCOE’ to reflect integration cost, but not other system-related cost. UK Department for Business, Energy & Industrial Strategy, BEIS Electricity Generation Costs, August 2020, available at https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020 (“Levelised costs provide a straightforward way of consistently comparing the costs of different generating technologies with different characteristics, focusing on the costs incurred by the generator over the lifetime of the plant. However, the simplicity of the measure means that there are factors which are not considered, including a technology’s impact on the wider system given the timing, location and other characteristics of its generation. For example, a plant built a long distance from centres of high demand will increase transmission network costs, while a ‘dispatchable’ plant (one which can increase or decrease generation rapidly) will reduce the costs associated with grid balancing by providing extra power at times of peak demand. For the first time, we present enhanced levelised costs which capture some of the wider system impacts of adding a marginal unit of a technology to a range of generation mixes. The enhanced levelised costs provide an indication of the relative marginal impacts of different technologies to the system in different scenarios – the full system costs of different pathways are considered in BEIS’s power sector modelling.”)

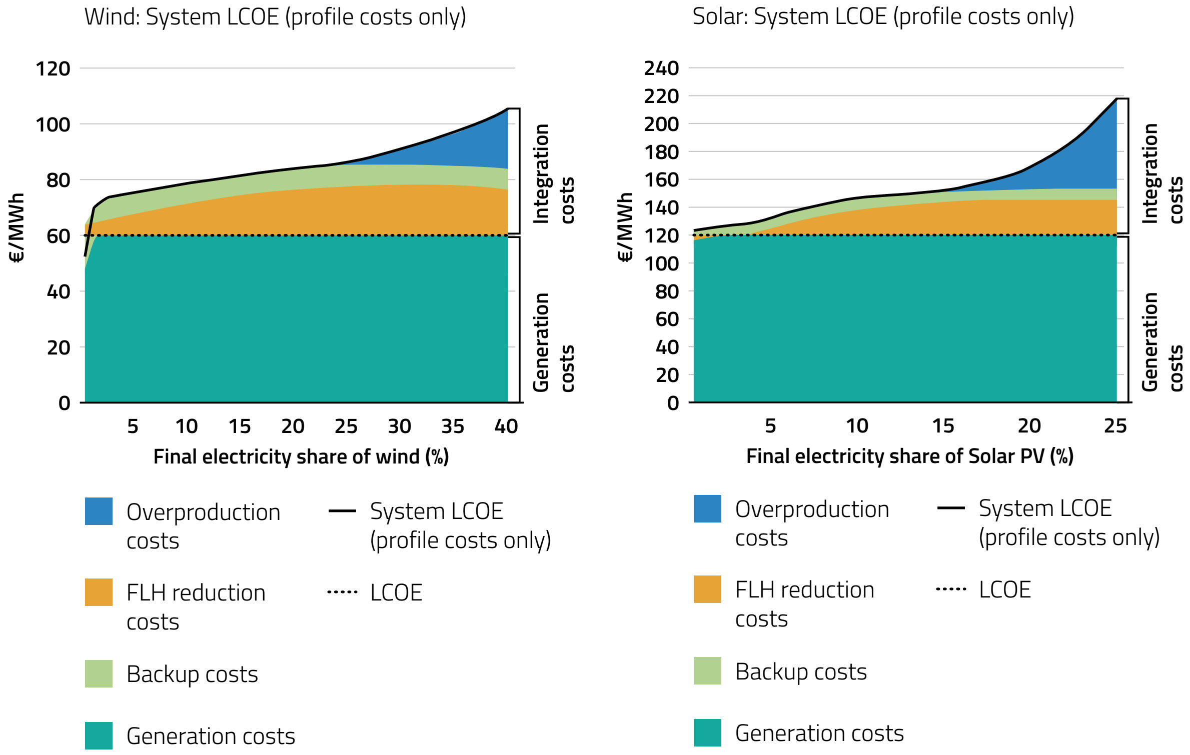

Figure 7.3. System LCOE (profile costs only) for increasing generation shares of wind (above) and solar PV (below) for Germany estimated with a power system model that is designed for calculating profile costs. These costs are decomposed into three costs drivers. The full-load hour (FHL) reduction of conventional plants is the largest cost driver at moderate shares, while overproduction costs significantly increase integration costs at high shares. From: Falko Ueckerdt, Lion Hirth, Gunnar Luderer, Ottmar Edenhofer, System LCOE: What are the costs of variable renewables?, Energy 63 (2013) 61-75.

Because integration cost is both technology-specific[516] and substantial, it should feature prominently in energy policy making. An analysis conducted for six OECD countries found that including the system costs of variable renewables at the level of the electricity grid **increases the total costs** of electricity supply by **up to one-third,** depending on technology, country and penetration levels.[517]

Indeed, integration cost increases disproportionately at the margin as the penetration of variable renewable power increases. In one study, it was found that **"*wind shares above 20%, marginal integration costs can be***

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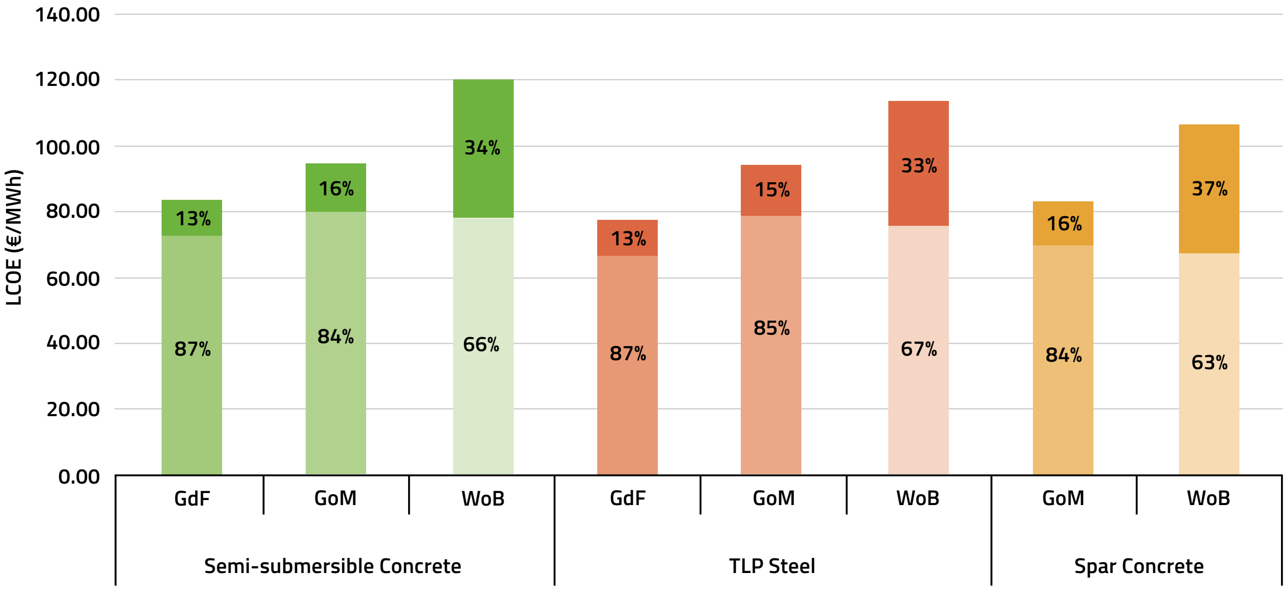
[516] For instance, integration- and system cost vary significantly as between wind power and residential solar. See for further discussion Planbureau voor de leefomgeving, Regionale Energie Strategieën; Een tussentijdse analyse, Beleidsstudie, 01-10-2020, available at https://www.pbl.nl/publicaties/regionale-energie-strategieen-een-tussentijdse-analyse

[517] OECD, Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems Organisation for Economic Co-operation and Development and NEA. Paris: OECD Publishing, 2012.

in the same range as generation costs if integration options like storage[518] ***or long-distance transmission are not deployed."***[519] Likewise, integration costs for solar exhibit an exponentially increasing pattern for shares of 20% and above, suggesting that at higher levels, integration costs are likely to overtake the costs of generating electricity. These findings imply that integration cost is a very substantial cost factor in energy policy decision-making.[520]

Further, the integration cost of remote renewable projects and projects at sea are likely substantially higher again; one study found that ***only transmission cost can add between 13% and 37% to the LCOE of***



Source: Lerch M, De-Prada-Gila M, Molins C, Benveniste G. Sensitivity analysis on the levelized cost of energy for floating offshore wind farms. Sustainable Energy Technologies and Assessments, Vol. 30, December 2018, pp. 77-90.

M. Lerch et al.
Sustainable Energy Technologies and Assessments 30 (2018) 77-90

Figure 7.4. LCOE results for each concept and offshore site. The upper parts of the bars represent the portion of transmission asset costs of the LCOE.

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[518] Matsuo et al. investigated the economic likelihood of achieving a zero-emission power system with high penetration of variable renewable energy (VRE) in Japan by 2050, using multi-annual meteorological data from 1990 to 2017. Their calculations suggest that "the required storage capacity is determined mainly by the duration of "windless and sunless" periods, or "dark doldrums", and the greatest risk under high VRE penetrations is the possibility of supply disruption during such periods." Yuhji Matsuo, Seiya Endo, Yu Nagatomi, Yoshiaki, Shibata, Ryoichi Komiyama, Yasumasa Fujii, Investigating the economics of the power sector under high penetration of variable renewable energies, Applied Energy, Volume 267, 1 June 2020, 113956.

[519] Falko Ueckerdt, Lion Hirth, Gunnar Luderer, Ottmar Edenhofer, System LCOE: What are the costs of variable renewables?, Energy 63 (2013) 61-75, at p. 71. Cf. Hirth L, Ueckerdt F, Edenhofer O. Integration costs and the value of wind power. Thoughts on a valuation framework for variable renewable electricity sources; 2013. USAEE Working Paper 2335386. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2335386

[520] "System LCOE and integration costs significantly increase with VRE penetration and can thus become an economic barrier to further deployment of wind and solar power." Falko Ueckerdt, Lion Hirth, Gunnar Luderer, Ottmar Edenhofer, System LCOE: What are the costs of variable renewables?, Energy 63 (2013) 61-75, at p. 71.

offshore power.[521] This explains why, for instance, the cost involved with building power transmission infrastructure in the North Sea to accommodate an offshore wind farm, should be included in the cost comparison. The figure below gives us an idea of the significance of only ***transmission cost of offshore wind***, up to 37% of the LCOE cost.

A recent OECD/NEA report provides an illustration of the integration (grid-level system) costs for various electricity generation technologies. While the study is not intended to estimate the system costs for a specific technology, it does give a good sense of the order of magnitude of these costs. As the figure below suggests, the ***integration cost of renewable energy is at least one order of magnitude higher*** than that of conventional and nuclear energy.

Thus, the assumption that if the LCOE of a variable renewable electricity technology (wind or solar) is lower than the LCOE of a conventional power plant, deployment of wind or solar power is competitive and economically efficient, is erroneous. Likewise, the low marginal cost of wind and solar power does not imply that therefore wind and solar are more efficient. Once the concept of integration cost, and the effect of adding renewable power on this cost at the margin, is understood, this becomes self-evident. Policy makers are therefore well advised to **consider these system-related costs in the planning decisions,** in particular now that the share of variable renewable energy is reaching levels at which these costs will increase substantially.

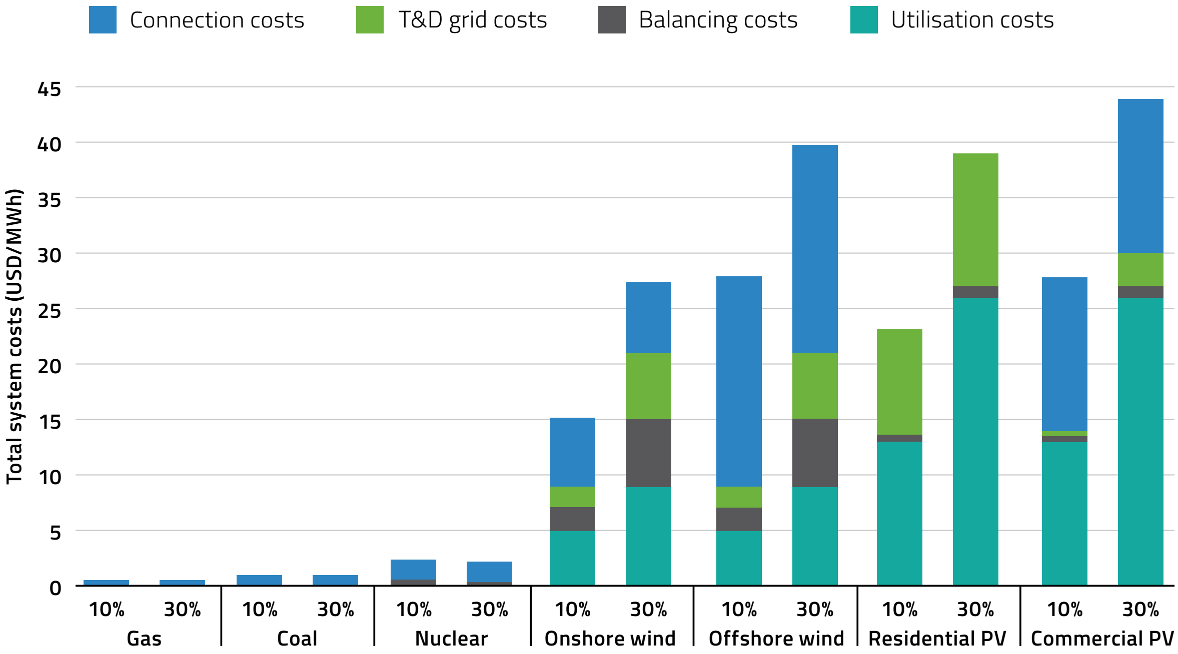

Figure 7.5. Grid-level system costs of selected generation technologies for shares of 10% and 30% of VRE generation.

Source: OECD, Nuclear Energy Agency, The Full Costs of Electricity Provision, NEA No. 7298, Paris, OECD, 2018.

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[521] Markus Lerch, Mikel De-Prada-Gila, Climent Molins, Gabriela Benveniste, Sensitivity analysis on the levelized cost of energy for floating offshore wind farms, Sustainable Energy Technologies and Assessments, Volume 30, December 2018, pp. 77-90.

We use the ETM model to assess the integration cost of renewable energy (wind, solar) in The Netherlands. Specifically, building on the analysis done by Berenschot and Kalavasta, we conduct sensitivity analysis on some of the specific energy technologies deployed in the Dutch energy system.

c. Estimating Integration Costs for The Netherlands

Estimating integration costs is a difficult, non-trivial exercise. The exact costs depend on numerous, interdependent factors that are country- and even locality-specific. In cases in which the same infrastructure serves multiple technologies, allocation questions issues. While supranational organizations have attempted to provide reasonable estimates of integration costs for energy technologies,[522] critics have typically discredited their use on the basis of their limited extrapolation potential.[523]

Country-specific modelling, of course, can address the issue that integration cost is country-specific. For The Netherlands, an attempt has been made to build a complex energy model that mimic the country's energy system and allows for manipulation and sensitivity analysis of various factors. We refer to the "Energie Transitie Model" (Energy Transition Model or "ETM").[524] This model has been used in reports submitted to the Dutch government for purposes of policy making and planning; while we are critical of the ETM model, it appears to be widely accepted as providing reasonable and reliable system cost estimates for the energy transition. We use the ***ETM model to assess the integration cost of renewable energy (wind, solar) in The Netherlands.*** Specifically, building on the analysis done by Berenschot and Kalavasta, we conduct sensitivity analysis on some of the specific energy technologies deployed in the Dutch energy system.

Specifically, we built on the study for the Dutch government by Berenschot/Kalavasta (the "CNS Study"), which made projections for energy infrastructure in 2050 based on four climate neutral scenarios (the "CNS Scenarios").[525] To explore these scenarios, Berenschot/Kalavasta used the ETM.[526] The ETM is an open-source energy model created by Quintel Intelligence.[527] The model can be used to estimate **total energy system costs,** i.e. all costs related to the production and distribution of energy (e.g. electricity, gas, hydrogen,

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[522] NEA No. 7057, 'Projected costs of generating electricity'; NEA/IEA; 2015

[523] See, for example, a recent rebuttal by Kalavasta, available at https://www.nvde.nl/wp-content/uploads/2020/09/Vergelijking_rapporten_nucleair_ezk-_.pdf

[524] Energy Transition Model, available at https://energytransitionmodel.com/

[525] Berenschot/Kalavasta, Klimaatneutrale energiescenario's 2050: Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, maart 2020, available at https://www.berenschot.nl/actueel/2020/april/nederland-klimaatneutraal-2050/ For the study on the cost of nuclear, see Kalavasta/Berenschot, Systeemeffecten van nucleaire centrales in Klimaatneutrale Energiescenario's 2050, 8 april 2020 (the "Nuclear Study"), available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-in-klimaatneutrale-energiescenarios-2050

[526] Energie Transitie Model, available at https://energytransitionmodel.com/

[527] "Quintel aims to accelerate the energy transition. This is why we make the Energy Transition Model, allowing you to explore future energy systems." "For their Infrastructure Outlook 2050, Gasunie and TenneT base their own infrastructure calculations on ETM scenarios in both Germany and the Netherlands." Quntel Intelligence, available at https://quintel.com/about

etc.). The ETM can be used to model a large variety of power mixes, including wind/solar and nuclear energy. According to Quintel, the ETM is **"independent, comprehensive and fact-based."**[528]

i. Objective

We conduct limited, focused sensitivity analysis on the ETM model. The objective of our analysis is to determine how the model outputs respond to ***a drastic change in the power mix away from the main renewable energy sources (wind on land, wind on sea, and solar PV plants have been set to zero) and towards nuclear power (set at the maximum available for each scenario in the ETM***). Note that this still leaves energy sources that the model considers to be "renewable" in the energy system, such as solar on roofs, some forms of biomass, geothermal, etc. This means that the level of renewables is still substantial in all variations.

ii. Scenario Variants

Our starting points are the CNS Scenarios used in the Berenschot study. These scenarios are: (i) Regional Governance ("Regionale Sturing"), (ii) National Governance ("Nationale Sturing"), (iii) European Governance ("Europese Sturing"), and (iv) International Governance ("International Sturing"). We use the (corrected) links provided in the CNS Study to load the CNS Scenarios, and then proceed to make changes to them, as described below. We do not make any other changes to the default model assumptions that Berenschot has proposed, which are saved in the CNS Scenarios.

We modified the CNS Scenarios only in the following ways (the "Modifications"):

- We ***removed the electricity supply of three commercial renewable technologies (onshore wind, offshore wind, and solar PV plants)*** by putting their value at 0. We have left the settings for solar on roofs on residential and industrial buildings as is. Furthermore, we have removed idle gas CCGT capacity, where specified (the only scenario where this applies is the European Governance scenario).
- We ***added the maximum amount of nuclear capacity that the ETM accommodates***. The ETM caps the number of nuclear power plants that can be built, as it argues that permit lead times and public opinion would limit the number of nuclear power plants that could reasonably be built,[529] thus importing policy status quo bias into the modelling. As a result, the ETM is limited in the scenarios it can accommodate and model.[530] A ***maximum of roughly 15 GW of capacity can be added for each of two types of nuclear power plants*** (3rd Generation and conventional), for a maximum total of 30 GW. As a comparison, the ETM allows for 500 GW of onshore wind capacity, 300 GW of offshore wind capacity, and 2,250 GW of solar PV capacity to be built (without making any comment on "public opinion" on such a high level of renewable penetration).

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[528] ETM, https://pro.energytransitionmodel.com/ The ETM is "independent, comprehensive and fact-based."

[529] Per the note in the ETM: "Of all power plants, obtaining the necessary permits and building a nuclear power plant takes the longest (11-12 years on average). It is questionable if it is possible to build more than a few nuclear power plants per country in the coming three decades. This becomes even more evident when you factor in public opinion, an imminent shortage of technicians with the required expertise and a shortage of production capacity for nuclear reactor vessels on a mid-term basis." No comments are provided regarding potential public opinion on large-scale wind turbine or solar PV deployment.

[530] This raises a question as to whether the model is fit for the purpose of policy making aimed at considering all climate neutral options.

- We put the ***nuclear power plants first in the merit order*** by switching the button for nuclear from dispatchable to '***must-run***.'

We did not make any other changes to the default model assumptions that Berenschot has proposed, which are saved in their scenarios. In other words, we performed sensitivity analysis on the ***specific carbon-neutral technologies*** that were used in the CNS Scenarios to achieve climate neutrality, and ***test the isolated effect substituting nuclear for renewable***.

iii. Outcomes

To assess the effects of the Modifications in the four CNS Scenarios, we looked at eight key model outputs (the key performance indicators, or "KPI"), including:

1. CO_2 reduction relative to 1990;
2. electricity production (PJ/yr);
3. total system costs (€bln/yr);
4. cost of electricity production (€bln/yr);
5. cost of gas and electricity network (€bln/yr);
6. cost per household (€/yr);
7. percentage of renewable energy in the mix; and
8. blackouts (hrs/yr);

We present the results of the Modifications for each of the four CNS Scenarios below. In the tables, we refer to the original CNS Scenario concerned as "Renewable Variant" and to the scenario modified by the Modifications as "Nuclear Variant."
For each of the four CNS Scenarios, we identify the specific changes to the assumptions and provide links to both the Renewable Variant and the Nuclear Variant upfront.

We note here too that for purposes of the Nuclear Study, Kalavasta/Berenschot manipulated some elements of the ETM model.[531] These manipulations are intended to fit the LCOE values computed by the authors into the ETM. They do so by changing some input parameters to achieve their predetermined outcome parameters. They justify this approach by arguing that the ETM employs calculation methods that generate output values that are too low, in particular in relation to financing cost. As they do not provide sufficient details, we have not been able to verify the validity of their argument. For reasons that are not explained, the authors did not treat the place of nuclear in the merit order as a variable.

We now proceed to review the result of our Modification for each of the four scenarios. We describe the Modifications and then present the impacts on the KPIs.

- ***Scenario Regional Governance***
- Renewable Variant link: https://pro.energytransitionmodel.com/scenarios/606411
- Nuclear Variant link: https://pro.energytransitionmodel.com/saved_scenarios/9514

  - *Modifications:*
    In the Regional Governance scenario, the Nuclear Variant involves the following changes to the assumptions underlying the Renewable Variant:

	Renewable Variant	**Nuclear Variant**
Nuclear conventional[532]	0 MW	14,789 MW
Nuclear 3rd Gen	0 MW	15,168 MW
Wind turbines – onshore inland	20,000 MW	0 MW
Wind turbines – offshore	31,000 MW	0 MW
Solar PV plants	66,918 MW	0 MW
Gas CCGT	0 MW	0 MW

Table 7.1.

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[531] Nuclear Study, Appendix 2: Links naar het Energietransitiemodel en vertaling kosten naar het ETM.

[532] In all cases, as noted above, nuclear is set to "must-run" such that it appears first in the merit order.

- *Impacts on KPIs:*
  In the Regional Governance scenario, the impact of the Modifications on the KPIs are as follows. Superior performance is highlighted in green; worse performance is highlighted in red; equal performance is shown in grey.

	Renewable Variant	**Nuclear Variant**
CO_2 relative to 1990	-99.9%	-99.9%
Electricity production (PJ/yr)	1,251	1,042
Costs (€bln/yr)[533]	€ 46.5	€ 38.1
Cost of electricity production (€bln/yr)	€ 16.5	€ 10.8
Cost of gas & electricity network (€bln/yr)	€ 13.6	€ 6.8
Total Cost per home (€/yr)	€ 5,281	€ 4,330
Renewables' share in power mix	95.4%	54.8%
Blackouts (hrs/yr)	0	0

Table 7.2.

We observe that, while overall electricity production is lower in the Nuclear Variant, this does not impact domestic consumption, because electricity exports decrease.

- ***Scenario National Governance***

\- Renewable Variant link: https://pro.energytransitionmodel.com/scenarios/606415

\- Nuclear Variant link: https://pro.energytransitionmodel.com/saved_scenarios/9515

- *Modifications*:
  In the National Governance Scenario, the Nuclear Variant involves the following changes to the assumptions underlying the Renewable Variant:

	Berenschot Variant	**Nuclear Variant**
Nuclear conventional	0 MW	14,789 MW
Nuclear 3rd Gen	0 MW	15,168 MW
Wind turbines – onshore inland	20,000 MW	0 MW
Wind turbines – offshore	51,500 MW	0 MW
Solar PV plants	57,600 MW	0 MW
Gas CCGT	0 MW	0 MW

Table 7.3.

- *Impacts on KPIs:*
  In the National Governance scenario, the impact of the Modifications on the KPIs are as follows. Superior performance is highlighted in green; worse performance is highlighted in red; and equal performance is shown in grey.

	Renewable Variant	**Nuclear Variant**
CO_2 relative to 1990	-99.1%	-99.3%
Electricity production (PJ/yr)	1,521	1,030
Costs (€bln/yr)	€ 50.4	€ 41.4
Cost of electricity production (€bln/yr)	€ 15.9	€ 10.6
Cost of gas & electricity network (€bln/yr)	€ 15.9	€ 6.0
Total Cost per home (€/yr)	€ 5,728	€ 4,701
Renewables' share in power mix	94.7%	46.3%
Blackouts (hrs/yr)	0	0

Table 7.4.

- ***Scenario European Governance (used in Nuclear Study)***

\- Renewable Variant link: https://pro.energytransitionmodel.com/scenarios/606418

\- Nuclear Variant link: https://pro.energytransitionmodel.com/saved_scenarios/9516

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[533] This is the total cost of the energy system, and includes, in addition to cost of electricity production and cost of gas & electricity network, also heat production and network, insulation of buildings, transport and non-energetic fuels, hydrogen, carbon capture in industry, etc.

- *Modifications:*
  In the European Governance Scenario, the Nuclear Variant involves the following changes to the assumptions underlying the Renewable Variant:

	Renewable Variant	Nuclear Variant
Nuclear conventional	0 MW	14,789 MW
Nuclear 3rd Gen	0 MW	15,168 MW
Wind turbines – onshore inland	10,000 MW	0 MW
Wind turbines – offshore	30,000 MW	0 MW
Solar PV plants	34,588 MW	0 MW
Gas CCGT	46,000 MW	0 MW

Table 7.5.

The capacity figures for the nuclear power plants listed above are the maximum amounts of nuclear power that the ETM allows to be built. Due to these restrictions, the ETM has to resort to importation of some electricity. The amount is relatively minimal, however, at less than 80 PJ per annum.

- *Impacts on KPIs:*
  In the European Governance scenario, the impact of the Modifications on the KPIs are as follows. Superior performance is highlighted in green; worse performance is highlighted in red; and equal performance is shown in grey. The impact on the KPIs is as follows:

	Renewable Variant	Nuclear Variant
CO_2 relative to 1990	-95.8%	-96.5%
Electricity production (PJ/yr)	1,076	1,005
Costs (€bln/yr)	€ 55	€ 47.3
Cost of electricity production (€bln/yr)	€ 12.3	€ 8.2
Cost of gas & electricity network (€bln/yr)	€ 10.1	€ 6.7
Total Cost per home (€/yr)	€ 6,246	€ 5,380
Renewables' share in power mix	69.3%	34.6%
Blackouts (hrs/yr)	0	0

Table 7.6.

- ***Scenario International Governance***

- Renewable Variant link: https://pro
- energytransitionmodel.com/scenarios/606388
- Nuclear Variant link: https://pro.energy
  transitionmodel.com/saved_scenarios/9517

- *Modifications*:
  In the International Governance Scenario, the Nuclear Variant involves the following changes to the assumptions underlying the Renewable Variant:

	Renewable Variant	Nuclear Variant
Nuclear conventional	0 MW	14,789 MW
Nuclear 3rd Gen	0 MW	15,168 MW
Wind turbines – onshore inland	10,000 MW	0 MW
Wind turbines – offshore	27,500 MW	0 MW
Solar PV plants	34,588 MW	0 MW
Gas CCGT	0 MW	0 MW

Table 7.7.

The capacity figures for the nuclear power plants listed above are the maximum amounts of nuclear power that the ETM allows to be built. Due to these restrictions, the ETM has to resort to importation of some electricity. The amount is relatively minimal, however, at less than 80 PJ per annum.

- *Impacts on KPIs:*
  In the European Governance scenario, the impact of the Modifications on the KPIs are as follows. Superior performance is highlighted in green; worse performance is highlighted in red; and equal performance is shown in grey. The impact on the KPIs is as follows:

	Renewable Variant	Nuclear Variant
CO_2 relative to 1990	-98.5%	-99.2%
Electricity production (PJ/yr)	1,026	984
Costs (€bln/yr)	€ 64.9	€ 59
Cost of electricity production (€bln/yr)	€ 13.0	€ 10.2
Cost of gas & electricity network (€bln/yr)	€ 9.7	€ 6.6
Total Cost per home (€/yr)	€ 7,375	€ 6,706
Renewables' share in power mix	58.5%	26.3%
Blackouts (hrs/yr)	0	0

Table 7.8.

iv. Conclusions

Our methodology is straightforward. To obtain an estimate of the integration cost of renewable power in The Netherlands, in the four scenarios presented by Berenschot and Kalavasta, we substitute all onshore wind, offshore wind, and commercial solar plants for 3rd gen and 2nd gen nuclear power plants.

The outcomes of our sensitivity analysis are very robust across all scenarios and variants, and demonstrate clearly the favorable effects of the addition of nuclear to the power mix. In reality, the cost savings of replacing renewable energy by nuclear energy may be greater, if the cost of imported energy turns out to be greater than assumed in the ETM model.

The overall conclusion is that in all four CNS Scenarios, the **Nuclear Variants shown superior performance on all relevant KPIs**, with one insignificant exception of CO_2 emission in the Regional Governance scenario where the Nuclear Variant and the Renewable Variant perform equally well. In other words, in all four scenarios, the **nuclear substitution resulted in reduced energy system costs** and, in all but one scenario, lower CO_2 emissions.

Even though the rate of substitution was limited by the restrictions imposed by ETM model, the **performance improvements** realized by substituting renewable energy with nuclear energy are **substantial**, as detailed below.

- In each of the four CNS Scenarios, substituting renewables with nuclear led to **economically more efficient electricity production**. The table below shows the electricity price in € per MWh for the two variants in each of the CNS scenarios. The cost includes both the cost of production and the cost of the network (i.e. grid costs).

Scenario	Renewable Variant Electricity Cost in € per MWh	Nuclear Variant Electricity Cost in € per MWh
Regional Governance	€ 86.61	€ 60.78 (-30%)
National Governance	€ 75.21	€ 57.97 (-23%)
European Governance	€ 75.23	€ 53.13 (-29%)
International Governance	€ 79.46	€ 61.63 (-22%)

Table 7.9.

- Thus, in the European Governance Scenario, which is used in the Nuclear Study and is a preferred scenario under current government policy, **the Nuclear Variant reduces the cost of electricity by approximately 29%**.
- In each of the CNS Scenarios, the substitution of renewable with nuclear caused **the total energy system cost to decline**. This size of the decline appears to corelate with the size of the reduction in renewable energy.

  - The smallest cost decline is 9%, which occurs in the International Governance scenario in which the least renewables are used.
  - The largest cost decline is 18%, which occurs in the regional and national scenarios in which more renewable energy is included.

- In three out of four scenarios, substituting nuclear for renewables even led to **greater declines in CO_2 emissions**, the supposed goal of the shift to renewable energy.

These conclusions are important because the CNS Scenarios and their outputs, which are the basis for advice to the Dutch government and key stakeholders, are currently shaping the policy debate in The Netherlands. Moreover, the ETM model is widely used by Dutch decentral governments in relation to the energy transition.[534]

We note here that the ETM model does not model land and space use, even though this is a major consideration in policy making. As discussed elsewhere in this report, in terms of land and space use, **nuclear also appeared to be superior** to renewable energy.

These results are quite surprising, and suggest that the energy system cost estimates found by Kalavasta/Berenschot are an artifact resulting from the choices made by the authors, not of the inherent properties of the power generation technologies that are being analyzed. For instance, by assigning nuclear energy a fixed place in the merit order, the authors introduce bias into the analysis that prevents the identification of substantial cost savings by switching to nuclear energy. By making the Modifications to the CNS Scenarios, we have been able to throw the spotlight on this blind spot in energy policy making in The Netherlands.

As demonstrated above, ***total energy system costs could be reduced by as much as 18%, with more cost savings for those scenarios that initially had more renewables in the energy mix***. Importantly, ***grid connection costs***, only one part of the integration costs but those that are most easily accessed from the model,[535] were ***reduced by over 60%*** in one scenario, which would save the

In the European Governance Scenario, a preferred scenario under current government policy, the Nuclear Variant reduces the cost of electricity by approximately 29%. In each of the CNS Scenarios, the substitution of renewable with nuclear caused the total energy system cost to decline. The smallest cost decline is 9%, and the largest is 18%, which occurs in the regional and national scenarios in which more renewable energy is included.

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[534] "The ETM currently supports 9 countries, 9 provinces, 25 regions, 290 municipalities and 134 neighbourhoods in the Netherlands." Quintel Intelligence, available at https://quintel.com/about

[535] Although Kalavasta/Berenschot argue with various features of the ETM, they have accepted this feature.

In The Netherlands, by replacing renewable with nuclear power, total energy system costs could be reduced by as much as 18%, with more cost savings for those scenarios that initially had more renewables in the energy mix. Importantly, grid connection costs, only one part of the integration costs, were reduced by over 60% in one scenario, which would save the Dutch government almost EUR 10 billion per year.

Dutch government almost EUR 10 billion per year. In all other scenarios, grid connection costs also went down substantially.
Thus, these ETM models runs confirm that the integration cost of wind/solar are much higher than the integration cost of nuclear. Because grid connection costs and other integration costs can be very substantial in an electricity system with a high share of renewables, it is crucial that all integration costs are taken into account when both energy policy and energy technology investment decisions are made.

d. Integration Costs in Germany, France and the EU

i. The Example of Germany versus France

With household electricity prices breaking the **30 cents per kWh** barrier in Germany in recent years, the integration costs of renewables have come under the spotlight. High electricity prices in Germany, a country that despises nuclear and relies heavily on renewables, have been contrasted with those in France, which relies much more on nuclear power. In 2019, average household electricity prices in France were **18 cents per kWh.**[536]

While Germany is no by means the only country with a high share of renewables, it has been one of the more transparent in passing on renewable subsidies and costs to the end consumer. It is estimated that at least 21% of the electricity expenditure by households was for the so-called "renewables surcharge,"[537] which are paid out as subsidies to renewable power plant operators. Another 1.3% was for offshore liability levies, a direct result of offshore wind farms in the country's energy mix. Grid charges accounted for another 24% of the electricity cost.[538] While surely some of these grid costs would certainly have been incurred if the system had a lesser share of renewables, grid operators in Germany have been

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[536] For data on electricity prices, see Eurostat at https://ec.europa.eu/eurostat/databrowser/product/page/NRG_PC_204

[537] What German households pay for power, Clean Energy Wire, 2020, available at: https://www.cleanenergywire.org/factsheets/what-german-households-pay-power

[538] Note that some of these levies and taxes differ region by region in Germany. So the exact percentage make-up of these might differ for households in different regions.

Ooutspoken about the fact that much of these costs are being driven by investments needed to connect renewables to the grid.

Importantly, the grid operators in Germany have updated their estimates for ***additional grid investments*** that need to be made, almost doubling them from previously estimated 32 billion euros to ***52 billion***.[539] Note that ***9 billion euros of that increase was due to the increased cost of linking up offshore wind farms***. One study estimated that German electricity consumers paid around ***€200 billion for renewable energy installations built before the end of 2011***, but actual costs probably exceeded these estimates.[540] Not just the sheer amount of costs related to linking renewables to the grid is important, but their apparent uncertain nature, which could lead to undesirable surprises down the line. Right now, ***between a third and half of German households' electricity costs are directly related to renewable energy*** (in the form of subsidies or additional grid costs), but this could increase as grid operators require higher grid connect levies due to increased integration costs.

Germany stands in stark contrast to France, a country that has relied to a large extent on nuclear energy for electricity, in part helping to keep France's electricity costs low.[541] The International Energy Agency reports that about ***40% of the country's energy supply is provided by nuclear energy***.[542] France's electricity production is already more than 90% decarbonized, due to a high share of nuclear and some renewables and it has one of the lowest CO_2 emissions per capita in the developed world.[543]

To comply with EU mandates, however, France's new 10-year energy strategy plan calls for a ***doubling in renewable capacity***.[544] Within that context, a recent study summarized scenario

Between a third and half of German households' electricity costs are directly related to renewable energy (in the form of subsidies or additional grid costs), but this could increase as grid operators require higher grid connect levies due to increased integration costs.

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[539] As reported by Reuters, see https://www.reuters.com/article/us-germany-powergrids-plan/german-grid-firms-see-extra-costs-to-meet-renewable-power-target-idUSKCN1PT1LS

[540] Kreuz, Sebastian, Müsgens, Felix, Measuring the cost of renewable energy in Germany, The Electricity Journal, 2018-05, Vol. 31 (4), pp. 29-33.

[541] France's electricity costs are, as of 2019, lower than those of Belgium, Denmark, Germany, Spain, Italy, The Netherlands, Sweden, and the U.K. See footnote 26 for source.

[542] See EIA, World energy balances and statistics, https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics

[543] Berthélemy, M. et al. (2018), "French Nuclear Power in the European Energy System", p. 31, SFEN, Paris, www.sfen.org/sites/default/files/public/atoms/files/french_nuclear_power_in_ the_european_energy_system_sfen.pdf.

[544] France to double renewables capacity under 10-year energy plan, Reuters, Jan. 25, 2019, available at https://www.reuters.com/article/us-france-energy-idUSKCN1PJ1T0

In France, the scenarios with 60% renewables were 55 billion euros more expensive than the scenario that kept nuclear power capacity constant and renewables at 35%.

analysis done on basis of a model of France's energy system.[545] As part of the analysis, scenarios in which France would ***increase its share of renewables drastically to a 60% share of electricity production*** were compared against a scenario in which nuclear power capacity was maintained, with more modest investments in renewables leading to a 35% share of electricity for renewables. The cumulative capital expenditures for the power grid from 2020 through 2050, not including the actual investment costs for the power plants, for the scenarios with 60% renewables were ***55 billion euros more expensive*** compared to the scenario that kept nuclear power capacity constant and renewables at 35%.[546]

The case study of German and French electricity prices, and the make-up of their energy mixes, points once again to the ***importance of accounting for all integration costs*** that arise from power plant investments. Furthermore, Germany's experience with unexpected cost estimate increases from grid operators reveal that past policy decisions may have been made based on outdated or inaccurate cost estimates. We focused predominantly on grid costs, given that these are more easily estimated. The scale of those grid costs alone illustrates that integrating renewables into the energy system can become ***increasingly expensive as the penetration of renewables in the electricity mix increases.***[547]

The problem of integration cost can be illustrated for the EU as a whole with the following facts. In 2019, the EU combined capacity of wind turbines and solar photovoltaic was 258.9 GW, which, in total, produced 435.50 TWh.[548] Intermittent electricity was produced for 1,682 hours (approximately ten weeks per year); thus, on average, only 19% of the time was electricity produced by this installed base of wind and solar,[549] implying that, on average, ***81% of the time no electricity was available from these renewable sources***. To cover this extended period of unavailability, an equivalent amount of capacity in non-variable electricity production should be installed (or pre-existing capacity should be made available to fill the gap in supply). Needless to say,

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[545] See Berthélemy, M. et al. (2018), "French Nuclear Power in the European Energy System", SFEN, Paris, p. 31,

[546] These costs are adjusted for inflation. See Berthélemy, M. et al. (2018), "French Nuclear Power in the European Energy System", p. 31, SFEN, Paris, pp. 68-69.

[547] Sepulveda, N.A. (2016), Decarbonization of Power Systems: Analyzing Different technological Pathways, Master Degree Thesis, Massachusetts Institute of Technology (MIT).

[548] European Commission, EU energy in figures, Statistical pocketbook, available at https://op.europa.eu/en/publication-detail/-/publication/87b16988-f740-11ea-991b-01aa75ed71a1/language-en

[549] For wind and solar the numbers are 23% and 11%, respectively.

such ***'doubling up' of electricity generation capacity*** requires additional investments that could be avoided with non-variable electricity generation. ***Germany has been able to produce more intermittent renewable electricity than other Member States, because it has installed capacity available to fill the gap*** (either within Germany or through import from neighbouring Members States). In ***countries where there is not already enough installed capacity, intermittent renewable electricity plants are much more difficult to realize, because they would necessitate also additional investments in 'back up' non-renewable electricity plants***.[550]

ii. The EU As A Whole

If intermittent renewable electricity (wind and solar) were cheaper than non-intermittent electricity, one would expect to find two results:

i electricity prices within the same country would drop over time (i.e. electricity prices would gradually decrease as the penetration of wind and solar increases), and

ii in countries with higher penetration of wind and solar, electricity prices would be lower than in countries with lower penetration rates for wind and solar. If nuclear were cheaper, you would expect to find corresponding results. These expectations, of course, can be empirically verified.

If one reviews the available data, it turns out that ***higher penetration rates for wind and solar do not lead to lower electricity prices within the same country over time, nor do they result in lower prices in countries with higher penetration rates for wind and solar***. Over the period 2010-2019, ***electricity prices for household consumers has increased as the EU was working towards its goals of 20% renewable energy in 2020*** (see the figure 7.6.).[551]

A study conducted for the European Commission confirms this trend (see figure 7.7.).

In countries where there is not already enough installed capacity, intermittent renewable electricity plants are much more difficult to realize, because they would necessitate also additional investments in 'back up' non-renewable electricity plants.

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[550] This explain also why it is necessary to develop the capacity market. European Commission, Capacity mechanisms, available at https://ec.europa.eu/energy/topics/markets-and-consumers/capacity-mechanisms_en

[551] European Commission, COMMISSION STAFF WORKING DOCUMENT -- Energy prices and costs in Europe, COM(2020) 951 final, Part 1 though 6, available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020SC0951&from=EN See also Trinomics et al., Study for the European Commission on energy prices, costs and their impact on industry and households, Final report, October 2020, available at https://op.europa.eu/en/publication-detail/-/publication/16e7f212-0dc5-11eb-bc07-01aa75ed71a1/language-en

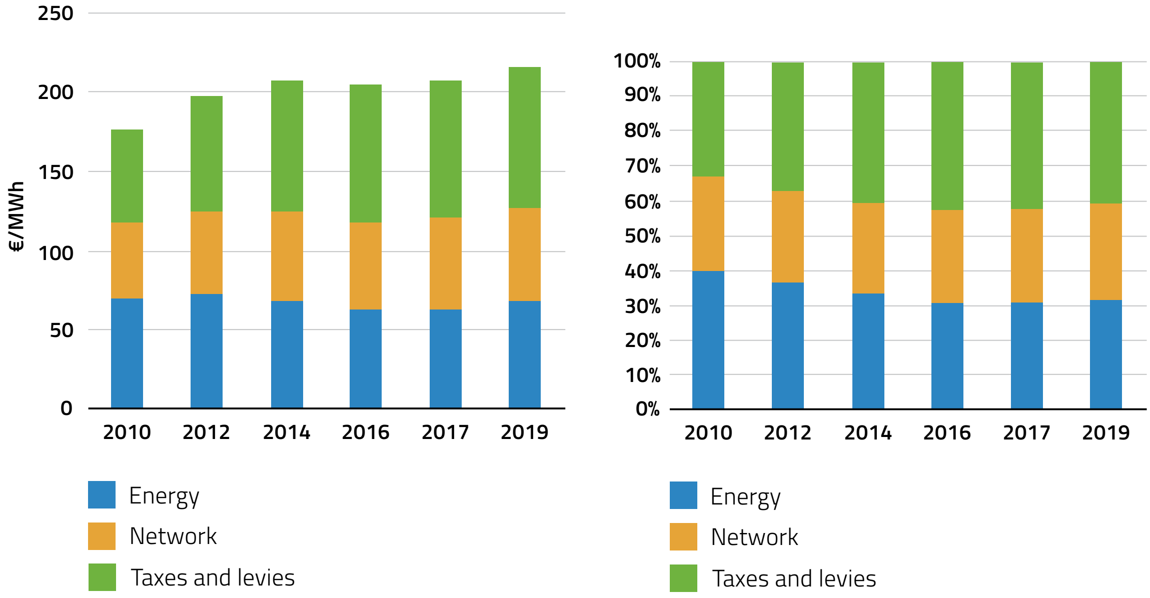
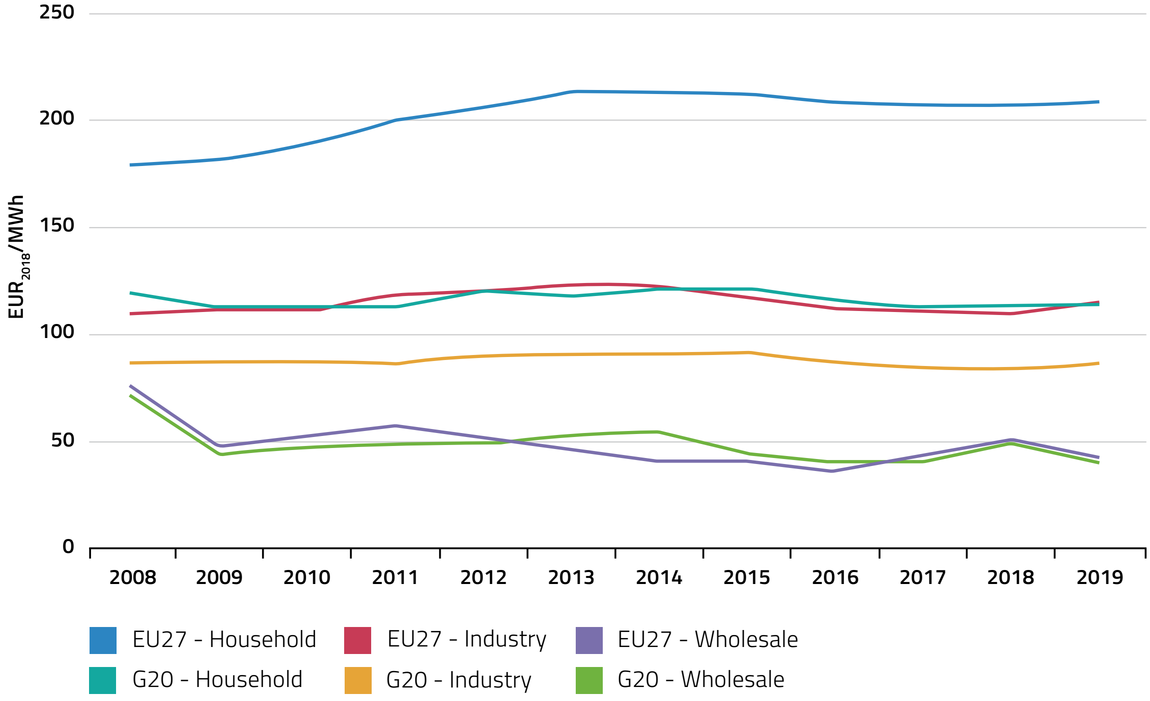


Figure 7.6. Evolution and composition of the EU household price (DC band)

Source: DG ENER in-house data collection, Eurostat

Electricity prices

Figure 0-1 Comparison of EU27 weighted average with G20 (trade) weighted average



Source: Own calculation, Note: the G20 weighted averages are calculated on the basis of all available price data for a particular year, weighted in the total price by the share a country had in EU imports + exports 2017-2019. Coverage ratios of total trade range from 84-99% (household prices), 76-99% (industrial prices) and 36-74% (wholesale prices).

Figure 7.7. From: Trinomics et al., Study for the European Commission on energy prices, costs and their impact on industry and households, Final report, October 2020

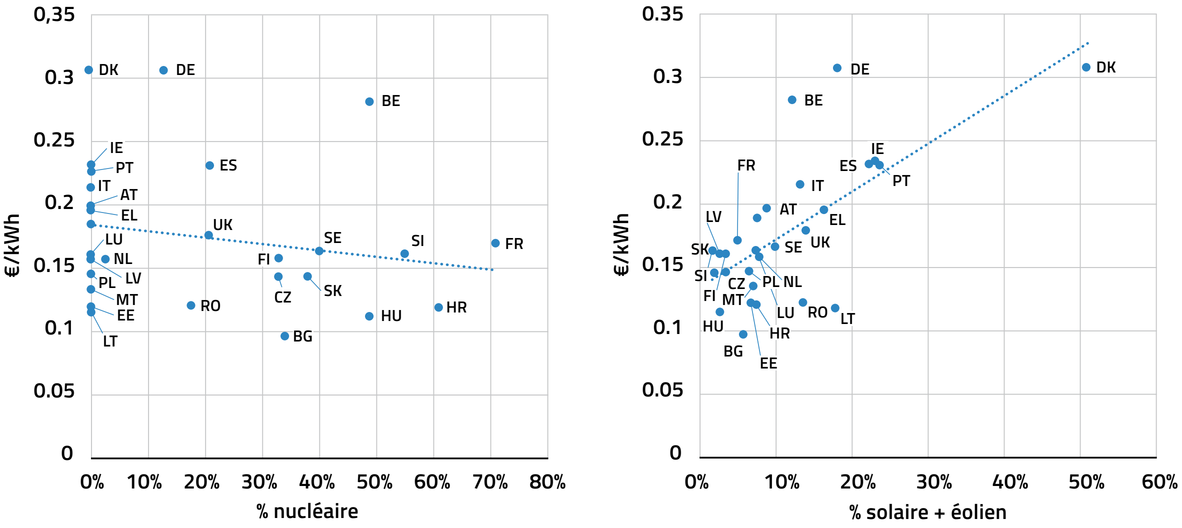


Figure 7.8. From: Prof. Samuel Furfari, Uinversite Libre de Bruxelles, 2019.

Source: Eurostat (Dec 2018)

The data presented (7.6. and 7.7.) are averages for the EU as a whole, so there is diluting effect since not all Member States have made the same level of investment in renewable energy. If household electricity prices by country are plotted against the penetration rate of renewable energy by country, the ***inflating effect of renewables on electricity prices becomes starker*** (see figure 7.8.).

As the graph (figure 7.8) shows, if household electricity prices in countries with high penetration rates of renewable energy are compared to countries with a high share of nuclear energy in the electricity generation mix, the strong suggestion is that ***renewable energy has an inflating effect on electricity prices, in particular if compared to nuclear energy***.

e. Other systems-related cost

Beyond integration costs, a shift to renewable power may impose cost on society beyond the power system and the fully-loaded cost of electricity. The ***design of an electricity system and the cost of electricity affect the economy and society in several ways***. Policy makers may be pressed to issue additional policies to address issues associated with these wider societal effects of the electricity system.

The broader system-related costs ***include direct and indirect costs***. Direct costs are, for instance, the land costs related to building power plants; indirect cost include, for instance, the costs of power plants on people's enjoyment of the landscape. There are many categories of these broader costs or impacts; in the next section we discuss these impacts in more detail. Specifically, we explore ***the wider impacts of the land and space requirements, which are an important element of this study***. We discuss negative externalities imposed on society by the disparate land requirements of renewables and nuclear.

In The Netherlands, wind turbines cause property values to drop by some 2 to 5%; higher wind turbines have a stronger adverse effect (wind turbines higher than 150 meters cause a drop in property values of 5%).

Renewable power, as we have seen in part 5 of this report, demands much more land and sea space,[552] and commands higher cost based only on LCOE (disregarding integration costs, which are much greater for renewable power). However, ***the cost of land is not fully reflected in the cost basis for wind and solar***.

- ***High land demand means that the price of land will go up***. This means not only that the cost of renewable energy will increase, but also that all other land users face increased cost in connection with land use. Inflated land prices, in turn, means that agriculture, certain industrial activities, etc. will become more expensive and may have to relocate or shut down. To prevent this effect, ***governments are inclined to keep the cost of land destined for renewable power projects down through regulations that reduce the land's value for other uses***; for instance, environmental regulations may increase the cost of farming and make it less profitable, thus making it more attractive to utilize the land for renewable projects. This strategy, however, also imposes costs, in this example on farmers and, indirectly, on the rest of society, as farming is displaced by power generation.[553]
- ***The location of a wind or solar facility in an area adversely affects land and property prices in the vicinity due to their "horizon pollution" effect***. A 2016 study found that wind farms caused property prices within an area of 2 km from a wind farm (wind turbines are clearly visible from up to 2 km) to drop by an average of 1.4%-2.3%.[554] A specific wind farm affected the value of some 6,300 houses causing a total decrease in property value of approx. €40,000,000.[555] It has been reported that in some cases property values drop by as much as 5% due to wind turbines in the vicinity.[556] A 2019 study commissioned by the Dutch government concluded that wind turbines cause property values to drop by some 2 to 5%; higher ***wind turbines have a stronger adverse effect (wind turbines higher than 150 meters***

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[552] This has also been confirmed by Shellenberger in his recent book. Michael Shellenberger, APOCALYPSE NEVER: Why Environmental Alarmism Hurts Us All, Harper, 2020. ("100% renewables would require increasing the land used for energy from today's 0.5% to 50%. We should want cities, farms, and power plants to have higher, not lower, power densities … The evidence is overwhelming that our high-energy civilization is better for people and nature than the low-energy civilization that climate alarmists would return us to.")

[553] In the Czech Republic, renewable subsidies have corrupted the soul of the farmers. Frantál B, Prousek A. It's not right, but we do it. Exploring why and how Czech farmers become renewable energy producers. Biomass & Bioenergy, Vol. 87 (2016), pp. 26-34.

[554] Dröes, M. en H. R. A. Koster (2014). "Renewable Energy and Negative Externalities: The Effect of Wind Turbines on House Prices". In: Tinbergen Institute Discussion Paper TI 2014-124/VIII. Dröes, M. en H. R. A. Koster, "Renewable Energy and Negative Externalities: The Effects of Wind Turbines on House Prices". In: Journal of Urban Economics 2016, 96, pp. 121–141.

[555] Mannus van der Laan, 'Woningen rond windparken dalen sterker in waarde dan gedacht', Dagblad van het Noorden, 19 juni 2019, available at https://www.dvhn.nl/groningen/Woningen-rond-windparken-dalen-sterker-in-waarde-dan-gedacht-24559823.html

[556] 'De geleden schade door windmolens moet worden vergoed', RTV Noord, 28 nov 2019, available at https://www.rtvnoord.nl/nieuws/216199/De-geleden-schade-door-windmolens-moet-worden-vergoed

cause a drop in property values of 5%).[557] For solar parks, the adverse effect seems to be limited to a radius of 1 km and an average of 3%. These so-called ***'zoning' or 'planning damages' are not included in the cost basis of renewable power, but they should be***.

- ***If the EU continues to pursue its renewable energy strategy, more and more land (and sea) will be converted for renewable power generation use***. As a result, there will be less countryside, fewer nature conservation areas, fewer recreation areas, higher noise levels, more natural resource damage, more health impacts, etc. These costs will be borne by the public at large and are ***not charged to the operators of wind turbines and solar farms***. The impact of the changing landscape and nature will be far-reaching, from recreation to tourism, and might have economic consequences (e.g. lower tourism revenues) as well as consequences for the well-being of residents that typically use those spaces for recreational use.

- ***Lastly, there is the environmental impact that cannot be ignored***. Due to their significantly higher footprint, renewables will likely disturb ecosystems (agrarian land, forests, etc.). The various ways in which wind and solar might ***displace or even kill animals, establish migration barriers, and alter animals' habitats*** are well documented.[558] For solar, reflections can also present issues. Given that the actual impacts of renewable projects are site-specific, case-by-case impact assessment should be done to identify and mitigate any impacts. This case-by-case approach further increases the costs of renewable energy power plants.

Of course, nuclear power plants and conventional power plants also require land and may cause a reduction of property value. However, because the area required for nuclear power is so much smaller, the adverse effect of nuclear power plants on the value of property in the vicinity will be minimal. In addition, nuclear plants, unlike wind turbines, do not (or only to a very limited extent) cause horizon pollution and disturb nature.

If the EU continues to pursue its renewable energy strategy, more and more land (and sea) will be converted for renewable power generation use. As a result, there will be less countryside, fewer nature conservation areas, fewer recreation areas, higher noise levels, more natural resource damage, more health impacts, etc. These costs will be borne by the public at large and are not charged to the operators of wind turbines and solar farms.

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[557] Martijn I. Dröes & Hans R.A. Koster, Windturbines, zonneparken en woningprijzen, UvA/VU, Amsterdam, december 2019, available at https://www.rvo.nl/sites/default/files/2020/01/windturbines-zonneparken-en%20woningprijzen-2019.pdf

[558] "Renewable energies and ecosystem service impacts" by Hastik et al., 2015, available at https://doi.org/10.1016/j.rser.2015.04.004

Wind and solar power generation have disadvantages, such as (1) the problem of intermittency and unresponsiveness to demand (i.e. their stochastic character), and the need for back-up, conversion, and/or battery or other storage, (2) their impacts on nature, wild life, sea life, and landscapes, (3) their impacts on human health, and (4) the management of the waste resulting from end-of-life wind turbines and solar cells.

f. Adverse Impacts of Power Generation Technologies

In this section, we attempt to provide a ***brief overview of other adverse impacts (negative externalities) of the power generation technologies at issue (wind, solar, nuclear***). In the overview attached to this report as Annex IX, we identify 10 broad categories of such impacts, including the impacts related to the power system, each of which has several sub-categories. Because the number of such impacts is high, we cannot discuss them all in the context of this study. In the previous section, we briefly explored the wider impacts of the land and space requirements.

In this section, we briefly discuss only some adverse impacts and negative externalities imposed on society by renewables and nuclear. We also point to some risks and uncertainties that are specifically associated with high shares of renewable energy. For other impacts, costs, and externalities, such as impacts on a country's energy security and on technological innovation, economic development or competitiveness, we refer to Annex IX attached to this report. The table in Annex IX should be taken as a rough approximation of some important aspects of the power generating technologies at issue in this study; it is not intended to prejudge any issue relevant to further in-depth analysis. We offer it as a general ***thought-starter for policy makers and other non-experts for thinking about strengths and weaknesses of alternative electricity options***.

i. Selected Adverse Impacts and Externalities

The EU's ambition is for Europe's power generation in 2050 to be dominated by renewable energy. In practice, as the European Commission projects, this will mean that the energy sector will be dominated by wind and solar power, in particular now that biomass no longer receives broad support. Forest biomass may result in deforestation,[559] which reduces carbon sink capacity; biomass

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[559] In October 2020, the European Parliament adopted a resolution calling for new rules to stop deforestation, including mandatory due diligence and civil liability for businesses. European Parliament resolution of 22 October 2020 with recommendations to the Commission on an EU legal framework to halt and reverse EU-driven global deforestation (2020/2006(INL)), available at https://www.europarl.europa.eu/doceo/document/TA-9-2020-0285_EN.html Cf. Guido Ceccherini, Gregory Duveiller, Giacomo Grassi, Guido Lemoine, Valerio Avitabile, Roberto Pilli & Alessandro Cescatti, Nature, Abrupt increase in harvested forest area over Europe after 2015, Nature volume 583, pp. 72–77 (2020) (Finding no evidence for direct correlation, the study suggests several reasons for the rise in European deforestation; scientists theorize the link arises from biofuel industry demands and the emerging wood markets).

combustion, of course, also results in carbon dioxide emissions,[560] and is currently being challenged within member states.[561] Until recently, other renewable energy options were viewed more positively.

Two ***main advantages of wind and solar power*** are believed to be (1) their renewable nature as far as the power itself is concerned (wind and sunshine are natural and free of charge), and (2) their decreasing inflating effect on the cost of power.[562] On the other hand, wind and solar power generation are also believed to have disadvantages, such as (1) the problem of intermittency and unresponsiveness to demand (i.e. their stochastic character[563]), and the need for back-up, conversion, and/or battery or other storage,[564] (2) their impacts on nature, wild life, sea life, and landscapes, (3) their impacts on human health, and (4) the management of the waste resulting from end-of-life wind turbines and solar cells.[565]

The ***adverse impacts of wind and solar power on the environment*** have been well documented, in particular

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[560] John D Sterman, Lori Siegel and Juliette N Rooney-Varga, Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy, Environmental Research Letters, 2018, Volume 13, Number 1, p. 015007. ("Projected growth in wood harvest for bioenergy would increase atmospheric CO_2 for at least a century because new carbon debt continuously exceeds Net Primary Production. Assuming biofuels are carbon neutral may worsen irreversible impacts of climate change before benefits accrue.")

[561] "In 2014, biomass accounted for 40% of the EU's renewable energy; in 2020, it's projected to make up over 60%." Jessica Xing, Europe is losing significant forest area to timber harvesting, which has seen an 'abrupt increase' since 2015, new study finds, The Rising, available at: https://therising.co/2020/07/08/timber-harvesting-europe-deforestation/#:~:text=European%20deforestation%20linked%20to%20biofuel%20industry%20For%20the,all%20timber%20imports%20come%20from%20verified%2C%20sustainable%20sources. Davine Janssen, The Dutch have decided: Burning biomass is not sustainable, Euractiv, 21 July 2020, available at https://www.euractiv.com/section/energy/news/the-dutch-have-decided-burning-biomass-is-not-sustainable/ Challenges for the biomass plants in Germany, 25 October 2018, available at https://altholzverband.de/2018/10/25/challenges-for-the-biomass-plants-in-germany/?lang=en.

[562] For discussion of the costs and benefits of the renewable energy, see Notton, Gilles ; Nivet, Marie-Laure ; Voyant, Cyril ; Paoli, Christophe ; Darras, Christophe ; Motte, Fabrice ; Fouilloy, Alexis, Intermittent and stochastic character of renewable energy sources: Consequences, cost of intermittence and benefit of forecasting, Renewable & Sustainable Energy Reviews, 2018, Vol.87, pp. 96-105 ("This review syntheses the reasons to predict solar or wind fluctuations, it shows that variability and stochastic variation of renewable sources have a cost, sometimes high. It provides useful information on the intermittence cost and on the decreasing of this cost due to an efficient forecasting of the source fluctuation.") Much of the relevant literature is slanted towards renewable energy, including only direct monetary cost, but several immaterial benefits. See, for example, Trieu Mai, Ryan Wiser, Galen Barbose, Lori Bird, Jenny Heeter, David Keyser, Venkat Krishnan, Jordan Macknick, and Dev Millstein, A Prospective Analysis of the Costs, Benefits, and Impacts of U.S. Renewable Portfolio Standards, NREL, Berkeley, 2016, available at https://www.nrel.gov/docs/fy17osti/67455.pdf

[563] Loukatou, Angeliki, Sydney, Howell, Paul Johnson, Peter Duck, Stochastic wind speed modelling for estimation of expected wind power output, Applied Energy, Vol. 228, 15 October 2018, pp. 1328-1340. ("[T]he first stage involves stochastic variations in wind speed; wind speed typically presents noisy short-term variations, plus cyclicality over periods of 24 h and longer. The second stage refers to stochastic variations of the resulting wind power output, a non-linear function of wind speed.")

[564] "When it comes to energy systems, back-up in the form of so-called "system services" is traditionally provided by fossil fuel-based generators. They must be ready to quickly balance the grid should there be any peaks in demand or sudden disruption in supply and, in some situations, be capable of getting power stations back up and running when a generator trips offline. The problem is that thermal generators take some time to fire up, meaning they can't react instantly, especially when they first have to cold start. Given the grid must be able to immediately accommodate the loss of the largest generator in its network with little interruption in service, a slow lead time isn't an option. Instead, these thermal generators stay on constant standby, so that they are ready when called upon to support primary generators. This makes them a physical ''spinning reserve'. Whilst this means that power can be reliably backed up, it also results in higher carbon emission and fuel costs, as thermal assets continue to generate power even when the grid is already fully supplied by renewable sources. In some cases, this may even lead to a situation whereby renewable generation has to be kicked off the grid to make space for the so-called "must-run" spinning reserve capacity. … In recent years, battery storage technology has developed to the point that it provides a much better alternative. With its ability to provide grid services within milliseconds, a battery storage system can effectively replace spinning reserve generators through so-called "synthetic inertia". This battery-based model not only removes the need for fossil fuel-based generators to be running constantly to provide resilience, it means that the other generators in the system, which no longer require the extra headroom of spinning reserve, can be utilised more efficiently, increasing their average load." Sriram Emani, Spinning reserve displacement: Using batteries for a more efficient and cleaner way to back up power, Renewable Energy World, 6.23.20, available at https://www.renewableenergyworld.com/2020/06/23/spinning-reserve-displacement-using-batteries-for-a-more-efficient-and-cleaner-way-to-back-up-power/

[565] See also Annex IX attached to this report.

for wind – wind turbines kill large birds and bats,[566] and disturb wildlife,[567] ecosystems,[568] and marine animals.[569] The possibility to move renewable power generation offshore (e.g. into the sea) will alleviate the pressure on land, but raise another set of issues around impacts on the marine environment, whales, birds, ship routes, fishing, etc.[570]

Nuclear power has adverse impacts too, despite its advantages[571] ***over renewable power as far as land usage requirements and cost are concerned***. Based on its enormous GHG emissions reducing effect, nuclear power has been advocated, including by climate scientists of the first hour like James Hansen, as an alternative to wind and solar energy.[572] Advantages of nuclear power include: (1) its reliability and flexibility or responsiveness to demand, and (2) its inherent climate-neutrality. Nuclear power generation is believed to raise three main issues: (1) radiation safety, (2) radioactive waste management, and (3) the high cost of power.[573] Now that this last point has been

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[566] Benny Peiser (editor), THE IMPACT OF WIND ENERGY ON WILDLIFE AND THE ENVIRONMENT, Papers from the Berlin Seminar, Global Warming Policy Foundation, GWPF Report 35, 2019. "A key challenge facing the wind industry is the potential for turbines to adversely affect wild animals both directly, via collisions, as well as indirectly due to noise pollution, habitat loss, and reduced survival or reproduction. Among the most impacted wildlife are birds and bats, which by eating destructive insects provide billions of dollars of economic benefits to the country's agricultural sector each year." USGS, Can wind turbines harm wildlife?, available at https://www.usgs.gov/faqs/can-wind-turbines-harm-wildlife#qt-news_science_products

[567] Benny Peiser (editor), THE IMPACT OF WIND ENERGY ON WILDLIFE AND THE ENVIRONMENT, Papers from the Berlin Seminar, Global Warming Policy Foundation, GWPF Report 35, 2019.

[568] Annie Sneed, Wind Turbines Can Act Like Apex Predators, Scientific American, Nov. 14, 2018, available at https://www.scientificamerican.com/article/wind-turbines-can-act-like-apex-predators1/ ("Wind farms can cause a cascade of ecological effects").

[569] How do offshore wind farms affect ocean ecosystems?, 22 Nov. 2017, available at https://www.dw.com/en/how-do-offshore-wind-farms-affect-ocean-ecosystems/a-40969339

[570] See, for instance, Slavik, Kaela ; Lemmen, Carsten ; Zhang, Wenyan ; Kerimoglu, Onur ; Klingbeil, Knut ; Wirtz, Kai W, The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea, Hydrobiologia, 2018, Vol.845 (1), p.35-53. Regina Bispo, Joana Bernardino, Helena Coelho, José Lino Costa (editors), Wind Energy and Wildlife Impacts: Balancing Energy Sustainability with Wildlife Conservation, Springer, 2019.Bergström, Lena ; Kautsky, Lena ; Malm, Torleif ; Rosenberg, Rutger ; Wahlberg, Magnus ; Åstrand Capetillo, Nastassja ; Wilhelmsson, Dan, Effects of offshore wind farms on marine wildlife—a generalized impact assessment, Environmental Research Letters, 2014-03-01, Vol.9 (3), p.34012. Kirchgeorg, T ; Weinberg, I ; Hörnig, M ; Baier, R ; Schmid, M.J ; Brockmeyer, B, Emissions from corrosion protection systems of offshore wind farms: Evaluation of the potential impact on the marine environment, Marine Pollution Bulletin, 2018-11, Vol.136, p.257-268.

[571] It may also offer advantages that are further explored in this study. Mark Fischetti, Safer Nuclear Reactors Are on the Way: Resilient fuels and innovative reactors could enable a resurgence of nuclear power, Scientific American, July 1, 2019, available at https://www.scientificamerican.com/article/safer-nuclear-reactors-are-on-the-way/ Much progress has also been made in mitigating the disadvantages of nuclear power generation (nuclear waste management, radiation risk). "Most low-level radioactive waste (LLW) is typically sent to land-based disposal immediately following its packaging for long-term management. This means that for the majority (~90% by volume) of all of the waste types produced by nuclear technologies, a satisfactory disposal means has been developed and is being implemented around the world. For used fuel designated as high-level radioactive waste (HLW), the first step is storage to allow decay of radioactivity and heat, making handling much safer. Storage of used fuel may be in ponds or dry casks, either at reactor sites or centrally. Beyond storage, many options have been investigated which seek to provide publicly acceptable, safe, and environmentally sound solutions to the final management of radioactive waste. The most widely favoured solution is deep geological disposal. The focus is on how and where to construct such facilities. Used fuel that is not intended for direct disposal may instead be reprocessed in order to recycle the uranium and plutonium it contains. Some separated liquid HLW arises during reprocessing; this is vitrified in glass and stored pending final disposal. Intermediate-level radioactive waste (ILW) that contains long-lived radioisotopes is also stored pending disposal in a geological repository." World Nuclear Association, Storage and Disposal of Radioactive Waste, March 2020, available at https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste.aspx The risks of radiation may also be much less than commonly thought. On radiation safety, see Edward Calabrese and Mikko Paunio, Reassessing radiation safety, Global Warming Policy Foundation, GWPF Essay 12, 2020.

[572] Gayathri Vaidyanathan, Nuclear Power Must Make a Comeback for Climate's Sake, ClimateWire (E&E News), December 4, 2015, available at https://www.scientificamerican.com/article/nuclear-power-must-make-a-comeback-for-climate-s-sake/

[573] For a cost-benefit analysis of nuclear power, see, for instance, Lombaard, Andries Lodewikus ; Kleynhans, Ewert P.J., The feasibility of a nuclear renaissance: A cost-benefit analysis of nuclear energy as a source of electricity, AOSIS Acta commercii, 2016, Vol.16 (1), pp. e1-e11. Adler, David B ; Jha, Akshaya ; Severnini, Edson, Considering the nuclear option: Hidden benefits and social costs of nuclear power in the U.S. since 1970, Resource and energy economics, 2020-02, Vol.59, pp. 101-127. Brook, Barry W; Bradshaw, Corey J. A., Key role for nuclear energy in global biodiversity conservation, Conservation Biology, 2015-06, Vol. 29 (3), pp. 702-712

Nuclear power generation is believed to raise three main issues: (1) radiation safety, (2) radioactive waste management, and (3) the high cost of power. This last point has been disproven in this study, and nuclear safety and safe nuclear waste management are not only possible, but already required by law.

dispelled, the debate will shift to the issues of safety and waste management. These issues have received much public attention after the Fukushima tsunami and the German 'Atomaustieg.'[574] Needless to say, ***public risk perception and pressure groups have played important roles in the political debate on nuclear energy***.[575] From scientific and technical viewpoints, however, nuclear safety and safe nuclear waste management are not only possible, but already required by law.

ii. Transition-Related Risks and Uncertainties

There is a separate set of issues that relate to the transition as such. These issues have to do with the way the EU pursues the energy transition and the timing thereof. In this section, we review three such issues: '***stranded assets,' financial risks, and engineering challenges***.

If renewable energy is forced into the power mix through subsidies and carbonized power generation technologies are pushed out at the same time (through financial disincentives, etc.), power generation assets may have to be retired before they reach their end of life. We refer to the problem of the so-called '***stranded assets***.'[576] Two questions arise in connection with such assets. First, ***should policies be designed in a way that they minimize the stranded assets problem, so as to minimize the related costs***? A good case can be made that at the very least policy makers should explicitly and carefully consider these costs, and decide whether they are comfortable imposing them. Second, if these costs cannot be entirely avoided, ***how should these costs be allocated*** – should these costs be borne by the public purse (and, thus, by tax payers), by their owners, or by the consumers of power? Again, careful consideration needs to be given to cost allocation so as to ensure that the costs are placed on those in the best position to minimize them. Current policies appear not to have given the level of attention to these questions that they merit.

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[574] Jochen Bittner, The Tragedy of Germany's Energy Experiment -- The country is moving beyond nuclear power. But at what cost?, New York Times, Jan. 8, 2020, available at https://www.nytimes.com/2020/01/08/opinion/nuclear-power-germany.html

[575] See, for instance, de Groot, Judith I. M ; Schweiger, Elisa ; Schubert, Iljana, Social Influence, Risk and Benefit Perceptions, and the Acceptability of Risky Energy Technologies: An Explanatory Model of Nuclear Power Versus Shale Gas, Risk Analysis, 2020-06, Vol.40 (6), pp. 1226-1243. Huhtala, Anni ; Remes, Piia, Quantifying the social costs of nuclear energy: Perceived risk of accident at nuclear power plants, Energy Policy, 2017, Vol.105, pp. 320-331.

[576] Löffler, Konstantin ; Burandt, Thorsten ; Hainsch, Karlo ; Oei, Pao-Yu, Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem, Energy Strategy Reviews, 2019, Vol.26, p.100422 (estimating a worst case of € 200 billion stranded assets by 2035).

Obviously, a slower pace of transition would avoid some or even most of the issues around stranded assets.

Obviously, a slower pace of transition would avoid some or even most of the issues around stranded assets.

This brings us to the broader issues around the financial risks associated with the energy transition. Due to the EU's policy choices, most energy investments in the EU flow into renewable energy, in particular wind and solar.[577] As a result, ***risk diversification in energy supply is adversely affected and energy investments become concentrated in the least efficient technologies***, as societies come more and more to depend on wind and solar.[578] If solar and wind were economically efficient and were built without subsidies and government pressure, this would arguably be comparable to the situation we had before with predominantly fossil fueled power plants. The current situation is very different, however. As Hughes has pointed out, when subsidies expire and renewable energy facilities under the then current market conditions are no longer able to continue operations, there may be large numbers of projects that become unprofitable and subsequently insolvent.[579] The EU, however, is actively promoting investments into renewable energy projects, and discouraging investments into other energy facilities.[580] As a result, ***either the electricity price will increase to extremely high levels*** (under which renewable energy projects can survive), or ***financial institutions and energy investors will become exposed to huge losses and write-offs***, possibly threatening the stability of the financial sector. "It is no different from urging financial institutions to finance speculative property developments at the beginning of a property crash," according to Hughes. Again, a slower transition pace and less selective energy and financial policies would alleviate, if not eliminate, these risks.

In addition to the financial exposure, there are ***challenges and uncertainties around engineering and innovation***.[581] Driven by a sense of urgency, the EU embarked on an ambitious renewable energy policy program without considering all challenges, risks and uncertainties. With the share of renewable energy and the degree of electrification due to rapidly increase, electricity systems face challenges and grid upgrades have become urgent.[582] Moreover, the resolution of the problem of intermittency is

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[577] Cf. European Commission, EU energy in figures, Statistical pocketbook, available at https://op.europa.eu/en/publication-detail/-/publication/87b16988-f740-11ea-991b-01aa75ed71a1/language-en

[578] Cf. ÓhAiseadha, Coilín, Gerré Quinn, Ronan Connolly, Michael Connolly and Willie Soon, Energy and Climate Policy—An Evaluation of Global Climate Change Expenditure 2011–2018, Energies 2020, 13, 4839; doi:10.3390/en13184839

[579] Hughes, Gordon, Wind Power Economics – Rhetoric and Reality, Renewable Energy Foundation, 4th November 2020, available at https://ref.org.uk/ref-blog/364-wind-power-economics-webinar

[580] See the discussion of the EU's sustainable finance initiative in Section 2.e, above.

[581] Cf. Sterner, Michael, Ingo Stadler, Handbook of Energy Storage: Demand, Technologies, Integration, Springer, 2019.

[582] Kelly, Michael, Electrifying the UK and the Want of Engineering, The Global Warming Policy Foundation, Essay 11, GWPF 2020.("The electricity grid will require upgrading from top to bottom.")

Due to the EU's policy choices, risk diversification in energy supply is adversely affected and energy investments become concentrated in the least efficient technologies.

becoming urgent, but there are no obvious solutions to this problem. The limits of battery storage at grid scale are well known,[583] apart from the widespread environmental and social impacts that production of batteries at this scale would cause.[584] In addition to costly continental-scale transmission networks,[585] the ***EU is betting on highly uncertain break-through innovations*** in energy storage and conversion, including hydrogen.[586]

The combined impact of these three categories of risks and uncertainties can be disastrous. To mitigate these contingencies, the EU should pay more attention to them, and actively pursue policies promoting ***risk diversification in energy policies***, as the precautionary principle requires.

g. Conclusion

In this chapter, we have dispelled the myth that just because an energy technology's LCOE is low, its deployment would be competitive and economically efficient. In fact, integration and other system-related costs are significant and could, if all are accounted for, be as high as or even higher than the energy generation costs. Although LCOE provides a simple and useful yardstick for comparing various energy technologies, due to its inherent limitations, attention must be given to the increasingly important area of integration and system-related costs.

System costs include the dynamic effects of integrating power generation technologies into the electricity system, and their long-run impacts on the

The EU is betting on highly uncertain break-through innovations in energy storage and conversion, including hydrogen.

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[583] Id. (referring to the low energy density of batteries). See also OECD, Nuclear Energy Agency, The Full Costs of Electricity Provision, NEA No. 7298, Paris, OECD, 2018. Sonter LJ, Dade MC, Watson JEM, Valenta RK. Renewable energy production will exacerbate mining threats to biodiversity. Nature Communications, Vol. 11 (1) September 2020, pp. 4174-4174.

[584] ÓhAiseadha, Coilín, Gerré Quinn, Ronan Connolly, Michael Connolly and Willie Soon, Energy and Climate Policy—An Evaluation of Global Climate Change Expenditure 2011–2018, Energies 2020, 13, 4839; doi:10.3390/en13184839

[585] It has been argued that this "appears to be based more on wishful thinking than pragmatism." Id.

[586] See, for instance, Furfari, Samuel. The Hydrogen Illusion, September 2020.

structure and operation of electricity markets. The main system costs are incurred as integration costs, which are ***much higher for renewables*** due to the inherent adverse effects on the process of matching electricity demand and supply.

We used sensitivity analysis on existing models as well as a case study on electricity prices in France and Germany and the rest of the EU to illustrate how ***integration costs***, including grid connection costs, can inflate electricity prices when renewables are added to an energy system. Likewise, as we have seen, data for the EU as a whole does not suggest that renewable energy lowers the cost of the energy system; to the contrary, it may well substantially increase the cost of energy. Studies that come to different conclusions are usually deficient in treating the background costs, or consider only the marginal cost for the last unit of electricity generated, rather than the whole system cost.

Beyond integration costs and the electricity system, power generation technologies have other impacts and externalities. ***Total system costs*** are also inclusive of those effects that are difficult to monetize, which we called other system-related costs, such as the land costs and environmental externalities. These impacts also tend to be greater for renewables than for nuclear, and are often not integrated into the evaluation of policy options.

Our message here is that the findings of this study need to be placed in the broader context of the ***costs and benefits of renewable power and nuclear power***.

Although spatial requirements and cost are important, they are not the only relevant factors. Nevertheless, there are reasons to believe that ***space and cost will become main drivers*** of the energy transition in the course of this decade:

- First, further deployment of wind and solar are likely to increasingly involve ***locations that not only escalate project costs but also raise tough social issues*** (e.g. wind farms close to residential areas[587] or nature protection areas), resulting in increased citizen opposition and social rejection;[588] and

- Second, since costs and cost-effectiveness will become increasingly important in the energy transition and the fight against climate change, the ***relative costs will of alternative power generating technologies will become more important***, since lower cost increases the chances of policy success, reduces the burden imposed on the purse and citizens, and enables policy makers to meet needs other than the climate.

In our view, the other benefits and impacts associated with two technologies are not likely to be as important in cost/benefit-analysis for policy purposes. For instance, problems of waste management, although different in nature, are common to wind/solar and nuclear. To some degree, impacts of wind and solar on nature, wild life, sea life, and landscapes are reflected in the crude measure of the required land and space necessary for its full deployment. In that sense, a policy aimed at minimizing the use of land and space

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[587] Bertsch, Valentin ; Hall, Margeret ; Weinhardt, Christof ; Fichtner, Wolf, Public acceptance and preferences related to renewable energy and grid expansion policy: Empirical insights for Germany, Energy (Oxford), 2016-11-01, Vol.114, pp. 465-477 ("the distance between places of residence and places of energy infrastructure construction is crucial" for public acceptance of renewable energy facilities).

[588] There are significant differences between The Netherlands and the Czech Republic in this regard. See, for example, Ćetković, Stefan ; Buzogány, Aron, The Political Economy of EU Climate and Energy Policies in Central and Eastern Europe Revisited: Shifting Coalitions and Prospects for Clean Energy Transitions, Politics and governance, 2019-03-28, Vol.7 (1), pp.124-138 ("The article shows that the contestation of energy policies, particularly of climate-related legislation, in the Council of Ministers has increased over time and that these six CEE countries have indeed most often objected to the adoption of EU [climate] legislation.")

Policy-makers should be aware of the pros and cons of the various power generation technologies when making energy policy decisions, and should avoid denying or downplaying pros and cons to push their favorite technology. Sound evidence and neutral policy principles can help to achieve good policy outcomes.

for electricity production can serve as proxy for nature and biodiversity protection.

To conclude, it is necessary for policy makers to consider system costs, when making policies affecting investment decisions for the energy system. In addition, risks and uncertainties associated with the energy transition require their attention. Otherwise, renewables might be deployed inappropriately, leading to future challenges in relation to the security and affordability of the electricity supply and adverse effects on the economy and society.

Policy-makers should be aware of the pros and cons of the various power generation technologies when making energy policy decisions, and should ***avoid denying or downplaying pros and cons to push their favorite technology***. Sound evidence and neutral policy principles can help to achieve good policy outcomes.

On these grounds, climate and energy policies are best guided by the idea that the external costs associated with power generation technologies are internalized. We refer to this idea as the ***"generator pays" principle***.[589] In the next part, it is discussed further.

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[589] A 2012 OECD report addressed the interactions of variable renewables and dispatchable energy technologies, such as nuclear power, in terms of their effects on electricity systems. As the OECD noted, "these effects add costs to the production of electricity, which are not usually transparent." The OECD found also that, "unless the current market subsidies for renewables are altered, dispatchable technologies will increasingly not be replaced as they reach their end of life and consequently security of supply will suffer." To achieve "an economically viable coexistence of nuclear energy and renewables," the report recommended that decision-makers internalize system costs in accordance with a "generator pays" principle. OECD, Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems Organisation for Economic Co-operation and Development and NEA. Paris: OECD Publishing, 2012.

8

Policy Recommendations

Policy Recommendations

This part provides recommendations to policy makers. These recommendations are based on the findings of this study, and supported by further evidence referenced in the footnotes. The aim of these policy recommendations is to improve policy-making relevant to electricity generation technologies.

To make sound energy policy, policy makers should have a basic understanding of the electricity system and electricity generation. To this end, before we present our recommendation, we give a brief, somewhat simplified description of the electricity system and generation. Further, this section discusses a few basic tenets of electricity economics and energy finance, in particular those aspects that are directly relevant to energy policy-making. Before presenting our recommendations, we rephrase the findings of our study in non-technical language so that policy makers without the relevant professional backgrounds can also easily grasp their essence.

Let's first start with describing the background that triggered this analysis. Current EU policies favor renewable energy over nuclear energy, although both are decarbonized technologies. Massive funding found its way into the development and deployment of wind and solar energy solutions.[590] According to Frankfurt School's UNEP Collaborating Centre for Climate & Sustainable Energy Finance, "Europe as a whole invested $698 billion in 2010 to first-half 2019, with Germany contributing the most at $179 billion";[591] the vast majority has been for wind and solar power plants. We estimate that in the period 2000 to 2018,

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[590] Only in 2020, The Netherlands makes some €4 billion available in direct subsidies. Netherlands doubles 2020 green subsidies in rush to hit climate goals. Reuters, 4 March 2020, available at https://www.reuters.com/article/us-climate-change-netherlands-idUSKBN20R2DT

[591] Frankfurt School-UNEP Centre, Global Trends in Renewable Energy Investment 2019, Frankfurt, 2020, available at http://www.fs-unep-centre.org

In liberalised energy markets, renewable energy subsidies are believed to be necessary, because the expected number of renewable generation hours is insufficient to induce private investment. These subsidies had the effect of reducing the cost to renewable energy investors, leading to the current renewable market shares.

the EU and its Members States have spent more than one thousand billion euros to promote renewable energy. Renewable energy subsidies are necessary in liberalised, open energy markets, because the expected number of renewable generation hours is insufficient to induce private investment.[592] This had the effect of reducing the cost to renewable energy investors, leading to the current renewable market shares.[593]

While these EU programs focused on displacing fossil electricity generation with renewable electricity generation, their side effect was a relative inflating effect on the cost of nuclear electricity and the deployment thereof in the EU. In addition, Germany's '*Atomausstieg*' following the Fukushima nuclear incident *not* only caused electricity prices to rise, including in Austria,[594] but also further stigmatized nuclear electricity. This caused the EU and some influential Member State governments to disfavor nuclear energy, which, in turn caused financing cost to rise. The combined effect of the pro-renewable policies and the anti-nuclear sentiment weakened the case for nuclear energy in the EU. It is important to note, however, that the root causes of the weak case for nuclear energy are not the intrinsic properties or economics of nuclear electricity.[595] As demonstrated throughout this report, EU and national government policies are the root causes of the deteriorated climate for nuclear electricity in Europe.

To prevent that the road to EU climate neutrality will cause unintended adverse economic and societal effects, nuclear energy may need to be added to the energy mix in Europe. Policy makers thus face the question what they can do to fix the current unfavorable nuclear policy climate.

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[592] Lawrence Haar, An empirical analysis of the fiscal incidence of renewable energy support in the European Union, Energy Policy 143 (2020) 111483.

[593] For an overview of renewable market shares, see Eurostat, Renewable energy statistics, available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics ("In 2018, renewable energy represented 18.9 % of energy consumed in the EU, on a path to the 2020 target of 20 %.") Cf. Samuel Furfari, L'électricité intermittente: Une réalité et un prix, Science, climat et énergie, 21 aout 2018, available at http://www.science-climat-energie.be/2018/08/21/lelectricite-intermittente-une-realite-et-un-prix/

[594] Luigi Grossia, Sven Heim, Michael Waterson, The impact of the German response to the Fukushima earthquake, Energy Economics, Volume 66, August 2017, pp. 450-465.

[595] As the World Nuclear Association observes, "[t]ypically it is the responsibility of owners or operators of nuclear power plants to secure financing for new nuclear power plants. For investors, the confidence provided by clear, long-term governmental commitment to a nuclear power programme remains critical." World Nuclear Association, Financing Nuclear Energy, Updated May 2020, available at https://www.world-nuclear.org/information-library/economic-aspects/financing-nuclear-energy.aspx

a. The electricity system

Electricity, if it meets the applicable technical requirements, is fungible. For electricity to do its job, it needs to be generated and instantaneously delivered to consumers that demand electricity. We refer to these two steps as (1) electricity generation and (2) electricity delivery (including transmission, distribution, and consumption). Four basic facts need to be understood to grasp the issues associated with generating and delivering electricity to consumers:

- All electricity generation technologies have ***strengths and weaknesses***, which, among other things, have cost implications. There is not one electricity generation technology that outperforms all others on each relevant parameter. Both renewable electricity and nuclear electricity are decarbonized, i.e. their operations do not emit carbon dioxide.[596]

- All electricity generation technologies need to function within a ***common electricity distribution network*** (a 'natural monopoly'), which imposes certain requirements and constraints on electricity generators (e.g. network balancing is a crucial technical requirement, see further below).

- There is a relation between ***flexibility*** in ***electricity generation*** (on demand generation) and ***flexibility*** in the ***electricity network*** (grid flexibility[597]) – if flexibility in electricity generation is low (due to a lot of renewable sources), grid flexibility has to be high (i.e., a large network with many interconnections, substantial storage capacity, etc.[598]), which entails substantial costs.[599] This is the concept of the smart grid.

- The ***total cost of the electricity generation and delivery system*** determines the total cost that will be passed on to consumers of electricity and the taxpayers.[600] In other words, policy makers need to focus on the total cost of the entire system, not only on electricity generation cost. Further, they should consider all effects and impacts, including both positive and negative externalities, of alternative electricity systems.

Consumers want ***a reliable, performant electricity system*** at the lowest total cost. A performant electricity system at lowest cost implies that the ***cost of electricity generation*** plus the cost ***of electricity delivery*** should be ***minimized***. There is a tendency to ignore or hide the cost of electricity delivery, but this does not make it go away; one way or another, it will have to be added to the cost of electricity generation to arrive at total cost of electricity.[601]

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[596] The carbon dioxide emitted during production of power generating equipment and construction of power plants can be calculated by doing life cycle analyses, but system boundaries are likely to determine the outcomes of any such analyses. The argument that nuclear emits more carbon dioxide in construction than wind emits in production of turbines, runs into this problem. Cf. Pehl, M., Arvesen, A., Humpenöder, F. et al. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. Nature Energy 2, 939–945 (2017). https://doi.org/10.1038/s41560-017-0032-9

[597] Demand flexibility is also part of the equation in the case of renewable power. Cf. Lund, Peter D, Lindgren, Juuso, Mikkola, Jani, Salpakari, Jyri, Review of energy system flexibility measures to enable high levels of variable renewable electricity, Renewable & sustainable energy reviews, 2015, Vol.45, pp. 785-807.

[598] Denholm, Paul, Hand, Maureen, Grid flexibility and storage required to achieve very high penetration of variable renewable electricity, Energy policy, 2011, Vol.39 (3), pp. 1817-1830.

[599] These costs are referred to as integration- and system-related costs. For further discussion, see part 7 of this report.

[600] Some cost related to the electricity system is paid for from the general state budget, and not added to the cost of electricity.

[601] Even if such costs are paid from general tax revenues, they are costs that are properly allocable to the electricity system.

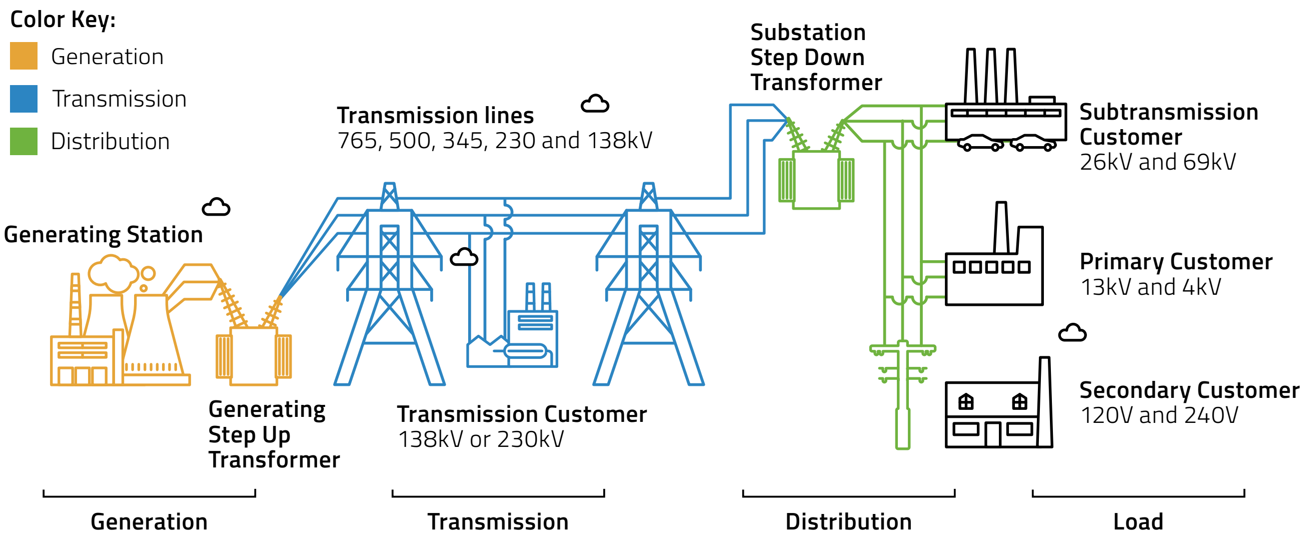

Figure 8.1. Electricity system

From: ERCOT, 2012

To understand what this means and implies, we need to consider some basics of both electricity generation, specifically, electricity generation technologies, and the system of electricity delivery with its specific characteristics. The next several sections cover each of these two topics in brief.

b. Power Generation Technologies

At the electricity supply side, there are various electricity generators operating various technologies, including conventional, wind/solar, other renewable (such as biomass) and nuclear. As noted above, each of these technologies have their own strengths and weaknesses. Wind/solar electricity, for instance, are intermittent (a weakness), but their 'fuel' is free, so they have low marginal cost (a strength). Nuclear electricity can run continuously (a strength), but requires substantial investments (a weakness). The same applies to conventional plants; gas-fired power plants tend to be among the most flexible sources.

Due to ***technical limitations*** (and the related delays and costs) it is not totally possible or desirable to turn a nuclear or conventional power plant on and off on a regular basis during a day, although both can play a role in flexibility (to meet peak demand).[602] For economic reasons, it is preferred that these plants run at some minimum level during extended period of time; they are therefore referred to as "base load". Gas-fired power plants are the most flexible, but this technology is not decarbonized, although its carbon-intensity is lower than that of other fossil fuel-fired power plants, such as coal plants.[603]

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[602] For nuclear energy's flexibility, see NICE Future, Flexible Nuclear Energy for Clean Energy Systems, Technical Report, NREL/TP-6A50-77088, September 2020, available at https://www.nrel.gov/docs/fy20osti/77088.pdf ("Nuclear energy has the potential to couple with many other energy sources in a synergistic fashion that results in integrated systems that are more than the sum of their parts.")

[603] These plants can be combined with carbon capture and storage. See further Smith, Neil, Miller, Geoff, Aandi, Indran, Gadsden, Richard, Davison, John, Performance and Costs of CO_2 Capture at Gas Fired Power Plants Energy procedia, 2013, Vol. 37, pp. 2443-2452.

The cost basis of power plants includes (i) ***fixed costs (CAPEX)***, i.e. the costs of the investments in equipment, buildings, etc., and (ii) ***variable costs (OPEX)***, i.e. the incremental costs of producing electricity, i.e. the cost of fuel, variable maintenance, etc. Variable cost is also referred to as marginal cost in this context; it represents the extra cost associated with producing an extra unit of electricity, excluding a share of the fixed cost. In other words, variable or marginal cost of electricity generation is only a part of the total cost of electricity production.

It is important for policy makers to understand that power generation technologies are not necessarily interchangeable and substitutable. Specifically, wind and solar are ***no substitutes*** for nuclear power. Because wind and solar energy is ***intermittent, stochastic, and statistically dependent***, it cannot replace 'base load' electricity without further investments (e.g. in storage and conversion, or in back-up facilities). Electricity delivered at a specific location and a specific time is fungible, but electricity **is not fungible over time or space**; put differently, comparing nuclear and variable renewable energy is like comparing apples and oranges. This has very significant consequences, including:

- An electricity system that relies to a significant degree on intermittent renewables thus requires **over-investment in capacity** to meet peak demand and needs **storage and conversion solutions** if surplus generation is to be utilized.

- Consequently, in such a system, the **amount of land and space** required for electricity generation **inflates** because the required capacities must be increased to compensate for intermittency (which requires additional land and space), and the storage and conversion solutions likewise take up land and space.

- The levelized **cost of electricity** (LCOE) is a useful parameter for nuclear energy, but does **not represent the real cost of variable renewable energy**, because this energy necessitates further investments in storage and conversion technologies and back-up facilities, and imposes additional integration cost.

- The **economic value of variable (intermittent) renewable energy** is not constant, but **varies** over time and place, and may even be **negative**, which means that its **LCOE is idiosyncratic** and **cannot be used for purposes of comparing with non-intermittent technologies**.

- As discussed in Part 7 of this report, due to the issues associated with variable renewable energy discussed above, the price of electricity in Member States is a function of the degree of penetration of variable renewable energy – **the more renewable there is in the mix, the higher the price of electricity**.

c. Electricity delivery through the network

Electricity should be ***consumed when generated***; a sound control system is required to ensure that at any moment electricity generation matches demand. If electricity generation exceeds demand, electricity needs to be stored in batteries or converted, which involves additional cost. If the cost of storage and conversion (including the cost of externalities) is sufficiently low, however, it may be economically attractive to utilize these options. Hydrogen synthesis is one of the ways to convert electricity on which Germany and now also the EU have set their hopes. It remains to be seen whether hydrogen can meet the expectations.[604]

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[604] Samuel Furfari, The Hydrogen Illusion, September 2020.

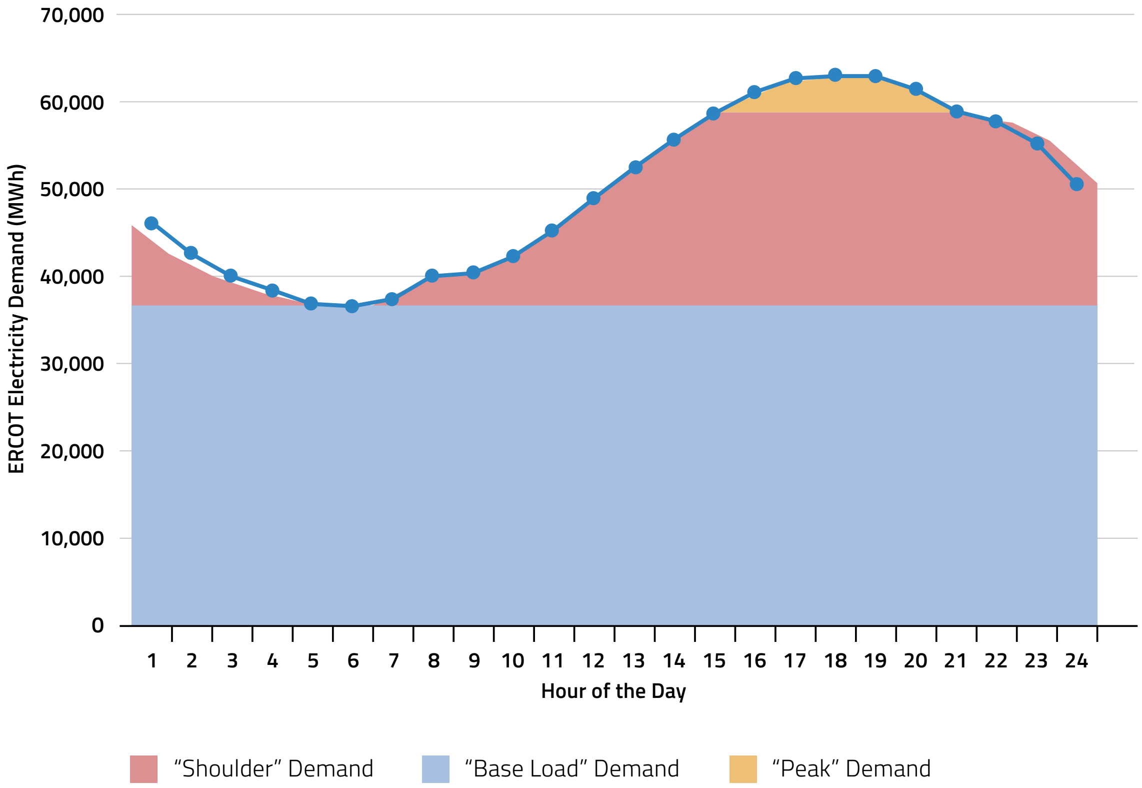

Figure 8.2. Typical electricity demand curve (for illustration purposes only)

From: ERCOT 2012

Conversely, if electricity supply is insufficient to meet demand, the shortfall can cause power plants and transmission equipment to automatically disconnect or shut down to prevent damage. A cascade of such shut downs can cause a regional blackout with large economic and possibly disastrous consequences; blackouts should therefore be avoided.

To ensure that electricity is delivered on time, conventional power plants run according to the demand schedule of various groups of consumers (industrial, households, etc.), which can be estimated ahead of time. A typical ***demand curve*** shows a certain minimum level of electricity usage throughout the 24-hour day, with lows during the night, increased demand from sun rise until sun set, and peaks during breakfast, lunch, and diner/evening. The variations in demand can be referred to as base load (continuous demand), shoulder load (only part of the day), and peak load (even fewer hours). Refer to figure 8.2. for the graphic depiction.

There is not only variation in electricity consumption during the day, but also over the seasons (e.g. as a function of the need for heating or lighting) and in response to events (e.g. the COVID-19 epidemic results in different patterns of electricity consumption). These fluctuations need to be anticipated and managed appropriately to keep the network stable.

Network operators deliver the electricity from the generators to the consumers. They are faced with mix of electricity generated from various primary energy (coal, gas, nuclear, wind, solar etc.) from which consumer can get the electricity they need. Electricity distribution companies buy electricity in wholesale markets and sell to consumers. They need the transmission system, which is operated by the ***Transmission System Operator*** ("TSO"), and the local distribution network, operated by the **Distribution System Operator** ("DSO") to get the electricity from the generator to the consumers.

For an electricity network to function properly, there has to be a balance between the electricity delivered to the network and the electricity consumed; as noted above, if there is a serious disbalance, this may cause electricity outage or blackout. TSOs are responsible for maintaining the balance between electricity generation and consumption.[605] This process is called '***balancing***.'

Because the transmission and distributions systems are natural monopolies, they are heavily regulated, and typically, in part, government-owned or -controlled. Typically, TSOs and DSOs do not charge the electricity utilities for their services, but the fees for their services are passed on to electricity consumers, on the basis of fixed charges or levies, or on the basis of the volume of electricity they consume.

d. Load dispatch and merit order

As discussed above, the technical characteristics of electricity generation technologies vary, and these variations have consequences for the process of ***load dispatch***, i.e. the direction of the flow of electricity from power plants into the network to meet demand. If the electricity produced by generators threatens to exceed the demand, network operators can use various criteria to determine the order in which generators may deliver the electricity they (can) generate. These criteria are referred to as the "***merit order***."

In the electricity industry, the term 'merit order' describes the sequence in which power plants are designated to deliver electricity. The aim of this order is optimizing the electricity supply from an overall cost perspective. Criteria for dispatch management include (1) '***must run***,' (2) ***minimum technical limit***, (3) ***variable or marginal cost***, and (4) ***transmission constraints***.[606]

- 'Must run' refers to power plants that offer electricity at lowest total price, including fixed cost and variable cost, with total cost including both electricity generation and delivery cost. Electricity from 'must run' power plants will be dispatched in all conditions, precisely because they have the lowest total cost.

- The 'minimum technical limit' refers to the fact that certain power plants should not fall below a certain minimum output in order for them to perform optimally.[607]

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[605] To achieve balancing, TSOs use different types of control reserve (primary control reserve, secondary control reserve, and tertiary control reserve).

[606] "In the market clearing process, internal transmission constraints are essentially ignored and the possible congestion issues are solved via re-dispatch. Because the network constraints are not taken into account in the commitment decisions of the generating units, the outcome of the re-dispatch process will differ from the optimal one. With further RES integration, this is expected to become ever more costly." R.A. Verzijlbergh, L.J. De Vries, G.P.J. Dijkema, P.M. Herder, Institutional challenges caused by the integration of renewable energy sources in the European electricity sector, Renewable and Sustainable Energy Reviews 75 (2017) 660–667. Cf. Staffell, Iain, Green, Richard, Is There Still Merit in the Merit Order Stack? The Impact of Dynamic Constraints on Optimal Plant Mix, IEEE Transactions on Power Systems, 2016-01, Vol.31 (1), pp. 43-53.

[607] A thermal power plants, such as a coal- or gas-fired power plant, may have a minimum technical requirement, for instance, 60% (the plant load factor), which implies that this plant can lower its production from close to 100% to 60% when demand is low.

Under a policy aimed at creating a sustainable electricity system, an unsustainable electricity pricing policy has been implemented that inflates the total cost of producing and delivering power to consumers.

- Variable or marginal cost is the incremental cost of the production of electricity at any given time;[608] as discussed above, variable cost is only a part of the total cost.

- Transmission constraints refer to the fact that it may not be possible to receive large volumes of electricity over certain transmission lines; in that case, other options need to be explored.

The introduction of intermittent renewable energy has caused the traditional merit order to be overthrown by an order that focuses solely on marginal cost. As one group of authors put it, "[m]any low-carbon generators are inflexible or intermittent, and the remaining stations will need to change their operating regimes."[609] As a result of this development, the "merit order" is now based solely on the lowest marginal costs. In other words, power plants that offer electricity at lowest prices are the first to be called upon to supply electricity; power plants with higher marginal costs and, thus, higher offered prices, are subsequently added until demand is met. This "merit order" assumes that power plant operators treat the cost related to their investments and overhead as 'sunk' cost, and price their output at a level sufficient to cover at least the cost of producing the next megawatt hour, which, of course, is an unsustainable practice.

In the past, like fossil fuel-fired power plants, nuclear plants were regarded as 'must run' providers of continuous 'base load.' Due to the large scale introduction of intermittent renewable energy, in some Members States, nuclear power plants are now forced to convert to load-following plants. This means that nuclear plants are effectively required to reduce their output on short notice, which presents both technical and economic challenges for nuclear plants, as prices drop below the variable cost of nuclear plants.[610]

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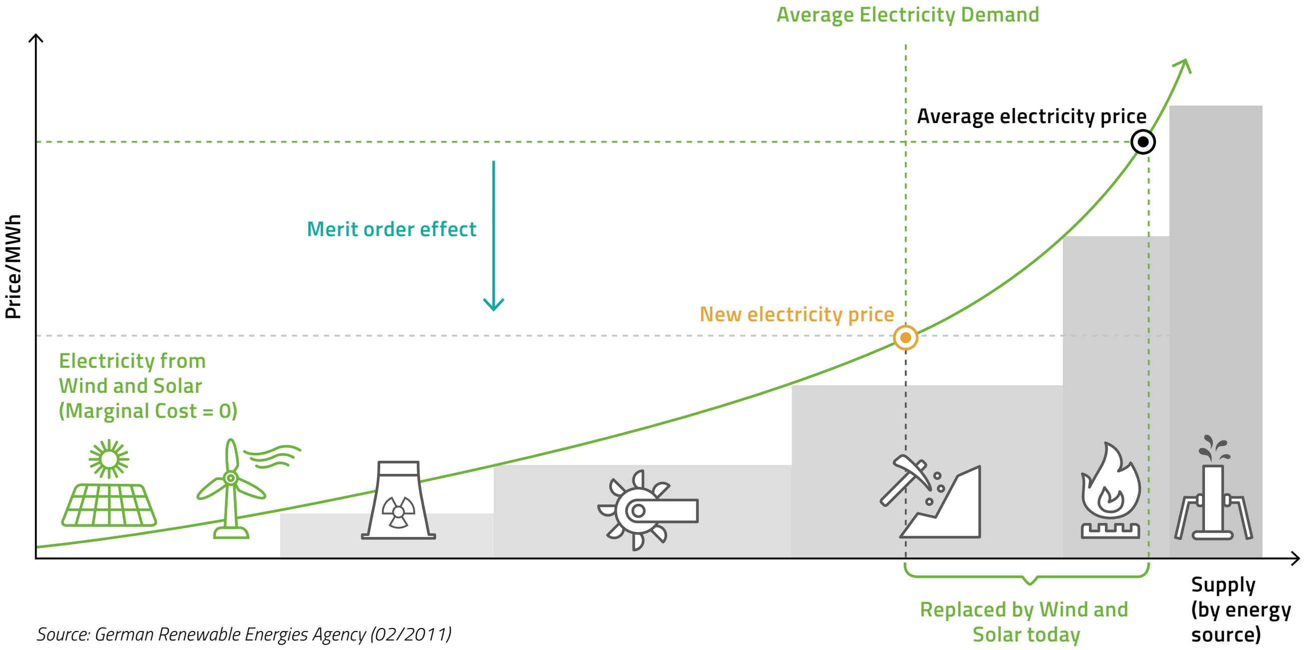
[608] Traditionally, variable cost was applied to thermal power plants that can easily scale back to determine which plants will run at 100% and which plants will have to scale back.

[609] Staffell, Iain, Green, Richard, Is There Still Merit in the Merit Order Stack? The Impact of Dynamic Constraints on Optimal Plant Mix, IEEE Transactions on Power Systems, 2016-01, Vol.31 (1), pp. 43-53.

[610] "Due to the sudden influx of large amounts of wind power, German, Dutch, Czech and Austrian power markets have experienced several hours of negative electricity prices in recent years and many more hours with prices that were lower than the variable costs of nuclear power plants, which have the lowest variable costs among the large-scale established power sources." Nuclear Power, Base load vs Load Follow, available at https://www.nuclear-power.net/nuclear-power/reactor-physics/reactor-operation/normal-operation-reactor-control/base-load-vs-load-follow/ "Negative prices … are caused by the combination of large volumes of zero-price offers from renewable suppliers and thermal producers that are willing to incur occasional losses to avoid wear-and-tear of their units." Juan M. Morales, Salvador Pineda, On the inefficiency of the merit order in forward electricity markets with uncertain supply, European Journal of Operational Research 261 (2017) 789–799.



Source: German Renewable Energies Agency (02/2011)

Figure 8.3. From: Next-Kraftwerke, What does merit order mean?, available at https://www.next-kraftwerke.com/knowledge/what-does-merit-order-mean

To accommodate intermittent renewables, the European Utilities Requirements demand that a nuclear power plant be capable of daily load cycling operation between 50% and 100 % of its rated electricity, with a rate of change of electric output of 3-5% of rated electricity per minute.[611]

e. Electricity market and 'merit order effect'

A distinction should be made between (i) the market for investment in electricity-generating technologies, and (ii) the market for electricity as a product (i.e. the market for the electricity generated by the technologies). The former is discussed below; here, we focus on the second, i.e. the electricity market. There are several markets (or exchanges) for electricity. There are the forward and 'real time' (spot) markets,[612] and wholesale and retail markets. In addition, electricity can be sold ahead of production through long-term contracts (typically called 'power purchase agreements').

On an open electricity market, supply and demand determine electricity prices. In an "***energy only***" market, selling electricity is the only way electricity generators can obtain revenues. The way this market works is that the lowest offer is accepted first, followed by the offer that is the second cheapest, and so on, until demand is met. Because renewable generators have low marginal cost and, thanks to subsidies, do not need to recover

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[611] European Utility Requirements for LWR Nuclear Power Plants, available at http://europeanutilityrequirements.org/EURdocument/EURVolume1,2,4.aspx

[612] "A central role in liberalized power systems is played by the spot-market, also referred to as wholesale market or day-ahead market: a market place where electricity can freely be traded between producers and consumers, that are usually represented by retailers." R.A. Verzijlbergh, L.J. De Vries, G.P.J. Dijkema, P.M. Herder, Institutional challenges caused by the integration of renewable energy sources in the European electricity sector, Renewable and Sustainable Energy Reviews 75 (2017) 660–667.

The 'merit order effect' may seem to provide a benefit to consumers in the short term, but consumers end up paying the price in any event. In the end, it is the total system cost that determines the fees payable by consumers (or tax payers).

the full cost of the investment, they generally make the lowest offers.

In an energy only market, the so-called "***merit order effect***" of renewables concerns the lowering of electricity prices due to an increased supply of renewable electricity. The low offers made by the intermittent renewable electricity generator, who have the lowest variable cost (zero fuel cost and very low personnel cost), drive down electricity prices for all generators.

Conventional and nuclear power plants end up providing only the residual load, i.e. the remaining electricity demand that renewables cannot meet.

In an early phase, there was enthusiasm in Germany about the merit order's salutary effect on electricity prices; one study found that savings for electricity consumers resulted from the merit order effect.[613] Dissatisfaction started to grow, however, when so-called "non-privileged" consumers were faced with substantially increased electricity bills.[614] There is now is a growing body of evidence that the merit order effect, while it may reduce electricity prices in wholesale markets in the short run, ***inflates the total cost of the electricity system in the long run***[615] and reduces the incentives for investment in needed non-renewable power capacity.[616]

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[613] "In the case of the year 2006, the volume of the merit-order effect exceeds the volume of the net support payments for renewable electricity generation which have to be paid by consumers." Sensfuß, Frank, Ragwitz, Mario, Genoese, Massimo, The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany, Energy Policy, Volume 36, Issue 8, August 2008, pp. 3086-3094.

[614] Johanna Cludius, Hauke Hermann, Felix Chr. Matthes, The Merit Order Effect of Wind and Photovoltaic Electricity Generation in Germany 2008-2012, CEEM Working Paper 3-2013, May 2013

[615] In Germany, arguments against variable renewable energy sources include that "they are too expensive, contribute little or not at all to reducing CO_2 emissions, present risks to the security of supply and require large grid investment." Anke, Carl-Philipp, How Renewable Energy Is Changing the German Energy System—a Counterfactual Approach, Zeitschrift für Energiewirtschaft, 2019-06-01, Vol.43 (2), pp. 85-100. Juan M. Morales, Salvador Pineda, On the inefficiency of the merit order in forward electricity markets with uncertain supply, European Journal of Operational Research 261 (2017) 789–799. Emma Jonson, Christian Azar, Kristian Lindgren, Liv Lundberg, Exploring the competition between variable renewable electricity and a carbon-neutral baseload technology, Energy Systems (2020) 11:21–44, https://doi.org/10.1007/s12667-018-0308-6

[616] Anke, Carl-Philipp, How Renewable Energy Is Changing the German Energy System—a Counterfactual Approach, Zeitschrift für Energiewirtschaft, 2019-06-01, Vol.43 (2), pp. 85-100. ("In the counterfactual scenario, where no German RES-E are installed, the conventional capacity increases up to 8 GW (about 8% of the overall conventional capacity) compared to reality in 2016. That indicates that RES-E prevented investments in conventional capacities. Furthermore, power prices in the counterfactual scenario increase up to 18 €/MWh compared to real power prices, which equals the long-term merit order effect. It is composed of three parts: a changed power plant dispatch, higher CO_2 prices and additional conventional capacity. The changed power plant dispatch and higher CO_2 prices increase the power prices up to 12 €/MWh, in contrast the additional conventional capacity decreases the power price up to 3.5 €/MWh.")

f. The Electricity Bill for Consumers

In theory, the electricity could function in a way that fosters competition between electricity generators. Under the applicable EU legislation, the market is opened, consumers have rights, including rights to engage in joint purchasing and to switch supplier, and, in principle, electricity generators get paid only for the energy they deliver.[617] These features might be taken to suggest that the electricity market is an open, competitive market that will work to deliver electricity to consumers in the most efficient ways, thus keeping their bills to the minimum.

In practice, however, that is not how the electricity market works. There are structural problems that prevent efficient market operation. For instance, some of the costs related to the generation and delivery of electricity are not borne by electricity generators and do not find their way into the bills issued to consumers. In addition to electricity consumers, tax payers bear various costs related to the electricity system. For instance, the cost of government oversight over the electricity system is generally charged to tax payers; in some cases, tax payers also pay for electricity infrastructure, such as transmission lines.

Even those costs that are charged to electricity consumers, however, are not subject to a market mechanism; rather, these costs, including, but not limited to, network- and transportation cost, are passed on to consumers directly in the form of costs, taxes, and levies.[618] These charges typically include a renewable energy surcharge, which is used to sponsor renewable projects. In The Netherlands, this surcharge is called **surcharge renewable energy** ('opslag duurzame energie');[619] the fees payable to the network operator will go up in 2021.[620]

Because consumers are charged for both (i) the electricity they consume, and (ii) the cost associated with the delivery of that electricity (e.g. network, transmission, balancing, etc.), they have an interest in ***keeping the combined total cost as low as possible***, as long as quality standards are met. If the cost of the electricity they consume is low, but the cost of delivery (network cost) is high, they may be worse off compared to somewhat higher cost of electricity and lower cost of delivery. Since, as explained above, a significant portion of the electricity bill is not subject to consumer choice, however, the consumer cannot exercise any influence on the decisions in relation to network operation and renewable subsidies.

Thus, electricity consumers must pay cost shares, taxes, levies, and surcharges, but these costs are independent of their choice of electricity supplier. As a result, there effectively is no free market with respect to the operation of the network and the investment in electricity generation technologies.

In addition, due to intermittent renewable electricity generation, consumers are expected to ***change their behavior and invest to save and store energy (e.g. in batteries, which currently are not commercially viable***

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[617] See Part 2 of this report.

[618] For The Netherlands, see, for instance, Samenstelling van de elektriciteitsprijs, available at https://www.energievergelijking.nl/samenstelling-van-de-elektriciteitsprijs/

[619] This surcharge is levied pursuant to the Act on Surcharge for Renewable Energy (wet Opslag Duurzame Energie), and is in addition to the energy tax imposed on energy use. The resulting revenues are used to subsidize renewable energy projects. Opslag Duurzame Energie (ODE), available at https://www.energievergelijking.nl/energie/opslag-duurzame-energie-ode/

[620] Energiekosten 2021, available at https://www.energievergelijking.nl/energie/energiekosten-2021/

The electricity investment market is unfree ('subsidies rule'), and the electricity market, in name, is free ('pricing rules'). Through the subsidies, however, pricing is distorted, and both markets become unfree, to the detriment of the consumer.

at the scale needed to support a transition[621]***)***, and make a host of other changes so that their demand coincides better with the weather conditions that enable renewable generators to produce electricity.[622] The hope is that a smart grid can help to smoothen the discrepancies between supply and consumer demand, but whether, and, if so, at what cost, this can be workable, is an open question. Further, electricity consumers may be exposed to much ***greater price volatility*** and the resulting uncertainty around cost, as the share of renewables in the electricity mix continues to grow.[623]

g. Investing in private electricity generation markets

There is a clear tension, if not conflict, between various EU policies relevant to electricity generating technologies. In the market for investment in electricity-generating technologies, investors make investment decisions based on the expected return on their entire, fully loaded investment, i.e. the total cost, including fixed and variable costs (which explains why they will hesitate to invest in renewable electricity and why renewable subsidies are necessary to generate the necessary incentives). Electricity purchasers at wholesale level make purchasing decisions based on the prices of electricity offered by various generators,

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[621] Sterner, Michael, Franz Bauer, Fritz Crotogino, Fabian Eckert, Christian von Olshausen, Daniel Teichmann, Martin Thema, Chemical Energy Storage, in: Sterner, Michael, Ingo Stadler, Handbook of Energy Storage: Demand, Technologies, Integration, Springer, 2019. ("In terms of capacities, the limits of batteries (accumulators) are reached when low-loss long-term storage is of need. Chemical-energy storage and stocking fulfills these requirements completely. The storing itself may be subject to significant efficiency losses, but, from today's point of view and in combination with the existing gas and fuel infrastructure, it is the only national option with regards to the long-term storage of renewable energies. Chemical-energy storage is the backbone of today's conventional energy supply. Solid (wood and coal), liquid (mineral oil), and gaseous (natural gas) energy carriers are 'energy storages' themselves, and are stored using different technologies. In the course of energy transition, chemical-energy storage will be of significant importance, mainly as long-term storage for the power sector, but also in the form of combustibles and fuels for transport and heat.") See also the example of the serious limitations of battery storage in: Kelly, Michael, Electrifying the UK and the Want of Engineering, The Global Warming Policy Foundation, Essay 11, GWPF, 2020. ("[I]f you wanted to be able to cover a week's power outage after a major storm, it would cost around 1300 times as much using batteries as it would with diesel generators.")

[622] Because renewable power eliminates flexibility on the supply side, the need for flexibility on the demand side increases. These forms of flexibility include smart grids and demand response, also called demand side Management, defined as "electricity demand that can be shifted in time to anticipate or react to certain signals." R.A. Verzijlbergh, L.J. De Vries, G.P.J. Dijkema, P.M. Herder, Institutional challenges caused by the integration of renewable energy sources in the European electricity sector, Renewable and Sustainable Energy Reviews 75 (2017) 660–667.

[623] "When production of energy will be largely driven by fluctuating weather conditions, it seems inevitable that stronger energy price fluctuations will be the result. While such price volatility may currently be perceived as undesirable, it is not unthinkable that some day it will be socially accepted, like is the case for many other commodities with volatile prices." R.A. Verzijlbergh, L.J. De Vries, G.P.J. Dijkema, P.M. Herder, Institutional challenges caused by the integration of renewable energy sources in the European electricity sector, Renewable and Sustainable Energy Reviews 75 (2017) 660–667.

which can drop to the level of only **variable cost**, thus ignoring fixed costs.

This tension between the power plant investment market and the electricity market can be explained on the basis of what has been discussed above:

- The EU energy market, subject to limited exceptions (including capacity mechanisms), is based on the concept of '***energy only***' – only electricity generated, as opposed to capacity, has a market price and is compensated.[624] In theory, electricity generators compete freely in this market, and those which offer the lowest electricity price at any point in time will make the sale.

- Both wind/solar and nuclear are relatively ***capital-intense technologies***. The renewable support schemes reduce the amounts of investment required and/or the commercial investment risks, but for renewables only, to the exclusion of nuclear. In other words, in this market, government subsidies favour one decarbonized electricity technology over another. The claim that any renewable electricity project is "***subsidy-free***" is misleading, as long as government policy requires a minimum share of renewable in the electricity mix or otherwise, directly or indirectly, subsidizes renewable (e.g. by paying for the infrastructure necessary for remote renewable projects to connect to the network).[625] If intermittent renewable energy were an efficient option, it would not have been necessary to impose its production by EU legislation; the latest reiteration of the Renewable Energy Directive requires the addition of further renewable energy facilities at least up to 2030.

- Due to the ***very low variable (marginal) cost of generation*** (wind and sun are free of charge), the price of wind/solar electricity can go very low, if necessary. In other words, because a significant portion of the capital cost or commercial risk is already covered through the subsidy or other support program, wind and solar occupy attractive competitive positions.[626]

- Another decarbonized electricity generation technology, ***nuclear electricity is a victim*** of these programs, and has a hard time to compete when wind and solar electricity are generated abundantly. There may simply be too few hours during a day left for selling electricity at good profit margins to reach profitability, despite the fact that the fully loaded cost of nuclear electricity is significantly lower than the fully loaded cost of wind or solar electricity.

The cost of the renewable support is not borne by the renewable energy generators, but charged to electricity consumers, irrespective of whether they prefer nuclear, renewable or another electricity technology. Nuclear investors, on the other hand, bear all of the costs of their investments, and are thus

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[624] A capacity market compensates mere power generation capacity. The 'energy-only market' is supplemented by flexibility options, such as reserve markets, to guarantee supply.

[625] It has been claimed that wind farms in the Dutch North Sea were subsidy-free. Nuon bouwt subsidievrij windmolenpark in Noordzee, 22 maart 2018, available at https://www.zuidoost.nl/nuon-bouwt-subsidievrij-windmolenpark-in-noordzee/ Cf. Thijs ten Brinck, Brekend: 'Subsidie' op subsidievrij windpark al in 2013 openbaar, 28 nov 2018, available at https://www.wattisduurzaam.nl/12731/energie-opwekken/wind/ez-vereffent-pad-subsidievrij-windpark-hollandse-kust/ These offshore wind turbines benefit from at least two types of government subsidies: (i) exclusion of competing power technologies such as nuclear (the tender was only for wind turbines), and (ii) the construction, free of charge to the power generator, of the necessary infrastructure to get the power on shore.

[626] It has been argued that renewable support schemes result in "overly generous and economically inefficient" incentives. LAURA N. HAAR and LAWRENCE HAAR, An option analysis of the European Union renewable energy support mechanisms, Economics of Energy & Environmental Policy, Vol. 6, No. 1, pp. 131-147.

put in a competitively disadvantageous position. As the investment climate for nuclear is unfavourable, financing cost rises further, resulting in little investment in nuclear in the EU.

In light of these circumstances, the argument that nuclear is more expensive than renewable energy makes no sense, because, even if it is true, the cause of nuclear being more expensive is not inherent to nuclear technology, but is the result of government policies. As we have seen in this study, however, once the cost of capital (which reflects nuclear-hostile policy) is taken out of the equation, ***any cost-based argument against nuclear evaporates*** – nuclear turns out to be cheaper in all cases. Once all indirect subsidies (e.g. electricity market rules, planning, land use) and the externalities are internalized to the electricity generation technology that causes them, the case for nuclear becomes even stronger.

In short, investment in wind and solar is not made unless subsidies are made available, and nuclear, another decarbonized electricity generation technology, does not qualify for any subsidy. As a result, there is ***over-investment in wind and solar*** and ***under-investment in nuclear, to the detriment of the consumer***.

h. Subsidies, free-riding, and externalities in electricity markets

Throughout the analysis presented in this report, we have encountered multiple types of subsidies, free-riding and externalities that distort the market for investment in electricity generation technologies. In this section, we provide a comprehensive overview of all such subsidies, direct and indirect, in cash and in kind, and other advantages extended to renewable electricity generators, in particular wind and solar.

As demonstrated throughout this report, the opened 'energy only' market is an ideal that has not been realized; it assumes that pricing in the electricity market will reflect fully loaded costs, but it does not – entire costs categories are externalized (e.g., integration- and system-related cost), there is extensive free-riding (e.g., renewable energy rides for free on capacity provided by other sources), etc. As a result, the majority of consumers' bills is not for energy consumed, but for all sorts of other costs and charges. In addition to the 'free' energy only market that glorifies marginal cost, rather than total cost, several unfree side markets have arisen to sustain the 'energy only' market – there is a market exclusively for intermittent renewable electricity generation, a market for intermittent renewable subsidies, a market for capacity and capacity payments, a market for transmission infrastructure, a market for electricity delivery, etc. These are segmented, restricted markets that are strictly necessary to keep the ideal of the 'energy only' market alive.

The term subsidy is broad and covers any form of government support that a company receives. A subsidy gives a company an advantage over its competitors, and thus distorts competition, which harms consumers. The EU Treaty therefore generally prohibits subsidies, also known as "state aid," subject to limited exceptions.[627] The European Commission is in charge of ensuring that state aid complies with EU rules.[628] The state aid in relation to renewable energy has been approved by the EU, although it distorts competition.

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[627] Article 107, Treaty on the Functioning of the European Union ("Save as otherwise provided in the Treaties, any aid granted by a Member State or through State resources in any form whatsoever which distorts or threatens to distort competition by favouring certain undertakings or the production of certain goods shall, in so far as it affects trade between Member States, be incompatible with the internal market.")

[628] European Commission, State aid control, available at https://ec.europa.eu/competition/state_aid/overview/index_en.html

The following categories of government support available to renewable electricity generators could be qualified as subsidies, free-riding, or negative externalities that should be eliminated or compensated:

1. ***Direct subsidies (grants) for research and development*** of renewable electricity technologies, including wind and solar technologies;
2. ***Direct subsidies (investments grants, loan guarantees, soft loans)*** for actual renewable electricity projects, including wind and solar projects;
3. ***Indirect subsidies by paying for infrastructure*** required specifically by renewable electricity projects out of general budget, tax revenues, or levies;
4. ***Mandatory, guaranteed minimum shares for renewable energy*** in the energy mix imposed through minimum targets for renewable energy, with renewable energy defined to exclude a competing decarbonized technology;
5. ***Priority and privileged access to the energy market*** through priority dispatch, feed-in tariffs (FiT), feed-in premiums (FiP), to the detriment of competing electricity generators, including decarbonized electricity producers;
6. ***Quota obligations with tradable green certificates***, and similar minimum purchase requirements for renewable electricity;
7. ***Tax incentives*** available only to renewable electricity generation, not to other decarbonized electricity generation technologies;
8. ***Tendering schemes that favor renewable electricity*** generators over other decarbonized electricity generators;
9. ***Expedient permitting and regulatory procedures that reduce the risks for renewable electricity projects, but are not available to other decarbonized electricity projects;***
10. ***Procedures and rules relating to grid access and operation that favor renewable generators or disadvantage other electricity producers;***
11. ***Other features of electricity market design, structure, and functioning that favor renewable electricity projects;***
12. ***Land-related policies that keep the price of land use for renewable electricity projects low,*** including, but not limited to, agricultural policies;
13. ***Lack of obligation for renewable electricity generators to compensate property owners that suffer damage*** (e.g. reduced property value) as a result of location of renewable power plants;
14. ***No internalization of negative externalities*** (e.g. adverse environmental impacts) into the price of renewable electricity generation; and
15. ***Free riding on other technologies that keep the electricity system stable and flexible***, such as base load generators and flexibility providers.

Through combinations of these forms of government support, which vary between EU member states and over time, intermittent renewable energy providers have secured a privileged, priority position in the electricity markets that is incompatible with the principles of the open market, unrestricted competition, and non-discrimination. The cost renewable electricity generators impose on other electricity generators, including other decarbonized generators, transmission and network operators, and consumers, can be politically hidden, but are real nonetheless.

There are strong vested interests in the current renewable policies. The energy transition reflects a mix of ideology and rent-seeking that resist change of the privileged *status quo* enjoyed by intermittent renewable energy. While these privileges have accelerated the transition in the short term by rapidly increasing the share of renewable energy in the mix, there now is a serious risk that the vested interests will prevent policy change to make renewable self-supporting and eliminate government support. Member states face the risk of a 'lock-in' into unsustainable renewable energy policies that are inefficient, threaten the electricity system's stability, and hinder the EU's quest to create a framework for sustainable electricity supply at least cost.[629]

i. Policy Recommendations

Efficient public policy-making is not just some arcane economic concept, it is a ***moral imperative***, because efficient public policy-making allows more needs to be met. Climate change is only one of many major public policy ends. The more resources the energy transition requires, the fewer resources are left over to meet other needs. Conversely, the more efficient the climate issue is addressed, the more resources are available for other important public policies. ***Climate policy-making therefore should avoid wasting resources and be guided by efficiency, including spatial and cost efficiency***.

As discussed in this report, nuclear energy offers significant advantages both from the perspective of spatial demand and from a cost perspective. Our main findings can be summarized in one powerful conclusion:

While nuclear requires a tiny bit of land to provide a whole lot of electricity at a low cost, wind and solar require a whole lot of land to provide a tiny bit of intermittent electricity at a high cost. Government and EU policies obscure this simple fact.

In addition, in terms of other adverse effects, negative impacts, and negative externalities, nuclear electricity would appear to perform better than wind and solar electricity. Thus, as a general rule, nuclear electricity is superior to renewable electricity. Studies that come to different conclusions tend to import policy bias, ignore system cost and externalities, exaggerate the nuclear safety risk and the problem of waste storage, or are otherwise deficient.

The cracks in the EU's regime for the renewable energy revolution can no longer be kept out of sight, as the system is beginning to reach its limits. As the Dutch say, "the shore will turn the ship." ***Given the advantages of nuclear electricity from spatial and economic viewpoints, Member State governments will likely need to add nuclear electricity to their energy mixes to stay on track to meet the EU climate neutrality's objective***. Moreover, with penetration rates of variable renewable electricity increasing, there will soon be pressure on the electricity systems of the Member States. High rates of renewable penetration cause a strong increase in the total cost of the electricity system, which will further drive up the total cost of the electricity system. In anticipation of the rapidly growing need for reasonably priced, reliable source of electricity supply, the EU should take action now.

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[629] Sebastian Strunz, Erik Gawel, Paul Lehmann, The political economy of renewable energy policies in Germany and the EU, Utilities Policy, Volume 42, October 2016, pp. 33-41.

To meet the public demand for nuclear electricity, the EU should place renewable and nuclear on equal footing and endorse a '***Nuclear Renaissance***' program. This program would be aimed at creating a level playing field for renewable and nuclear energy, undistorted by direct or indirect subsidies and other support mechanisms, such as feed-in tariffs, premiums, minimum purchasing, etc.

The EU's '***Nuclear Renaissance***' program would comprise twelve key building blocks:

1. ***Equal treatment***: All decarbonized electricity generation technologies (wind, solar, nuclear) receive equal treatment by the EU and member state governments on the basis of technology-neutrality. Privileges and priorities for intermittent renewable energy are abolished, so that electricity generation technologies can compete on their merits.

    - In all areas of EU policy making, ***nuclear electricity is recognized as a decarbonized electricity technology***, and treated on equal footing with renewable energy – the RED-II (Renewable Energy Directive-II) is amended to become the DED (Decarbonized Energy Directive).
    - National rules granting discriminatory dispatching priority and other subsidies to renewable energy (as identified in the preceding section) are to be prohibited.

2. ***Generator pays principle***: Based on the principles of cost internalization and "polluter pays," all EU policies ensure that the *fully loaded costs, including integration- and system-related costs as well as relevant externalities*, are taken into account in policy making with respect to both renewable and nuclear electricity. This is the generator pays principle.

3. ***No discriminatory subsidies***: *All open and hidden subsidies, direct and indirect, in cash or in kind, and other advantages for renewable energy* (e.g. targets, priority rules, higher or guaranteed feed-in tariffs, subsidized infrastructure necessary for wind on sea, deflated land use prices, etc., as reviewed in the preceding section) are eliminated, so that nuclear can compete on a *level playing field*.

    - In particular, *renewable targets* provide a protected market, eliminate competition by other technologies, and are abolished.
    - Other EU policies are not skewed to provide benefits to renewable energy.
    - For a list of all ways in which an electricity generation technology may be subsidized, refer to the discussion in this part, above.

4. ***Total system cost rules***: *The electricity* market is redesigned so that *total system costs*, rather than marginal cost of subsidized electricity generation technology, drives carbon-neutral investments.

    - In auctions for electricity generations and bidding for electricity development projects, electricity developers are required to reflect the cost of transmission in their bids, and must include delivery to a designated point of delivery, which does not run afoul of the generator pays principle, in their bids.

5. ***Differentiated electricity products***: Based on the idea that unequal cases are not treated the same way, the concept of 'energy only' is no longer construed in a way that favors the marginal cost of stochastic, demand-unresponsive power generation, but recognizes the fundamentally different nature of constant, on demand power supply, and demand-unresponsive power supply.

- Intermittent, demand-unresponsive electricity sources and constant or on demand sources are simply not the same and policies therefore do not discriminate arbitrarily based on marginal cost.

6. ***Holistic assessment:*** The extent to which electricity generation technology, whether wind, solar, or nuclear, has *favorable or adverse effects on other EU interests and policies* (such as habitat and species protection, toxic-free environment, agricultural policy, energy policy, etc.) and causes other externalities, is identified and objectively assessed in connection with policy making at EU and member state levels.

   - As appropriate, the externalities of any such electricity technology are prevented or internalized in the cost of the technology.
   - The extent to which an option represents a '*no regrets*' solution, is explicitly considered in this assessment.

7. ***Expedient regulatory procedures***: Like renewable energy, nuclear electricity equally benefits from *expedited, efficient permitting and regulatory procedures*, and the EU requires that the Member States eliminate privileged treatment of any electricity generation technology in their administrative procedures.

8. ***Legal and policy certainty***: To encourage investment in the best electricity generation technology and keep the finance cost down, *legal and policy certainty* is guaranteed to both renewable and nuclear electricity. This, in and of itself, will already have a salutary effect on the cost of capital of energy projects.

9. ***Adequate compensation of damage***: The EU requires that Member States provide for reasonable compensation for EU persons that suffer damage or harm, or are otherwise disadvantaged, by siting decisions in relation to electricity generation facilities and transmission lines.

10. ***Access to finance on the merits***: Access to private and public finance is a function of the merits of electricity generation technologies.[630] Privileges and discrimination in this area are eliminated.

    - In the context of *sustainable finance*, both renewable and nuclear electricity projects are recognized as decarbonizing, sustainable technologies – the Taxonomy Regulation and the Sustainable Finance guidelines are amended to explicitly recognize nuclear energy projects as sustainable.
    - In the context of *state aid*, nuclear and renewable electricity projects are treated on equal footing, and public financing of all decarbonized electricity generation technologies is explicitly permitted – the Commission's State Aid Guidelines for Environmental Protection and Energy are amended to refer to 'decarbonized energy' instead of renewable energy. Facilities for public finance of electricity generation that comply with these principles, are explicitly permitted.

11. ***EU nuclear energy regulation for the new era***: *EU nuclear energy regulations* are reviewed and updated, as necessary, to ensure that they are fit for purpose and for the new era in electricity

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[630] The World Nuclear Association observes that "[a] significant number of models have been used in recent years to facilitate investment. Most combine a long-term power purchase contract, to reduce revenue risk, and a means of capping investor exposure, for example through loan guarantees." World Nuclear Association, World Nuclear Association, Financing Nuclear Energy, Updated May 2020, available at https://www.world-nuclear.org/information-library/economic-aspects/financing-nuclear-energy.aspx

Based on the principles of cost internalization and "polluter pays," all EU policies ensure that the fully loaded costs, including integration- and system-related costs as well as relevant externalities, are taken into account in policy making with respect to both renewable and nuclear power. This is the generator pays principle.

generation. Nuclear regulation is necessary, but also *effective and efficient*. The safety of nuclear installations and spent nuclear disposal are paramount, but excessive bureaucracy and red tape are to be avoided.

12. ***EU nuclear liability and compensation program***: The EU enacts *EU regulation on nuclear liability* on the basis of the Paris and Vienna Conventions to ensure that there are further incentives for prevention and compensation is available if a nuclear accident were to happen. Even though any such accidents are extremely unlikely, adequate and prompt compensation of any damage due to nuclear accidents is important to restore the public's confidence in nuclear energy.

The case of nuclear energy in the EU is like the case of the bird in the hands of the young boy. The young boy came up to the wise old man, intending to fool him. He held a bird in his hand, and asked the old man: "Is the bird dead or alive?" If the old man were to say "the bird is dead," the boy would open his hands and let the bird fly away. If the old man were to say "the bird is alive," he would first squeeze the bird to death and then open his hands. The wise old man saw through the boy's cunning, and answered "the bird is in your hands."

And so it is with nuclear energy in Europe, the bird is in your hands. EU policy makers have the electricity to make nuclear energy a success.

If EU policy makers treat nuclear electricity on equal footing with wind and solar electricity, they will ensure that the EU's climate neutrality program will not become the disappointment it is destined to be. With its tiny footprint and long lifetime, nuclear energy is a 'no regrets' solution that will continue to give back for decades to come.

The EU now has an opportunity to enrich the energy mix, to prevent electricity cost from spiraling out of control, to guarantee a secure electricity system, and to protect the natural resources and beautiful scenery of its Member States.

All the ***Nuclear Renaissance*** program requires is the courage to reject misinformation, insist on neutral, objective assessment, and require non-discriminatory, science-based decision-making.

Fortunately, these are principles the EU holds dear.

9

Conclusions

Conclusions

The EU is committed to achieving climate neutrality (i.e. net zero GHG emissions) by 2050. Electrification of the energy system is a key component of this strategy. This implies that the electricity (or power) system must be completely '**decarbonized**' over the next three decades. Based on the analysis presented in this study, we found that the EU needs a **realistic 'no regrets' solution** to the climate problem.

This study focused on two main categories of decarbonized power generation technologies – renewable, specifically, wind/solar, and nuclear energy. It examined the likelihood of success of the EU climate neutrality strategy, the spatial impacts of the technologies studied, and their respective cost implications. We found that **the nuclear solution is not only as climate-effective as the renewable solution, but is much less space-demanding, significantly cheaper, and has fewer, lesser side effects.**

Effectiveness of EU Climate Neutrality

There is no plan or roadmap that demonstrates how the EU will achieve climate neutrality in an interdependent world.

EU emissions are declining, but constitute no more than 10% of global emissions, and global emissions continue to increase. Even if the EU achieves zero emissions in 2050, it is highly unlikely that the rest of the world will also reduce its emissions substantially. ***Achieving a net-zero global economy by 2050 is tremendously complex, and there is no agreed, coordinated and detailed technology roadmap demonstrating how we could possibly get there***. As Kelly aptly observes, "we have a positive tower of Babel – many people are doing their own little thing, but with no sense that what others are doing will be coordinated to make an overall successful whole."[631]

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[631] Kelly, Michael, Until we get a proper roadmap, Net Zero is a goal without a plan, CAPX, 8 June 2020, available at https://capx.co/until-we-get-a-proper-roadmap-net-zero-is-a-goal-without-a-plan/

There is no detailed plan that demonstrates how the EU will achieve climate neutrality in an interdependent world. EU emissions are declining, but constitute no more than 10% of global emissions. Even if the EU achieves zero emissions in 2050, it is highly unlikely that the rest of the world will also reduce its emissions substantially.

EU 2050 climate neutrality, if achieved, will likely cause a decrease of at most a few tenths of a degree in the global average atmospheric temperature increase. Relative to current policies, 2050 EU carbon neutrality will add ***no more than between 0.02 and 0.06 C average temperature reduction in 2050 and between 0.05 and 0.15 C in 2100, if no carbon leakage occurs, which the EU is probably unable to prevent***.

- For the EU to achieve carbon neutrality in 2050, it must begin now deploying renewable energy at a ***rate at least 4 to 7 times higher*** than the average rate over the last 12 years. Even if the EU can do so over three decades, there still is a very high likelihood that other countries will not limit their emissions, thus frustrating the EU's efforts.

- To prevent this unfortunate outcome, the EU must also stop, either directly or indirectly,[632] carbon emissions from outside EU territory anywhere in the world. This effectively requires acquiring the current estimated reserves of fossil fuels. Such a purchasing program would involve a ***minimum cost of € 560,000.00 per household***, or a total expense of € 109,200,000,000,000, which is approximately 7 times the entire EU's annual GDP and thus would be prohibitively expensive. Thus, the only sure way to ensure the EU's climate neutrality efforts will not be in vain is unrealistic, rendering the EU climate neutrality policy ineffective.

At the global level, climate policy's track record is abysmal. Aggregate global emissions of greenhouse gases have continued to rise since the 1990s when the United Nations Framework Convention on Climate Change was adopted. There is no reason to believe that this will change any time soon.

A counter-factual variation on an English historical quote, we might ask: "***On what principle is it that, when we look we see nothing but failure behind us, we are to expect nothing but improvement before us?***"[633]

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[632] Indirect means of curbing emissions outside the EU's territory include diplomacy, trade restrictions, and a carbon border adjustment tax, none of which will likely be effective, given the economic value of fossil fuels, as discussed below.

[633] "We cannot absolutely prove that those are in error who tell us that society has reached a turning point — that we have seen our best days. But so said all who came before us, and with just as much apparent reason… On what principle is it that, when we see nothing but improvement behind us, we are to expect nothing but deterioration before us?'' quoted in: Gilder G., Time Is on Our Side, June 20, 2020, available at https://dailyreckoning.com/time-is-on-our-side/

For the EU to achieve carbon neutrality in 2050, it must begin now deploying renewable energy at a rate at least 4 to 7 times higher than the average rate over the last 12 years. Even if it will do so, to prevent an unfortunate outcome, the EU must also stop carbon emissions from outside EU territory anywhere in the world, which requires acquiring the current reserves of fossil fuels. Such a purchasing program would involve a minimum cost of €560,000.00 per household.

No Regrets Solutions

The likely ineffectiveness of the EU climate neutrality program makes '***no regrets***' solutions attractive to policy makers. The question thus arises whether nuclear energy, relative to wind and solar, is such a solution. To answer that question, this study examined the spatial requirements and cost of wind/solar versus nuclear power.

'No regrets' solutions should also consider the problem of ***stranded assets*** and ***other public needs***. From a precautionary perspective, policy makers need to consider the ***risk that the renewable energy revolution will not deliver***, and that enormous amounts of resources may turn out to be wasted. In addition, the cost of the energy transition should not be treated as a 'whatever it takes' moral mandate, but as a question of the allocation of scare resources. An ***efficient energy transition will ensure that we can achieve two objectives: establish a reliable, affordable energy system and leave resources for other important public needs***.

Spatial Requirements

For the Czech Republic, the amount of space required to generate 1,800 PJ by wind and solar would range from 14,630 km² to 43,758 km². To put this into perspective, the area required to provide this energy would **cover 19% and 55% of the Czech Republic's available land**. Achieving the same level of electricity output with **nuclear power** would require no more 269km², i.e. **only between 0.6 and 1.8% of the surface** required by renewable energy.

We found that the amount of space required to provide annually 3000 PJ of power to The Netherlands by wind and solar power in 2050 would range from 24,538 to 68,482 km². To put this in perspective:

- 24,538 km² is roughly the size of the **five largest provinces of The Netherlands** combined (Friesland, Gelderland, Noord-Brabant, Noord-Holland, and Overijssel); and
- 68,482 km² corresponds to about **1.8 times the entire land territory of The Netherlands**.

To generate the same amount of energy, nuclear power would require, on average, only 120 km², which is less than half the size of the city of Rotterdam. Thus, due to their **low power density, wind energy requires at least 266 (offshore) to 534 (onshore) times more land and space than nuclear** to generate an equal amount of electricity; for solar on land, at least 148 times more land is required (disregarding, in all cases, the additional land required for the necessary network expansion and energy storage or conversion solutions).

Costs of Power Generation

The cost of nuclear power generation is lower than the cost of wind/solar, in most scenarios by a significant margin. In the best-case scenario for wind/solar, the cost of nuclear is still slightly lower. In the worst-case scenario for wind/solar, ***nuclear is almost 4 times cheaper***.

For an average ***Czech household***,[634] this means an annual electricity bill that is **at least € 50 more expensive for wind/solar** compared to nuclear energy; for the ***Dutch***, it implies an annual household electricity bill that is ***at least € 165 more expensive for wind/solar*** compared to nuclear energy.

Integration- and System-Related Cost

In reality, the cost of wind/solar is even higher because these technologies require other expenses to bring the power where it is needed and integrate it into the electricity system (so-called integration- and system-related costs). It has been estimated that at penetration rates in excess of 35%, the additional integration cost of wind/solar can spiral out of control,[635] further deteriorating the economic case for wind/solar. ***Other studies that come to different conclusions typically do not fully account for integration and system cost***, or focus only on marginal cost, which is just one cost element, not the whole system cost.

Based on modelling with the ETM, for The Netherlands, ***total energy system costs could be reduced by as much as 18%***, with more cost savings for those scenarios that initially had more renewables in the energy mix. Importantly, grid connection costs, only one part of the integration costs, were ***reduced by over 60% in one scenario, which would save the Dutch government almost EUR 10 billion per year***.

> At the global level, climate policy's track record is abysmal. A counter-factual variation on an English historical quote, we might ask: "On what principle is it that, when we look we see nothing but failure behind us, we are to expect nothing but improvement before us?"

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[634] Based on average per capita electricity usage of 5,800 kWh per annum, or 32,200 kWh per household.

[635] Berthélemy, M. et al. (2018), "French Nuclear Power in the European Energy System", p. 31, SFEN, Paris, pp. 68-69.

Due to their low power density, wind/solar require at least 200 times more land and space than nuclear to generate an equal amount of electricity.

Hydrogen

The EU expects that clean hydrogen will play a possibly key role in the decarbonisation of sectors where other alternatives might not be feasible or be more expensive, such as heavy-duty and long-range transport and energy-intensive industrial processes. This study did not examine hydrogen technology. We note, however, that hydrogen is a possible option with respect to both wind/solar (but only when there is excess power production) and nuclear (any time consumer power demand is low or constantly if so desired). ***If hydrogen-technology can be developed and commercially deployed at scale at reasonable cost, it could play a key role in supporting the European transportation and automobile sectors***.

Other Impacts

EU energy policy-making should also consider impacts of various power generation technologies on other EU policies and interests, such as environmental and health policies, including their respective externalities. To supplement the picture, we produced an inventory of impacts of wind/solar and nuclear energy on pertinent EU policies and interests. These impacts involve adverse effects, risks, and other externalities of the three technologies - wind, solar, and nuclear.

While highly relevant to policy-making, these impacts are hard to quantify. Although the overview this report provides is qualitative, it suggests that there is reason for concern about the adverse impacts of wind/solar beyond spatial demand and cost. For instance, their environmental and health impacts are potentially serious, in particular for wind, at the scale at which these technologies are planned to be deployed. Based on this analysis, we conclude that, ***for the majority of policy concerns, wind/solar, relative to nuclear, present additional, and different or stronger adverse impacts***.

The 'Optimal' Power Mix

The conventional wisdom is that the 'optimal' mix of clean power generation technologies includes ***all technologies***, including fossil fuel-powered generation technologies if combined with air emission controls and carbon capture and storage or similar carbon removal technologies. There is something to this wisdom, because it is generally a good idea to diversify and to avoid 'putting all eggs in one basket.' In this vein, ***nuclear energy*** is sometimes positioned as a ***supplement*** to dominant renewable energy. According to the NICE initiative, nuclear energy "***complements and enables*** other clean energy sources, including renewables."[636]

Given the findings of this study, there is reason to be sceptical of this claim. As we have seen, ***nuclear energy outperforms renewable energy*** with respect to both spatial requirements and costs. In addition, as discussed in Part 7 of this report, the drive towards more and more renewable energy creates ***risks*** for our

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636 NICE Future. Flexible Nuclear Energy for Clean Energy Systems. Technical Report, NREL/TP-6A50-77088, September 2020, p. iii, available at https://www.nrel.gov/docs/fy20osti/77088.pdf

electricity network and financial system. The risks and uncertainties associated with an electricity network dominated by renewable sources are significant and hard to manage, in particular now that the EU also attempts to put the force of finance behind the renewable energy drive. If engineering or technical solutions to renewable energy's intermittency problem can be found at all, such solutions may impose very substantial additional cost. From a risk management perspective, ***betting on break-through innovations to ensure a functioning grid is irresponsible policy making***.

Instead of positioning renewable energy as a dominant source and nuclear energy as a complement to it, on economic and environmental grounds, a strong case can be made that ***non-intermittent carbon-neutral power technologies should form the backbone of our electricity system***. Diversification among such technologies is to be encouraged. In such a system, renewable energy sources would play a limited role, due to their enormous space demand, high direct and indirect cost, and high social cost.[637]

Policy Implications

The question arises as to whether current EU policies are '***fit for purpose***.' There are inherent tensions, if not conflicts, between various policy areas, but overall EU policy favors renewable energy over nuclear energy. Massive funding found its way into the development and deployment of wind and solar energy solutions. This had the effect of hampering the deployment of nuclear power in the EU.

Given the advantages of nuclear power from spatial and economic viewpoints, however, ***Member State governments will likely need to add nuclear power to their energy mixes to stay on track to meet the EU climate neutrality's objective***[638] ***and ensure security of supply***. EU policy makers have not yet recognized this new reality. As the European Commission stated correctly in 2016, nuclear energy "contributes to improving the dimension of energy security

Based on modelling, for The Netherlands, total energy system costs could be reduced by as much as 18% by replacing renewable with nuclear, with more cost savings for those scenarios that initially had more renewables in the energy mix.

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[637] Social cost includes environmental cost. Coase, R. H. (1960). The problem of social cost. Journal of Law and Economics, 3, 144. See Part 7 of this study and Annex IX.

[638] Based on data of the International Energy Agency, the European Commission has aptly observed that "limiting temperature rise below 2 °C would require a sustained reduction in global energy CO_2 emissions (measured as energy-related CO_2/GDP), averaging 5.5 % per year between 2030 and 2050. A reduction of this magnitude is ambitious, but has already been achieved in the past in Member States such as France and Sweden thanks to the development of nuclear build programmes." European Commission, STAFF WORKING DOCUMENT Accompanying the Communication from the Commission: Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty for the opinion of the European Economic and Social Committee, Brussels, 4.4.2016, SWD(2016) 102 final, p. 5, available at https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v10.pdf

On economic and environmental grounds, a strong case can be made that non-intermittent decarbonized power technologies should form the backbone of our electricity system. In such a system, renewable energy sources would play a limited role, due to their enormous space demand, high direct cost, and high social cost.

(i.e. to ensure that energy, including electricity, is available to all when needed), since:

a. fuel and operating costs are relatively low and stable;
b. it can generate electricity continuously for extended periods; and
c. it can make a positive contribution to the stable functioning of electricity systems (e.g. maintaining grid frequency)."[639]

To meet the public demand for nuclear power, the EU could place renewable and nuclear on equal footing and endorse a '***Nuclear Renaissance***' program. This program would be based on ***equal treatment, non-discrimination*** and the ***generator pays principle***, and reform the electricity market based on the concept of ***minimizing total system cost***, given performance objectives. It would comprise twelve key elements, which are outlined in Part 8 of this report.

Overall Conclusions

The research and analysis presented in this report demonstrate that ***nuclear power generation outperforms wind and solar energy*** in the Czech Republic and The Netherlands on two key factors: spatial requirements and cost. The positive arguments for nuclear power are compelling, irrespective of whether or not the EU climate policies are appropriate.

There is increasing realization that wind and solar energy are not going to be able to support the European economy, or only at excessive economic and social cost. Other technologies are needed, and nuclear energy is the most prominent candidate. The nuclear power option is a ***'no regrets' solution*** that would meet the EU policy objectives of ***energy security,***

The key lesson to be learned from this study is that nuclear energy and renewable energy are both decarbonized technologies, but, based on its much lower spatial requirements, lower costs, lower energy system risks, and lower environmental and social impacts, only nuclear energy is a 'no regrets' solution.

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[639] Id.

affordability, and social acceptability,[640] and, thanks to its high power density, ***save Europe's landscapes, nature, and scenery***.

The '***no regrets***' approach explicitly focuses the attention on possible policy failure, and asks whether a policy option is still attractive if it does not solve the problem it was intended to remedy. In this study, the two main considerations from a 'no regrets' perspective are (i) the risks of system failure and stranded assets, and (ii) the risk of excessive costs and other adverse impacts. Table 9.1, presents the relevant considerations for renewable and nuclear energy from this decision theoretical perspective.

This approach is not intended to suggest that we are dealing with a black-and-white picture. In reality, it is possible that there is a good case to be made for deployment of renewable energy at small scale in specific situations. Nevertheless, the general picture is clear and hard to ignore.

The key lesson to be learned from this study is that ***nuclear energy and renewable energy are both decarbonized technologies, but, based on its much lower spatial requirements, lower costs, lower energy system risks, and lower environmental and social impacts, only nuclear energy is a 'no regrets' solution***.

In the introduction to this report, we referred to Commissioner Timmermans' invitation to "do the numbers." We did, it turned out he was wrong – ***rather than being "very, very expensive," nuclear energy is a spatially attractive, relatively inexpensive, reliable energy option***. That cannot be said of wind and solar energy.

Since space- and cost-efficiency can no longer be downplayed in climate- and energy policy-making, the EU should urgently revisit its policies.

Technology	**Risk of energy system failure and stranded assets**	**Risk of costs spiraling out of control and other adverse impacts (spatial, environmental, etc.)**
Renewable energy (wind, solar)	High	High
Nuclear energy	Low	Low

Table 9.1.

Since space- and cost-efficiency can no longer be downplayed in climate- and energy policy-making, the EU should urgently revisit its policies.

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[640] This should not be taken for granted, however. Social acceptability of nuclear energy is an issue, as is social acceptability of renewable energy. As discussed in this report, while nuclear energy's social acceptability appears to be growing, that of renewable energy appears to be on the decline.

10

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Annexes / Exhibits

Annex I. Space Model

The model estimates the area across land, waters, sea, and roofs required by a specific power technology to meet a portion of the country's electricity demand.

It is able to estimate the required area for a given mix of renewable and nuclear power.

Model Mechanics

The model explicitly incorporates the following technologies:

- Onshore wind (both land and water)
- Offshore wind
- Solar (both land and roof)
- Nuclear

For each of these technologies, the model requires two user inputs:

- Capacity factor: MWh electricity generated annually as a percentage (%) of capacity
- Density factor: MW of capacity (assuming a capacity factor of 100%) per square km

The assumptions underlying these inputs are discussed in the next section. We use a range, comprised of a minimum value and a maximum value, which correspond to optimistic and pessimistic scenarios. We also present outcomes based on the average of the minimum and maximum values.

The amount of electricity (power) that a technology needs to generate is a function of the total electricity demand and the share of that technology in the energy mix (e.g. onshore wind generates 1/8th of the total electricity demand of 800 PJ). Electricity demand, in turn, is a function of the total energy demand and the portion of total energy demand supplied by electricity:

Electricity Demand = Total Energy Demand in PJ * % supplied by electricity

This approach allows for the model output that can be interpreted in broader contexts, for example in the context of other models that also incorporate other energy sources (e.g. natural gas).

For each power technology, given a certain demand of electricity (in MWh), the inputs are used to calculate the area required by that technology through the following formula:

$$\mathit{Area} = \frac{\mathit{share\ of\ energy\ mix} * \mathit{electricity\ demand}}{\mathit{capacity\ factor} * \mathit{density\ factor} * 365 * 24}$$

To calculate the percentage (%) of land, water, sea, or roof that will be covered as a result of the energy demand and energy mix, the model relies on inputs regarding total land/sea area and available land/sea area. We discuss these inputs in the next section.

Data Inputs & Sources

There are four variables for which inputs into the model are necessary:

- Capacity factors (for each technology)
- Density factor (for each technology)
- Area available (for each type of surface and country)
- Energy demand (for each country)

These variables are country-specific. For each of these variables, we provide the minimum and maximum inputs and the sources therefor, for each of the Czech Republic and The Netherlands.

Furthermore, we use historical data. In other words, the model relies on what has so far been realized with today's technologies. We do not take into account any projections, as these are inherently uncertain. For the purposes of sensitivity analysis (e.g. as it relates to energy demand), we use a broad range of values that reflects the majority of plausible future scenarios.

The Netherlands

Below, we provide the minimum and maximum values we used for each of the inputs into the model for The Netherlands. We contextualize the inputs by referencing the CNS Study prepared by Berenschot/ Kalavasta (hereafter, the "CNS Study").

Capacity Factors

For the capacity factors in The Netherlands, the model uses the value ranges in Table 1, the sources are referenced in the final column and provided in full with links at the end of this annex:

Technology	Min.	Max.	Sources
Onshore Wind	20.0%	25.0%	[4], [24]
Offshore Wind	30.0%	45.0%	[5], [24]
Solar	8.0%	9.5%	[25], [26]
Nuclear	85.0%	93.0%	[17], [18]

Table 1. Capacity Factors

Explanation:

- For onshore wind, based on CBS data, annual capacity factors have predominantly been between 20% and 25% over the last five years, with only one year above 25% (2019: 25.9%, note that this is still a preliminary estimate). Data from Wind Europe (2019) has confirmed that a range of 20-25% is in line with a European average capacity factor of 24%. A recent Enco report confirms that a reasonable onshore capacity factors for the Netherlands would be 24%, fall within our range. [32] Wind Europe predicts that capacity factors for new wind turbines will be in the 30-35% range; we have not used this unrealized prediction because (i) historical data is more reliable, (ii) we do not take future improvements and innovations into account for any technology, and (iii) actual power generated in the case of wind is also a function of the weather (wind), which is uncontrollable.

- For offshore wind, according to CBS data, annual capacity factors have never reached 45%, and have been below 30% for several years. Data from Wind Europe (2019) has confirmed that a range of 30-45% is in line with a European average capacity factor of 38%. A recent Enco report specifies an offshore capacity factor of 43% for the Netherlands, within our range. [32] Again, we note that certain companies have boasted new offshore wind turbines with capacity factors well above 50%. These capacity factors are, for now, theoretical and will vary according to the technological performance, location and atmospheric conditions. For the reasons discussed above, we are not including these unproven technologies in our range.[641]

- For solar, according to CBS data, annual capacity factors have ranged from 7.1% to 9.3% from 2008 through 2019, with only one year above 9.0% (2018). Thus, a range of 8-9.5% is representative.

- Given the lack of nuclear power generation in The Netherlands (there is only one nuclear reactor, at Borssele, which is not being run all the time, hence its capacity factor is not representative), our primary data is limited. However, the capacity factor of a specific type of nuclear power plant is not country-specific. Since The Netherlands is not wedded to any specific type of nuclear power plant, data from types of plants other than the Borssele type is relevant. According to data from the U.S. Energy Information Administration and Office of Nuclear Energy, annual capacity factors are typically above 90% and can reach 93.5%. We set the minimum capacity factor in the model at 85%, which is just below the minimum capacity factor reported in the U.S. data for the last decade or so.

Table 2, is a comparison of our inputs to the assumptions made in the CNS Study.

Technology	Model Min.	Model Max.	Berenschot Report
Onshore Wind	20.0%	25.0%	34.2% (3,000 hours)
Offshore Wind	30.0%	45.0%	51.4% (4,500 hours)
Solar	8.0%	9.5%	9.9% (867 hours)
Nuclear	85.0%	93.0%	n/a

Table 2. CNS Study Assumptions Compared to This Study's Model Inputs

The capacity factors used by Berenschot have been derived from the "Energietransitiemodel" or ETM [27]. In the ETM, under the header "Flexibility" and "Weather

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[641] Specifically, General Electric's new Haliade-X 12 MW offshore wind turbine boasts a capacity factor of 63%. As mentioned on their website, this estimate is based on wind conditions typical in the German North Sea, is not backed up with any data, and cannot reliably be extrapolated to the Dutch North Sea. [31]

conditions," the capacity factors are stated, expressed as full load hours. Berenschot uses much more optimistic capacity factors relative to those used in this study, and hence its model is prone to underestimate the capacity required to meet energy demand (all else equal). Notably, the CNS Study does not include any nuclear power generation, which has a much higher capacity factor than any renewable technology. The ETM does give users the option to include nuclear power generation, but does not feature a capacity factor; it provides a toggle to determine whether the nuclear reactor is "must run" or "dispatchable". In the must run case, the ETM model description states that "maximum capacity" is "more than 80%," but does not provide greater detail. Hence, even if nuclear power were included in the scenarios of the CNS Study, a direct comparison of the capacity factors would have been skewed to the detriment of nuclear.

Furthermore, we note that Berenschot's CNS Study deviates from the default options in the ETM with regards to wind energy, which are notably lower by default: onshore wind full load hours of 1,920 (21.9%) and offshore wind full load hours of 3,500 (40.0%). No explanation is provided by Berenschot for these deviations.

Density Factors

The model uses the inputs for the density factor (expressed as MW of capacity per square km) stated in Table 3.

Technology	Min.	Max.	Sources
Onshore Wind Land	4	9	[1], [2], [3]
Onshore Wind Water	6	8	[3]
Offshore Wind	6	10	[6], [7], [8], [9], [10], [11], [3]
Solar Roof	160	195	[12], [13], [3]
Solar Land	35	88	[3], [28], [29], [30]
Nuclear	250	1,541	[14], [15], [16]

Table 3. Area required per unit of capacity (MW/km2)

- For onshore wind on land, we relied on two sources. The first is a comprehensive 2019 study on the wind power potential in Europe, which provides a method for calculating the area required to build a wind turbine based on the size of its blades [1]. We corroborated these figures with a study from the U.S. [2], as well as the figures from the 'Ruimtelijke Uitwerking' (Space Impact Study) by Generation Energy.[642] Ultimately, we found that the calculation taking into account the rotor diameter was slightly more optimistic than both the U.S. report and the Space Impact study. The range incorporates all values; it therefore is wide, which reflects the reality of the variation in land required to build wind farms. We have not adjusted the range based on possible inefficiencies in wind farm locations, as the best locations are likely to be used first.
- For onshore wind on water, we have relied primarily on the Space Impact Study. These values fall within the range for onshore wind on land and hence appear reasonable.

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[642] Generation Enerhy/Posad Maxwan, Ruimtelijke Uitwerking Energiescenario's, maart 2020, link: https://nlslash.nl/Energietransitie.net/Ruimtelijke_uitwerking_energiescenarios.pdf, p. 14

- For offshore wind, we collected primary data on current Dutch wind farms set up in the North Sea [6, 7, 8, 9, 10, 11], as these are actual, realized numbers. The North Sea wind farms included in the numbers provide a total of 957 MW in capacity and have been built on an area of 134 square km. The implied power density figure falls within the range utilized by Berenschot in the Space Impact study.[643] The range used in our model incorporates the primary data, as well as the values from Berenschot.

- For solar on roof, we relied on estimates from the Dutch advisory body 'Planbureau voor de Leefomgeving' (PBL) [12], which are corroborated by publicly available data on residential solar solutions available through private companies (in this case, Tesla [13]). Our estimates fall well within the range used by Berenschot in the Space Impact study.[644] The range incorporates all values.

- For solar on land, we relied on primary data on existing solar farms in The Netherlands [30]. Research papers and other hypothetical data [28, 29] tend to give lower density factors. The density factors utilized by Berenschot in the Space Impact study vary from plausible to highly optimistic. The authors are incorporating unrealized, hypothetical technological progress in their estimates,[645] hence we have not relied on the Berenschot values for our range. Our range incorporates the generally acceptable standard of 50 MW per square km.

- For nuclear, we relied on primary data on a handful of nuclear plants in Europe, including Borssele [15, 16]. A selection was made based on those with the highest capacity, since prior generation nuclear reactors with low capacity will not be built. We supplemented our primary data with metadata from Cheng and Hammond [14] which gave higher figures. We incorporated these into the range of area used.

For all of these inputs, we checked our initial estimates against data used by Berenschot. Where necessary, we have broadened our ranges to include Berenschot's assumptions, if evidence-based.

Area Available

In general, our approach has been to use the available area after considering "hard restrictions" as defined in the Space Impact Study. The reason is that the areas currently permitted for a particular use are available without amendment to the laws and policies of The Netherlands. The theoretically available area used by Generation Energy is a hypothetical number that is less useful to energy policy making, because utilization of this theoretically available area would require amendments to zoning laws and policies and the elimination of conflicting uses of such space. Even authorized land use changes to permit power generation require political decisions, because they change the living environment and detract from the land available for other uses, such as residential. Land use changes present political choices that should be clearly articulated for policy makers.

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[643] Ruimtelijke Uitwerking Energiescenario's, p. 14

[644] Ruimtelijke Uitwerking Energiescenario's, p. 14

[645] Berenschot uses estimates developed by IRENA. IRENA has based their future cost estimates primarily on two factors: the historic learning curves and a "technology-based analysis of the cost reduction potential along the manufacturing value chain." Both of these might introduce severe optimism bias and might not be replicable or are hypothetical. See IRENA, 2016, "The Power to Change: Solar and Wind Cost Reduction Potential To 2025," p. 37 for a discussion of their general approach to cost estimates. Available at: https://www.irena.org/publications/2016/Jun/The-Power-to-Change-Solar-and-Wind-Cost-Reduction-Potential-to-2025

Category	Total (sq. km)	Available after restrictions (sq. km)	% of total	Technologies Considered
Land	37,390	21,230	57%	Wind, Solar, Nuclear
Waters	7,872	700	9%	Wind
Roof	1,250	286	23%	Solar
North Sea	57,800	18,000	31%	Wind

Table 4. Areas available for power generation

Table 4, summarizes the various areas/spaces (land, waters, roof, North Sea) available under current policies for the power generation technologies stated. We also indicate the total surface area so that a percentage can be calculated. These numbers are derived from work done by Generation Energy published in the Space Impact Study.

As this table shows, the percentage of available space is very high for land, at 57% of the total land area of The Netherlands. The area of available North Sea space is also high at 31%. Given that wind power is regarded as an important part of the electricity mix in The Netherlands, these high portions of available space necessitate deliberate policy choices (see further below).

To provide additional context, we offer the following comments:

- For wind and solar, we have identified 21,230 square km that are available under current policies. Although Generation Energy does not explicitly state so, this figure presumably includes predominantly agricultural terrain as well as some nature and conservation areas. This represents about 57% of the total land area of 37,390 square km, excluding so-called internal surface waters.
- Surface waters (both internal and coastal) are also considered for onshore wind turbines. Given policy restrictions, the area adds up to 700 square km. All waters in the Netherlands (excluding the North Sea) add up to 7,872 square km, so the available area is just below 10%. We are considering these waters as an option only for wind.
- For roofs, which are considered technically an option only for solar, the total area is about 1,250 square km. Given policy restrictions, about 23% is available for solar technology, or 286 square km. Note that this number includes solely current roof area, not projected roof area. The Space Impact Study also makes projections for the future available roof area, but we focus on what is currently available. Generation Energy forecasts an additional 200 square km or so in total roof area, only 30% of which is ultimately available for solar. Hence, the difference between existing and projected is not significant enough to have a meaningful impact on the model output.
- With respect to the North Sea, the area available given restrictions is 18,000 square km, or about 31% of the total 57,800 square km.

These numbers only encompass areas that can and may be authorized for the construction of power generation facilities under current policies. Note, however, that these numbers do not reflect what is desirable from other standpoints (e.g. political, socio-economic, nature conservation, etc.). For example, for land area, The Netherlands has about 22,000 square km in agrarian terrain. Given that the model considers

57% of all land to be available for power generation, a very large portion of agrarian land could potentially be commissioned for power generation. For policy reasons, such an extensive use of land for power generation may not be deemed desirable, despite being technically feasible.

Energy Demand

Unlike the CNS Study by Berenschot,[646] our model regards energy demand as an exogenous variable, given that it is extremely difficult to predict energy demand 30 years from now and that energy policy choices at one point in time (as in the ETM model) cannot be used to accurately predict energy demand. This is so because energy demand is a function of many variables, such as general economic development and welfare, industrial mix, innovation, etc. This is why the sensitivity analysis of the model accounts for broad ranges of energy demand and electricity production.

In addition to total energy demand, the percentage of energy provided by electricity is a critical factor. This is the degree of 'electrification' of the energy demand. The general thinking, as reflected in the CNS Study, is that the degree of electrification of the energy demand is bound to increase over the next several decades, as activities such as heating and transport increasingly move away from fossil fuel and switch to power or batteries. We believe that, like total energy demand, the degree of electrification in 2050 is hard to predict and necessitates a wide range.

Table 5 below compares the CNS Study by Berenschot to historical figures, as well as the range used in our model sensitivity analysis.

	Energy Demand (PJ)	% supplied by electricity
Berenschot Report	1,600 - 2,500 PJ	30 – 45%
Historically (L20Y)	3,000 – 3,500 PJ	10 – 20%
Sensitivity Analysis	1,500 – 4,000 PJ	10 – 100%

Table 5. Comparison of Energy Demand and Degree of Electrification

Ultimately, what determines the amount of nuclear and renewables capacity necessary is the electricity demand. To simplify the analysis, we make the assumption that nuclear and renewables (wind, solar) are the only sources generating electricity.[647] So if overall energy demand were 3,000 PJ and 50% is supplied by electricity, the remaining 50% being supplied by other sources such as fossil fuels, the model will give us the land requirements for a given mix of nuclear and renewables such that all nuclear and renewable assets jointly generate an expected 1,500 PJ annually.

Czech Republic

Below, we provide the minimum and maximum values we used for each of the inputs into the model for the Czech Republic. Note that the Czech Republic does not have jurisdiction over any seas, so they do not have the option of producing electricity from offshore wind. Their internal waters are also not substantial enough to warrant onshore wind in waters.

The discussion on the inputs for the Czech Republic will be more limited than that of The Netherlands; a lot of the general comments made in the above section for The Netherlands also apply for the Czech Republic. In general, most of the inputs are based on data provided by the Ministry of Industry and Trade of the

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[646] The CNS Study relies on the ETM model, which treats energy demand as an endogenous variable that is determined by a series of policy choices made by planners (i.e. model users).

[647] Thus, we exclude other potential power sources, such as H2, gas, or import. The share of these other sources in the power mix in 2050 in the CNS Study varies from just over 20% to 40%.

Czech Republic. Where noted, we have corroborated these data with data from other public sources (mainly academic studies, international energy agencies, etc.).

Capacity Factors

For the capacity factors in the Czech Republic, the model uses the value ranges in Table 6, below; the data provided by the Department of Energy is primarily based on realized data from the last few years:

Technology	Min.	Max.
Onshore Wind	20%	25%
Solar	10%	14%
Nuclear	85%	93%

Table 6. Capacity Factors

Explanation:

- For onshore wind, estimates provided by the Department of Energy point to a capacity factor estimate of 23% over the last few years. Our range is a bit broader to account for two potential developments: future wind turbines being placed in locations that are inferior from a wind perspective and the potential for improvements in technology that could lead to higher capacity factors (e.g. larger blades). We note that the range is the same as the range we have for onshore wind in The Netherlands. Based on research mapping of wind speeds above 100 meters across Europe, this appears consistent with the fact that The Netherlands and the Czech Republic broadly experience similar wind speeds. [1]

- For solar, estimates provided by the Department of Energy point to capacity factors of just over 11% for residential solar and just over 12% for commercial solar plants. This data is consistent with data from the Global Solar Atlas released by the World Bank, which suggests a rough average capacity factor of 12% for the Czech Republic. [33] Other sources corroborate these estimates further. [36] These estimates are all included in our range.

- Different from The Netherlands, the Czech Republic has been more friendly towards nuclear energy and hence has historic data available. Based on triangulated data from the International Energy Agency and the Nuclear Energy Agency, the Czech Republic's capacity factor for nuclear energy was around 88% for the years 2018 and 2017 (data for 2019 was not available in this publication). [34, 35] As such, we stick to a similar range as for The Netherlands.

Density Factors

The model uses the inputs for the density factor (expressed as MW of capacity per square km) stated in Table 7.

Technology	Min.	Max.
Onshore Wind Land	4	9
Solar Roof	134	176
Solar Land	35	88
Nuclear	250	1,541

Table 7. Area required per unit of capacity (MW/km2)

- For onshore wind land, solar land, and nuclear we have made the same assumption as we did for The Netherlands, assuming similar technologies would be used in the Czech Republic. We refer the reader to the section of The Netherlands for a discussion on these technologies. The relevant figures provided by the Department of Energy fell within this range.

- For solar on roof, the data provided by the Department of Energy pointed to slightly lower density factors in the Czech Republic compared to The Netherlands and have hence lowered the range slightly to account for these data.

Category	Total (sq. km)	Available after restrictions (sq. km)	% of total	Technologies Considered
Land	78,865	5,738	7.2%	Wind, Solar, Nuclear
Waters	7,872	0	0%	Wind
Roof	N.A.	78		Solar

Table 8. Areas available for power generation

Area Available

For the area available in the Czech Republic, we have relied on two Czech studies conducted to estimate the potential for both wind and solar. [37, 38] General limitations that have been accounted for include national parks, roads, other infrastructure, military areas, etc. Table 8, below, summarizes the various areas/spaces available under current policies for the power generation technologies stated.

As this table shows, the percentage of available space is much lower than what was available in The Netherlands. Notably, the Czech Republic has no access to the sea, so it cannot build any offshore wind, and has predominantly rivers as its internal waters, which are not suitable for wind energy. The Czech Republic has generally been more neutral in the nuclear and renewables trade-off, and hence has been able to draw clearer lines as to which land is available for energy technologies.

However, these conclusions align directionally with the available research. Two studies in particular, one that estimates the potential of wind power [1] and one that estimates the potential of solar power [36] in Europe, use high-resolution land cover maps and spatial raster datasets (where available) to estimate the potential land and roof available. The studies point to available space in the Czech Republic that is about twice as high, i.e. roughly 10,000 km^2 of available land and 185 km^2 of available rooftop. Given that the Czech studies are a bit more conservative, we use those figures. Estimates based on high-level data, including maps, is likely to overestimate the available space given their insensitivity to potential protected status of pieces of land, land spaces that are used for other purposes (e.g. military exercises) but look otherwise free, etc.

Energy Demand

As for The Netherlands, we approach energy demand as an exogenous variable, and, as such, will perform sensitivity analysis with broad ranges. In general, the Czech Republic has a lower energy demand than The Netherlands. As such, the range for our sensitivity analysis will not be as broad.

Table 9 lists the primary energy sources as provided by the Department of Energy. We also list the figures that will be used in the sensitivity analysis.

	Energy Demand (PJ)	% supplied by electricity
2019	1,801 PJ	20%
2050 projections	1,017 PJ	27%
Sensitivity Analysis	1,000 – 3,000 PJ	10 - 100%

Table 9. Energy Demand and Degree of Electrification

As discussed above, what determines the amount of nuclear and renewables capacity necessary is the electricity demand.

To simplify the analysis, we make the assumption that nuclear and renewables (wind, solar) are the only sources generating electricity.[648]

Model Outcomes & Sensitivity Analysis – The Netherlands

In this Appendix, we present several model outputs for The Netherlands:

1. Comparison of the various technologies to establish the space trade-offs involved in choosing between technologies
2. Spatial restraints to assess maximum power capacity of The Netherlands for the power technologies concerned
3. Impact of increasing share of renewables on land and sea usage
4. Sensitivity analysis of a 100% renewables scenario
5. Sensitivity analysis of a 50% / 50% nuclear and renewables scenario
6. Sensitivity analysis of a 100% nuclear scenario

Comparing Technologies

As a first exploratory step, we compare the technologies by imposing the same energy demand requirements on each. In our first scenario, we require that each technology meet 100% of the electricity demand. In this scenario, total energy demand supplied by electricity is 800 PJ per annum, which represents 40% of the total energy demand of 2,000 PJ per annum, somewhere in the middle of the Berenschot ranges and consistent with our ranges as stated in Table 5, above. The outcomes are presented in Table 10.

Explanation:

- As mentioned earlier, we employ ranges for each of capacity and density factors. Given we use ranges with minima and maxima, we effectively have two corner points that represent extremes for the required land. The pessimistic corner point uses the minima for both the capacity and density factors, whereas the optimistic corner point uses the maxima for both those factors. We also represent an "average" scenario that corresponds to the simple of average of both the capacity and density factors.

- In other words, if solar roof installations must produce 800 PJ of electricity annually, it would require at least 479% of the available roof space. Thus, at this level of demand, solar roof exceeds

	Area Required (km^2)			Area Required (% of Available)		
	Pessimistic	**Average**	**Optimistic**	**Pessimistic**	**Average**	**Optimistic**
Onshore wind land	31,710	16,987	10,941	149%	80%	52%
Onshore wind water	21,140	16,107	12,684	3020%	2301%	1812%
Offshore wind	14,093	8,456	5,637	78%	47%	31%
Solar roof	1,982	1,633	1,369	693%	571%	479%
Solar land	8,983	4,722	3,052	42%	22%	14%
Nuclear	119	32	18	1%	0%	0%

Table 10. Area Required At Full Demand Met By Specific Power Technology

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[648] Thus, we exclude other potential power sources, such as H2, gas, or import.

the available roof space. More realistically, if the full demand is met through onshore wind on land, at least 52% and up to 149% of the available area is required. On the other hand, if nuclear is to meet 800 PJ of electricity demand, it would require at most 120 square km of land. This scenario, of course, is not realistic, because it is unlikely that policy makers would want only one power technology to supply all power, but it is useful to illustrate the relative land/space demand.

The absolute and relative space demands can be more realistically illustrated by requiring that each technology supply an equal share of the demand. Specifically, if each of the six technologies is to generate 16.67% of the annual 800 PJ of electricity demand, the areas required are set forth in Table 11.

Thus, for onshore wind on water and solar on roof, the scenario whereby all the available space is exceeded is within our reasonable range of possible outcomes.

Table 12, summarizes the impact on the total land, water, roof, and sea usage for this scenario of equal share.

As the table shows, a perfectly equal power mix implies that the space demand of onshore water and roof space could exceed the available space. Thus, this mix might not be feasible. However, this exercise allows us to get a better feel for the impact of each technology on their spatial environment.

In the CNS Study, in the scenario with the highest output of wind and solar, the "Nationale sturing," 15% is generated by solar on roof, 17% by solar on land, about 8.5% by onshore wind, and 32% by offshore wind. If we put this in our model, the space demand would be as set forth in Table 13.

In this scenario, renewables generate 580 PJ of energy per annum. While this scenario is relatively conservative in terms of its final energy demand, already a quarter of the available North Sea is covered in wind turbines, and a fifth of the available land. Furthermore, solar on roof might already exceed the available space.

Spatial Restraints and Power Produced

A scenario that takes restraints into account is probably more relevant to policy makers who by necessity operate under restraints. Under this kind of scenario, policy makers, confronted with conflicting demands on land and space, ex- or implicitly set limits on any land or space demand by an activity, be it residential, industrial, power generation, agriculture, fishery, recreation, nature protection, landscape, horizon and silence protection, transportation or yet nother demand.

	Area Required (km^2)			Area Required (% of Available)		
	Pessimistic	**Average**	**Optimistic**	**Pessimistic**	**Average**	**Optimistic**
Onshore wind land	5,285	2,831	1,824	25%	13%	9%
Onshore wind water	3,523	2,684	2,114	503%	383%	302%
Of fshore wind	2,349	1,409	940	13%	8%	5%
Solar roof	330	272	228	115%	95%	80%
Solar land	1,497	787	509	7%	4%	2%
Nuclear	20	5	3	0%	0%	0%

Table 11. Area Required By Each Technology If Each Produces Equal Share of Total Electricity Demand

	Area Required (km²)			Area Required (% of Available)		
	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
Onshore land	6,802	3,623	2,335	32%	17%	11%
Onshore water	3,523	2,684	2,114	503%	383%	302%
Sea	2,349	1,409	940	13%	8%	5%
Roof	330	272	228	115%	95%	80%

Table 12. Impact on Space If Each Technology Produces Equal Share of Total Electricity Demand

	Area Required (km²)			Area Required (% of Available)		
	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
Onshore wind land	2,695	1,444	930	13%	7%	4%
Onshore wind water	0	0	0	0%	0%	0%
Offshore wind	4,510	2,706	1,804	25%	15%	10%
Solar roof	297	245	205	104%	86%	72%
Solar land	1,527	803	519	7%	4%	2%
Nuclear	0	0	0	0%	0%	0%

Table 13. Area Required By Each Technology In Berenschot Scenario "Nationale Sturing"

In the scenario that is explored here, the model operates under the following restraints: (i) no more than 50% of any available space may be used for power generation, and (ii) priority should be given to the various technologies in the following hierarchical order, which is based on space efficiency, with the more efficient ranked higher:

- offshore wind (sea, few competing uses)
- solar roof (few competing uses)
- solar land (many competing uses)
- onshore wind land (many competing uses)
- onshore wind water (many competing uses)

In this scenario, nuclear is not regarded as an option, and is added only for purposes of comparison. Furthermore, we are operating in the pessimistic case.

The hierarchy demands that the higher ranked technology be exhausted first up to the 50% space limit before the next technology is added. We first explore how much power is produced if all of these technologies, except nuclear, are fully utilized up to maximum limit; we then add nuclear up to 50% of the space to compare with renewable. Table 14, below, presents the results.

Technology	Land	Water	Sea	Roof	Electricity Production (PJ p.a.)
Offshore Wind	-	-	50%		510
Solar Roof	-	-	-	50%	58
Solar Land	50%	-	-	-	950
Onshore Wind (Land)	n/a (full)	-	-	-	
Onshore Wind (Water)	-	50%	-	-	13
TOTAL RENEWABLE	50%	50%	50%	50%	**1,531**
Nuclear (as alternative)	50%				**71,800**

Table 14. Area Required If Restraints Are Put in Place (no more than 50% of space, hierarchical order for technology)

Technology	Land	Water	Sea	Roof	Electricity Production (PJ p.a.)
Offshore Wind	-	-	20%	-	204
Solar Roof	-	-	-	20%	23
Solar Land	20%	-	-	-	380
Onshore Wind (Land)	n/a (full)	-	-	-	
Onshore Wind (Water)	-	20%	-	-	5
TOTAL RENEWABLE	**20%**	**20%**	**20%**	**20%**	**612**
Nuclear (as alternative)	20%				28,720

Table 15. Area Required If Restraints Are Put in Place (no more than 20% of space, hierarchical order)

Thus, the expected electricity production if we use 50% of the available space for renewable power in this a scenario would be about 1,500 PJ per annum. For context, The Netherlands had energy demand of over 3,000 PJ for the last 20 years. There is no scenario in the CNS Study where renewables are tasked to generate this much energy. However, Berenschot assumes that in its most ambitious scenario almost half of the available energy demand is met by electricity from renewables. Hence, this scenario would mean that if overall energy demand in the Netherlands stays flat at about 3,000 PJ, but we ensure that renewables provide about half of it, we would hit the area usage restraint of 50%.

A maximum space utilization of 50% for power generation still is an enormous portion of available space allocated to power generation. Given other competing uses of space (residential use, recreation, industrial use, agriculture, fishery, nature and fauna protection, etc.), a maximum percentage that is politically probably more realistic and feasible is 20%. The model now determines how much power is generated by renewable power under this constraint, and then compares to nuclear. Table 15, presents the results.

With total power generated at 612 PJ per annum, power production would be insufficient to meet the power demand in our middle range scenario of 2,750 PJ per annum and 30% electrification, which results in a power demand of 825 PJ per annum. Under these conditions, there would not be enough power to meet the power demand in Berenschot's lowest demand scenario (lowest energy demand of 1,600 PJ per annum, and 40% electrification, resulting in power demand of 700 PJ per annum.

Space Impact of Increasing Share of Renewables

We now proceed to explore the space impact of renewable power more systematically. To illustrate the impact of increasing the share of renewables on area usage, we plot the percentage (%) of available land and sea utilized for energy (the y-axis) for different shares of electricity generated by renewables (the x-axis). We assume that whatever electricity is not being generated by renewables is being generated by nuclear.

We map out three different scenarios:

- "*2019 Baseline*" – This resembles the current (2019) make-up of energy demand and electricity mix: 3,000 PJ of annual energy demand, with 15% being met by electricity. In other words, every combination of nuclear and renewables supplies 450 PJ of energy per annum.

- "*2050 H/H*" – This represents an extreme scenario that projects 4,000 PJ per annum and a 50% rate of electrification (high/high). Renewable and nuclear power jointly supply 2,000 PJ per annum.

- "*2050 Berenschot*" – This resembles Berenschot's "Regionale sturing" scenario from the CNS Study, with energy demand dropping to 1,750 PJ per annum and 45% of that being met with electricity. In other words, every combination of nuclear and renewables supplies roughly 790 PJ per annum. This, in combination with the "Nationale sturing" scenario, are the most demanding Berenschot scenarios when it comes to renewables power.

We assume a renewable power mix that is one part onshore wind, four parts offshore wind, and three parts land solar. This is very roughly in-line with the Berenschot electricity make-up from the Space Impact Study.[649] For simplicity, we have not included roof solar and onshore wind on water, which make only small contributions to total power in the Berenschot scenario.

Figure 1, presents the results.

The graph demonstrates the spatial trade-offs between nuclear and renewables. At the extremes, it shows that 100% renewable power requires substantial portions of the available space -- from approximately 19% up to 86% of available land, and from 22% to 98% of available sea. Put differently, the pressure on space and the potential for conflicting demands continue to increase as the share of renewable power in the mix increases, even if policy makers are willing to dedicate very large portions of available space to power generation in order to avoid having to resort to renewable.

The 2050 Berenschot scenario begins to show what increasing shares of renewable power will mean for space utilization. At a low level of power demand, 100% renewable power imposes serious requirements on land and sea space, at 34% and 39%, respectively; these ratios may exceed the amount of space policy makers are willing to allocate to power generation.

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[649] Space Impact Study, p. 13. The Space Impact focuses on what Berenschot calls the 'European Governance' scenario.

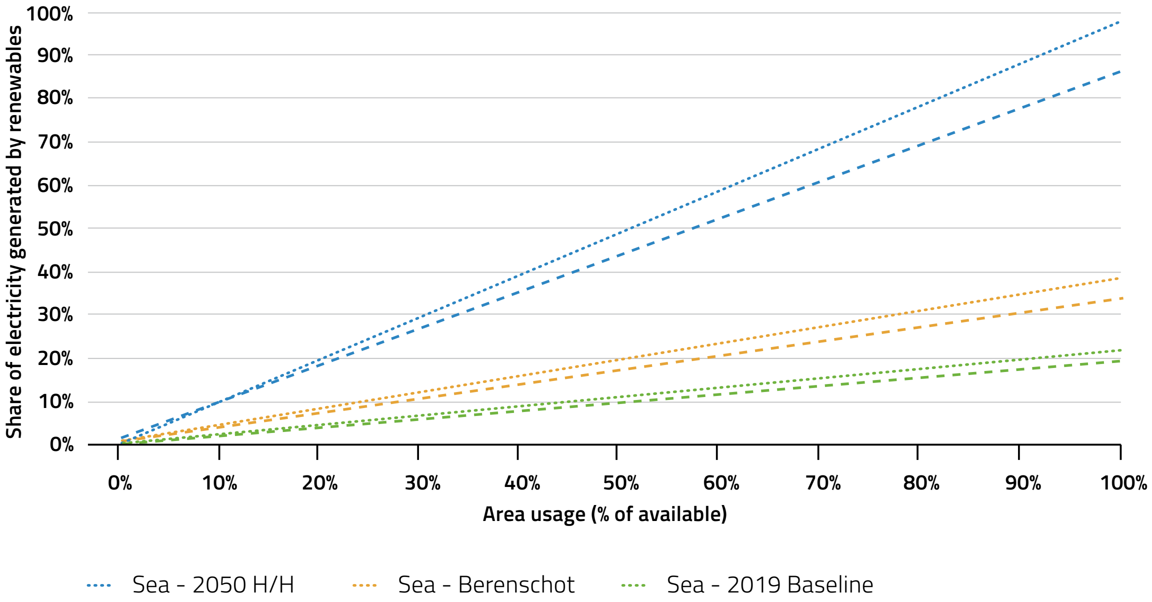

Figure 1. Impact of Increasing Share of Renewables on Area Usage

In the 2050 H/H scenario, the limits of available space are reached or exceeded. At 100% renewables, 98% of the available sea is utilized and 86% of the available land. These findings highlight the importance of potentially integrating other sources of energy (e.g. nuclear), as relying solely, or to a significant extent, on renewables can lead to issues if by 2050 electricity demand increases by more than the CNS Study is willing to assume.

In the 2019 Baseline scenario, based on 2019 data from the CBS [26], of the roughly 3,000 PJ in total energy demand, about 232 PJ came from renewables, just below 8%. This suggests that if policies were to move towards 100% renewables, we would need to increase the area currently covered by renewable energy sources by a factor of 12, both on sea and on land; in other words, the same surface of land and sea allocated to renewable power up to and including 2019, would have to be allocated 11 more times up to 2050 to provide sufficient space for renewable power.

100% Renewables

In this sensitivity analysis, the energy demand (y-axis) and rate of electrification (x-axis) vary, and all of the electricity demand is met by renewables (non-electricity energy demand is met by other energy sources[650]). We assume a renewable power mix of 30% onshore wind, 40% offshore wind, and 30% solar (thus, 60% is generated onshore, 40% is generated offshore). We have used the low end of the range for both the capacity factor and the required land for installation, i.e. the "pessimistic" case. Table 16, below, presents the results for both land area required and sea area required.

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[650] For the purposes of this model, if not the full 100% of energy is supplied by renewable power, the remainder is supplied by other energy sources. The model focuses solely on the space impact of renewable power and does not consider the impact on space usage of other energy sources.

Available Land Occupied

Energy Demand (PJ)	% of Energy Demand Supplied by Renewables								
	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	10.8%	16.2%	27.0%	37.7%	48.5%	53.9%	59.3%	80.9%	107.8%
1,750	12.6%	18.9%	31.4%	44.0%	56.6%	62.9%	69.2%	94.3%	125.8%
2,000	14.4%	21.6%	35.9%	50.3%	64.7%	71.9%	79.1%	107.8%	143.8%
2,250	16.2%	24.3%	40.4%	56.6%	72.8%	80.9%	88.9%	121.3%	161.7%
2,500	18.0%	27.0%	44.9%	62.9%	80.9%	89.8%	98.8%	134.8%	179.7%
2,750	19.8%	29.6%	49.4%	69.2%	88.9%	98.8%	108.7%	148.2%	197.7%
3,000	21.6%	32.3%	53.9%	75.5%	97.0%	107.8%	118.6%	161.7%	215.6%
3,250	23.4%	35.0%	58.4%	81.8%	105.1%	116.8%	128.5%	175.2%	233.6%
3,500	25.2%	37.7%	62.9%	88.1%	113.2%	125.8%	138.4%	188.7%	251.6%
3,750	27.0%	40.4%	67.4%	94.3%	121.3%	134.8%	148.2%	202.2%	269.5%
4,000	28.8%	43.1%	71.9%	100.6%	129.4%	143.8%	158.1%	215.6%	287.5%

% of Available Sea Occupied

Energy Demand (PJ)	% of Energy Demand Supplied by Renewables								
	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	6%	9%	15%	21%	26%	29%	32%	44%	59%
1,750	7%	10%	17%	24%	31%	34%	38%	51%	69%
2,000	8%	12%	20%	27%	35%	39%	43%	59%	78%
2,250	9%	13%	22%	31%	40%	44%	48%	66%	88%
2,500	10%	15%	24%	34%	44%	49%	54%	73%	98%
2,750	11%	16%	27%	38%	48%	54%	59%	81%	108%
3,000	12%	18%	29%	41%	53%	59%	65%	88%	117%
3,250	13%	19%	32%	45%	57%	64%	70%	95%	127%
3,500	14%	21%	34%	48%	62%	69%	75%	103%	137%
3,750	15%	22%	37%	51%	66%	73%	81%	110%	147%
4,000	16%	23%	39%	55%	70%	78%	86%	117%	157%

Table 16. Sensitivity Table of Area Occupied by Renewable Power As a Function of Energy Demand and Share Supplied by Renewables % of

The black dividing line running through these tables indicates where the available space is exceeded (i.e. percentages of more than 100% in the lower right area under the line colored yellow/red). As these tables show, in this scenario, if only half of the power is generated by renewables, all available land is occupied with wind and solar at a power demand of 3,000 PJ. The available North Sea space is exhausted if renewable supplies 75% of the power and the demand is 3,500 PJ.

50% Nuclear / 50% Renewables

In this scenario, half of the electricity demand is met by nuclear power, 15% by onshore wind, 20% by offshore wind, and 15% by solar on land; the other assumptions as for the 100% renewable case above apply here too. Table 17, presents the results.

% of Available Land Occupied

Energy Demand (PJ)	% of Energy Demand Supplied by Renewables & Nuclear								
	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	5.4%	8.2%	13.6%	19.1%	24.5%	27.2%	29.9%	40.8%	54.4%
1,750	6.4%	9.5%	15.9%	22.2%	28.6%	31.8%	34.9%	47.6%	63.5%
2,000	7.3%	10.9%	18.1%	25.4%	32.7%	36.3%	39.9%	54.4%	72.6%
2,250	8.2%	12.2%	20.4%	28.6%	36.7%	40.8%	44.9%	61.2%	81.7%
2,500	9.1%	13.6%	22.7%	31.8%	40.8%	45.4%	49.9%	68.0%	90.7%
2,750	10.0%	15.0%	24.9%	34.9%	44.9%	49.9%	54.9%	74.8%	99.8%
3,000	10.9%	16.3%	27.2%	38.1%	49.0%	54.4%	59.9%	81.7%	108.9%
3,250	11.8%	17.7%	29.5%	41.3%	53.1%	59.0%	64.9%	88.5%	117.9%
3,500	12.7%	19.1%	31.8%	44.5%	57.2%	63.5%	69.9%	95.3%	127.0%
3,750	13.6%	20.4%	34.0%	47.6%	61.2%	68.0%	74.8%	102.1%	136.1%
4,000	14.5%	21.8%	36.3%	50.8%	65.3%	72.6%	79.8%	108.9%	145.2%

% of Available Sea Occupied

Energy Demand (PJ)	% of Energy Demand Supplied by Renewables & Nuclear								
	10%	15%	25%	35%	45%	50%	55%	75%	100%
1,500	3%	4%	7%	10%	13%	15%	16%	22%	29%
1,750	3%	5%	9%	12%	15%	17%	19%	26%	34%
2,000	4%	6%	10%	14%	18%	20%	22%	29%	39%
2,250	4%	7%	11%	15%	20%	22%	24%	33%	44%
2,500	5%	7%	12%	17%	22%	24%	27%	37%	49%
2,750	5%	8%	13%	19%	24%	27%	30%	40%	54%
3,000	6%	9%	15%	21%	26%	29%	32%	44%	59%
3,250	6%	10%	16%	22%	29%	32%	35%	48%	64%
3,500	7%	10%	17%	24%	31%	34%	38%	51%	69%
3,750	7%	11%	18%	26%	33%	37%	40%	55%	73%
4,000	8%	12%	20%	27%	35%	39%	43%	59%	78%

Table 17. Sensitivity Table of Area Occupied by Renewable and Nuclear Power As a Function of Energy Demand and Increasing Electrification Share

As the numbers demonstrate, the addition of nuclear has greatly reduced the total demand for land and space. In this scenario, all available land is occupied by renewable power (and, to an insignificant degree also by nuclear power), when the 50/50 nuclear/ renewable power mix delivers 75% of the total energy demand of 3,750 PJ per annum, or 100% of the total energy demand of 2,750 PJ per annum.

100% Nuclear

In this scenario, all of the electricity demand is met by nuclear power.[651] Table 18, presents the results.

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[651] As for 100% renewable, for the purposes of this model, if not the full 100% of energy is supplied by nuclear power, the remainder is supplied by other energy sources. The model focuses solely on the space impact of nuclear power and does not consider the impact on space usage of other energy sources.

% of Available Land Occupied

Energy Demand (PJ)	10%	15%	25%	35%	45%	50%	55%	75%	100%
	% of Energy Demand Supplied by Nuclear								
1,500	0.1%	0.2%	0.3%	0.4%	0.5%	0.5%	0.6%	0.8%	1.1%
1,750	0.1%	0.2%	0.3%	0.4%	0.6%	0.6%	0.7%	0.9%	1.2%
2,000	0.1%	0.2%	0.4%	0.5%	0.6%	0.7%	0.8%	1.1%	1.4%
2,250	0.2%	0.2%	0.4%	0.6%	0.7%	0.8%	0.9%	1.2%	1.6%
2,500	0.2%	0.3%	0.4%	0.6%	0.8%	0.9%	1.0%	1.3%	1.8%
2,750	0.2%	0.3%	0.5%	0.7%	0.9%	1.0%	1.1%	1.4%	1.9%
3,000	0.2%	0.3%	0.5%	0.7%	0.9%	1.1%	1.2%	1.6%	2.1%
3,250	0.2%	0.3%	0.6%	0.8%	1.0%	1.1%	1.3%	1.7%	2.3%
3,500	0.2%	0.4%	0.6%	0.9%	1.1%	1.2%	1.4%	1.8%	2.5%
3,750	0.3%	0.4%	0.7%	0.9%	1.2%	1.3%	1.4%	2.0%	2.6%
4,000	0.3%	0.4%	0.7%	1.0%	1.3%	1.4%	1.5%	2.1%	2.8%

Table 18. Sensitivity Table of Area Required by Nuclear Power As a Function of Energy Demand and Share Supplied by Nuclear

Thus, even if the power demand is high, nuclear power has only a marginal effect on land use, and no effect on sea use. Even if total energy demand in the Netherlands were 4,000 PJ and 100% of that were supplied by nuclear, less than 3% of the available land would have to be used, and no sea would be affected. This implies that 97% of the available land and 100% of the sea would be available for other uses. Compared to renewable power, nuclear power thus has such a low space impact that even in extreme situations, presents very little potential for space usage conflicts.

Model Outcomes & Sensitivity Analysis – the Czech Republic

Below, we present several model outputs for the Czech Republic:

1. Comparison of the various technologies to establish the space trade-offs involved in choosing between technologies
2. Spatial restraints to assess maximum power capacity of the Czech Republic for the power technologies concerned
3. Impact of increasing share of renewables on land usage
4. Sensitivity analysis of a 100% renewables scenario
5. Sensitivity analysis of a 75% / 25% nuclear and renewables scenario
6. Sensitivity analysis of a 100% nuclear scenario

Comparing Technologies

As a first exploratory step, we compare the technologies by imposing the same energy demand requirements on each. In our first scenario, we require that each technology meet 100% of the electricity demand. In this scenario, total energy demand supplied by electricity is 700 PJ per annum, which represents roughly 40% of the total energy demand of 1,800 PJ per annum, in-line with the Czech Republic's 2019 primary energy usage, as stated in Table 9, above. The outcomes are presented in Table 19, below.

	Area Required (km²)			Area Required (% of Available)		
	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
ONSHORE WIND LAND	27,746	14,864	9,574	484%	259%	167%
SOLAR ROOF	1,653	1,194	903	2119%	1530%	1157%
SOLAR LAND	6,288	3,005	1,806	110%	52%	31%
NUCLEAR	104	28	15	2%	0%	0%

Table 19. Area Required At Full Demand Met By Specific Power Technology

	Area Required (km²)			Area Required (% of Available)		
	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
ONSHORE WIND LAND	6,937	3,716	2,393	121%	65%	42%
SOLAR ROOF	413	298	226	530%	383%	289%
SOLAR LAND	1,572	751	451	27%	13%	8%
NUCLEAR	26	7	4	0%	0%	0%

Table 20. Area Required By Each Technology If Each Produces Equal Share of Total Electricity Demand

Explanation:

- As mentioned earlier, we employ ranges for each of capacity and density factors. Given that we use ranges with minima and maxima, we effectively have two corner points that represent extremes for the required land. The pessimistic corner point uses the minima for both the capacity and density factors, whereas the optimistic corner point uses the maxima for both those factors. We also represent an "average" scenario that corresponds to the simple of average of both the capacity and density factors.

- In other words, if solar roof installations must produce 700 PJ of electricity annually, it would require at least 1,157% of the available roof space. Thus, at this level of demand, solar roof far exceeds the available roof space. More realistically, if the full demand is met through solar on land, at least 31% and up to 110% of the available area is required. On the other hand, if nuclear is to meet 700 PJ of electricity demand, it would require at most 104 square km of land. This scenario, of course, is not realistic, because it is unlikely that policy makers would want only one power technology to supply all power, but it is useful to illustrate the relative land/space demand.

The absolute and relative space demands can be more realistically illustrated by requiring that each technology supply an equal share of the demand. Specifically, if each of the four technologies is to generate 25% of the annual 700 PJ of electricity demand, the areas required are set forth in Table 20.

Thus, for onshore wind and solar on roof, the scenario whereby all the available space is exceeded is within our reasonable range of possible outcomes.

Table 21, summarizes the impact on the total land and roof usage for this scenario of equal share.

	Area Required (km^2)			Area Required (% of Available)		
	Pessimistic	**Average**	**Optimistic**	**Pessimistic**	**Average**	**Optimistic**
Onshore Land	8,535	4,474	2,849	149%	78%	50%
Roof	413	298	226	530%	383%	289%

Table 21. Impact on Space If Each Technology Produces Equal Share of Total Electricity Demand

As the table shows, a perfectly equal power mix implies that the space demand of onshore water and roof space could exceed the available space. Thus, this mix might not be feasible. However, this exercise allows us to get a better feel for the impact of each technology on their spatial environment.

Spatial Restraints and Power Produced

A scenario that takes restraints into account is probably more relevant to policy makers who by necessity operate under restraints. Under this kind of scenario, policy makers, confronted with conflicting demands on land and space, ex- or implicitly set limits on any land or space demand by an activity, be it residential, industrial, power generation, agriculture, fishery, recreation, nature protection, landscape, horizon and silence protection, transportation or yet another demand.

In the scenario that is explored here, the model operates under the following restraints: (i) 100% of any available space may be used for power generation, and (ii) priority should be given to the various technologies in the following hierarchical order, which is based on space efficiency, with the more efficient ranked higher:

- solar roof (few competing uses)
- solar land (many competing uses)
- onshore wind land (many competing uses)

In this scenario, nuclear is not regarded as an option, and is added only for purposes of comparison. Furthermore, we are operating in the pessimistic case. The hierarchy demands that the higher ranked technology be exhausted first up to the 100% space limit before the next technology is added. We first explore how much power is produced if all of these technologies, except nuclear, are fully utilized up to maximum limit; we then add nuclear up to 100% of the space to compare with renewable. Table 22, presents the results.

Thus, the expected electricity production if we use 100% of the available space for renewable power in this a scenario would be about 670 PJ per annum. For context, the Czech Republic's primary energy demand for 2019 was just over 1,800 PJ, and hence would generate shy of 40% of its energy demand.

A maximum space utilization of 100% for power generation is an enormous portion of available space allocated to power generation. Given other competing uses of space, a maximum percentage that is politically probably more realistic and feasible is 50%. The model now determines how much power is generated by renewable power under this constraint, and then compares to nuclear. Table 23, below, presents the results.

Technology	Land	Water	Sea	Roof	Electricity Production (PJ p.a.)
Solar Roof	-	-	-	100%	33
Solar Land	100%	-	-	-	640
Onshore Wind	n/a (full)	-	-	-	
TOTAL RENEWABLE	100%	n/a	n/a	100%	**673**
Nuclear (as alternative)	100%				**38,500**

Table 22. Area Required If Restraints Are Put in Place (no more than 100% of space, hierarchical order for technology)

Technology	Land	Water	Sea	Roof	Electricity Production (PJ p.a.)
Solar Roof	-	-	-	50%	16.5
Solar Land	50%	-	-	-	320
Onshore Wind	n/a (full)	-	-	-	
TOTAL RENEWABLE	50%	n/a	n/a	50%	**336.5**
Nuclear (as alternative)	50%				**19,250**

Table 23. Area Required If Restraints Are Put in Place (no more than 50% of space, hierarchical order)

With total power generated at 337 PJ per annum, power production would be insufficient to meet the power demand in a conservative scenario of 1,500 PJ per annum and 25% electrification, which results in a power demand of 375 PJ per annum.

Space Impact of Increasing Share of Renewables

We now proceed to explore the space impact of renewable power more systematically. To illustrate the impact of increasing the share of renewables on area usage, we plot the percentage (%) of available land utilized for energy (the y-axis) for different shares of electricity generated by renewables (the x-axis). We assume that whatever electricity is not being generated by renewables is being generated by nuclear.

We map out three different scenarios:

- "*2019 Baseline*" – This resembles the current (2019) make-up of energy demand and electricity mix: 1,800 PJ of annual energy demand, with 20% being met by electricity. In other words, every combination of nuclear and renewables supplies 360 PJ of energy per annum.
- "*2030 Target*" – This represents the Czech Republic's official target for 2030 that projects 1,600 PJ per annum and a 25% rate of electrification. Renewable and nuclear power jointly supply 400 PJ per annum.
- "*Conservative Scenario*" – This represents a more conservative scenario in which energy demand increases to 2,000 PJ per annum as does the electronification to 30%. Renewable and nuclear power jointly supply 600 PJ per annum.

We assume a renewable power mix that is one quarter onshore wind and three quarters land solar. For simplicity, we have not included roof solar, which makes only a small contribution to total power. Furthermore, we are operating in the pessimistic case.

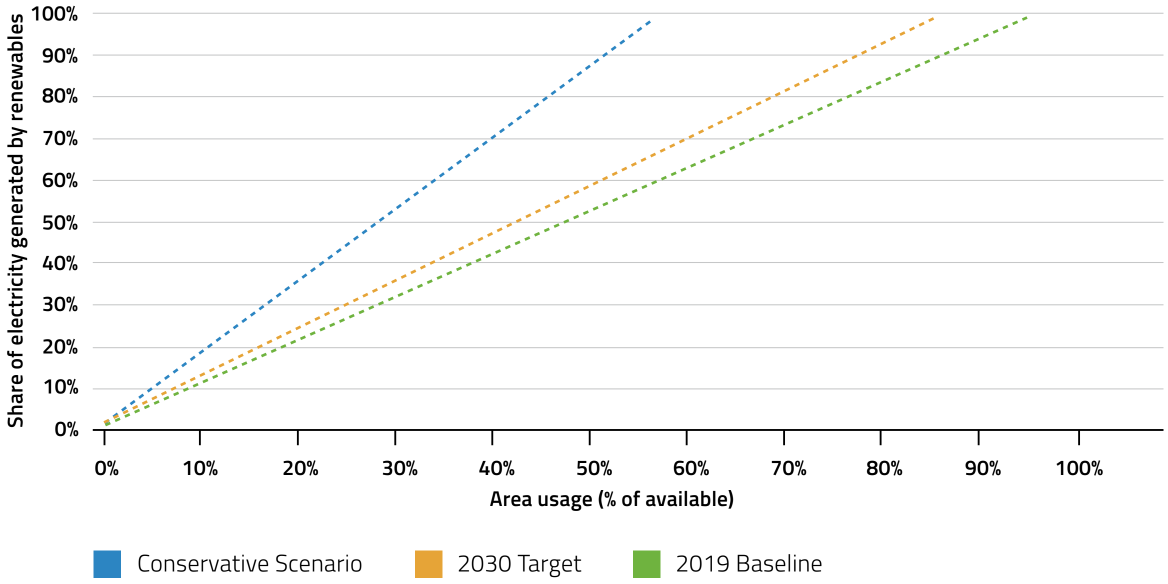

Figure 2. Impact of Increasing Share of Renewables on Area Usage

Figure 2, presents the results.

The graph demonstrates the spatial trade-offs between nuclear and renewables. At the extremes, it shows that 100% renewable power requires more than the available space and, as such, is not a realistic scenario for the Czech Republic. Put differently, the pressure on space and the potential for conflicting demands continue to increase as the share of renewable power in the mix increases, even if policy makers are willing to dedicate very large portions of available space to power generation in order to avoid having to resort to nuclear.

The 2019 Baseline scenario begins to show what increasing shares of renewable power will mean for space utilization. Even at constant levels of demand, relatively modest levels of renewable energy impose serious requirements on land space.

In the 2030 Target scenario, the limits of available space are reached or exceeded even earlier. At 90% renewables, there is not enough land available. These findings highlight the importance of integrating other sources of energy (e.g. nuclear), as relying solely, or to a significant extent, on renewables can lead to issues if by 2030 electricity demand increases by more than projections.

In the Conservative scenario, the pressure on land usage becomes clearer. Hence, if there is some modest growth in energy demand and electrification increases, renewables would occupy all the available space at just over 50% of the energy mix. This further emphasized the potential benefit of having higher density energy technologies represented significantly in the overall mix.

100% Renewables

In this sensitivity analysis, the energy demand (y-axis) and rate of electrification (x-axis) vary, and all of the electricity demand is met by renewables (non-electricity energy demand is met by other energy sources[652]). We assume a renewable power mix of 25% onshore wind and 75% solar. We have used the low end of the range for both

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[652] For the purposes of this model, if not the full 100% of energy is supplied by renewable power, the remainder is supplied by other energy sources. The model focuses solely on the space impact of renewable power and does not consider the impact on space usage of other energy sources.

% of Available Land Occupied

	% of Energy Demand Supplied by Renewables								
Energy Demand (PJ)	**10%**	**15%**	**20%**	**25%**	**30%**	**40%**	**60%**	**75%**	**100%**
1,000	29.0%	43.5%	58.0%	72.5%	87.0%	116.0%	174.1%	217.6%	290.1%
1,200	34.8%	52.2%	69.6%	87.0%	104.4%	139.3%	208.9%	261.1%	348.1%
1,400	40.6%	60.9%	81.2%	101.5%	121.8%	162.5%	243.7%	304.6%	406.2%
1,600	46.4%	69.6%	92.8%	116.0%	139.3%	185.7%	278.5%	348.1%	464.2%
1,800	52.2%	78.3%	104.4%	130.5%	156.7%	208.9%	313.3%	391.6%	522.2%
2,000	58.0%	87.0%	116.0%	145.1%	174.1%	232.1%	348.1%	435.2%	580.2%
2,200	63.8%	95.7%	127.6%	159.6%	191.5%	255.3%	382.9%	478.7%	638.2%
2,400	69.6%	104.4%	139.3%	174.1%	208.9%	278.5%	417.8%	522.2%	696.3%
2,600	75.4%	113.1%	150.9%	188.6%	226.3%	301.7%	452.6%	565.7%	754.3%
2,800	81.2%	121.8%	162.5%	203.1%	243.7%	324.9%	487.4%	609.2%	812.3%
3,000	87.0%	130.5%	174.1%	217.6%	261.1%	348.1%	522.2%	652.7%	870.3%

Table 24. Sensitivity Table of Area Occupied by Renewable Power As a Function of Energy Demand and Share Supplied by Renewables

% of Available Land Occupied

	% of Energy Demand Supplied by Renewables & Nuclear								
Energy Demand (PJ)	**10%**	**15%**	**20%**	**25%**	**30%**	**40%**	**60%**	**75%**	**100%**
1,000	7.4%	11.2%	14.9%	18.6%	22.3%	29.8%	44.7%	55.9%	74.5%
1,200	8.9%	13.4%	17.9%	22.3%	26.8%	35.7%	53.6%	67.0%	89.4%
1,400	10.4%	15.6%	20.9%	26.1%	31.3%	41.7%	62.6%	78.2%	104.3%
1,600	11.9%	17.9%	23.8%	29.8%	35.7%	47.7%	71.5%	89.4%	119.2%
1,800	13.4%	20.1%	26.8%	33.5%	40.2%	53.6%	80.4%	100.5%	134.1%
2,000	14.9%	22.3%	29.8%	37.2%	44.7%	59.6%	89.4%	111.7%	149.0%
2,200	16.4%	24.6%	32.8%	41.0%	49.2%	65.5%	98.3%	122.9%	163.9%
2,400	17.9%	26.8%	35.7%	44.7%	53.6%	71.5%	107.2%	134.1%	178.7%
2,600	19.4%	29.0%	38.7%	48.4%	58.1%	77.5%	116.2%	145.2%	193.6%
2,800	20.9%	31.3%	41.7%	52.1%	62.6%	83.4%	125.1%	156.4%	208.5%
3,000	22.3%	33.5%	44.7%	55.9%	67.0%	89.4%	134.1%	167.6%	223.4%

Table 25. Sensitivity Table of Area Occupied by Renewable and Nuclear Power As a Function of Energy Demand and Increasing Electrification Share

% of Available Land Occupied

	% of Energy Demand Supplied by Nuclear								
Energy Demand (PJ)	10%	15%	20%	25%	30%	40%	60%	75%	100%
1,000	0.3%	0.4%	0.5%	0.7%	0.8%	1.0%	1.6%	2.0%	2.6%
1,200	0.3%	0.5%	0.6%	0.8%	0.9%	1.2%	1.9%	2.3%	3.1%
1,400	0.4%	0.5%	0.7%	0.9%	1.1%	1.5%	2.2%	2.7%	3.6%
1,600	0.4%	0.6%	0.8%	1.0%	1.2%	1.7%	2.5%	3.1%	4.2%
1,800	0.5%	0.7%	0.9%	1.2%	1.4%	1.9%	2.8%	3.5%	4.7%
2,000	0.5%	0.8%	1.0%	1.3%	1.6%	2.1%	3.1%	3.9%	5.2%
2,200	0.6%	0.9%	1.1%	1.4%	1.7%	2.3%	3.4%	4.3%	5.7%
2,400	0.6%	0.9%	1.2%	1.6%	1.9%	2.5%	3.7%	4.7%	6.2%
2,600	0.7%	1.0%	1.4%	1.7%	2.0%	2.7%	4.1%	5.1%	6.8%
2,800	0.7%	1.1%	1.5%	1.8%	2.2%	2.9%	4.4%	5.5%	7.3%
3,000	0.8%	1.2%	1.6%	2.0%	2.3%	3.1%	4.7%	5.9%	7.8%

Table 26. Sensitivity Table of Area Required by Nuclear Power As a Function of Energy Demand and Share Supplied by Nuclear

the capacity factor and the required land for installation, i.e. the "pessimistic" case. Table 24, above, presents the results for the land area required.

The black dividing line running through these tables indicates where the available space is exceeded (i.e. percentages of more than 100% in the lower right area under the line colored yellow/red). As these tables show, in this scenario, if only 30% of the power is generated by renewables, all available land is occupied with wind and solar at a power demand of 1,000 PJ.

75% Nuclear / 25% Renewables

In this scenario, 75% of the electricity demand is met by nuclear power, 6.3% by onshore wind and 18.7% by solar on land; the other assumptions as for the 100% renewable case above apply here too. Table 25, above, presents the results.

As the numbers demonstrate, the addition of nuclear has greatly reduced the total demand for land and space. In this scenario, all available land is occupied by renewable power (and, to an insignificant degree also by nuclear power), when the 75/25 nuclear/ renewable power mix delivers 75% of the total energy demand of 1,800 PJ per annum, or 100% of the total energy demand of 1,400 PJ per annum.

100% Nuclear

In this scenario, all of the electricity demand is met by nuclear power.[653] Table 26, above, presents the results.

Thus, even if the power demand is high, nuclear power has only a marginal effect on land use. Even if total energy demand in the Czech Republic were 3,000 PJ and 100% of that were supplied by nuclear, less than 8% of the available land would have to be used. This implies that 92% of the available land would be

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[653] As for 100% renewable, for the purposes of this model, if not the full 100% of energy is supplied by nuclear power, the remainder is supplied by other energy sources. The model focuses solely on the space impact of nuclear power and does not consider the impact on space usage of other energy sources.

	Average GWh / km2		**Indexed to Nuclear (i.e. nuclear produces x times more electricity per km2)**	
	NL	CZ	NL	CZ
Onshore Wind Land	13	13	534	534
Onshore Wind Water	14	n/a	506	n/a
Offshore Wind	26	n/a	266	n/a
Solar Roof	136	163	51	43
Solar Land	47	65	148	108
Nuclear	6,982	6,982	1	1

Table 27 Power Density

available for other uses. Compared to renewable power, nuclear power thus has such a low space impact that even in extreme situations, presents very little potential for space usage conflicts.

Conclusions

To conclude, we present the key power density parameters for the Czech Republic and The Netherlands in Table 27, above, to demonstrate the differences in space impact between renewable power and nuclear power.

If electricity in the Czech Republic and The Netherlands is solely or chiefly provided by nuclear power, nuclear power plants will take up only a minute fraction of the land and space necessary for wind and solar. This is due to the very high power density of nuclear, which is at least 150 to 500 times higher than the power density of large-scale wind and solar.[654]

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[654] If the Borssele nuclear power plant is representative, this factor may even be higher.

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Annex II. Cost Model

The model estimates the cost of electricity generated from renewable (wind and solar) and nuclear power sources. As output, the model produces a € / MWh figure that can be compared to other estimates.

Importantly, the model allows users to scale certain inputs to test the output for sensitivity to assumptions. Additionally, the model allows the user to specify whether realized or expected costs should be used.

The model does not take into account integration- and system-related costs. At several points in this report, these integration- and system-related costs are discussed qualitatively and, to some extent, quantitatively; a fuller discussion of such costs is included in Part 7of the main body of this report.

Our model is broadly similar to the model used by Kalavasta and Berenschot in their recent study for the Dutch government entitled "Systeemeffecten van Nucleaire Centrales in Klimaatneutrale Energiescenario's 2050" (the "Nuclear Study") with respect to the formula and methodology. [5] There are important differences, however, with respect to some of the calculations, as well as the inputs. Below, we note those differences and provide explanations for the divergence.

In the interest of transparency, the model and all data necessary to produce the results reported here, are made available to the reader. This way, all of the outcomes can be reproduced by any interested party.

We run our model for both The Netherlands and the Czech Republic. As with spatial (area requirements) model (see Annex I), the formulas and methodologies are the same, the inputs and outputs differ. To provide an accurate picture, we conduct sensitivity analysis on key assumptions. In the discussion of the model outputs, we identify the main drivers so that specific attention can be paid to these inputs.

This annex includes the following sections, in order:

- Model Mechanics: a brief explanation of the workings of the model, including the precise calculations

- The Netherlands
    - Data Inputs & Sources
    - Cost of Capital Assumptions (including WACC)
    - Model Outcomes & Sensitivity Analysis

- The Czech Republic
    - Data Inputs & Sources
    - Cost of Capital Assumptions
    - Model Outcomes & Sensitivity Analysis

In the section "Data Inputs & Sources" we aim to provide a systematic overview of all the data inputs and the sources from which they are derived. We have added some additional comments to place this data into context.

In relation to the cost of electricity, cost of capital is an important factor. The weighted average cost of capital, or WACC, plays a key role in calculating the cost of electricity. We therefore dedicate a separate section to a discussion as to how we arrived at our cost of capital inputs.

Model Mechanics

The model incorporates the following electricity technologies:

- Onshore wind
- Offshore wind
- Solar (commercial, not residential)[655]
- Nuclear

The model calculates the cost of electricity as follows:

$$\textit{present value cost of electricity} = \frac{\textit{discounted sum of all costs (€)}}{\textit{discounted sum of all electricity produced (MWh)}}$$

Formula 1

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[655] Residential solar is not included because the economics of small-scale solar make them generally less desirable than commercial solar projects from a generation cost perspective (there are other issues associated with balancing the load provided by widespread residential solar, since solar panels tend to generate high power loads at the same time). Furthermore, estimates for residential solar vary much more than for commercial solar due to exogenous factors that are typically less controlled than in a commercial setting, e.g. the placement of the panels and the resulting capacity factor. The expectation is that this does not have any significant effect on the model outcomes since residential solar is not projected to be a significant portion of a country's energy supply, and therefore does not drive significant cost changes. The 'solar plus' concept uses battery and load control technologies to increase the value of PV and addresses some of the disadvantages associated with residential solar photovoltaic (PV). O'Shaughnessy, Eric ; Cutler, Dylan ; Ardani, Kristen ; Margolis, Robert, Solar plus: A review of the end-user economics of solar PV integration with storage and load control in residential buildings, Applied Energy, 2018, Vol.228 (C), p.2165-2175. For an estimate of the LCOE of residential solar in the US, see Mundada, Aishwarya S ; Shah, Kunal K ; Pearce, J.M., Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems, Renewable & sustainable energy reviews, 2016, Vol.57, p.692-703

The costs included in the model are those costs incurred during design and construction as well as operation and end-of-life. Of course, energy is only produced during the operational period. As we discuss further below, by default, energy production is not discounted (i.e. discount rate of 0%), although the option to discount exists for the user, and we run several scenarios with discounting of electricity production. The justification for not discounting the electricity produced is provided in Part 6 of this report, and below. In short, from a planning perspective (as opposed to an investment and trading perspective), the present value of future electricity is not relevant, because the task of the planner is to ensure that electricity is available at defined points in the future.

Nevertheless, to resolve the controversy in relation to discounting electricity, we apply a synchronization approach under which different technologies produce the same amount of power over the same period of time; in this scenario, whether or not power is discounted, is irrelevant (see further below). Note that the present value cost of electricity in our model is as of prior to the start of construction, not after construction.[656]

We note here too that our model does not discount renewable electricity produced when there is no demand for electricity. Economically, the stochastic nature of renewable electricity generation means that electricity may be produced when there is no demand for such electricity. Of course, such electricity does not have the same value as electricity produced when there is demand; to the contrary, it may even have a negative value. As said, in our model, the value of renewable electricity is not discounted to account for this problem.

To calculate both the costs and energy production, the model requires the inputs listed in Table 1, by category. The last column denotes the technologies to which these inputs apply.

The model cost estimates for these technologies represent simplified cost structures that might not take into account every and all costs, or potential externalities. Specific costs and externalities that this model has not taken into account include:

- Many solar and wind turbine installation impose negative externalities on surrounding land. Frequently, other land usages become impossible because they would restrict the sun rays or wind flow. Other negative externalities of renewables that are not taken into account include the impact on surrounding nature and the impact on surrounding home values. A report commissioned by the Dutch government found that wind turbines built within 2 km of residential areas resulted in a 2% to 5% reduction in value of home prices, for example. [12] While this negative externality is not directly borne by the energy producers, households experience a decrease in their asset values, which in turn could negatively impact tax revenues (through, for example, reduced real estate taxes, wealth taxes, etc.). Nuclear power plants also impose negative externalities on the surrounding land, but given their much more limited footprint, the scale of such externalities is

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[656] This is different from some interpretations of cost of electricity. Notably, the Nuclear Study considers the cost of electricity as of right before the plant enters operation, after construction has taken place. We believe the methodology used in our model is superior and aligns better with how public policy and project finance decisions are made, namely before construction takes place. After all, once construction has taken place, cost-benefit analyses are no longer relevant since the investment decision has already been made and executed.

		Units	Applies to
Technical parameters	Capacity per power plant unit	MWe	All
	Full load hours	Hours per annum	All
Cost parameters	Capital costs	€ / MWe	All
	WACC (for investment and costs)	%, annualized	All
	Discount rate (for energy production)	%, annualized	All
	Fixed maintenance and operation costs	€ / MWe per annum	All
	Variable maintenance and operation costs	€ / MWh	All (except where specified otherwise)
	Fuel costs	€ / MWh	Nuclear
	Waste processing and storage costs	€ / MWh	Nuclear
	Decommissioning costs	% of capital costs	All
Other parameters	Construction time	Years	All
	Technical lifetime	Years	All
External parameters	Exchange Rate	EUR per USD	n/a

Table 28. Model Inputs

considerably smaller than those of renewables.[657] Clearly, these externalities are relevant for energy policy, even if their costs are not taken into account in this model and most other models (including the model used in the Nuclear Study).

- The model simplifies the fixed and variable cost structure of the renewables to some extent. Wind turbines, for example, require more intensive maintenance and repairs as a result of torque-related stress. Hence, as they produce more electricity, more maintenance and repairs would be required. [13, 14] As such, it would typically be conceived of as a variable cost. Especially as wind turbines become taller and potentially increase their capacity factors, this variable cost element might become increasingly important. Given the complexity and highly variable nature of these variable costs and how to project them, the historical data in the model contains all relevant costs in either the fixed or the variable annual maintenance and operation ("M&O") costs, depending on the country. For The Netherlands, historic data for renewables' M&O costs was only available as fixed, while for the Czech Republic, the data was provided as a variable cost figure that encompasses all operational costs. For expected costs, however, the fixed and variable costs are indeed disaggregated for both countries, as we rely on the same source for both.

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657 Chapter 7 of [24] provides a brief overview of the land externalities imposed by renewables and nuclear power plants. Note that in relation to both renewable and nuclear energy the relevant supply and value chains (mining, waste disposal, etc.) also require land and may cause externalities.

The total capital costs are calculated as follows:

$$\text{total capital costs} = \text{capital costs} \left(\frac{€}{MWe} \right) \text{*capacity per unit (MWe)}$$

Formula 2

- It is also true that the model may include costs that, in the future, will no longer be incurred, or will be greatly reduced. For instance, as a result of innovation or technological developments. For example, molten salt reactors produce much less waste than current nuclear technology.[658]

The assumptions underlying the inputs for each of the technologies are discussed in the next section. The data sourced for our model comes in varying currencies, typically EUR and USD. To convert all data to EUR, we also specify an exchange rate. This exchange rate is uniformly used for all technologies in the model for purposes of consistency.[659]

Based on these inputs, all necessary costs and the power produced are calculated. The costs and energy production calculations are more easily understood if we consider them to be incurred in two phases: the planning and construction phase, followed by the operational and decommissioning phase. The formula is the same for each technology, although, as noted in Table 1, not all technologies incur all types of costs.

Construction Phase

During the construction phase, there are two costs:

- Capital expenditure (i.e. capital investment, also referred to as "overnight construction costs")
- Financing costs

The resulting total capital costs are assumed to be incurred uniformly over the construction period. For example, if the construction period is seven years, as is the case with a nuclear power plant, each year the project is assumed to incur one seventh of the total capital costs.

The financing costs in a given year are calculated as a percentage of the average of the capital costs incurred up to and including the prior year and the total capital costs incurred through the current year.[660] In other

$$\text{Financing costs}_t = \text{WACC} * \frac{1}{2} \sum_{i=0}^{t-1} \text{capital costs}_i + \sum_{i=0}^{t} \text{capital costs}_i]$$

Formula 3

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[658] Gehin, Jess C ; Powers, Jeffrey J, Liquid Fuel Molten Salt Reactors for Thorium Utilization, Nuclear Technology, 2016-05-01, Vol.194 (2), pp. 152-161: "Both the MSBR (molten salt breeder reactor) and the DMSR (denatured molten salt reactor) have significantly lower actinide and TRU (transuranics) mass per unit of energy generation than current LWRs (light-water reactors)" (text in parenthesis added).

[659] The Nuclear Study is not consistent with the exchange rate used, as noted below in more detail.

[660] The underlying assumption is that capital costs are drawn out unfirmly across the year. Some models, including the one used in the Nuclear Study, assume a full drawdown at the beginning of the year. This ultimately increases the financing costs of a project.

words, at the end of a given year, interest is charged on all capital costs incurred previously, as well as on capital costs incurred during the year, assuming uniform drawdown of new capital during the year: (see formula 3).

In this formula, the subscripts indicate the year number.

During the construction phase, the projects are assumed not to be generating any power.

Operating Phase

During the operating phase, costs can be categorized as follows:

- Principal and interest payments
- Operating costs (including maintenance, fuel, and waste disposal), both fixed and variable[661]
- Decommissioning costs (including disposal cost)

With regard to principal and interest payments, the project is assumed to spread out its principal payments uniformly across its operating years, in other words:

$$\text{Annual principal payments} = \frac{\text{total capital costs}}{\text{technical lifetime}}$$

Formula 4

Annual principal payments are assumed to be paid uniformly across the year.

Annual interest payments, or financing costs, are assumed to be levied on the average of the total outstanding principal as of the end of last year and the total outstanding principal at the end of the current year, net of the additional principal payments. In other words: (see formula 5)

Note that capital costs are only incurred during the construction phase, and principal payments only occur during the operating phase.

With regard to annual maintenance and operation costs ("M&O"), these have several components. The fixed component is calculated as follows: (see formula 6)

The variable component of M&O costs is calculated as follows: (see formula 7)

These M&O apply to all technologies, although, as noted above, in some cases all the M&O costs might be accounted for in one number (either the fixed or variable costs) due to data limitations.

$$\text{Financing costs}_t = \text{WACC} * \frac{1}{2} \left[\sum_{i=0}^{t-1} (\text{capital costs}_i - \text{principal payments}_i) + \sum_{i=0}^{t} (\text{capital costs}_i - \text{principal payments}_i) \right]$$

Formula 5

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661 As discussed below, no CO_2 tax is included in the operation cost.

$$\text{Annual fixed M\&O costs} = \text{M\&O costs}\left(\frac{€}{MWe}\right) * \text{capacity per unit (MWe)}$$

Formula 6

$$\text{Annual variable M\&O costs} = \text{M\&O costs}\left(\frac{€}{MWe}\right) * \text{capacity per unit (MWe)} * \text{full load hours (h)}$$

Formula 7

$$\text{total decommissioning costs} = \% * \text{capital costs}\left(\frac{€}{MWe}\right) * \text{capacity per unit (MWe)}$$

Formula 8

Nuclear power plants have additional cost components that do not apply to wind and solar, specifically: fuel costs and costs related to nuclear waste processing. These are calculated by multiplying the costs expressed in € / MWh by the actual annual MWh production of the nuclear power plant, similar to how the variable M&O costs are calculated.

Given electricity production is assumed to be equal across all operating years (which is a reasonable approximation of reality[662]), these cost components are constant year-after-year.

Lastly, the decommissioning costs are assumed to be incurred annually, uniformly across the operating lifetime of the project. This is based on the assumption that decommission costs are prepaid into a fund, with contributions made every year of operation.[663] The decommissioning costs themselves are calculated as a percentage of the capital costs:[664] (see formula 8)

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[662] While there are deviations in monthly capacity factors and electricity produced due to the timing of annual maintenance, annual figures are fairly constant. See, for example, annual capacity factors for nuclear energy generation in the U.S. at https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b

[663] This is a requirement for nuclear plants in the United States, for example. They have to provide financial assurance for decommissioning costs, typically through the establishment of a trust fund. Another option would be to obtain a guarantee from another creditworthy party (e.g. parent company) or contract insurance coverage; these options are not considered here. For more information, see https://www.nrc.gov/waste/decommissioning/finan-assur.html In the EU, funding of decommissioning of nuclear plants is not required by EU law, but a Commission recommendation suggests a decommissioning funding regime. COMMISSION RECOMMENDATION of 24 October 2006 on the management of financial resources for the decommissioning of nuclear installations, spent fuel and radioactive waste, 2006/851/Euratom, OJ L 330/31, 28.11.2006. See also World Nuclear News, EU recovery fund includes R&D and nuclear decommissioning, 21 July 2020, available at https://www.world-nuclear-news.org/Articles/EU-recovery-fund-includes-R-D-and-nuclear-decommis

[664] Although it is common practice to estimate decommissioning cost as a percentage of capital cost, we have not found empirical evidence to support this practice as applied to the power generation technologies at issue. The idea that there is constant ratio between decommissioning cost and capital cost for these technologies does not appear intuitive. Nevertheless, we used this fixed percentage for lack of empirical data.

$$\text{total decommissioning costs} = \% * \text{capital costs} \quad \frac{\text{total decommissioning costs}}{\text{technical lifetime}}$$

Formula 9

$$\underline{\text{Annual electricity production (MWh)} = \text{full load hours (h)}* \text{capacity (MWe per unit)}}$$

Formula 10

To obtain to an annual figure, these are spread out uniformly over the operating lifetime of the project: (see formula 9)

During the operating phase of the energy project, the model assumes that each year electricity production is the same and calculated as follows: (see formula 10)

Discounting & Inflation

The model allows for discounting. The user of the model can choose to discount both the costs and the energy production, at differentiated rates for various technologies (nuclear and renewables) or at an equal rate for all technologies.

Most levelized cost of electricity (LCOE) calculations discount the energy produced to account for the fact that different technologies have different lifetimes and different energy production schedules. For example, a nuclear plant can only start producing seven years into the future due to its long construction time, while a solar installation can start producing electricity much sooner. On the other hand, that same nuclear plant will still be producing electricity in 50 years, whereas the solar installation will have been decommissioned by then. That said, we argue that discounting the energy produced is not a proper method to solve for this issue – it implicitly assumes that energy produced 50 years from now is worth less than a similar unit of electricity produced next year. This is because the discount factor will be greater 50 years from now and the same unit of electricity will be discounted more, decreasing its present value. A policy maker, presumably, is more interested in ensuring that a certain amount of electricity is produced in year 50, as well as year 1, and a unit electricity of electricity produced in year 50 is not necessarily worth less than the same unit produced in year 1. We do recognize, however, that there is a time difference between the two units of electricity. To account for such differences, we employ a synchronized lifetime analysis, which equalizes the amount of electricity produced over a number of years and then compares the absolute costs of the different electricity generation technologies producing that amount of electricity.
Furthermore, the model does not take inflation into account. Hence, the user should use real rates (as opposed to nominal) for the purpose of discounting. This subject is further discussed below in the section on 'Cost of Capital Assumptions'.

Realized vs. Expected Costs

The model allows users to specify whether the output should be based on realized or expected costs. We specify below, in turn, for The Netherlands and the Czech Republic, the details of the realized and expected cost inputs. In general, the expected costs are lower given most technologies are expected to decrease in costs over time. Note that these expected costs are not adjusted for inflation.

Conclusion

The model allows each of these inputs, with some exceptions, to be modified by the user to assess the impact on the ultimate costs per unit of electricity produced. The final result is the sum of the discounted annual costs divided by the sum of the discounted annual electricity produced. If not discounted, the discount rate is set to 0%.

THE NETHERLANDS

In this section, we run the model for The Netherlands. Below, we first describe the data inputs and sources we used for each of the power generating technologies, and then proceed to present the model outcomes. We also run a sensitivity analysis on the key drivers.

Data Inputs & Sources

As laid out in Table 1, the model takes numerous inputs and for every input, assumptions are required. We look at each category of inputs, in turn, to explain the default assumptions used in the model, as well as the rationale for these assumptions.

As we did for the spatial model, we compare the assumptions of this model directly to those used in the Kalavasta and Berenschot study titled "Systeemeffecten van nucleaire centrales, in Klimaatneutrale Energiescenario's 2050." [5] Hereafter, we refer to this study as the "Nuclear Study."

Technical Parameters

Table 29 lists the assumptions for the technical parameters for each technology. We list the assumptions from the Nuclear Study in italics and parentheses for reference. A discussion of the assumptions follows the table.

- The size of the power units, i.e. the capacity, is the same as in the Nuclear Study and corresponds to the assumptions listed in the European scenario in the study. For purposes of the model, capacity as such is not directly relevant, as all costs scale linearly with capacity. In other words, given that the ultimate output is cost per unit of electricity produced, the capacity of the power plants has no bearing on the output. If system costs had been taken into account, not all costs would scale linearly with capacity. Some costs might increase non-linearly (for example, network balancing cost in systems with high penetration of renewable power), other costs might decrease with economies of scale (e.g. the cost of nuclear waste disposal and decommissioning), and yet other system costs could be avoided (e.g., if multiple wind turbines were built on the same plot of land). Hence, this assumption would become more impactful if system costs are taken into account.

- For the full load hours, we utilized the capacity factors we calculated in the spatial (area requirements) model; we refer to Annex I for sources and a broader discussion of the capacity factors and the resulting full load hours. From the spatial model, we take the maxima of the ranges, so our values represent optimistic full load hours. The Nuclear Study has lower full load hours for nuclear, and higher for renewables than our model. Hence,

	Units	Nuclear	Solar	Onshore Wind	Offshore Wind
Capacity per unit	MWe	1,600 *(1,600)*	20 *(20)*	3 *(3)*	3 *(3)*
Full load hours	Hours per annum	8,147 *(7,800)*	832 *(895)*	2,190 *(3,000)*	3,942 *(4,500)*

Table 29. Technical Parameters by Technology

it would overestimate the costs of nuclear relative to renewables because a significant portion of the costs are fixed and thus with lower production for nuclear relative to renewables, the relative costs will be higher.

Cost Parameters

Table 3 below lists the assumptions for the cost parameters for each technology. We list the assumptions made by the authors of the Nuclear Study in italics and parentheses for reference at the bottom end of each field. A discussion of the assumptions follows the table.

As we have discussed above, the model allows the user to specify whether realized or expected cost inputs should be used. In Table 30, we denote the realized cost estimates by (1) and the expected cost estimates by (2).

Realized cost estimates, denoted by (1) in Table 3, are based on historical 2018 or 2019 data for representative countries (e.g., OECD countries, other European countries). In cases where data was available for multiple countries, we have used averages for countries neighboring The Netherlands. In some cases, where data was sparse, we have included other representative OECD countries, such as the U.S. In one case, there was data specifically for The Netherlands. Table 4 outlines in more detail the sources for these estimates. We have aimed to be consistent in our use of sources for different categories of costs. For example, we use the same source for both capital and O&M costs.

For the expected costs, these are sourced from a report commissioned by the European Commission that triangulates literature cost estimates, industry stakeholder expectations, and expert input. [26] We believe that these estimates are more robust than those in any one study given that they are based on input from

	Units	Nuclear	Solar	Onshore Wind	Offshore Wind
Capital costs	€ / kWe	(1) 5,451 (2) 4,700 *(5,135)*	(1) 1,039 (2) 454 *(278)*	(1) 1,681 (2) 943 *(711)*	(1) 3,447 (2) 1,891 *(1,000)*
Real WACC (for costs)	% per annum	3.0% *(7.0%)*	3.0% *(4.3%)*	3.0% *(4.3%)*	3.0% *(4.3%)*
Discount rate (for energy production)	% per annum	0% *(7.0%)*	0% *(4.3%)*	0% *(4.3%)*	0% *(4.3%)*
Fixed maintenance and operation costs	€ / MWe per annum	(1) 105,900 (2) 105,000 *(89,000)*	(1) 16,287 (2) 9,200 *(4,170)*	(1) 32,337 (2) 12,000 *(17,775)*	(1) 88,555 (2) 28,000 *(32,000)*
Variable maintenance and operation costs	€ / MWh	(1)2.1 (2)7.8 *(7.4)*	(1) n/a (2) n/a *(n/a)*	(1) n/a (2)0.18 *(n/a)*	(1) n/a (2)0.39 *(n/a)*
Fuel costs	€ / MWh	5.50 *(6.27)*	n/a	n/a	n/a
Waste processing and storage costs	€ / MWh	2.07 *(2.07)*	n/a	n/a	n/a
Decommissioning	% of capital cost	12.5% *(15%)*	5% *(5%)*	5% *(5%)*	5% *(5%)*

Table 30. Cost Parameters by Technology

	Categories	Source	As of	Country/ Region for the data
Nuclear	Capital cost, M&O cost (fixed and variable)	[3] NREL	2018	U.S.
Wind onshore	Capital cost	[25] IRENA	2018	Average of U.K., Denmark, Germany
	O&M cost (fixed, which includes variable)	[25] IRENA	2018	Average of U.S., Norway, Denmark
Wind offshore	Capital cost	[25] IRENA	2019	Average of Belgium, Denmark, Germany, U.K.
	O&M cost (fixed, which includes variable)	[25] IRENA	2018	OECD, average of range provided
Solar	Capital cost	[25] IRENA	2018	Netherlands
	O&M cost (fixed, which includes variable)	[25] IRENA	2019	OECD, utility-scale

Table 31. Sources for Realized Cost Estimates

multiple credible sources, eliminating the distorting effect of outliers. These cost estimates were presented to the European Commission and ultimately published with the expressed intent to be used in modeling exercises exploring the decarbonization of Europe. [26]

A brief note on the units of the cost estimates. Most literature reports these numbers in USD. The model expresses them in EUR using the same, constant exchange rate of 0.89 EUR for each USD. This is applied to all estimates. More information on the exchange rate used can be found below under the heading external parameters.

We provide more context for the cost inputs our model uses relative to the Nuclear Study, below:

- In terms of capital costs, the Nuclear Study is inconsistent in its treatment of 2050 cost, since it uses a 2015 realized figure for nuclear, and adjusts it for some learning effect, but a projected capital costs for renewables that is based on hypothetical cost reductions. The hypothetical costs for renewables are based on a global estimate, which incorporates countries that have structurally lower costs such as India and China, as a more recent IRENA study points out [25], which distorts the numbers. Furthermore, the Nuclear Study, without explanation, uses an arbitrary exchange rate different from the one the Nuclear Study uses elsewhere; elsewhere, a 0.89 EUR / USD rate is used, for capital costs it is 0.86. Lastly, because the Nuclear Study incorporates these estimates into a broader system model, they have removed a portion of the offshore wind capital costs earmarked for grid connection; an assumption is made regarding the size of that portion. IRENA, the source for the figures in the Nuclear Study, is clear, however, that these costs are for "connection to the local distribution [...] network".[665]
  - As mentioned above, the model gives the user two options: either realized capital costs or projected capital costs in 2050, for all technologies (i.e. no discrimination is allowed, and the user cannot use realized costs for one and expected cost for another in the same calculation).

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[665] See the footnote on p. 47 of [1].

- For the realized capital costs for renewables, we sourced 2018 figures from an IRENA study. [25] We used the data that are most representative for The Netherlands, as laid out in Table 4. For nuclear, in the absence of more representative data, we rely on the NREL's 2020 Annual Technology Baseline, and although this data originates from the United States, we believe the estimate to be reasonable. [3] For example, the figure from the U.S. data is a bit higher than that from a recent French study prepared by their nuclear energy agency. [22] The realized cost figure used in our model is also slightly higher than the one used in the Nuclear Study.

- For projected capital costs in 2050, we rely on report for the European Commission, which provides cost estimates for a number of technologies for several points in the future. [26] For renewables, we use figures for "medium potential" technologies. The "potential" reflects variations in wind velocity and solar irradiation. Our underlying assumption is that these would balance out on the country level, such that "medium potential" is representative for The Netherlands. With regards to nuclear, we picked the cost estimates that include a learning effect, because such an effect is likely. Recent reports by Enco and a French study confirm that this expected cost figure for nuclear power plants is indeed reasonable. [21, 22]

- For the WACC, the Nuclear Study uses different rates for nuclear and renewables, based on whether the authors believe a technology has been "proven" or not. To retain flexibility in this regard, and to allow for various scenarios, our model leaves the option to the user as to which WACCs to use for which technologies. In our model outputs, we always specify what WACC was used. The default is a uniform WACC of 3%. This is in-line with the Nuclear Study's public WACC. For other outputs, we also apply a 0% rate, as is requested in the questionnaire; this rate, of course, would require government back-up or a further substantial decrease in central bank interest rates. We discuss the WACC in more detail below.

- The Nuclear Study takes the same approach to the discount rate for electricity produced as it does for the WACC. Our model allows the user to specify whether energy should be discounted and, if so, at what rate. The default is not to discount electricity produced (i.e. discount rate of 0%). We also apply a method that avoids the issue of the discount rates – we call this 'synchronization' (synchronized lifetime analysis) and it involves a comparison of (1) the total cost of a nuclear plant over its entire useful life to (2) the total costs of consecutive renewable power installations over the same period of time that produce the same electricity output at the same time.

- For fixed maintenance and operating costs, the Nuclear Study uses a realized 2015 figure for nuclear from the NEA report [4] and relies on projected costs (as a percentage of capital costs) for renewables. For these projected costs, the Nuclear Study relies on a 2018 Agora-commissioned report [6], which in turn cites another report by the IEA [7], for which we ultimately couldn't find any reliable source or data. Hence, the fixed maintenance and operating costs the Nuclear Study uses for renewables are unverifiable. In general, selecting different sources for different parts of the cost structure is not best practice given the variations in underlying assumptions for each source. Hence, we believe the estimates in the Nuclear Study might not be realistic.

    - Our model once again provides the user with two options: realized costs in 2018 or expected costs in 2050.
    - The realized costs for nuclear are sourced from the NREL report [3], while for renewables we rely on the same IRENA study as we did for capital costs [25].

  - For expected costs, we relied again on the European Commission report for all technologies. [26]

- For variable maintenance and operating costs, the Nuclear Study uses a 2018 value with an exchange rate of 0.89 EUR per USD, but from an entirely different source (an MIT report [8]) than for any of the other costs. It is unclear why the Nuclear Study switches to this MIT report in this specific context only. The Nuclear Study only specifies variable cost estimates for nuclear.

  - To ensure consistency, our model uses the same sources as for the fixed M&O costs for realized cost estimates. Note that for renewables, historic data incorporates both fixed and variable into one figure so there is no separate variable component. For nuclear, however, the NREL [3] specifies a variable component. The NREL report's variable cost estimate is significantly lower than that of the MIT study cited by the Nuclear Study. [8]
  - For expected cost estimates, we rely again on the European Commission report for all technologies. [26] This report does report variable cost estimates for renewables.

- For fuel costs, this input is only relevant for nuclear power. Projecting future fuel costs (i.e. uranium) is a highly speculative exercise, as is the case with any commodity where prices depend heavily on demand. The uranium price used in the Nuclear Study ($135/kg) is derived from two sources, the World Nuclear Association and the International Atomic Energy Agency. [9, 10] The primary driver of the Nuclear Study's high assumed uranium price is the 20-year old IAEA study. Since then, the literature has taken a generally less pessimistic view. A 2018 MIT study states that there are enough sources so as not to present an obstacle to demand growth (see reference [8], p. 180). Indeed, since the IAEA study was published in 2001, uranium prices increased to their peak in 2008 of $125-150/kg, before coming back to more moderate levels of around the $100/kg. Prices have remained steady at that level for half a decade (2010-2015). The World Nuclear Organization's website on the Economics of Nuclear Power [9] uses a uranium price of $68/kg for its cost estimate; the Nuclear Study also references this website for other purposes, so apparently it is regarded by Kalavasta and Berenschot as a reliable source. In conclusion, it appears the Nuclear Study used outdated beliefs about the uranium price. Our model uses $100/kg instead, which is below the peak prices reported above, but higher than the optimistic price used by the World Nuclear Organization. The 2015 Nuclear Energy Agency study on the projected costs of generating electricity also uses this figure. [11] This results in fuel costs of € 5.50/MWh.

- For the waste management costs, this input applies also only to nuclear (although wind and solar also generate waste at end of life, but this cost is not yet generally recognized). These costs include processing and storage. The Nuclear Study relies on a 2015 Nuclear Energy Agency study. [11] Other sources, such as the MIT study, the World Nuclear Organization's website on the Economics of Nuclear Power, and the more recent NEA report do not specifically split out waste management costs. It appears this is typically not done because these costs are included in other costs. Our model also uses the 2015 NEA study [11] and applies the same waste management cost as the Nuclear Study.

- For decommissioning costs, the Nuclear Study relies on the 2015 NEA study and expresses decommissioning costs as a percentage of the capital costs. [11] Other sources for nuclear broadly agree, with the World Nuclear Association stating that decommissioning costs are 9-15% of the initial capital costs. Hence, the figure used in the Nuclear Study is on the high end of the range, but still reasonable. Given the lack of other sources that specifically provide decommissioning costs for all technologies, our model also uses 5% for renewables, but 12.5% for nuclear to better represent the range of possible values. We have not taken into account any efficiency gains (economies of scale) associated with large scale decommissioning and nuclear waste disposal.

The Nuclear Study at times remarks that labor costs are different in the Netherlands compared to other areas of the world. While this is undoubtedly true, all of the cost estimates in the study are from other developed countries, including the U.S. The MIT study cited earlier discussed labor costs across countries specifically (see p. 40, reference [8]). It appears that it is difficult to determine whether labor cost in The Netherlands will be significantly different from the U.S. or France, for example. The U.S. has a strong labor market with competition for talent, leading to higher salaries, while France has a tradition of unions that artificially inflate salaries above what would be obtained in a free market. In general, we believe that the estimates are relatively representative of what it could be in The Netherlands. If anything, given some of these estimates are U.S.-centric, the labor costs could even be somewhat lower. Any differences in labor costs would affect both nuclear and renewable power plants, albeit potentially at different rates due to the differing labor intensity of each technology. Since we do not expect this to be a significant driver of cost, our model does not take into account any differences in labor costs between The Netherlands and other developed countries.

Other Parameters

Table 32 lists the assumptions for the other parameters for each technology. We list the assumptions from the Nuclear Study in italics and parentheses for reference. A discussion of the assumptions follows the table.

- The assumptions around construction time and technical lifetimes in the Nuclear Study were based on assumptions imposed by the European scenario the study was trying to mimic. We have made no changes to these assumptions.

As highlighted in a recent report by Enco, while nuclear power plants are designed for a 60 years life, they are typically planned to operate for 80 years by providing further extensions (for GEN III nuclear power plants).[21] This would increase the technical lifetime by a third and have a significant impact on the cost of electricity. Given that the design is for 60 years, and most cost-benefit analyses are done for a 60 years' operating life, we continue with that assumption in our model. The lifetime extension option for nuclear, however, may add significantly to its economic performance.

The same report by Enco also sheds greater light on the construction time for nuclear power plants. As the report mentions, these have averaged just below 10

	Units	Nuclear	Solar	Onshore Wind	Offshore Wind
Construction time	Years	7 (7)	0.5 (0.5)	1 (1)	1.5 (1.5)
Technical lifetime	Years	60 (60)	25 (25)	25 (25)	25 (25)

Table 32 Other Parameters by Technology

years over the last decade, a slight improvement over the preceding decade. That said, the report specifically mentions that the lengthy construction periods in some countries are due to changes in regulatory requirements and time periods necessary for obtaining all necessary licenses. ([21], p. 28) Part of these delays can also be attributed to increased safety scrutiny, specifically after the occurrence of an accident (e.g. as happened following Fukushima in 2011, when the European Union launched a stress tests program for all proposed nuclear power plants). Given that our model assumes a neutral policy regime for nuclear, we have adopted the seven-year period laid out in the Nuclear Study.

External Parameters

Table 33 lists the assumptions for the external parameters.

	Units	Value
Exchange Rate	EUR per USD	0.89

Table 33 External Parameters

- This exchange rate is based on the average from January 2015 through January 2020. As long as the exchange rate is uniformly applied, the interpretation of the model output should not change. The Nuclear Study also uses this exchange rate for most of its calculations (but not all, as noted above).

While the model is set up to incorporate potential CO_2 taxes, these have not been included in the calculations, because no such taxes are currently imposed.

Cost of Capital Assumptions

General Approach

The model analysis presented below reveals that the WACC is one of the most important factors in determining the electricity costs. For example, the cost of electricity generated by nuclear power increases by almost 85% when the WACC is decreased from 3% to 0%.[666] As a result, being realistic about the WACC used to finance these projects is crucial in making the right policy choices.

Typically, studies on electricity costs assume a WACC that might appear reasonable at first glance. This is also what the Nuclear Study does; it assumes that the WACC is technology-specific and uses a nuclear WACC based on a generic assumption about the WACC rate for power generating companies in the OECD. [4] Similarly, the WACC assumption used in the Nuclear Study for renewables is based on a study from 2015 that only discusses solar PV, but this WACC is then extrapolated to onshore and offshore wind as an assumption. [15] While these WACCs might be the best information available, given the sensitivity of the electricity costs to the WACC, it is important to underpin any WACC assumptions with stronger logic and, where available, data.

WACC, i.e. the weighted average cost of capital, represents the expected returns to all investors (typically a combination of equity and debt) that invested in the project. The WACC is determined by three components: the cost of equity, the after-tax cost of debt (given that interest payments lower taxable profits in most jurisdictions), and the capital structure (i.e. the levels of debt and equity in the

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[666] The WACC is used to discount the future costs back to the present. A higher rate at which future values are discounted results in a lower present value. The WACC in this case also determines the financing costs, meaning a higher WACC should lead to higher costs and hence a higher cost of electricity. However, the effect of the increased financing costs is more than offset by the effect of the discounting, resulting in decreasing costs as the WACC increases.

project).[667] The cost of debt is typically lower than the cost of equity, given that debt investors take on less risk[668] and hence need not to compensated for the additional risk that equity investors take on. Hence, projects financed with higher levels of debt (relative to other projects with higher equity levels) would typically have a lower WACC. To a substantial degree, the costs of equity and debt are driven by project risks. Investors command premiums for risks that cannot be mitigated or diversified. These risks that command higher expected returns are referred to as "premiums" to indicate the returns are in addition to the risk-free returns, typically government-issued debt.

As noted below, the cost of capital for most energy projects is not publicly shared, nor is the debt to equity ratio. Hence, our approach relies on the data that is available regarding WACCs and assumes a similar debt to equity ratio. In other words, we rely on information that does not disaggregate the various components of the WACC.

Risks Driving Cost of Capital for Energy Projects

In theory, investors in an energy generation project are exposed to several categories of risks that could cause them to lose money, and for which they need to be compensated in the form of a higher expected return. Such risks could either decrease the expected revenues or delay them, leading to lower returns. On the other hand, these risks can also be managed and mitigated, as discussed below:[669]

- <u>Project development and regulatory risk:</u> Revenues can be delayed due to regulatory barriers and burdens that delay the development such as zoning and permit issues. Policies and the risk of policy changes increase these risks. Note, however, that these risks are directly controlled by the government, and, thus, by policy makers. In the case of renewable energy, but not nuclear, the government has lowered these risks by expediting procedures to ensure renewable energy projects are built to meet the targets imposed by law.

- <u>Commercial risk:</u> Future revenues could potentially fall short if the demand for energy decreases, supply increases, or the anticipated price otherwise is not realized. Governments address this risk by offering a 'captured market' through the electricity network and, in the case of renewable power, by guaranteeing a price to the supplier or by setting a price floor (the so-called 'feed-in-tariff'). Government subsidies (state aid) also work to reduce commercial risks.

- <u>Technology risk:</u> The potential failure of a new technology could lead to revenues not materializing. In our case, this risk is typically quite well managed as only proven technologies are (allowed to be) built. Newer, unproven energy technologies are typically not built at scale. Nevertheless, there still might be some technology risks as proven technologies may have been improved or applied in different, more challenging contexts. For example, offshore wind turbines are built higher (currently, up to

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[667] Typically, debt has a much lower cost than equity. Thus, the relative levels of debt and equity used to finance a project have an impact on the overall, weighted, cost of capital. A project financed for 100% with debt is likely to have a much lower WACC than a project financed for 100% with equity.

[668] For example, debt holders have senior claims relative to equity holders. Furthermore, debt investors may have access to security and typically benefit from a number of covenants (including collateral) that can be enforced.

[669] Note that we do not include country risk in this list given we are considering the WACC within the context of two specific countries, The Netherlands and the Czech Republic; in essence, we treat country risk as a risk within the control of the government. Country risks plays a (in some cases, large) role in WACC heterogeneity across countries. [16]

260 meter) and with larger blades (currently, up to 108 meter).[670] While the technology is proven, these new dimensions do not yet have a track record, and might lead to unforeseeable and unknown complications.

- Operational risk: This is the risk of operational breakdown of equipment (for example, wind turbines are susceptible to blade breakage, gear box malfunction, and fires[671]). These risks are managed and reduced by conducting regular maintenance, among other things. Furthermore, given the track record, these risks can be fairly well predicted and accounted for.

- External risk: Lastly, there is some uncertainty as it relates to external factors that cannot be controlled for, such as the amount of wind and sun (for renewable energy), or uranium prices (for nuclear energy).

Thus, most of these risks are mitigated through the combined actions of investors / operators (e.g. technology and operational risk) or are being directly minimized through government policy or government action. For instance, a main reason as to why Germany has such low WACCs for renewable energy projects is precisely because it has managed these risks and minimized them, for example, by locking in electricity rates such that investors are basically guaranteed to recoup their investment within a set timeframe. This kind of government back-up is critical in keeping the WACCs for energy generation low, and a significant portion of the variation in WACCs for energy projects across the globe, even across countries that are quite similar in other aspects, is due to diverging government policies.[672]

To derive a WACC for policy making, we cannot simply look at historical rates, because such rates are confidential (not publicly available[673]) and they reflect the status quo in differences in government backup (for further discussion, see Part 6 of this report). We therefore need to devise another method to arrive at plausible rates for policy decisions. Interest rates reflect risks, thus, on the basis of relative risks, rates can be estimated.

Estimating WACC

For simplicity, we can delineate the WACC into three components: (see formula 11)

The two premia correspond to the risks discussed above. The government risk premium is driven by the (i) policy and regulatory uncertainty and (ii) commercial uncertainty, insofar as it is caused by factors directly controlled by the government. The energy project

WACC = risk free rate + government risk premium + project risk premium

Formula 11

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670 Details released of a huge offshore wind turbine that can power 18,000 homes per year, May 19, 2020, available at https://www.cnbc.com/2020/05/19/siemens-gamesa-releases-details-of-huge-offshore-wind-turbine.html

671 “While turbine fires are greatly outnumbered by losses relating to blades and gearboxes, the majority of these incidents lead to high-profile losses with a dual financial and reputational impact on a project and its stakeholders. Moreover, there is clear potential for fires to spread and cause a larger environmental incident.” GCube Insurance, TOWERING INFERNO: Global Trends in Wind Turbine Downtime Events, 1 Dec 2015, available at http://www.gcube-insurance.com/reports/towering-inferno/

672 As proof of this point, government policy is identified as a main driver of diverging WACCs in a 2015 paper comparing solar PV WACCs. [15]

673 This point is specifically made in [16]: “Cost of capital is typically considered a trade secret, and thus, is often not disclosed.”

premium is driven by (i) technology, (ii) operational, and (iii) external risks that are inherent to energy projects. In this case, we are assuming that the premia reflect a typical debt and equity financing structure. The capital structure from which the underlying data is drawn is unknown, although they typically follow a 10-30% equity and 70-90% debt financing structure.

As a reference point, we regard the rate at which the Dutch government borrows money as a risk-free rate. As of September 2020, the Dutch government can borrow for 30 years at very modest negative rates in nominal terms, meaning investors are willing to pay the Dutch government for borrowing from them. This is currently the case for most governments in Western and Northern Europe. The nominal risk-free rate is roughly 0%.

Assessing the government risk premium is a difficult exercise because it is a function of a historic policy regime, actual government actions, and expectations of investors on the future policies and actions. If a specific government policy is taken into account in WACC calculations, such estimates might reflect a policy status quo bias and are not representative of the true costs should the government change its policy regime. For example, in the Netherlands, the WACC for nuclear is artificially inflated due to the policy regime's lack of support for nuclear, while the WACC for renewable energy benefits from the supportive government policies. The rationale for disregarding the inflated nuclear WACCs is simply that it is incoherent for a policy maker to first adopt nuclear-unfriendly policies and then to say that he does not like nuclear power because it is too expensive – this would be a self-fulfilling prophecy, because the higher cost of nuclear result from the nuclear-unfriendly government policy.

WACCs found in the literature often reflect significant government risk premia and do not provide a means to disentangle the government risk premium from the project risk premium. Theoretically, if a government were to adopt positive policies towards certain energy sources, the government risk premium would be reduced to very low levels. Germany is one such country, where the past policy regime has been extremely friendly towards renewables (the well-known '*Energiewende*' policies). In this kind of environment, WACCs for renewable energy projects should reflect predominantly the project risk premium, i.e. technological, operational, and other external risks, which are not subject to government control.

A broad review of the available data and literature[674] revealed that the after-tax, nominal premia above the risk-free rate for renewable energy projects in Germany are 2.9% for solar, 3.1% for onshore wind, and 6.3% for offshore wind, on average. [16] These are averages over a ten year period, but have broadly been declining. Germany's premia for solar and onshore wind have recently trended below 2.5%. [16] For offshore wind, the data also indicates a clear pattern of a decreasing premium to roughly 5%.[675] For offshore wind, however, the data is not as clear as it is for the other technologies, because offshore wind does not yet have a strong proven track record and datapoints are less plentiful. [16] That same study revealed higher premia in The Netherlands, but given that the number of datapoints was extremely limited, the data from Germany would be more reliable as a proxy for project risk premia.

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[674] The review in [16] covers available evidence of the cost of capital for renewables globally, focusing on a broad literature review that resulted, after appropriate filtering, in 19 articles. The evidence considered includes elicitation of project finance data, surveys of expert estimates, replication of auction results, and analysis of financial market data. The coverage is global, but Germany has the most datapoints (17 across the three technologies – solar, onshore wind, and offshore wind). The data considered is from 2007 through 2018.

[675] These WACCs reflect an 80% / 20% debt / equity financing structure.

These datapoints reveal that in an ideal government policy climate, where the risk premium for government policy is practically zero, WACCs for renewable projects could be as low as 2.5%. Given the mix of energy technologies, we assume a uniform 5% after-tax, nominal WACC for all renewables, roughly in-line with these latest estimates.

The model (and the expected cost data) do not account for inflation. Hence, the WACC should be a real WACC and not nominal. To adjust for a real WACC, we use the Fisher equation. The formula is as follows:

$$WACC_{real} = \frac{(1 + WACC_{nominal})}{(1 + inflation)} - 1$$

Formula 12

The European Central Bank targets 2% inflation[676], leading to a real WACC for renewables of roughly 3%:

Risk-free rate	~ 0%
Government policy premium	~ 0%
Energy project premium	~ 5%
RENEWABLE NOMINALWACC	**~ 5%**
RENEWABLE REAL WACC	**~ 3%**

Table 35

For nuclear, the data is even less reliable given that there are very few countries in the European Union that have fostered positive policy regimes for nuclear energy, where the WACC would truly reflect the energy project risks, as opposed to government policy risks. One country in the European Union that might be amongst those least hostile towards nuclear is the Czech Republic. (Again, the data is very limited.) The Czech government recently offered a loan for the expansion of a nuclear power plant at an interest rate of 2%. [20] The project financing was 70% debt to 30% equity. Of course, this was a government loan, not a market-based loan, but it offers a glimpse of how low the energy risk premium for nuclear power plants can be under a technology-neutral energy policy.[677] We assume that roughly another 3% points are added to the WACC due to the equity financing piece, which translates to a cost of equity of 10%. A cost of equity of 10% in nominal terms is exactly what the NREL estimates for nuclear projects in their latest technology baseline. [3] We again adjust for 2% inflation to arrive at a real WACC of 3%:

Risk-free rate	~ 0%
Government risk premium	~ 0%
Energy risk premium	~ 5%
NUCLEAR NOMINAL WACC	**~ 5%**
NUCLEAR REAL WACC	**~ 3%**

Table 36

In real terms, the WACC of 3% is close to the estimate of the NREL.

WACC Estimate

As a default, the model uses a 3% uniform policy-neutral, after-tax, real WACC for both renewables and nuclear. We believe this reflects a reasonable estimate of the project risks and reflects a cost of capital that can be achieved in a policy regime that is friendly towards these energy source technologies. Choosing a WACC reflective of a 0% government policy premium offers the best methodology for rationally evaluating

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[676] See https://www.ecb.europa.eu/mopo/html/index.en.html for more information on the ECB’s inflation targeting.

[677] There is plenty of evidence that the technological, operational, and other external risks for nuclear are very low. See, for instance, a post by the World Nuclear Association that outlines the safety record of nuclear energy globally: https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx . Of course, with the newer nuclear technologies, such as the molten salt reactor, risks might be higher, as is the case for offshore wind turbines.

the alternatives to meeting the country's energy needs.

Model Outcomes & Sensitivity Analysis

In this section, we present several model outputs, in the following order:

1. Synchronized lifetime analysis: a comparison of (1) the total cost of a nuclear plant over its entire useful life to (2) the total costs of consecutive renewable power installations over the same period of time that produce the same electricity output, using no discounting and WACCs of 0% and 3%
2. Comparison of technologies: impact of discounting and realized vs. expected costs
3. Sensitivity analysis: impact of changing key assumptions on the cost of electricity

A brief note on our decision to not discount the electricity produced. Ultimately, this means that we need to account for the fact that the electricity produced by different technologies is produced at different times in the future through a method other than discounting. At the extremes, our analysis does not distinguish between one unit of electricity produced in 50 years and the same unit of electricity generated next year. An issue that arises with this approach is that a higher WACC only decreases the costs, while the total electricity produced remains the same (which means that using a realistic WACC is very important). When using a realistic WACC, we believe the model output provides a valuable comparison tool. In any event, to reflect the timing issue, we favor the synchronized lifetime analysis described below as it completely removes the issue of discounting electricity produced.

That said, even if we discount the electricity produced, as we do below in the *Comparing Technologies* section, we find that nuclear is cheaper than renewables. On a realized cost basis, we find that nuclear is still about half as cheap as onshore wind, the cheapest renewable technology. On an expected cost basis, we expect nuclear to be roughly at par in 2050 with onshore wind, but still cheaper than solar and offshore wind. Again, we do not necessarily favor this approach, but it highlights the flexibility of the model and the robustness of nuclear energy's cost compared to renewables under different assumptions.

Further, in relation to discounting electricity, an issue much more acute than discounting to reflect the value of time, is discounting to reflect the stochastic nature of renewable electricity, which means its generation is unrelated to electricity demand. Economically, a unit of electricity produced when there is no demand is worth less than a unit of energy produced when there is demand. Accordingly, renewable electricity should be discounted to reflect its lesser value due to its stochastic nature. Our model, like most other models, does not account for this lesser value, however; if it did, the cost advantage of nuclear would increase further. Instead, these costs of renewables are typically reflected in profile costs, which are part of the system-related costs.

Synchronized Lifetime Analysis

Some of the main issues with comparing different electricity generating technologies are the varying lead times, varying lifetimes, and power output varying in time. By applying a chosen discount rate or WACC,[678] we could arrive at a EUR / MWh cost figure. This is not the most suitable and appropriate method for purposes of energy system planning, however.

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[678] An additional complication is that the discount rate applicable to capital does not necessarily have to be the same as the discount rate applicable to power. In the relevant literature, however, it typically is.

While a EUR / MWh cost figure is useful, it means that the cost of electricity generated by nuclear is much more sensitive to the WACC than the cost of electricity generated by offshore wind turbines, for example. To make the comparison more robust and more suitable and appropriate for planning and policy-making, we developed a synchronized lifetime analysis:

- The synchronized lifetime analysis' starting point is that a certain level of annual electricity production over a defined period of time is required.
- Based on this power output and timing requirement, it examines the costs of various energy sources to meet that requirement.
- To do so, it requires that different technologies produce the chosen level of power over the chosen time period, and subsequently the cost of producing that output over that time period is computed.
- This method provides relative cost estimates that are not sensitive to changes in the discount rate for electricity.

In the synchronized lifetime analysis, we assume an electricity production requirement of just over 13mn MWh per annum, which is equal to the output of a 1,600-MW nuclear power plant. The required time period during which this production level is to be sustained is 300 years, which is the time period necessary to synchronize and equalize the consecutive lifetimes of nuclear plants and renewable power facilities, such that at the end of the 300-year period, all energy sources have met the ends of their respective useful lives.

The required output level of 13mn MWh is equivalent to the production of 1,984 onshore wind turbines, 1,103 offshore wind turbines, and 784 solar farms. The analysis also accounts for the differences in lead times/construction periods, but is unable to account for the intermittency of renewable energy.

Table 12 below provides the results of this analysis. We use a 0% WACC for all technologies and a 3% WACC for comparison. For each technology, the total costs of meeting the electricity requirements for 300 years are provided.

Note that the amounts are expressed as billions, i.e. 109.

Figure 3, shows these results graphically.

The synchronized lifetime analysis reveals that nuclear power is a much more cost-efficient solution to meet chosen levels of electricity production over a given period of time. Even at a WACC of 3%, nuclear provides a given level of electricity at about half the cost as solar.

The cost advantage of nuclear decreases, however, as the WACC increases. This is due to the fact that nuclear has a larger share of its costs early in the time period. At a WACC of 6.7% nuclear and onshore wind cost roughly the same. This result is independent of the level of power output required. It is also independent of the time period over which the analysis is conducted, assuming the lifetime of the technology is exhausted.

	Nuclear	Solar	Onshore Wind	Offshore Wind
Present Value of Costs at 0% WACC	€138bn	€282bn	€184bn	€232bn
Relative to nuclear	1.0x	2.0x	1.3x	1.7x
Present Value of Costs at 3% WACC	€17bn	€33bn	€21bn	€26bn
Relative to nuclear	1.0x	1.9x	1.2x	1.5x

Table 37. Synchronized Lifetime Analysis

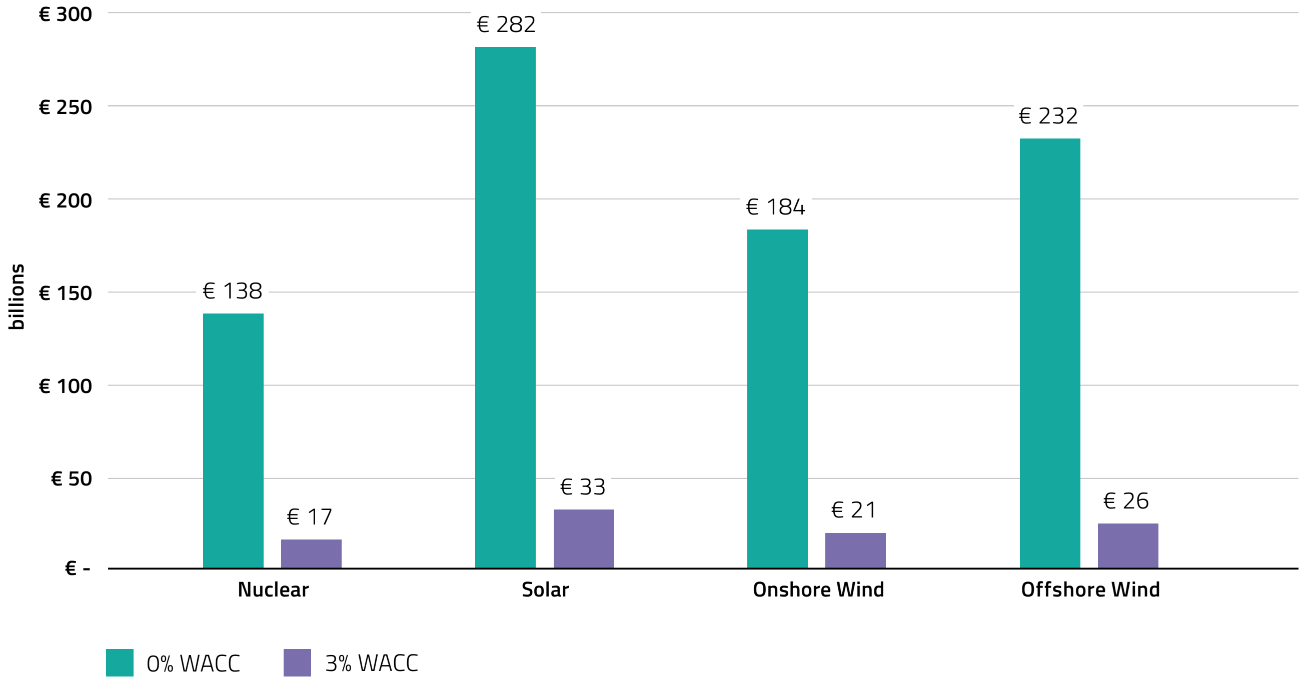


Figure 3 Synchronized Lifetime Analysis

The only reason as to why we applied a long period of 300 years is that it avoids have to pro rate for a technology that has not yet reached end of life, which might introduce distortions.

Comparing Technologies

We present the cost of electricity (EUR/MWh) for various iterations of discount rates and cost structures, as well as a comparison to the results of the Nuclear Study. Table 7, below, gives the various WACC's, energy discount rates, and capital and fixed O&M costs used in the various scenarios.

The scenario that most closely resembles the values from the Nuclear Study is scenario 5. In Graph 1, below, we also include two different LCOE figures from the Nuclear Study, the only difference being whether a uniform 3% discount rate is used (2) or not (1).

	Nuclear WACC	Renewables WACC	Energy Discount Rate	Capital & Fixed O&M Costs
Scenario 1	3.0%	3.0%	0.0%	Realized
Scenario 2	3.0%	3.0%	0.0%	Expected
Scenario 3	7.0%	4.3%	0.0%	Realized
Scenario 4	7.0%	4.3%	3.0%	Realized
Scenario 5	7.0%	4.3%	3.0%	Expected

Table 38. Cost of Electricity (EUR/MWh) for Varying Discount Rates and Cost Assumptions

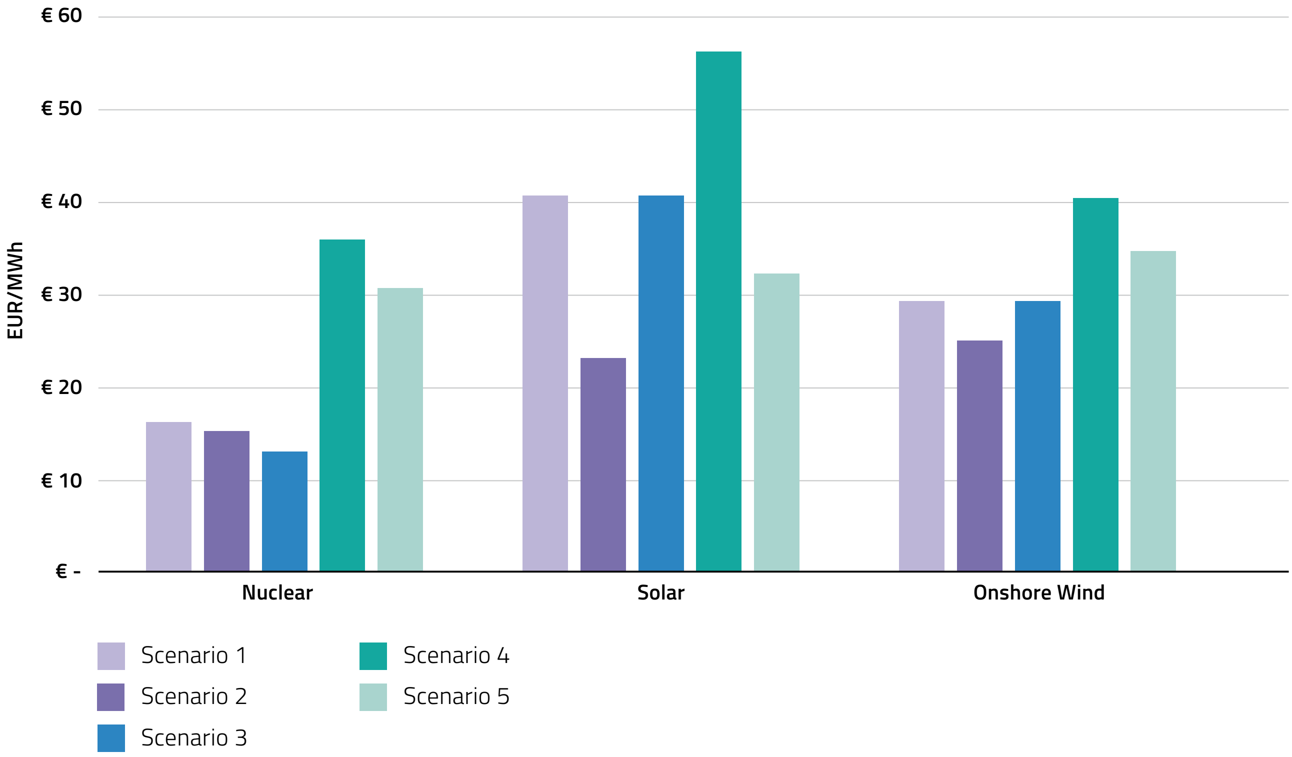


Figure 4. Comparison of Electricity Costs (EUR/MWh) for Various Scenarios

For renewables in particular, significant drivers of the different values across the scenarios are the capital costs and fixed O&M costs. Because the realized figures lie so much higher than expected values, which factor in substantial cost savings over the next 30 years, electricity costs can decrease by 50% or more for renewables if these cost savings materialize; we have not attempted to assess whether any such expectations are realistic and plausible. If these expectations materialize, it would put renewables at roughly equal footing as nuclear (around the 20 EUR per MWh). At realized costs, nuclear is substantially cheaper. Presumably, this means that, for the foreseeable future, electricity generated through nuclear would be cheaper than renewables.

In other words, for renewables to be at least somewhat competitive with nuclear, significant capital and O&M cost decreases need to materialize and nuclear power should not realize any significant cost reductions; if such substantial decreases and absence of reductions do not materialize, renewables remain uncompetitive.

For offshore wind, we note that the capital costs in the model include a connection to the distribution grid, which the Nuclear Study has removed. To be clear, this does not include actual grid costs, but solely the cables from the wind turbines to a point where grid connection is made available. There will be additional costs to expand the grid into the sea to allow offshore wind parks to connect.

These costs do not include any system-related costs yet, which, as discussed in part 7 of the main body of the report, would widen the cost differential between nuclear and renewables.

Sensitivity Analysis

For the sensitivity of the assumptions, we start with a default value that arises from scenario 1 as described above. We apply these changes to the following factors in turn to assess the relative impact on the electricity cost (i.e. % change in EUR/MWh):

- WACC
- Capital costs
- Capacity factor
- Fixed O&M costs

From the sensitivity analysis, the following general take-aways are notable:

- The sensitivity analysis reveals that the electricity costs are most sensitive to the following inputs (roughly in order of decreasing sensitivity):
    - WACC: a reduction in the WACC from 3% to 0% leads to increases in the electricity cost of 12% to 85%, with nuclear experiencing the largest increase (to clarify, a higher WACC decreases the present value of costs, and a lower WACC increases present value of costs).
    - capacity factors: a reduction in the capacity factor to more conservative levels leads to increases in the electricity cost of up to 30%
    - capital costs: increasing capital costs by 10% leads to an increase in electricity cost of up to 8%
    - fixed O&M costs: increasing fixed O&M costs by 10% leads to an increase in the electricity cost 2% to 3%

This reinforces the importance of forming realistic expectations regarding WACC and capacity factors and of assessing the impact of deviations in these expectations.

- Of all the technologies, nuclear is the most sensitive to changes in the WACC, primarily because costs are spread out over much longer time periods, which leads to the costs later in the lifetime of the nuclear power plant to be extremely sensitive to discounting. This further emphasizes the need for a synchronized lifetime analysis in the context of energy policy (see further below), as opposed to simply looking at electricity costs on a EUR / MWh basis.

- Capacity factors are likewise important to the electricity costs. This means that power plants with more predictable capacity factors, such as nuclear, have electricity cost estimates that are less subject to variation relative to power plants with more variable capacity factors, e.g. offshore wind.

- The impact of changing capital costs is relatively uniform across technologies.

Nuclear

For nuclear, we changed the four inputs (which are the main drivers) as set out in Table 8, below. In terms of costs, we evaluate two scenarios, one where the costs are reduced to 90% of the default level, and one where the costs increase by 10%.

Nuclear	**Base Level**	**Min**	**Max**
WACC (%)	3.0%	7.0%	0.0%
Capital Costs (€/MWe)		90.0%	110.0%
Capacity Factor (%)	93.0%	95.0%	85.0%
Fixed O&M Costs (€/MWe/ year)		90.0%	110.0%
Base Level EUR/ MWh	**€ 19.02**		

Table 39. Sensitivity Analysis Nuclear Power

The impact on the electricity costs is as shown in figure 5.

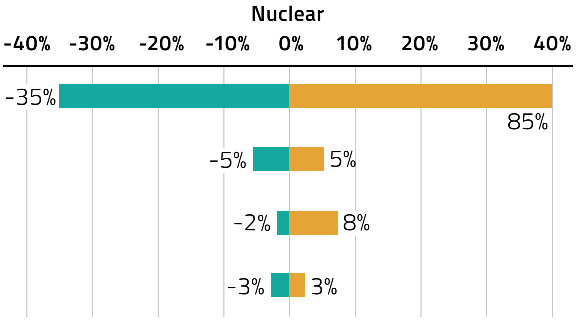


Figure 5 Impact of Variations in Main Drivers on Cost of Nuclear Power

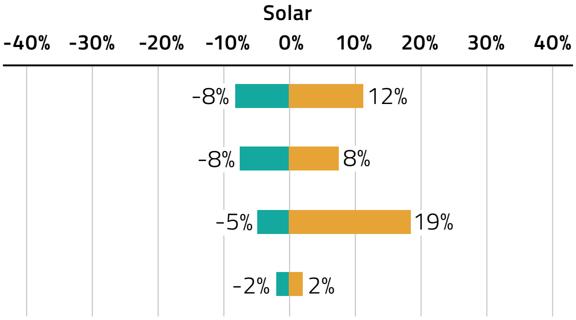
Solar

For solar, we changed the four inputs as set out in Table 40.

Solar	Base Level	Min	Max
WACC (%)	3.0%	7.0%	0.0%
Capital Costs (€/MWe)		90.0%	110.0%
Capacity Factor (%)	9.5%	10.0%	8.0%
Fixed O&M Costs (€/MWe/ year)		90.0%	110.0%
Base Level EUR/ MWh	**€ 64.60**		

Table 40. Sensitivity Analysis Solar Power

The impact on the electricity costs is as shown in figure 6.



Figuere 6. Impact of Variations in Main Drivers on Cost of Solar Power

Onshore Wind

For onshore wind, we changed the four inputs as shown in Table 41.

Onshore Wind	Base Level	Min	Max
WACC (%)	3.0%	7.0%	0.0%
Capital Costs (€/MWe)		90.0%	110.0%
Capacity Factor (%)	25.0%	30.0%	20.0%
Fixed O&M Costs (€/MWe/ year)		90.0%	110.0%
Base Level EUR/ MWh	**€ 40.97**		

Table 41. Sensitivity Analysis Onshore Wind Power

The impact on the electricity costs is as shown in figure 7.

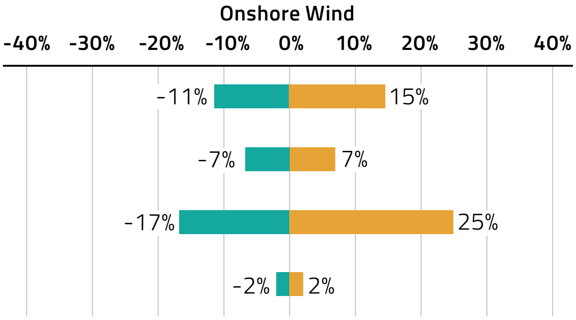


Figure 7. Impact of Variations on Cost of Onshore Wind Power

Offshore Wind

For offshore wind, we changed the four inputs as shown in Table 42.

Offshore Wind	Base Level	Min	Max
WACC (%)	3.0%	7.0%	0.0%
Capital Costs (€/MWe)		90.0%	110.0%
Capacity Factor (%)	45.0%	60.0%	35.0%
Fixed O&M Costs (€/MWe/ year)		90.0%	110.0%
Base Level EUR/ MWh		**€ 49.30**	

Table 42. Sensitivity Analysis Offshore Wind Power

The impact on the electricity costs is as shown in figure 8.

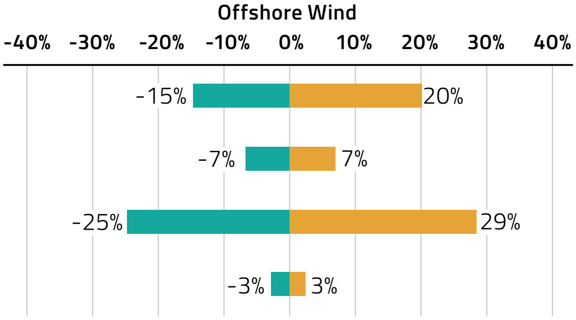


Figure 8. Impact of Variations on Cost of Offshore Wind Power

CZECH REPUBLIC

We now proceed to run the model for the Czech Republic. Below, we first describe the data inputs and sources we used for each of the power generating technologies, and then proceed to present the model outcomes. We also run a sensitivity analysis on the key drivers. Note that we do not estimate costs for offshore wind, given that the Czech Republic has no access to offshore waters.

The discussion of the inputs for the Czech Republic is more limited than that of the inputs for The Netherlands. Many of the general comments made in the above section for The Netherlands also apply to the Czech Republic; we do not repeat them here.

In general, most of the inputs for historical costs are based on data provided by the Ministry of Industry and Trade (Ministerstvo průmyslu a obchodu) of the Czech Republic.[679] These data are also partially reflected in an English language public report. [23] The government-provided data is originally in Czech koruna, but has been scaled to the EUR at an exchange rate of 25 CZK per EUR. This has been well within the average exchange range of the last ten years (see below for further discussion).

Data Inputs & Sources

As laid out in Table 1, the model takes numerous inputs and for every input, assumptions are required. We look at each category of inputs, in turn, to explain the default assumptions used in the model.

Technical Parameters

Table 13 below lists the assumptions for the technical parameters for each technology. A discussion of the assumptions follows the table.

	Units	Nuclear	Solar	Onshore Wind
Capacity per unit	MWe	1,200	0.005	1
Full load hours	Hours per annum	8,147	1,226	2,190

Table 43.Technical Parameters by Technology

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679 Czech Ministry of Industry and Trade, https://mpo.cz/en/

- The size of the power units, i.e. the capacity, is as reported by the Ministry of Industry and Trade. For purposes of the model, capacity as such is not directly relevant, as all costs scale linearly with capacity. We discussed this in more detail above in the section for The Netherlands.

- For the full load hours, we utilized the capacity factors we calculated in the spatial model; we refer to Annex I for sources and a broader discussion of the capacity factors and the resulting full load hours. From the spatial model, we take the maxima of the ranges, so our values represent optimistic full load hours. Note that solar has more full load hours in the Czech Republic than in The Netherlands, which should ultimately be beneficial for the relative cost of solar compared to other technologies (leaving aside the issue of the stochastic nature of solar).

Cost Parameters

Table 44 lists the assumptions for the cost parameters for each technology. A discussion of the assumptions follows the table. For some of the inputs, there are various options that the user can specify; we denote these in the table accordingly.

- In terms of capital costs,
  - The model gives the user two options: either realized capital costs or projected capital costs in 2050, for all technologies (i.e. no discrimination or differentiation between technologies in this respect is allowed, so the user cannot use realized costs for one and expected cost for another in the same calculation).
  - For realized capital costs, these figures were provided by the Ministry of Industry and Trade. We opted for the low end of the estimates. For renewables, they were in line with estimates for The Netherlands. For nuclear, they are slightly higher for reasons that have not been further explored.
  - For projected capital costs in 2050, we rely on the same sources as we did for The Netherlands, given that the source was a report commissioned for the European Union as a whole. [26]

	Units	Nuclear	Solar	Onshore Wind
Capital costs	€ / kWe	(1) 7,000 (2) 4,700	(1) 1,000 (2) 454	(1) 1,280 (2) 943
WACC (for costs)	% per annum	4.2%	4.2%	4.2%
Discount rate (for energy production)	% per annum	0%	0%	0%
Fixed maintenance and operation costs	€ / MWe per annum	(1) n/a (2) 105,000	(1) n/a (2) 9,200	(1) n/a (2) 12,000
Variable maintenance and operation costs	€ / MWh	(1) 8.28 (2) 7.80	(1) 0.04 (2) n/a	(1) 0.20 (2) 0.18
Fuel costs	€ / MWh	4.36	n/a	n/a
Waste processing and storage costs	€ / MWh	n/a	n/a	n/a
Decommissioning	% of capital cost[680]	8,172	5%	5%

Table 44. Cost Parameters by Technology

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[680] For nuclear, the units are €/MWe/year.

- For the WACC, the default is a uniform, real, post-tax WACC of 4.2%. We explain in more detail below how we arrived at this figure. In other models runs, we also apply a 0% rate, as requested in the questionnaire.

- For the discount rate for electricity produced, we employ a similar methodology as we did for The Netherlands: the default is not to discount electricity produced (i.e. discount rate of 0%), and, as discussed, we use a synchronized lifetime analysis to address the issue of timing differences in energy produced.

- For fixed maintenance and operating costs and waste processing and storage costs, the Ministry of Industry and Trade has collapsed these into one variable cost figure that is reported for each technology. While this might not give as much detail about the different cost components, it provides for easier comparisons between technologies given that it encompasses everything. If the user opts for expected costs, the cost structure defaults to one where fixed and variable costs are broken out, as it is for The Netherlands.

- For decommissioning costs for nuclear power plants, we have relied on data provided by the Ministry of Industry and Trade. The data estimates the decommissioning costs for two existing nuclear power plants in the Czech Republic: Dukovany and Temelin. Based on those data, we calculated an annual figure per MWe for nuclear power plants. For renewables, we use the same input as we did for The Netherlands.

A note on labor costs: given that the historical cost estimates were provided by the Ministry of Industry and Trade of the Czech Republic, they are already country-specific. The expected costs in 2050 were provided by the European Commission report referenced above. [26]

Other Parameters

Table 15 below lists the assumptions for the other parameters for each technology. A discussion of the assumptions follows the table.

	Units	Nuclear	Solar	Onshore Wind
Construction time	Years	8	1	1
Technical lifetime	Years	60	20	20

Table 45. Other Parameters by Technology

- The assumptions around construction time and technical lifetimes are as reported by the Ministry of Industry and Trade. We note that the construction time for nuclear is longer than for The Netherlands, and that the lifetime of the solar and wind power plants is lower, for reasons that have not been further explored.

External Parameters

Table 46 lists the assumptions for the external parameters.

	Units	Value
Exchange Rate	CZK per EUR	25

Table 46 External Parameters

- This exchange rate is as reported by the Ministry of Industry and Trade. For the last ten years, the exchange rate has hovered between 24 and 28, with long stretches of time around 25. Hence, we believe this is a reasonable exchange rate to employ consistently.

As with The Netherlands, while the model is set up to incorporate potential CO_2 taxes, these have not been included in the calculations, because no such taxes are currently imposed on either nuclear or renewable energy.

Cost of Capital Assumptions

Our general approach to the cost of capital assumption is exactly the same as for The Netherlands. As such, we refer the reader to our detailed explanation above.

Estimating WACC

For simplicity, we delineate the WACC into three components: (See formula 13)

As a reference point, we regard the rate at which the Czech Republic government borrows money as a risk-free rate. As of September 2020, the Czech Republic government can borrow for 20 years at a nominal rate of approximately 1.3%.

For the government risk premium, we employ the same methodology as we do for The Netherlands. We concluded based on that rationale that the government policy risk premium should be zero, if we want to evaluate these energy technologies on a level playing field.

The project risk premium is the same as it is for The Netherlands, given that there is no inherent cause for energy projects to be riskier in the Czech Republic than in The Netherlands – in other words, these projects carry similar amounts of risk.

The Czech National Bank also has an inflation target of 2%, similar to the European Central Bank.[681]

Hence, our model for the Czech Republic uses a 4.2% uniform, real, after-tax WACC for all renewables:

Risk-free rate	~ 1.3%
Government policy premium	~ 0.0%
Energy project premium	~ 5.0%
RENEWABLE NOMINAL WACC	**~ 6.3%**
RENEWABLE REAL WACC	**~ 4.2%**

Table 47

As discussed above, we use the Fisher equation to calculate the real WACC based on the nominal WACC and expected inflation rate.

With respect to nuclear, as discussed above in the section for The Netherlands, the Czech Republic recently issued a 2% loan for a nuclear energy project. We refer the reader to that section for more information. In short, we assumed an additional 3% for the equity financing. Hence, from an investor standpoint, the energy risk premium was about 5%, but needs to be added to the risk-free rate to calculate the approximate nominal WACC, which is then transformed to a real, after-tax WACC of 4.2%:

Risk-free rate	~ 1.3%
Government risk premium	~ 0.0%
Energy risk premium	~ 5.0%
NUCLEAR NOMINAL WACC	**~ 6.3%**
NUCLEAR REAL WACC	**~ 4.2%**

Table 48

WACC = risk free rate + government risk premium + project risk premium

Formula 13

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[681] See https://www.cnb.cz/en/monetary-policy/inflation-targeting/

WACC Estimate

As a default, the model uses a 4.2% uniform policy-neutral, real, after-tax WACC for both renewables and nuclear. We believe this reflects a reasonable estimate of the project risks and reflects a cost of capital that can be achieved in a policy regime that is friendly towards and does not discriminate between these energy source technologies. Choosing a WACC reflective of a 0% government policy premium offers the best methodology for rationally evaluating the alternatives to meeting the country's energy needs.

Model Outcomes & Sensitivity Analysis

All of the comments made for the model output from the model for The Netherlands also apply to the model output for the Czech Republic.

We present several model outputs, in the following order:

1. Synchronized lifetime analysis: a comparison of (1) the total cost of a nuclear plant over its entire useful life to (2) the total costs of consecutive renewable power installations over the same period of time that produce the same electricity output, using no discounting and WACCs of 0% and 4.2%
2. Comparison of technologies: impact of discounting and realized vs. expected costs
3. Sensitivity analysis: impact of changing key assumptions on the cost of electricity

Synchronized Lifetime Analysis

We have introduced the basics and rationale of the synchronized lifetime analysis above in the section for The Netherlands. The synchronized lifetime analysis has slightly different parameters for the Czech Republic, primarily due to the different technical lifetimes of their solar and wind technologies.

In the synchronized lifetime analysis for the Czech Republic, we assume an electricity production requirement of just under 10mn MWh per annum, which is equal to the output of a 1,200-MW nuclear power plant. The required time period during which this production level is to be sustained is 60 years, which is the time period necessary to synchronize and equalize the consecutive lifetimes of nuclear plants and renewable power facilities, such that at the end of the 60-year period, all energy sources have met the ends of their respective useful lives.

The required output level of 10mn MWh is equivalent to the production of 4,464 onshore wind turbines and 1,594,286 solar panels. The analysis also accounts for the differences in lead times/construction periods.

Table 48. provides the results of this analysis. We use a 0% WACC for all technologies and a 4.2% WACC for comparison. For each technology, the total costs of meeting the electricity requirements for 60 years are provided.

	Nuclear	Solar	Onshore Wind
Present Value of Costs at 0% WACC	€18bn	€25bn	€18bn
Relative to nuclear	1.0x	1.4x	1.0x
Present Value of Costs at 4.2% WACC	€9bn	€9bn	€7bn
Relative to nuclear	1.0x	1.0x	0.7x

Table 48. Synchronized Lifetime Analysis

Note that the amounts are expressed as billions, i.e. 10^9.

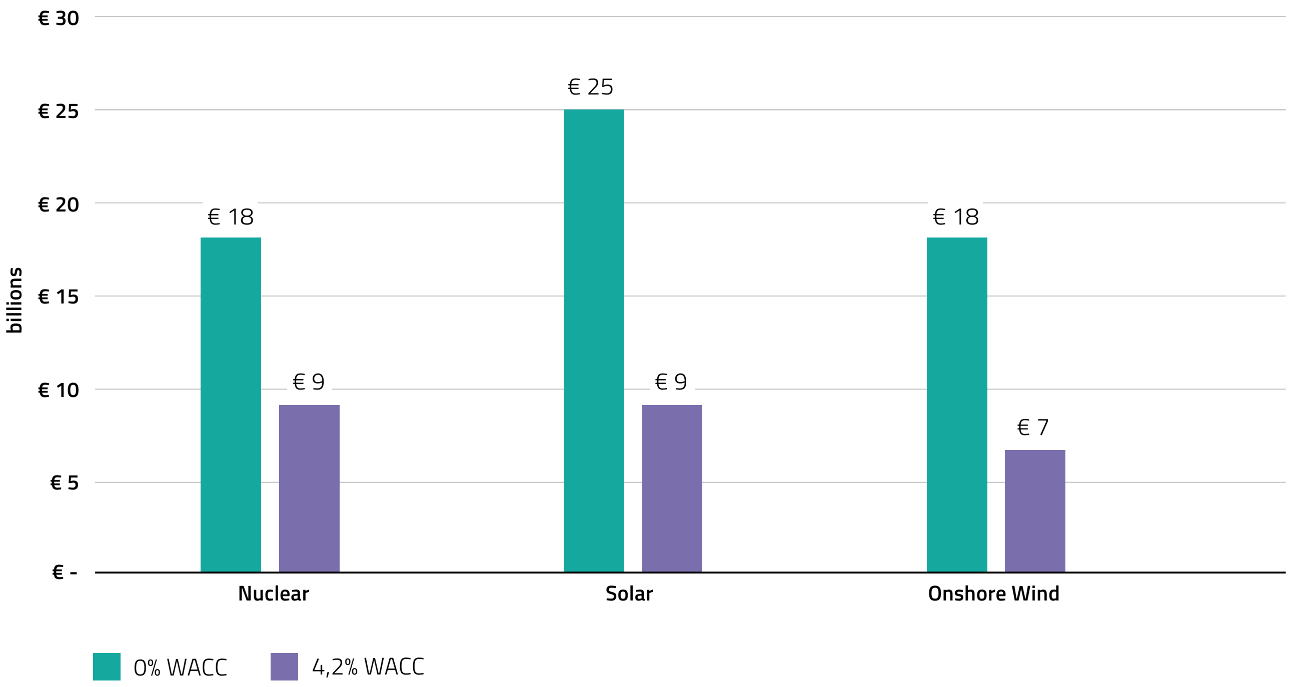

Figure 9. Synchronized Lifetime Analysis

Figure 9. shows these results graphically.

The synchronized lifetime analysis reveals that nuclear power is roughly on-par with renewables at both 0% and 4.2%, although at 4.2%, onshore wind is cheaper. This result is independent of the level of power output required. It is also independent of the time period over which the analysis is conducted, assuming the lifetime of the technology is exhausted. Note, however, that these LCOE cost estimates do not present a complete, accurate picture of total costs, since they ignore the reduced value of stochastic renewable electricity generation, only take into account the cost of generating the electricity, and not the broader system-related costs; once these are factored into the analysis, the result change.

Comparing Technologies

We present the cost of electricity (EUR/MWh) for various iterations of discount rates and cost structures. Table 17, below, gives the various WACC's, energy discount rates, and capital costs used in the various scenarios.

	Nuclear WACC	Renewables WACC	Energy Discount Rate	Capital & Fixed O&M Costs
Scenario 1	4.2%	4.2%	0.0%	Realized
Scenario 2	4.2%	4.2%	0.0%	Expected
Scenario 3	7.0%	4.2%	0.0%	Realized
Scenario 4	7.0%	4.2%	3.0%	Realized
Scenario 5	7.0%	4.2%	3.0%	Expected

Table 49 Cost of Electricity (EUR/MWh) for Varying Discount Rates and Cost Assumptions

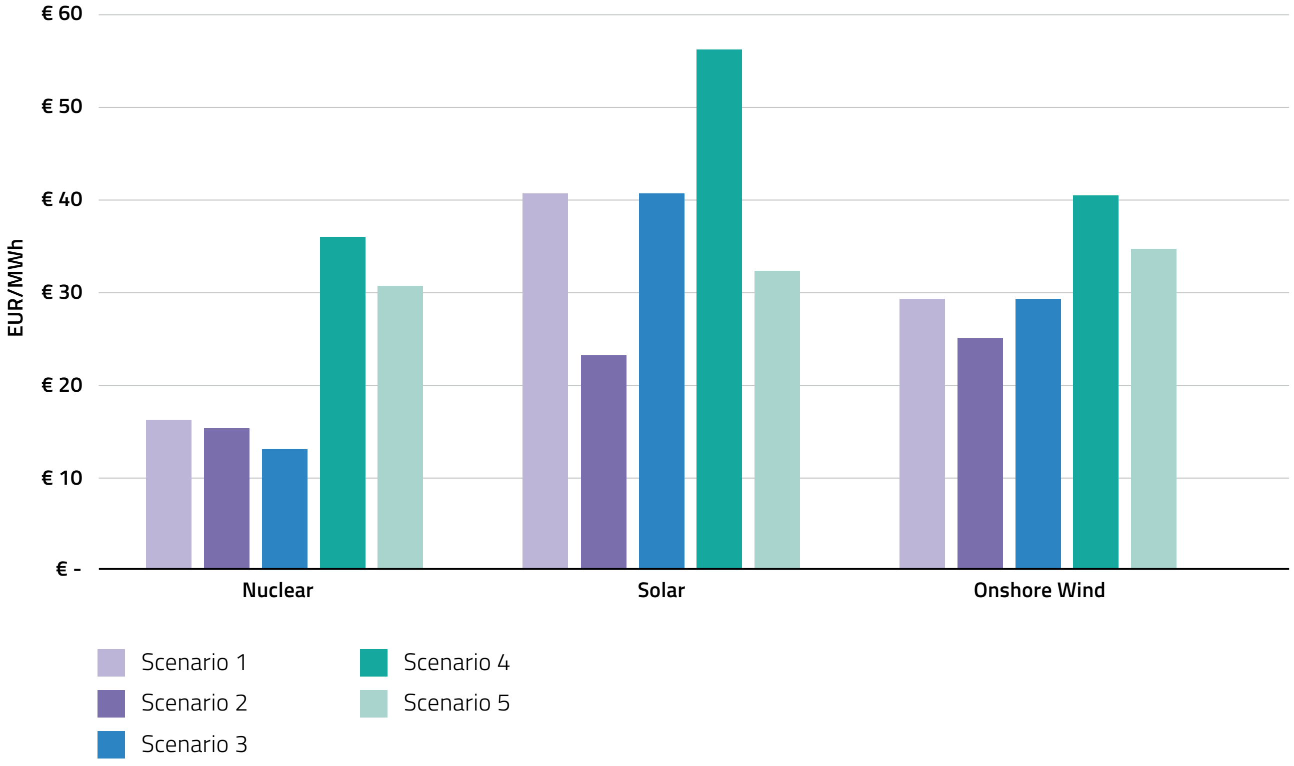

Figure 10. Comparison of Electricity Costs (EUR/MWh) for Various Scenarios

In figure 10 we show the resulting electricity costs for each of these scenarios.

For renewables, significant drivers of the different values across the scenarios are the capital costs. Because the realized figures lie so much higher than expected values, which factor in substantial cost savings over the next 30 years, especially for renewables, electricity costs can decrease by almost 50% depending on the type of technology. This means that for all renewables to be at least somewhat competitive with nuclear, significant capital cost decreases need to materialize and nuclear power should not realize any significant cost reductions; if such substantial decreases and absence of reductions do not materialize, renewables remain uncompetitive.

We also observe a relatively muted impact of the WACC. Between scenarios 1 and 3, the only difference is the WACC for nuclear, which is 7% in scenario 3 compared to 4.2% in scenario 1. The cost of electricity decreases from 16.23 euros in scenario 1 to 13.14 euros in scenario 3, essentially maintaining its significant cost advantage over wind and solar.

In no scenario is nuclear more expensive than either of the renewable options. Scenario 5 resembles the methodology most often used in the literature covering the topic, where energy is discounted, nuclear is discounted at a higher rate than renewables, and significant cost decreases are modeled in for renewables; even in this scenario, nuclear remains competitive.

Sensitivity Analysis

For the sensitivity of the assumptions, we start with a default value that arises from scenario 1 as described above. We apply changes to the following factors in turn to assess the relative impact on the electricity cost (i.e. % change in EUR/MWh):

- WACC
- Capital costs
- Capacity factor

From this sensitivity analysis, the following general take-aways are notable:

- The sensitivity analysis reveals that for nuclear, given the longevity of its costs, WACC is the most important variable in determining the costs. A decrease from 4.2% to 0% leads to an 85% increase in costs. The effects are much more muted for renewables, with the cost of solar and onshore wind increasing by 5% as the WACC decreased from 4.2% to 0%.
- For renewables, capacity factor and capital costs are more impactful. For nuclear, the effects of the changes in capital costs and capacity factor are always below +/- 7%. For solar, changes in capital costs lead to 10% changes in the electricity cost. A decrease in the capacity factor to 12% increases costs by 12%. For onshore wind, capacity factor changes are even more impactful: a decrease of 5% in the capacity factor increases costs by a fourth, an increase in the capacity factor by 5% decreases costs by 17%.

Nuclear

For nuclear, we change the three inputs as set out in Table 50. In terms of costs, we evaluate two scenarios, one in which costs are decreased to 90% of their original, and one in which they are increased by 10%:

Nuclear	Base Level	Min	Max
WACC (%)	4,2%	7.0%	0.0%
Capital Costs (€/MWe)		90.0%	110.0%
Capacity Factor (%)	93.0%	95.0%	85.0%
Base Level EUR/ MWh		**€ 16.23**	

Table 50. Sensitivity Analysis Nuclear Power

The impact on electricity costs is as shown in figure 11.

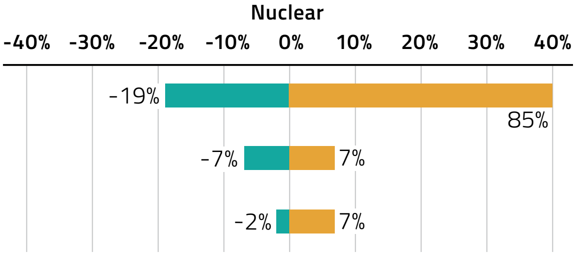

Figure 11. Impact of Variations in Main Drivers on Cost of Nuclear Power

Solar

For solar, we change the inputs as set in Table 60.

Solar	Base Level	Min	Max
WACC (%)	4,2%	7.0%	0.0%
Capital Costs (€/MWe)		90.0%	110.0%
Capacity Factor (%)	14.0%	15.0%	12.5%
Base Level EUR/ MWh	**€ 40.73**		

Table 60. Sensitivity Analysis Solar Power

The impact on the electricity costs is as show in figure 12.

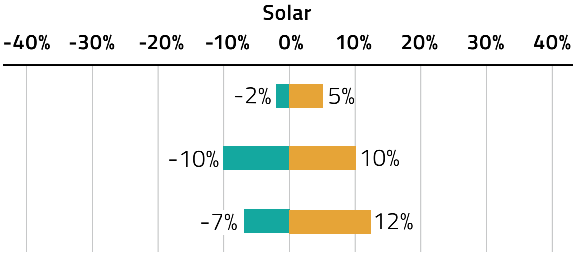

Figure 12. Impact of Variations in Main Drivers on Cost of Solar Power

Onshore Wind

For onshore wind, we change the inputs as shown in Table 61.

Onshore Wind	Base Level	Min	Max
WACC (%)	4,2%	7.0%	0.0%
Capital Costs (€/MWe)		90.0%	110.0%
Capacity Factor (%)	25.0%	30.0%	20.0%
Base Level EUR/ MWh	**€ 29.31**		

Table 61. Sensitivity Analysis Onshore Wind

The impact on the electricity costs is as shown in figure 14=3.

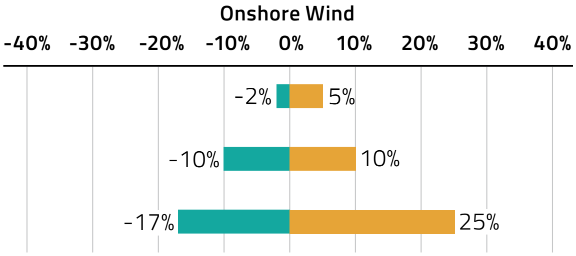

Figure 13. Impact of Variations in Main Drivers on Cost of Onshore Wind Power

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Annex III. List of Reviewers of 'Road to EU Climate Neutrality -- Spatial Requirements of Wind/Solar and Nuclear Energy and Their Respective Costs'[682]

1. **Professor William Nordhaus**, Sterling Professor of Economics and Professor of Forestry and Environmental Studies, Yale University, 2018 Nobel Laureate in Economics (Sveriges Riksbank Prize in Economic Sciences) for integrating climate change into long-run macroeconomic analysis.
2. **Dr. Joeri Rogelj**, Director of Research and Lecturer in Climate Change and the Environment, Imperial College, Faculty of Natural Sciences, The Grantham Institute for Climate Change, Lead Author, United Nations Emissions Gap Reports, Coordinating Lead Author, IPCC Special Report on 1.5°C of Global Warming, Lead Author, IPCC's Sixth Assessment Report.
3. **Dr. Fabien Roques**, Associate Professor, Florence School of Regulation, European University Institute, Associate Professor, Paris Dauphine University, Executive Vice President with Compass Lexecon, PhD in Energy Economics, University of Cambridge.
4. **Professor Samuele Furfari**, Ph.D., Energy Policy Expert, former Senior Official on Energy Policy, European Commission, Brussels, Professor of Energy Geopolitics and Energy Politics, Free University of Brussels.
5. **Dr. Kors Bos**, Nuclear Physicist, Secretary, Stichting Thorium MSR, formerly at Nuclear Data Group, Oak Ridge National Laboratories, USA, CERN, Geneva, and Fermilab, University of Chicago, Ph.D., University of Amsterdam.

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[682] Critical review and institutionalized scepticism help to ensure that facts and analysis are sound, conclusions are supported by the analysis, and ideas can withstand the scrutiny of argument. The authors thank the 15 academics and professionals who have reviewed this report and provided comments, guidance, insights, and critique. Their feedback and input have contributed greatly to its quality and incisiveness. In some cases, comments received from different reviewers were conflicting or inconsistent and could not be reconciled. In those cases, choices had to be made. The authors are solely responsible for such choices and the contents of this report. Listed by name are only those reviewers who gave permission by the deadline; all other reviewers are listed as 'N.N.' (nomen nescio) followed by their academic or professional discipline. Not all reviewers have assessed the full report; some reviewed only the parts within their area of expertise or selected sections, or offered high level comments. As always, listing does not imply that a reviewer has endorsed this report.

6. **Professor Gordon Hughes**, former Professor of Economics, University of Edinburgh, former Senior Adviser on Energy and Environmental Policy, World Bank.

7. **Drs. Richard Zijlstra**, M.Sc. Energy and Environmental Sciences (EES-RUG), University of Groningen, MBA, GeoICT Management, Technical Planology, University of Groningen.

8. **Professor Michael Kelly**, Emeritus Prince Philip Professor of Technology, University of Cambridge, former Chief Scientific Advisor, Department for Communities and Local Government, Ph.D. in solid state physics, University of Cambridge, M.Sc. Mathematics, M.Sc. Physics, Victoria University of Wellington, New Zealand.

9. **N.N.**, Environmental and climate scholar (Ph.D., Professor)

10. **N.N.**, Energy and transition specialist (M.Sc.)

11. **N.N.**, Climate researcher

12. **N.N**., Atmospheric scientist (Ph.D., Professor)

13. **N.N.**, Engineer (Ir.)

14. **N.N.**, Chemist (Drs.)

15. **N.N.**, Engineer (Ir.)

Annex IV. Review of CNS Study

The CNS Study[683] reviews four scenarios[684] that are claimed to represent "the four corners of the playing field."[685] This claim is based on the proposition that the scenarios are based on the 'Klimaatakkoord'[686] ('Climate Agreement') and reflect the insights of the market; the 'Klimaatakkoord', however, does not exclude nuclear power, which is not included in any of the scenarios but relegated to a separate cost study.

The four scenarios differ with respect to the level of governance of the energy transition (regional, national, European or global), and the responses of citizens and companies. The European governance scenario serves as reference scenario for the nuclear study. These scenarios are not intended to present choices to policymakers; rather, they serve to present stylized policy options elements of which can be combined to design actual policies.[687] Rather than accommodating uncertainty and accounting for unforeseeable events, they represent 'Goldilocks' scenarios that may no longer be useful in 5 or 10 years' time.

Each of the scenarios produces a climate neutral energy system in The Netherlands in 2050, with only a small amount of fossil fuel use (the carbon emissions of which are offset by carbon capture or other compensation mechanisms), and varying levels of import.

Interestingly, the scenarios treat both energy demand and energy production as an endogenous variable; each has their own, specific level of energy. As discussed in Part 5 of this report, we have decided not to do so, and treat power demand as an exogenous variable. This decision is based on the fact that the 2050 power demand is highly uncertain and depends on unknown variables, such as further energy efficiency gains that may be realized, the level of power usage by citizens in 2050, the level of power-intensive industries, innovations that may affect power demand (upwards or downwards), the general level of wealth, etc.

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[683] Berenschot/Kalavasta, Klimaatneutrale energiescenario's 2050, Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050, maart 2020, available at https://www.tweedekamer.nl/kamerstukken/brievenregering/detail?id=2020z06737&did=2020D14346 (the "CNS Study").

[684] These four scenarios are adaptations of the scenarios used in prior analysis, specifically "Net voor de Toekomst 2017", available at https://www.ce.nl/publicaties/2030/net-voor-de-toekomst For a discussion of the differences between the scenarios used in 2017 and the scenarios used for the CNS Study, see CNS Study, pp. 11-12.

[685] CNS Study, p. 10.

[686] Klimaatakkoord, https://www.klimaatakkoord.nl/

[687] Eric Wiebes, Brief "Aanbieding klimaatneutrale energiescenario's 2050", DGKE-WO / 20075821, 15/04/2020, available at https://www.rijksoverheid.nl/documenten/kamerstukken/2020/04/15/kamerbrief-klimaatneutrale-energiescenarios-2050

The scenarios analyzed in the CNS Study represent mixes of numerous items that affect energy demand and production, ranging from lighting in households to green gas production;[688] no explanation is provided as to why the particular mixes were chosen or why and how these combinations represent the corners of the playing field.

The use of the ETM model involves a large number (hundreds) of highly specific assumptions of fixed levels of activities relevant to the energy system and climate change, without regard to how exactly how all of these activities will be accomplished and coordinated, and how non-conforming behavior will be corrected (e.g., if fewer than the required percentage of car owners buy EVs instead of combustion engine cars).

It might be contemplated that each scenario should correspond to comprehensive, highly detailed government policies, and that central planning and micro-management systems will have to be put into place to achieve the outcomes projected by the scenarios. For instance, the scenarios include a specific trajectory of industrial development of The Netherlands – remarkably, while the regional governance scenario produces a decrease of industrial activities and the national governance scenario no growth, only the European and international governance scenarios produce industrial growth.[689] The authors do not defend these choices but merely suggest that those who disagree with their assumptions should examine what the influence is of revised assumptions on the outcomes of the scenarios.[690]

In short, the entire CNS study rests on the validity of the four enormous sets of specific assumptions and of the ETM model used to generate the outputs. We have not assessed the ETM model, except with respect to some specific features, such as the level of nuclear energy it is able to accommodate.

All scenarios assume no nuclear power at all and widespread deployment of renewable power, in particular wind and solar. They also include substantial 'electrification' of the energy mix, with more energy being derived from electricity (from roughly 15% to up to 45% in one scenario). In addition, in all scenarios, climate-neutral hydrogen plays a role as feedstock and back-up. Depending on the scenario concerned, the energy mix is completed with sustainable heat, green gas, CCS, import of hydrogen or additional electrification.

All four scenarios assume that the energy demand in 2050 will be lower than the current energy demand by a significant margin. The reduction of total energy demand varies from approximately 15 to 50%, depending on the scenario involved. The authors explain that these reductions result from "increased efficiency in all scenarios".[691] Among the scenarios, total energy demand varies as a function of industrial production, which will be higher in the case of the European and Global scenarios, and lower in the case of the Regional scenario.

The scenarios therefore are not relevant to a future in which energy and power demand in 2050 remains constant or grows; apparently, the authors are willing to bet on substantial decreases in energy demand.

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[688] Energietransitiemodel, https://energytransitionmodel.com/ The CNS Study provides links to the ETM-models for each of the scenarios. CNS Study, p. 20.

[689] CNS Study, pp. 6-7.

[690] CNS Study, p. 20.

[691] CNS Study, p. 36.

We believe that a higher power demand by 2050 than assumed in the scenarios is possible or even plausible, and therefore include such scenarios in our analysis as a precautionary measure to guard against higher power demands, also in light of the poor track record of projections of power demand.[692]

Another way in which the CNS Study reflects subjective choices is through the assumed capacity or load factors. The capacity factors are generally higher than the actual power production currently achieved and, thus, the currently valid capacity factors. This is based solely on expectations of interested parties. We have decided to treat capacity factors as variable and review a range of such factors. The low end of the capacity factor range may be lower than the currently prevailing capacity factor because the site conditions for additional wind and solar power production may be less favorable than those of the sites that have previously been utilized for wind and solar (e.g., the location may get less wind or sun, or the local conditions may be such that the lifespan of the equipment is adversely affected).

Further, the CNS Study fails to identify the main drivers of the energy transition. Instead, it draws attention to a massive amount of details that blur a clear view on the key issues. The failure to identify the main drivers makes it hard for policy makers to zoom in on the key policy choices. By using fixed scenarios that are deemed to present the corners of the playing field, the results of the CNS Study are also vulnerable to changing circumstances and unforeseen events. No sensitivity analysis has been conducted to determine how the outcomes change if the assumptions on key parameters such as energy demand and capacity factors are varied. This is major limitation of the CNS Study that this study has avoided.

Finally, the CNS Study does not, or only to a limited extent, consider the necessary infrastructure to utilize decentral renewable power (such as demand controls, smart appliances, storage, conversion and switching off), nor does it discuss storage for varying periods of time. These topics will be covered by the second phase of the research ("fase 2 II3050").[693]

Other issues in relation to the CNS Study are discussed in parts 5 and 6 of the report and Annexes I and II attached to the report.

Our conclusion is that the CNS Study provides useful information, but is not fit for purpose, if the purpose is to assist policy makers in making informed decisions with respect to the energy transition.

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[692] In 2014, a Dutch governmental advisory body projected energy demand reduction by 2020. Planbureau voor de Leefomgeving, EU-doelen klimaat en energie 2030: Impact op Nederland, september 2014, available at https://www.pbl.nl/sites/default/files/downloads/pbl-2014-eu-doelen-klimaat-en-energie-2030-impact-op-nederland_01394.pdf In fact, since 2014, the final energy demand in The Netherlands has increased from 3,009 PJ to 3,045 PJ in 2019 (source: CBS).

[693] CNS Study, p. 11.

Annex V. Review of Space Impact Study

The Space Impact Study[694] examines the impact of the four scenarios covered by the CNS Study (for a review of the CNS Study, see Annex IV attached to this report) on the use of land and space, and also on the use of inland water and marine areas. The subsoil is not included in the analysis.

The Space Impact Study does not consider nuclear power, possibly because the spatial requirements of nuclear power plants are negligible relative to the spatial requirements of renewable energy facilities. The study also does not assess the costs of the use of land and space in the various scenarios. It attempts to identify issues in relation to land use in each of the scenarios.[695]

In the introduction, the authors state that "climate change and international agreements accelerate the necessity of making clear choices and of drastic special changes."[696] The authors do not specify which choices they have made, and do not clearly articulate the choices that policy makers need to make.

As discussed in Annex IV attached to this report, the four scenarios used in the CNS Study were not chosen on the basis of their impact on land use. Rather, they reflect different levels of governance. Consequently, it remains unclear whether and, if so, how the scenarios are fit for the purpose of studying the spatial impacts of power generation technologies.

For each of the four scenarios, the various energy sources (technologies) and the extent of their deployment serve as starting points. On this basis, the Space Impact Study determines how much land, inland water and territorial sea is required in a particular scenario.

In doing so, the study uses three filters: (1) potential use of land/space for an energy source, (2) regulatory and policy restrictions of land use for a specific energy source, and (3) link with environment (conditions).[697] For wind on land, for instance, the study considers intensive and extensive options, available land if only hard restrictions are taken into account, or if also soft restrictions are taken into account, and possible additional conditions, such as that wind turbines are

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[694] Generation Energy, Ruimtelijke uitwerking Energiescenarios, maart 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/31/ruimtelijke-uitwerking-energiescenarios (the "Space Impact Study").

[695] Space Impact Study, p. 4.

[696] Space Impact Study, p. 6.

[697] Space Impact Study, p. 6.

placed only in large clusters.[698] The authors do not explain how they determined these hard and soft restrictions, and how those determinations resulted in estimates of available land/space. For each of the scenarios, the study identifies for each energy source and each category of land/space, which spatial impact results. Eight categories of land/space are used: roads and traffic infrastructure, semi-built terrain, agricultural land, recreational land, built terrain, inland surface waters, forest and natural terrain, and sea/coastal water.[699] No sensitivity analysis has been conducted.

Importantly, the study acknowledges that it focuses on theoretically available land/space, but does not consider the desirability of the necessary land/space use.[700] Further, in the summary tables the amount of land/space necessary for an energy source is expressed as a percentage of the theoretical maximally available land/space, disregarding hard and soft restrictions. For purposes of our analysis, we use available land/space consistent with hard restrictions as the primary point of reference. The reason is that other uses would require changes to existing laws and policies, which require decisions by policy makers. We provide the percentage of the theoretically available land only for purposes of comparison to the Space Impact Study.

A major limitation, the study does not assess other uses of land/space that may conflict with the necessary utilization of land/space for purposes of the energy system. For instance, the additional land necessary for residential housing, industrial activities and agricultural is not considered. We likewise do not consider these conflicting uses, although we recognize that these conflicts may present political choices and that policy makers may have an interest in avoiding such choices as much possible.

Additional comments on the Space Impact Study can be found in part 5 of the report and Annex I attached hereto.

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[698] Space Impact Study, p. 23.

[699] Space Impact Study, p. 21.

[700] Space Impact Study, p. 20.

Annex VI. Review of Nuclear Study

The Nuclear Study,[701] was necessary because nuclear energy was excluded from the CNS Study and the Space Impact Study, presents an alternative to the European governance scenario set forth in the CNS Study (see Annex IV for further discussion). This alternative includes 4 ways in which nuclear power could be added to the power mix in the European governance scenario.

The study reviews "system effects" of adding nuclear power. These "system effects," however, are limited to first order and second order effects on cost; there is no consideration of the effects on land use, impacts on nature and the environment, etc.[702] In Part 7 of this study, we discuss such impacts.

The four ways in which nuclear is considered in the European governance scenario are the following:

- "*Purely market-driven:*" This confusing term,[703] which is apparently used as a synonym for the term "*merit order*"[704] (which suggest something very different), supposes that nuclear power is produced only if there is not enough renewable energy. Unsurprisingly, the study concludes that this alternative would inflate cost.[705] Given that it makes little sense to deploy nuclear power in this manner in the power mix, we do not discuss it further.

- "*Merit order plus elektrolyzers:*" The elektrolyzers would be used to produce hydrogen when the

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[701] Kalavasta/Berenschot, Systeemeffecten van nucleaire centrales in Klimaatneutrale Energeiscenarios 2050, 9 maart 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-in-klimaatneutrale-energiescenarios-2050 (the "Nuclear Study"). For the related data sheets in English, see https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleairecentrales-in-klimaatneutrale-energiescenarios-2050.

[702] The authors note that the study "is not at all intended to discuss the political, societal or ethical issues associated with nuclear power." Nuclear Study, p. 2. Likewise, the study does not discuss the political, societal and ethical issues associated with wind and solar energy.

[703] As discussed in Parts 2 and 8 of this report, the electricity market is seriously distorted by a series of incentives aimed at promoting renewable energy.

[704] See, e.g., Nuclear Study, p. 25.

[705] Nuclear Study, p. 25.

nuclear power plant is not used to fill the renewable power gaps. The conclusion is that hydrogen produced in this manner is more expensive than hydrogen produced in other ways,[706] but the Nuclear Study did not consider alternatives to the production of hydrogen through electrification and electrolysis.[707] We do not further consider the use of nuclear power for the production of hydrogen, since since our focus is on nuclear power's use as 'base load' to provide electricity.

- "*Hydrogen production:*" Nuclear power would be used only for the production of hydrogen. The authors claim that the hydrogen produced in this manner would be more expensive than hydrogen produced through the use of renewable power in the European governance scenario.[708] There is no consideration of the scalability and predictability of hydrogen production, in particular if hydrogen supply were to exceed the presumed demand, or the other way around. For the reason discussed above, we do not consider this further.

- "*Must run:*" Under this alternative, the nuclear power plant would run by priority and provide base load.[709] The authors conclude that in this scenario nuclear power, in terms of 'system cost,' is approximately as expensive as renewable power, if the cost of capital is assumed to be equal.[710] We discuss this alternative, which is a plausible way to utilize nuclear energy, further below.

Review of Nuclear Study's Methodology and Data

We review the methodology used in the Nuclear Study, since this further clarifies how and why our approach differs. In Annex IV attached to this report, the CNS Study has been reviewed; some of the same issues also arise in the context of the Nuclear Study, but the Nuclear Study also present new problems. This section briefly discusses some of the main issues specific to the Nuclear Study.

- ***Limited scope*** – As noted above, the Nuclear Study focusses predominantly on direct cost of nuclear power, relative to wind and solar power, and, to limited extent, discusses some second order and system effects. It does not attempt to identify and quantity all second order effects of nuclear, wind and solar power. For instance, although its title suggests otherwise ("system effects"), the study pays only limited attention to the adverse impacts and negative externalities of wind, solar, and nuclear; even the costs of adaptations to the existing power infrastructure necessitated by wind and solar power, relative to nuclear power, receive little attention, possibly because all of these costs are deemed to be computed by the model used. As noted, the broader impacts of land and space demand by the various power technologies is ignored, and so are the broader impacts on human health, nature, etc. The authors acknowledge that their perspective is "not a study of the merits of nuclear, but of the effects of including nuclear power in the larger CO_2-free energy system in 2050."[711]

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[706] Nuclear Study, p. 3.

[707] Nuclear Study, p. 10.

[708] Nuclear Study, pp. 4-5.

[709] Nuclear Study, p. 8.

[710] Nuclear Study, p. 4. The weighted average cost of capital (WACC) used here is 3%. If a "technology-specific" WACC is used, nuclear power is more expensive. These WACCS are 7% and 4.3%, respectively. Nuclear Study, p. 2.

[711] Nuclear Study, p. 8.

This focus does not help to get a clear picture of the relative costs of nuclear power. We have attempted to avoid this problem, and provide fuller information required to inform policy-making. In addition, in Part 7 of this report and Annex IX attached hereto, we discuss 10 categories of adverse impacts and negative externalities associated with wind, solar and nuclear energy to complete the broad picture.

- ***Methodology*** – The authors claim that they apply "three cost perspectives,"[712] but their analysis relies heavily on calculations of the levelized cost of electricity (the "LCOE method").[713] The LCOE method, as applied in the Nuclear Study, computes the present cost of power[714] relative to the present value of that power (see further below). The other two methods, marginal cost of power and system-related, are selective and applied in a rather limited manner. Marginal cost of additional power generated through wind turbines or solar panels, of course, is low, but the assumption is made that it does not matter whether additional power is needed at that point in time, and the marginal cost of adding more renewable power to the electricity system is not adequately addressed.[715] There is little discussion of opportunity cost to be found in the Nuclear Study. With respect to system-related cost, the Nuclear Study assumes as a baseline an electricity system that is dominated by renewable technology and then attempts to assess only the costs associated with integrating a little nuclear energy into such a system.[716] By using this methodology, the integration cost and other system-related costs, which are large for renewable power and low for nuclear power, are devalued.[717]

- ***LCOE method*** -- There is a lot of confusion around the LCOE method, its limits,[718] its proper scope of application, and the discounting of power produced in the future.[719] The LCOE has been promoted by

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[712] Nuclear Study, p. 9.

[713] As the UK government explains, "levelised costs relate only to those costs accruing to the owner/operator of the generation asset, the metric does not cover wider costs to the electricity system." UK Department for Business, Energy & Industrial Strategy, BEIS Electricity Generation Costs, August 2020, available at https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020, p. 21.

[714] In principle, discounting costs that incur at different points in time to a common basis makes sense, because money has a time value, also in public finance. Since LCOE is transparent and easy-to-understand, it is often used as a basis of comparison of different power technologies with unequal life spans, project size, capital cost, maintenance cost, etc. It cannot be used in isolation, however. See IEA/NEA, Projected Costs of Generating Electricity, 2020 Edition, available at https://www.oecd-nea.org/jcms/pl_51110/projected-costs-of-generating-electricity-2020-edition?id=pl_51110&preview=true

[715] "It is important to take into account the "ramp-up" and "ramp-down" speed of nuclear power plants so that they can follow the power supply by wind and solar …" Nuclear Study, p. 10.

[716] The Nuclear Study is presented as "an exploration of the inclusion of nuclear power in a CO_2-free energy system in 2050 in which multiple other CO_2-reduction measures are taken, such as renewable energy, demand reduction, … Thus, it is not a study into the merits of nuclear power itself." Nuclear Study, p. 8.

[717] See Part 7 of this report for further discussion of these costs.

[718] See, for instance, UK Department for Business, Energy & Industrial Strategy, BEIS Electricity Generation Costs, August 2020, available at https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020

[719] See, for instance, Richard McCann, Comment: LCOE is an undiscounted metric that distorts comparative analyses of energy costs, The Electricity Journal, Volume 33, Issue 7, August–September 2020, 106812, available at https://doi.org/10.1016/j.tej.2020.106812. James Loewen, LCOE is an undiscounted metric that inaccurately disfavors renewable energy resources, The Electricity Journal, Volume 33, Issue 6, July 2020, available at https://doi.org/10.1016/j.tej.2020.106769. James Loewen, LCOE is an undiscounted metric that distorts comparative analyses of energy costs, The Electricity Journal 32 (2019) 40–42. J. Aldersey-Williams, T. Rubert, Levelised cost of energy – A theoretical justification and critical assessment, Energy Policy 124 (2019) 169–179.

Lazard, an investment services firm, in its annual publications on investing in electricity.[720] From the perspective of private investors (who need to decide in which projects to invest), discounting future power makes sense, because it corresponds to the present current value of a stream of revenue. From the perspective of a policy maker (who needs to decide on policy to ensure future electricity availability), however, there is no persuasive rationale for discounting future power.[721] Policy makers want to take the needs of future power users into account; in fact, the very rationale for climate policy and renewable energy is to serve the interests of future people and future generations. The concept of sustainable development laid down in the EU treaties refers to development meeting the needs of the present "without compromising the ability of future generations to meet their own needs."[722] Carbon-free energy was deemed necessary precisely because the interests of future generations are discounted; sustainable policies and climate policies are intended to counteract this kind of discounting.[723] Put differently, for policy and planning purposes, the relevant parameter is the availability of power at a particular point in time, not its present market value, to be distinguished from the present value of the cost thereof. Although the Nuclear Study uses LCOE with power discounting, we prefer to use LCOE without discounting the denominator (i.e. electricity generated).

- ***Assumptions*** – The Nuclear Study makes single assumptions on a series of important parameters; it does not employ ranges. It attempts to justify these choices by claiming that "everything is based on the most recent information, as published in reports by authoritative organizations."[724] By not using a range for key parameters, however, the Nuclear Study withholds important information to policy makers. There is no adequate justification for experts deciding uncertain values for policy makers.

- ***Bias*** – The Nuclear Study suffers from confirmation bias. For example, the public's attitude towards

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[720] "The annual publication by Lazard, a leading financial advisory firm, of LCOE numbers from different energy types is eagerly awaited each November … Prestigious national laboratories and independent think tanks use LCOE frequently in their publications. And state regulatory bodies use LCOE in their integrated resource planning to help decide which technologies will deliver the cheapest electricity over time." James Loewen, LCOE is not the metric you think it is, May 28, 2020, available at https://www.utilitydive.com/news/lcoe-is-not-the-metric-you-think-it-is/578360/

[721] Arguably, discounting power to present value for purposes of policy-making involves a category error, since government does not want to trade power now; the private investor perspective is irrelevant to government policy-making in this case. In the case of the 2050 scenarios, the government planner needs to decide how it can ensure that there will be a defined amount of electricity supplied in 2050 – the options are ensuring power technologies are deployed domestically, importing electricity from abroad, or (theoretically) buying power futures; the latter is not an option because power futures are not available that far in advance (see, e.g., ICE (https://www.theice.com/energy/power). Betting on the availability of imported electricity in 2050 and import prices involves significant risk, but does not require any discounting of electricity. So, discounting electricity in the context of planning is not obvious. Further, in investment planning in the oil and gas industry, the energy to be produced is not discounted. J. Aldersey-Williams, T. Rubert, Levelised cost of energy – A theoretical justification and critical assessment, Energy Policy 124 (2019) 169–179, at p. 171 ("DCCOE (discounted costs cost of electricity) is comparable to the net present cost per barrel measure commonly used in the oil industry (Brealey et al., 2006), which also discounts the financial side of the equation but not the energy side. We believe that this measure was adopted as NPV is routinely determined in investment appraisal in the oil and gas industry.")

[722] European Commission, Sustainable development, available at https://ec.europa.eu/environment/sustainable-development/

[723] Cedric Philibert, Discounting the future, in: Internet Encyclopaedia of Ecological Economics, available at from http://philibert.cedric.free.fr/Downloads/Discount2003.pdf

[724] Nuclear Study, p. 9.

technologies is treated as "bias" in the case of renewable power,[725] and as a cost of doing business in the case of nuclear. Further, the assumptions regarding future possible efficiency gains reflect bias in favor of renewable.[726] The LCOE method excludes integration- and system-related costs, which is high for renewable and low for nuclear, and cannot properly account for the direct and indirect effects of subsidies and other policy bias. The ETM is used selectively to account only for integration cost, but not for the cost of electricity (see further below).

- ***Data Quality*** – The issue of data quality is not discussed explicitly in the Nuclear Study.[727] In many cases, the study uses a single source for a particular input. Further, the sources selected by the authors are not necessarily unbiased; for example, the study relies heavily on data provided by the IRENA, the International Renewable Energy Agency.[728] Moreover, the study switches between data sources without a persuasive explanation, creating a risk of data shopping and cherry picking. Further, the switching between 'estimated' and 'realized' costs is not adequately explained and raises questions.

- ***Validation*** – The methodology used in the Nuclear Study has not been validated. The authors suggest otherwise, however, where they state: "To enable international validation by the OECD NEA of the costs and calculations used for purposes of the study, the ETM, the Excel spreadsheet with the cost calculations, and the data sheets with explanation on the sources used and the computation methods, are in the English language."[729] However, even their own summary of the NEA comments does not suggest that the NEA validated their model; for instance, the NEA commented that "it seems necessary that capital cost estimates for nuclear and VRE display the same optimism/pessimism bias. This is currently not the case."[730] This comment has been ignored by the authors.

- ***WACC/discount rates*** – The Nuclear Study employs confusing terminology with respect to interest rates, i.e. weighted average cost of capital or 'WACC.' Two different types of WACC rates are employed: (i) 'technology-specific public-private' WACCs, and (ii) a 'societal (uniform public)' WACC.[731]

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[725] "In Germany, the most recent bids for onshore wind projects have been heavily undersubscribed since 2018, with prices around 62 €/MWh. This has been attributed to issues with granting permissions for wind parks on a state level and has resulted in increasing risk for developers. In order to avoid including the bias, the mean of the tenders in early 2018 were chosen as representative. This results in a price of 52.23 €/MWh. The lowest weighted average of the bids was achieved in February 2018 with a price of 47.3 €/MWh." Nuclear Study Data Sheets, p. 22. Kalavasta/Berenschot, Systeemeffecten van nucleaire centrales in Klimaatneutrale Energiescenario's 2050: Data Sheets, 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-datasheets

[726] "But for renewables we see a cost reduction in the II3050 calculation and a cost increase in OECD NEA and IEA relative to current projects in The Netherlands and Germany. The latter appear to come from a neglect of recent cost reductions and future potential cost reductions and most likely constitute serious overestimations." Nuclear Study, p. 54.

[727] There is some discussion in the Nuclear Study Data Sheets. See Kalavasta/Berenschot, Systeemeffecten van nucleaire centrales in Klimaatneutrale Energiescenario's 2050: Data Sheets, 2020, available at https://www.rijksoverheid.nl/documenten/rapporten/2020/03/09/systeemeffecten-van-nucleaire-centrales-datasheets

[728] As Hughes explains, "the propensity of both governments and companies to understate the costs and overstate the performance of new projects has a history that is long and inglorious." Hughes, Gordon, Wind Power Economics – Rhetoric and Reality, Renewable Energy Foundation, 4th November 2020, available at https://ref.org.uk/ref-blog/364-wind-power-economics-webinar "Optimism bias in claims about the cost and performance of infrastructure and other projects has been endemic for millennia. Currently, the offshore wind business is trapped in a speculative bubble akin to property and financial bubbles in which claims and expectations lose their base in reality." Hughes, Gordon, WIND POWER ECONOMICS: RHETORIC & REALITY, Volume II -- The Performance of Wind Power in Denmark, Renewable Energy Foundation, Stratford-sub-Castle, 2020.

[729] Nuclear Study, p. 9.

[730] Nuclear Study, p. 42.

[731] Nuclear Study, p. 12.

According to the authors, the technology-specific WACCs are 7% for nuclear and 4.3% for wind and solar; the societal WACC is 3% for all technologies. The report explains the differentiated 'technology-specific' WACC rates as follows: "For third generation nuclear plants we work with a WACC of 7%. … In the system comparison made with the Energy Transition Model (ETM) we likewise work with a WACC for all technologies that the ETM regards as unproven."[732] The uniform societal WACC rate is explained as follows: "In the context of sensitivity analysis and also to connect with the [scenarios], we also explore calculations involving a societal WACC of 3%. … The reason for using a societal WACC is that it facilitates the comparison of different scenarios. The disadvantage of the societal WACC is that it ignores the different risks of the various technologies."[733] This reasoning is erroneous, and reflects status quo bias. The risks of nuclear power are not a function of any increased physical or commercial risk; they are a function of government regulations and policies. Conversely, the lower risks of renewable energy reflect the favorable government policies and subsidies. To suggest that the differentiated WACCs are a function of the technologies involved, is misleading, because, in this case, the differentiated WACCs are policy-dependent, not technology-dependent. Put differently, using differentiated WACCs for nuclear and renewable power merely imports status quo bias into the analysis and tends to perpetuate past policy errors. To ensure that past mistakes do not distort future policy choices, we use a policy-neutral WACC for both nuclear and renewable power. Such a WACC/discount rate is also important to ensure that policy-making is objective and meets the requirement of technology neutrality.

- ***Innovation, increased efficiency, learning effect, economies of scale*** – The Nuclear Study makes a series of assumptions about future evolution of both renewable and nuclear technology.[734] There is a risk that these assumptions have imported confirmation bias into the study, because these effects have not yet been demonstrated, but reflect possible future states of the technologies involved; the authors are optimistic about renewable power's potential for efficiency gains, much less so about nuclear energy's potential.[735] Given that government policies over the last decades have created strong incentives for the development of renewable technologies, such as wind and solar power, it might be surmised that the 'low-hanging fruit' has already been picked,[736] and that the rate of further innovation, learning, efficiency increases and economies of scale will be more limited. Optimism bias and self-interest need to be taken into account when using expected numbers provided by stakeholders. Nuclear power, on the other hand, has not benefited from favorable government policy; to the contrary, in large parts

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[732] Nuclear Study, p. 12.

[733] Nuclear Study, p. 12.

[734] "For all technologies, costs are calculated for greenfield projects. The technologies considered are nuclear, solar, onshore wind, and offshore wind. The calculations assume 2050 technologies, unless otherwise specified. Consequently, costs differ from current ones. For nuclear, the specific technology assumed is the EPR." Nuclear Study, p. 34.

[735] For example, the authors do not use the learning effect reported by the European Commission for the overnight construction cost for nuclear power plants; from FOAK (first of a kind) to NOAK (5th or higher of a kind) this cost drops by 27%. See European Commission, STAFF WORKING DOCUMENT Accompanying the Communication from the Commission: Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty for the opinion of the European Economic and Social Committee, Brussels, 4.4.2016, SWD(2016) 102 final, p. 11, available at https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v10.pdf

[736] For example, a study by the International Renewable Energy Agency (IRENA) shows that the global LCOE for solar PV has seen a significant drop of nearly 70% over the past seven (7) years, from USD 0.36/kWh in 2010 to USD 0.10/kWh in 2017; offshore and onshore wind LCOEs have also decreased in 2017 to USD 0.14/kWh and USD 0.06/kWh, respectively. IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi.

of the Western world, nuclear technology has been disparaged. If this line of reasoning is right, the expectation should be that there is much more potential for innovation, learning effects, efficiency gains, and economies of scale in nuclear power technology than there is in wind and solar power. The assumptions made by the authors of the Nuclear Study, however, reflect a strong belief in further innovation in renewable power, and relatively little potential for nuclear. We question this belief based on the logic articulated above.

- ***Sensitivity analysis*** – The Nuclear Study presents virtually no serious sensitivity analysis (with the exception of the WACC rates, where sensitivity analysis was necessary to correct obvious bias, as discussed above). Given the disputable assumptions made by the authors, this is a serious deficiency. Consequently, the Nuclear Study does not provide policy makers with adequate information for sound decision-making.

- ***Power demand*** – The lack of sensitivity analysis might be most problematic in relation to energy demand, which is treated as fixed input.[737] The total energy demand assumed by the authors of the Nuclear Study is low, and arguably unrealistically low (which keeps the spatial requirements of wind and solar energy artificially low). As a result, the Nuclear Study does not inform policy makers of the consequences of power demand that exceeds the assumed, low demand. To remedy this deficiency, our model uses a realistic range for power demand in 2050.

- ***Use of the Energy Transition Model (ETM)*** – The Nuclear Study uses the ETM to assess the 'system effects' of nuclear power,[738] Interpreted narrowly. As the authors acknowledge, the ETM has its limitations and is inflexible in some respects (e.g. fixed and variable maintenance cost). [739] We use the ETM to do further sensitivity analysis on the scenarios explored in the Nuclear Study, although we have not assessed the ETM model, and in some respects it serves as a non-transparent 'black box' that uses questionable assumptions (e.g. with respect to weather conditions, and wind hours). To supplement the ETM modelling, we conduct additional research on the relation between electricity prices and the renewable penetration rate and present a qualitative analysis of key issues for policy makers to consider in relation to the power mix (see Part 7 of this report).

- ***Cost of subsidies*** – As discussed in Part 2 of this report, renewable energy benefits from direct subsidies and indirect subsidies. Direct subsidies are available through programs such as the SDE++.[740] Indirect subsidies involve features such as (i) government finance of the infrastructure necessary for the deployment of renewable energy (for instance, construction of the transmission equipment at sea to accommodate offshore wind farms[741]), (ii) efficient, streamlined regulatory procedures through government assistance programs,[742] (iii) restrictions on competing power providers (for example, phasing out

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[737] The Nuclear Study assumes a total power demand of 2,406 PJ in 2050. Nuclear Study, p. 12.

[738] For links to the ETM and the translation of costs to the ETM, see Appendix 2, Nuclear Study.

[739] For the ETM, see https://energytransitionmodel.com/

[740] Features SDE++, see https://english.rvo.nl/subsidies-programmes/sde/features-sde

[741] WAT KOST HET NET OP ZEE?, available at https://windopzee.nl/onderwerpen-0/wind-zee/kosten/kosten-net-zee/ ("De Rijksoverheid heeft TenneT (netbeheerder van het landelijk hoogspanningsnet) aangewezen als netbeheerder van het net op zee. TenneT ontvangt een vergoeding voor de aanleg van het net op zee. De Rijksoverheid betaalt deze vergoeding uit de Opslag Duurzame Energie (ODE). Bedrijven en burgers betalen voor de ODE via hun energierekening.")

[742] See Part 2, Section d, of this report.

or closure of power plants using fossil fuels[743]), and (iv) government (or government-subsidized) awareness-raising and promotional programs to the advantage of renewable energy, and (v) land-related polices, in particular agricultural policies and zoning policies, which reduce the value of land and, thus, reduce the price of leasing land for wind or solar farms.[744] The Nuclear Study does not address these subsidies, does not account for them, and omits to include their value in the cost basis of renewable power (wind and solar).

- ***Cost of additional land and infrastructure*** – The additional cost of land and infrastructure necessary for the underground cabling to connect renewable energy sources to the network is apparently not included. This cost might be significant, as discussed further in Part 7 of this study.

- ***Other issues*** – There are additional issues with the Nuclear Study that we only point out here:
  - The authors use the average expected installation cost for renewable, which may well be biased low.
  - Capacity factors of 50% for wind and 33% for solar are not realistic, and reflect wishful thinking.
  - In relation to nuclear construction cost, budget exceedances and cost increases of 18% are assumed, which almost entirely cancels out the (biased low) entire learning effect assumed for nuclear energy.[745]
  - The lifespan of solar is assumed to be 40 years, which is unrealistic (25 years is more realistic).
  - The decrease in the market value of property adjacent to wind and solar farms is ignored; these are real costs associated with renewable energy though.[746]
  - The lead time, delays, are short for renewable and long for nuclear, which, to a degree, reflects policy bias.

Although we are not persuaded that the assumptions made in the Nuclear Study are necessarily accurate, we use many values that are comparable or even the same, but prefer realized over expected costs. Only where we have found better, more reliable data, we used it. We tried to be consistent in the use of sources and to avoid data-shopping and cherry-picking.

In short, the Nuclear Study is not a thorough analysis that provides adequate information to inform policy-making. The authors acknowledge as much, and may have been constrained in their analysis by the instructions they received. There is a risk, however, that this 'check the box study' will be regarded as a policy argument against exploring the nuclear power option any further.

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[743] See, for example, Kamerbrief over uitvoering Urgenda-vonnis, https://www.rijksoverheid.nl/documenten/kamerstukken/2020/04/24/kamerbrief-over-uitvoering-urgenda-vonnis (referring to the closure of the Hemweg power plant as of 1 January 2020).

[744] For a fuller discussion of subsidies, see Part 9 of this report.

[745] The European Commission estimates that the nuclear learning effect is approximately 27%, based on the difference in overnight construction cost between FOAK and NOAK nuclear plants. See European Commission, STAFF WORKING DOCUMENT Accompanying the Communication from the Commission: Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty for the opinion of the European Economic and Social Committee, Brussels, 4.4.2016, SWD(2016) 102 final, p. 11, available at https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v10.pdf

[746] The adverse impact of wind turbines on adjacent property values can be very substantial, up to 5% in market value reduction. For further discussion, see Part 7 of this study.

Annex VII. The Additional Temperature Reducing Effect of EU Climate Neutrality (CN) Relative to EU INDC in 2100 and 2050

This section discusses the question by how much, roughly estimated based on existing research, the 2100 and 2050 average global atmospheric temperature will be reduced as a result of EU climate neutrality, relative to current EU policy as laid down in the EU INDC. The focus thus is on a 'rough and dirty' assessment of the additional temperature reducing effect resulting from EU climate neutrality.

Method and data:

- EU INDC is 40% CO_2 reduction by 2030; EU CN is 100% reduction by 2050. We assume all (avoided) emissions are additive, linearly related to temperature reduction, and all realized in 2030.
- Assume linearity between emission reductions and temperature decrease, and no carbon leakage; this is not a likely assumption, because thus far carbon leakage has always happened.
- If 40% emission reduction produces a temperature drop of "x" C, 100% emission reduction produces a temperature drop of 100/40 = 2.5 x C (ignoring different target dates).
- To go from 2100 to 2050, we pro rate, linearly, with 2015 as baseline (research is as of 2015), thus, pro rate at 35/85, with 35 = 2050-2015 and 85= 2100-2015).
- We use two peer-reviewed academic publications – Lomborg 2016 and Rogelj et al. 2016. Both studies make assumptions, and use modelled scenarios to assess the effects of the INDCs submitted pursuant to the Paris Agreement on Climate Change on the average global atmospheric temperature in 2100. Because they employ assumptions and modelled

EU Climate Neutrality in 2050 will produce an additional reduction in the average global atmospheric temperature increase of between

- 0.05 and 0.15 °C in 2100; and
- 0.02 and 0.06 °C in 2050,

- if and only if no carbon leakage (or outsourcing) from the EU occurs, which thus far has occurred consistently.

scenarios, their studies provide neither predictions nor forecasts, but conditional projections. Thus, there are large uncertainties around their estimates.

Lomborg (2016):

The study by Lomborg arrives at the following estimates:

Change in temperature

°C year 2100	Pessimist ic	Optimistic
US INDC *USCPP*	0.008 *0.004*	0.031 *0.073*
EU INDC *EU 2020*	0.017 *0.007*	0.053 *0.026*
China INDC	0.014	0.048
RoW INDC	0.009	0.036
Global INDCs	0.048	0.170

Table 62. Impact of climate policies, optimistic and pessImIstIc, for RCP8.S, using MAGICC, summary of finds described throughout the text

For our purposes, the relevant numbers are EU INDC and Global INDCs – the EU's contribution to the change in temperature is 31.12% (pessimistic) to 35,42% (optimistic) of the Global INDCs' change in temperature; the average is approximately 33%, which we will use below for the Rogelj et al. study.

We now proceed to compute the additional effect of EU climate neutrality on the average global atmospheric temperature:

- In the pessimistic scenario, the temperature-reducing effect in 2100 is 2.5 x 0.017 = 0.0425 C. So, the additional temperature-reducing effect in 2100 is 0.0425 – 0.017 = 0.0255 C.
- In the optimistic scenario, the temperature-reducing effect in 2100 is 2.5 x 0.053 = 0.1325 C. So, the additional temperature-reducing effect in 2100 is 0.1325 – 0.053 = 0.0795 C.
- We use a simple average as neutral position, i.e. 0.0255 + 0.0795 = 0.0525 C.

Results based on Lomborg:

- The additional effect of EU climate neutrality on the average global atmospheric temperature in 2100 is 0.0525 C (rounded off: 0.05 C).

- In 2050, the additional temperature-reducing effect is 0.0525 x (35/85) = 0.0216 C (rounded off: 0.02 C).

Scenario	Global-mean temperature rise by 2100 (in °C) that is not exceeded with the given probability		
	50%	66%	90%
No-policy baseline	4.1 (3.5-4.5) [3.1-4.8]	4.5 (3.9-5.1) [3.4-5.4]	5.6 (4.8-6.3) [4.2-6.8]
Current policy	3.2 (3.1-3.4) [2.7-3.8]	3.6 (3.4-3.7) [2.9-4.1]	4.4 (4.2-4.6) [3.6-5.2]
INDC (unconditional)	2.9 (2.6-3.1) [2.2-3.5]	3.2 (2.9-3.4) [2.4-3.8]	3.9 (3.5-4.2) [2.8-4. 7]
INDC (conditional)	2.7 (2.5-2.9) [2.1-3.2]	3.0 (2.7-3.1) [2.2-3.6]	3.7 (3.3-3.9) [2.6-4.4]

Table 63. Estimates of global temperature rise for INDC and other scenarios categories. For each scenario, temperature values at the 50%. 66% and 90% probability levels are provided for the median emission estimates when also including scenario projection uncertainty (in brackets). Temperature increases are relative to pre-industrial levels (1850-1900), and are derived from simulations with a probabilstic set-up with the simple model MAGICC (refs 10, 68-70, Supplementary Text 3).

Rogelj (2016):

We use the 50% probability numbers, mean value.

The aggregated unconditional INDCs result in 0.3 C reduction (2.9 instead of 3.2 C).
Rogelj does not break out EU INDC, so we use Lomborg's figure for the EU's share of the temperature reduction, which is 33%:

- The EU's contribution to the 0.3 C temperature reduction in 2100 is 0.33 x 0.3 = 0.1 C.
- The temperature reduction in 2100 resulting from EU climate neutrality is 2.5 x 0.33 x 0.3 = 0.2475 C.
- The additional temperature reduction in 2100 resulting from EU climate neutrality is 0.2475 – 0.1 = 0.1475.

Answers based on Rogelj et al.:

- EU climate neutrality produces an additional reduction of the average global atmospheric temperature in 2100 of 0.1475 C (rounded off: 0.15 C), resulting in a temperature increase of 2.75 instead of 2.9 C
- EU climate neutrality produces an additional reduction of the temperature in 2050 of 0.15 x (35/85) = 0.0617 C (rounded off: 0.06 C).

Study	Temperature reduction due to 2050 EU CN in 2050	Temperature reduction due to 2050 EU CN in 2100
Lomborg 2016 [1]	0.02 C	0.05 C
Rogelj 2016 [2]	0.06 C	0.15 C

Table 64.

Verification:

To double-check that these estimates are reasonable and in line with current climate science, we verify the calculations based on a different method for roughly estimating the temperature reductions, given that both the 40% and 100% emission reductions are measured from 1990 levels. This method computes the temperature reducing effect of emission reductions by directly estimating this effect from the climate sensitivity to GHG emissions into the atmosphere.

- We use the 1990 EU ex UK carbon emissions in 1990 (1220 - 160 = 1060 MTC[747]) and multiply by 70 (2100 – 2030) to allow for them being reduced to zero in 2030.
- That's a reduction of about 75 GTC.
- Based on an assumed TCRE[748] of 1.6 K/1000 GTC (middle of the road per CMIP5 ESMs, IIRC[749]), that equates to a GMST reduction of **0.12 C** in **2100**.
- Allowing for CH_4 and N_2O and CFC emissions (i.e. using CO_2e not CO_2 emissions) would push this up; we did not calculate by how much.[750]
- Ex non-CO_2 emissions, the excess reduction in **2100** over that from a 40% reduction continuing after 2030 would be 60% of 0.12 C or **0.07 C**.
- If instead a TCRE of 1.3 C/GTC is used,[751] which is what Lomborg's final graph of temperature reduction vs $GTCO_2$ emissions 2016-2100 implies [1.6/(4500/3.664)], then the 2100 reduction in temperature from a 100% EU CO_2-only cut in 2030, relative to the 1990 level, would be 0.1 C, so the excess over a 40% cut would be **0.06 C** (again, ignoring CH_4, N_2O, etc. emissions).
- Both of these estimates **fall within the range we computed above**. Thus, the estimates provided above, appear to be reasonable based on this verification.

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[747] MTC stands for million metric tons of carbon dioxide. Note that this unit is different from standard units often used in the climate science literature.

[748] Note: TCRE only applies to CO_2, not to non-CO_2 emissions, even if they are expressed in CO_2-equivalence with Global Warming Potentials.

[749] This the midpoint of the 0.8 to 2.4 C/1000 GCT TCRE range for IPCC AR5 CMIP5 earth system models. Gillett, N. P., V. K.Arora, D.Matthews, and M. R.Allen, 2013: Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations. J. Climate, 26, 6844–6858, doi:https://doi.org/10.1175/JCLI-D-12-00476.1. We acknowledge that other values for climate sensitivity are used in some the literature. Cf. Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., Wehner, M., 2013. Long-term Climate Change: Projections, Commitments and Irreversibility, in: Stocker, V.B., T.F.,.D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029–1136.

[750] If CH_4 emissions are the same towards the end of this century as they have been over the last decade, then net warming for CH_4 would be the same then as it is now, with no contribution to warming over 2010-2100. If the EU's climate neutrality policy were to involve undoing all past warming caused by non-CO_2 gases, additional effects on the average global temperature would arise. Because none of these gases stay in the atmosphere for a very long time (CH_4 has a single exponential decay period of about 10 years), achieving net-zero emissions of non-CO_2 gases could cause cooling, whereas net-zero CO_2 emissions merely stabilises temperature (if one assumes that TCRE is a fixed, time-independent, value, which is also what the IPCC maintains). In principle, almost all the warming currently attributable to the EU's share of CH_4 forcing, and a proportion of that attributable to the EU's share of forcing by the longer lived N20, would by 2100 be reversed by a policy of climate neutrality from 2050 on. We have not attempted to estimate how much that would be.

[751] Cf. 1.35 C/ 1000 GTC (=1.35 C/1000 PgC) is the midpoint of the 0.7 to 2.0 C/1000 GTC observationally constrained range estimated by Gillett et al. 2013, which is relied upon in IPCC AR5. We acknowledge that other values for climate sensitivity are used in some the literature. Gillett, N. P., V. K.Arora, D.Matthews, and M. R.Allen, 2013: Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations. J. Climate, 26, 6844–6858, doi:https://doi.org/10.1175/JCLI-D-12-00476.1.

Annex VIII. Taking Climate Neutrality Seriously – Fossil Fuel Purchase Program

To date, despite the emission reductions achieved by the EU, global emissions do not show a downtrend. This is due to increased combustion of fossil fuels in non-EU countries. There is no reason to expect that this will change any time soon.

If the EU is serious about its climate neutrality ambitions, it will need to not only assist non-EU countries with their energy transition, it will also have to prevent that they continue to use fossil fuels.

To accomplish this objective, in the period from now up to 2050, all fossil fuels (oil, natural gas, coal) will need to be retired definitively. To be sure that fossil fuels are no longer available to non-EU countries by 2050, the only feasible method is for the EU to buy up all fossil fuels over this period. Estimates of what such a program would cost, have, to our knowledge, not been presented in the literature or policy discussions. We call this approach "Taking Climate Neutrality Seriously."

While ideally the EU would retire the commodities before they are extracted from the ground, it is impossible to estimate the value of all existing oil fields, mines, and other deposits of fossil fuels, as data are not publicly available. Our model therefore estimates the total cost of the fossil fuel purchase program based on spot prices in public markets for these commodities.

We do not account for any geo-political issues related to the fossil fuel purchase program. For example, some of the world's largest reserves are located in countries that would surely demand substantial premiums for the EU to buy these fossil fuels, or extract other concessions that might be onerous, or flat out deny the EU the opportunity to acquire their assets. We do not discuss these in this study, but they should nevertheless be kept in mind as the EU is pursuing a fossil fuel-free future.

Methodology, Calculations & Sources

We first identify the current estimated volumes of global reserves of oil, natural gas, and coal. Second, we identify the current market price of these commodities to calculate the value of these reserves. Lastly, we compare that value to last year's GDP figures for the world and the EU. We also calculate a per household figure for the EU to further contextualize the costs of the fossil fuel purchase program.

Table 65 lists current estimates of reserves for fossil fuels. These were estimated by WorldOMeters, based on data from the British Petroleum's Statistical Review of World Energy and the U.S. Energy Information Administration (EIA). [1, 2, 3]

	Estimated Reserves	Units
Oil	1,495,825,245,763	Barrels
Natural Gas	1,093,355,846,927	Barrels of Oil Equivalent
Coal	4,312,688,932,890	Barrels of Oil Equivalent

Table 65. Estimated Reserves as of September 27, 2020

Next, we convert these figures (expressed in Barrels of Oil Equivalent or "BOE") to units that correspond to how prices for these commodities are typically quoted. For example, spot prices for coal are denoted in tons, not barrels of oil equivalent. Alongside its Statistical Review of World Energy, British Petroleum publishes conversion factors [4]. Table 2 lists the conversion factors used.

Oil	n/a
Natural Gas	5.8 MMBTU per BOE
Coal	0.2087 tons per BOE

Table 66. Conversion Factors

On this basis, we arrive at reasonable estimates for how much oil, gas, and coal needs to be purchased by the EU.

Our estimates account for only 85% of the existing oil reserves, since the remainder (15%) would be used for other purposes, i.e. as feedstock for petrochemicals; in practice, the EU would have to purchase these quantities as well and resell them under restricted use conditions, while ensuring the circular economy feeds enough petrochemical-based compounds back into manufacturing processes. We assume 100% of the natural gas and coal will be bought up.

Furthermore, we have used rough estimates of spot prices during the month of September 2020 as an indicator of the expense associated with purchasing all fossil fuels. Of course, these prices would fluctuate as the EU started buying up fossil fuels, most likely leading to price increases and a higher average cost basis than the one we account for. Hence, we believe our estimate is very conservative. Table 3, below, provides the full value of these existing reserves.

For a cost of roughly $109 trillion, the EU would be able to retire all existing fossil fuels (net of 15% of oil for petrochemicals).

	Estimated Reserves to be Purchased	Price	Total Value ($bn)
Oil	1,271,451,458,899 barrels	$40 / barrel	$50,858
Natural Gas	6,341,463,912,177 MMBTU	$2 / MMBTU	$12,683
Coal	900,259,349,642 tons	$50 / ton	$45,013
Total			**$108,554**

Table 67. Estimated Value of Existing Reserves

Table 68. provides GDP figures for the world and the EU. These figures were obtained from the World Bank website and are as of 2019. [5, 6]

	GDP as of 2019 ($bn)
Global	$87,698
EU	$15,593

Table 68. GDP Figures

Conclusions

On the basis of these numbers, we conclude that the costs of retiring all fossil fuel reserves is about 1.2 times global annual GDP and 7 times EU annual GDP.

On a per capita basis (the EU's population is almost 450 million [6]), the costs of the EU's 'Taking Climate Neutrality Seriously' are about $243,000 per EU resident. Given that an average EU household has about 2.3 members [7], this represents a cost of almost $560,000 per EU household.

Between now and 2050, there are 29 years left for the EU to execute on this program. This would mean an average cost of $3.8 trillion per year (not adjusted for inflation) for 29 years. Given that the EU's budget was about $165 billion in 2019 [8], this cost alone represents almost 25 times the EU's budget on an annual basis.

These costs would appear to be prohibitively expensive, especially when considered in the broader context of fully moving the EU's economy towards "climate neutrality." Yet, the EU will need to take the costs of the fossil fuel purchase program into account if it wants to achieve the climate neutrality goal stated in its policies, if only because this cost is an indication of the economic value of fossil fuels that developing nations will want to capture.

In years to come, this cost will serve as reminder of the value of fossil fuels in the world economy. It also explains why 'carbon leakage,' carbon outsourcing, and fossil fuel-driven economic development outside the EU are problems that the EU cannot solve through the means identified in connection with the Green Deal. It is telling that a sure way to address the issue of the EU's climate neutrality efforts being in vain, lies outside the realm of realistic options for the EU.

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Annex IX. Impacts of Wind, Solar, and Nuclear Power on EU Policies and Protected Interests[752]

Impacts	Wind power	Solar power	Nuclear power
[1] SPATIAL IMPACTS[753]			
Land and space use/ demand per 1,000 PJ	13,700 – 39,600 (onshore, NL & CZ) 7,000 – 17,600 (offshore, NL) [1]	3,800 – 11,200 (land, NL) 2,600 – 9,000 (land, CZ) [1]	22 – 150 (NL & CZ) [1]
Power density -- surface required for given power output (annual average GWh per km^2)	13 (onshore, NL & CZ) 26 (offshore, NL) [1]	47 (land, NL) 65 (land, CZ) [1]	6,982 (NL & CZ) [1]
Landscape impacts (‘horizon pollution’, aesthetics, enjoyment)	High [1]	High [1]	Low [1]
[2] ELECTRICITY COST IMPACTS			
Cost of generation (range)	EUR 41-58 / MWh (realized, onshore NL) EUR 46-72 / MWh (realized, offshore NL) EUR 29-41 /MWh (realized, CZ) [1]	EUR 62-91 / MWh (realized, NL) EUR 41-56 / MWh [1]	EUR 19-32 / MWh (realized, NL) EUR 16 – 36 / MWh (realized, CZ)[754] [1]

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[752] In this table, the qualifications ‘high’, ‘medium’ and ‘low’ are used. These qualifications are intended as relative to the other power generation technologies set forth in the table.

[753] Two peer reviewers commented that our results are too high for nuclear energy, and, on the basis of detailed calculations relating to actual nuclear power plants currently in operation, argued that the spatial requirements of nuclear power plants are lower than reported here; they queried whether our numbers for nuclear include also the land required for mining and spent fuel storage. We have not been able to exclude this, but have chosen to stick to the source selected based on considerations of consistency and avoiding ‘data shopping.’

[754] Peer reviewers have suggested that the cost of nuclear energy seems low, acknowledging that this may be explained by the fact that this number is based on realized cost. In the body of this report, we defend this choice (see Part 6 and Annex II). Peer reviewers have pointed out that (i) the cost of nuclear new-built is currently higher (€45-60/MWh for the EPR, depending on the financing/WACC), but that (ii) for NOAK reactors, as a result of learning and efficiency gains, this cost could come down to €30-40/MWH, and (iii) could decrease to €10-20 as a result of automation and innovation (including regulatory innovation).

Impacts	Wind power	Solar power	Nuclear power
Total system cost (cost of generation & integration)[755]	High [1]	High [1]	Low [1]
Effect of substitution in ETM model (CNS Scenarios)	Up to +18% total system cost increase (for all renewables) [1]	Up to +18% total system cost increase (for all renewables) [1]	Up to -18% cost decline [1]
Effect on fully loaded consumer price of electricity of increasing renewable share[756]	Price increase [1]	Price increase [1]	Price decrease [1]
[3] PROFILE CHARACTERISTICS			
Intermittency/ unresponsiveness to demand	High [2]	High [2]	None, if used as base load Medium, if used as flexible load
Need for backup (including fossil), battery storage and/ or power conversion	High, increasing with penetration rate [3]	High, increasing with penetration rate [3]	None or little, and can be used for hydrogen production, as desired
Requirements for additions or changes to power distribution system	High (off-shore) [4] Medium (on-shore) [4]	Medium [4]	Low
Requirements for demand response and related measures	High [5]	High [5]	None
Useful life	Short (60 years) [6]	Short (25 years) [6]	Long (25 years) [6]
[4] CLIMATE-RELATED IMPACTS			
CO_2 emissions in construction	To be analyzed [7]	To be analyzed [7]	To be analyzed [7]
CO_2 emissions in operation	Low (due to transport, maintenance, etc.) [7]	Low (due to transport, maintenance, etc.) [7]	Low (due to transport, maintenance, etc.) [7]
CO_2 emissions in entire life cycle (steel production, mining, etc.)	To be analyzed based on LCA (system boundaries) [7]	To be analyzed based on LCA (system boundaries) [7]	To be analyzed based on LCA (system boundaries) [7]
CO_2 emissions due to land use change (due to construction of power plants) [7]	Potentially significant (e.g. where flora has to be cleared for construction) [7]	Potentially significant (e.g. where flora has to be cleared for construction) [7]	Insignificant (due to very small footprint) [7]
Warming effects due to fluorinated gases (such as SF6)	Potentially significant (if F-gases are used and gas leakage is not prevented) [8]	Insignificant	Insignificant

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755 Total system costs depend on the configuration of the entire system, and, thus, depend on a series of circumstances and choices. In addition, these costs raise issues of allocation – how should the system-cost be allocated over various power generation facilities? We acknowledge these issues, but feel comfortable that the 'high-low' designations used here, reflect realistic ranges of integration- and system-related costs for the various power generation technologies concerned.

756 A distinction should be made between wholesale electricity prices in the 'energy only' electricity markets, and consumer electricity prices. The wholesale 'energy only' price of electricity is based on the marginal cost of generation (which is low for renewable energy), and excludes integration- and system-related cost, thus, understating the true cost of electricity. In fact, intermittent renewable electricity drives down wholesale electricity prices, while increasing fully loaded consumer prices. 'Fully loaded' means that all electricity system-related costs, such as the cost of construction and maintaining an off-shore connection for off-shore wind power, are included, even if such costs are paid out of the general budget.

Impacts	Wind power	Solar power	Nuclear power
[5] ECONOMIC IMPACTS			
Need for state aid/ subsidies to incentivize investors	High [9]	High	Low
Adverse impacts on existing power generation assets (causing "stranded assets")	High, if promoted through subsidies [9]	High, if promoted through subsidies	Low
Adverse effects on technological innovation, competitiveness and economic development	High [9]	High	Low
Impact on land prices	Potentially high at high penetration rates [10]	Potentially high at high penetration rates [10]	Very low
Impact on value of adjacent property	High due to large areas required and size of turbines [10]	High due to large areas required	Very low
Impact on aesthetics' of landscape, tourism, and recreation	High [11]	High [11]	Very low
Impacts on agriculture	Medium for wind on land	High	Very low
Impacts on fishery, sailing, sea transport	Medium to potentially high for wind on sea [12]	Medium for solar on sea (if feasible)	Non-existent
Impact on employment	Medium, but not necessarily productive and highly skilled jobs (may require subsidies to be sustained) [13]	Medium, but not necessarily productive and highly skilled jobs (may require subsidies to be sustained) [13]	Low, but highly skilled jobs
[6] ENERGY POLICY IMPACTS			
Electricity security of supply/reliability	Low, unless storage and conversion can be deployed at scale [14]	Low, unless storage and conversion can be deployed at scale [14]	High
Energy independence	Low, unless storage and conversion can be deployed at scale [14]	Low, unless storage and conversion can be deployed at scale[757] [14]	High
Energy and resource efficiency	Medium	Medium	Very high
Clean energy	Yes	Yes	Yes
Energy affordability/ energy poverty	Low affordability (expensive) [15]	Low affordability (expensive) [15]	Medium affordability (less expensive)
Need for state aid, capacity or other market-distortive mechanisms	High [16]	High [16]	Medium [16]
Need for demand response measures	High [17]	High [17]	Low

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[757] Wind and solar could provide an acceptable level of security of supply and energy independence if, for instance, hydrogen technology will be deployed at large scale. Production, storage and conversion of hydrogen, however, will cause substantial losses and require very large expenditure.

Impacts	Wind power	Solar power	Nuclear power
[7] ENVIRONMENTAL IMPACTS			
Habitat impacts	Potentially high, in particular if penetration rate is high [18]	Potentially high, in particular if penetration rate is high [18]	Low
Impacts on birds, bats, insects, and other species	Potentially high, in particular if penetration rate is high [18]	Potentially high, in particular if penetration rate is high [18]	Low
Impacts on sea and marine environment	To be analyzed further for offshore wind [19]	To be analyzed further, if solar farms are built on sea	None
Impact on toxic-free environment	Potentially high, if chemicals (cooling agents, lubricants, etc.) leak/leach into environment [20]	Potentially high, if chemicals (cooling agents, lubricants, etc.) leak/leach into environment [20]	Low
Resource efficiency	Medium due to high number of units required to generate given quantity of power [21]	Medium due to high number of units required to generate given quantity of power [21]	Very high [21]
Mining-related impacts (within and outside EU)	Medium due to high number of units required to generate given quantity of power [22]	Medium due to high number of units required to generate given quantity of power [22]	Low due to uranium or other nuclear fuel mining [23]
Noise and public nuisance	High [23]	Medium (no noise, but reflection, etc.) [23]	Very low
Waste-related impacts	Potentially significant in relation turbine blades Low for metal and concrete [24]	Potentially significant in relation to PV parts/heavy metals. Low for remainder [24]	Potentially significant in relation to nuclear waste, but can be controlled through good practices (required by law) [24] Low for remainder
[8] HUMAN HEALTH-RELATED IMPACTS			
Noise- and infrasound-related health impacts	Potentially high for wind on land [25]	Low	Low
Cast shadow-related health impacts	Low, if safety distance is respected [26]	Non-existent	Non-existent
Radiation-related health effects	Non-existent	Non-existent	Very low, if safety measures are in place [27]
Indirect health impacts (e.g. through construction, mining, etc.)	Potentially significant due to large number of facilities required	Potentially significant due to large number of facilities required	Insignificant thanks to small number of facilities required
Deaths associated with power generation	Low [28]	Low [28]	Very low [28]
[9] PHYSICAL SAFETY RISKS			
Accident-related impacts	Low [28]	Low [28]	Potentially high, but can be controlled through safety measures (required by law) [28]
Terrorism-, sabotage, and war-related risks	Low	Low	Potentially high, but can be controlled through safety measures (required by law) [29]

Impacts	Wind power	Solar power	Nuclear power
[10] SOCIAL IMPACTS			
Impacts on local communities	High, given that many communities are required to install [30]	High, given that many communities are required to install [30]	Low, given that only a small number of communities will have to install
Potential for public opposition (assuming accurate information)	High (land) [30] Medium (sea)	High [30]	Medium [30]
Potential to propel lifestyle changes	High, due to features such as demand response [31]	High, due to features such as demand response [31]	Low, tends to make lifestyle changes unneccessary
Potential for policy backlash	Potentially high, if penetration rate is high, given widespread impacts [32]	Potentially high, if penetration rate is high, given widespread impacts [32]	Low, except if serious accident happens [32]
'No regrets' solution	Only to limited extent, if penetration rate is low (several adverse effects, such as land use impact, are unavoidable) [32]	Only to limited extent, if penetration rate is low (several adverse effects, such as land use impact, are unavoidable) [32]	'No regrets' solution, if potential adverse impacts are adequately controlled [32]

Table 69.

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Annex X. Data Request for the Czech Republic

There are 2 models for which we need data inputs for the Czech Republic. We would greatly appreciate your cooperation, and thank you very much for your attention and time.

We have included tables in this request, and highlighted the data we would like you to provide. Explanations and notes are provided to guide you.

MODEL 1 – SPATIAL REQUIREMENTS FOR WIND, SOLAR, AND NUCLEAR

The objective is to determine how much land/space is required (in absolute and relative terms) for wind, solar and nuclear to generate a fixed amount of electricity and meet the electricity demand of the country as a whole. This will enable a comparison of the spatial requirements of these technologies, which is relevant to policy making.

Part A requests data about the land/space requirements of wind, solar and nuclear in the Czech Republic. Part B requests data about the total energy/electricity demand for the country as a whole for 2019, and for the projected 2050 estimates based on best available information.

PART A. Land/space requirements of wind, solar and nuclear in the Czech Republic

Please provide the data in Table 1, below, for each of the following energy sources:

- Onshore wind (both on land and on internal water, such as lakes)
- Solar (both on land and on roof)
- Nuclear

Notes

- These data may be aggregated to the overall energy source level (e.g. onshore wind on land); we do not require power plant-specific datapoints. However, instead of aggregated average data, you may report data for a representative power plant/facility (in the latter case, briefly explain why the plant/facility is representative).
- Please state what you have regarded as a power plant, and to what kind of power plant (by technical parameters) the data reported by you relate.
- For both renewable and nuclear, your replies should be based on actual, realized capacities/capacity factors, not on unproven technologies or expected future innovations.
- Please provide the sources of the data you provide.

Energy Source	Electricity produced in MWh per annum[758]*	Capacity in MWe[759]*	Area covered in km^2 [760]*
ONSHORE WIND - ON LAND - ON SURFACE WATER	[insert]	[insert]	[insert]
SOLAR - ON LAND - ON ROOF	[insert]	[insert]	[insert]
NUCLEAR	[insert]	[insert]	[insert]

Table 70.

UNIT TABLE FOR GENERAL INFORMATION ONLY	Units
Electricity Produced:	MWh per annum
Capacity per power plant:	MWe
Area covered per power plant:	m^2 or km^2

Table 71. Spatial requirements for wind, solar and nuclear in the Czech Republic

Sources

[insert]

PART B. Country-level data regarding available land/space and energy demand

Please also provide the data set forth in Table 2, below, for the country as a whole. If no detailed measurement has been done, please provide an estimate based on best available information.

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[758] Please report average of aggregated data or data for a representative power plant/facility (or a subset of such plants or facilities).

[759] Please report average of aggregated data or data for a representative power plant/facility (or a subset of such plants or facilities).

[760] Please report average of aggregated data or data for a representative power plant/facility (or a subset of such plants or facilities).

For the country as a whole:

- *Available land/space* – Land/space that could technically be used for wind turbines, nuclear plants, or solar farms, taking into account regulatory restrictions (i.e. excluding land/space on which no such facilities may be constructed as a matter of law and policy).
  - Typically, this would include land currently used for agriculture, forestry, nature, woodlands, etc. The technical limitations should reflect safety (e.g. too close to residential area) or installation practicalities (e.g. steep mountains where no power plants can be built).
  - For internal waters, the area available for wind turbines, taking into account regulatory restrictions. This area should again reflect safety limitations and other technical limitations (e.g. other structures in the way, or naval routes that need to remain open).
  - For residential roof, the total area that could be used for solar panels. This should exclude buildings that cannot have solar panels, such as buildings with historical protections or roofs that do not technically allow for solar panels (e.g. too steep).
- *Energy and electricity demand* – This data is aggregated for the country as a whole. It may be expressed in PJ. Please also indicate the % of the energy demand met by electricity (degree of electrification).

Notes

- Please indicate the sources of the data.
- For your 2050 estimates/projections, please indicate a range that reflects plausible scenarios (e.g. from low, but plausible, to high, but plausible).

CZECH REPUBLIC	Available land/space in km^2	Energy Demand/Rate of Electrification
Wind on land	[insert]	N.A.
Wind on water	[insert]	N.A.
Solar on land	[insert]	N.A.
Solar on roof	[insert]	N.A.
Total surface of Czech territory - land - water	[insert]	N.A.
Total energy demand in 2019 in PJ	N.A.	[insert]
% of demand met by electricity in 2019	N.A.	[insert]
Total energy demand in 2050 (projection) in PJ	N.A.	[insert]
% of demand met by electricity in 2050 (projection)	N.A.	[insert]

Table 72. Available land/space and projected energy demand

Sources

[insert]

MODEL 2 – COST OF ELECTRICITY (LCOE) PRODUCED BY WIND, SOLAR AND NUCLEAR

The objective is to determine what the cost is of producing one unit of electricity by wind, solar and nuclear technology. This will enable a comparison of the relative cost of wind, solar and nuclear, which can be used to inform policy making.

Please insert in Table 3, below, the required cost data for each of the following energy sources:

- Onshore wind (on land and on surface water)
- Solar (commercial)
- Nuclear

Notes

- Please use the best available information, most recent representative. Please provide averages and ranges if available.
- Ideally, data should be based on realized power plants that have been built in the Czech Republic or comparable countries. If multiple types have been built (e.g. nuclear power plants of different capacities), refer to the ones that are most common or that are expected to be the most common going forward.
- If, for any of the datapoints, there are internal projections that are used for analysis, please provide these as well.
- We have assumed that onshore wind on land and on internal surface waters, such as lakes, have roughly the same cost structure; if you have differentiated data for wind on land and wind on water, please report them.
- Please provide sources of the data you report.
- Please refer to the table below for parameters (technical, cost, other), units and applicability:

Cost Data Wind, Solar, and Nuclear: Units and Applicability

WIND, SOLAR AND NUCLEAR		**Units**	**Applies to**
Technical parameters	Capacity per power plant unit	MWe	All
Cost parameters	Capital costs	€ / MWe	All
	WACC (financing costs)	%, annualized	All
	Typical Debt to Equity ratio for project	% / %	All
	Fixed maintenance and operation costs	€ / MWe per annum	All
	Variable maintenance and operation costs	€ / MWh	Nuclear
	Fuel costs	€ / MWh	Nuclear
	Waste processing and storage costs	€ / MWh	Nuclear
	Decommissioning costs	€ / MWe	All
Other parameters	Construction time	Years	All
	Technical lifetime	Years	All

Table 73.

Cost Parameter	Wind	Solar	Nuclear
Capacity per power plant unit in MWe	[insert]	[insert]	[insert]
Capital costs in €/MWe	[insert]	[insert]	[insert]
WACC (financing costs) in % per year	[insert]	[insert]	[insert]
Typical Debt to Equity ratio for projects in %/%	[insert]	[insert]	[insert]
Fixed maintenance and operation costs in € / MWe per annum	[insert]	[insert]	[insert]
Variable maintenance and operation costs in € / MWh	N.A.	N.A.	[insert]
Fuel costs in € / MWh	N.A.	N.A.	[insert]
Waste processing and storage costs in € / MWh	N.A.	N.A.	[insert]
Decommissioning costs in € / MWe	[insert]	[insert]	[insert]
Construction time in years	[insert]	[insert]	[insert]
Technical lifetime in years	[insert]	[insert]	[insert]

Table 74. Cost parameters for wind, solar and nuclear

Sources

[insert]

Annex XI. Correspondence Table (Questions Posed – Answers Provided)

QUESTION	WHERE CAN ANWER BE FOUND?
I. What is the expected effect on global warming (i.e. average global atmospheric temperature) in 2050 and 2100 if the EU will achieve net zero GHG emissions in 2050?	Part 4 answer this question. Annexes VII and VIII provide further detail.
a. This question is answered based on available studies/literature, and may involve a range. We include brief summaries of the findings.	Id.
b. We consider the effect of the assumption that the non-EU countries will comply with their INDCs pursuant to the Paris Climate Agreement, and will make proportional efforts in the period 2030-2050, and throughout the century. Other assumptions, unknown factors, and uncertainties are identified.	Id.
c. We consider the probability of the EU achieving net zero GHG emissions by 2050 from several perspectives, including the concept of 'taking climate neutrality seriously.'	Part 4 and Annex VIII
d. In answering these questions, we consider the EU and international policy contexts (including the Paris Agreement on Climate Change) within which the EU pursues its carbon neutrality objective. We pay attention to international climate-related obligations, and existing EU policies in the areas of climate and energy.	Part 2 provides an overview of relevant EU policies. Part 4 discusses the Paris Agreement and other relevant international law.
e. We provide a qualitative discussion of the issues relevant to answering this question, and the context within which carbon emission reductions are pursued, while reflect on the uncertainties inherent in answering this question, and the factors that impact the likelihood of success of the EU's emission reduction efforts.	Part 4 considers scientific and policy uncertainty. Part 4 considers the facts that impact the EU's likelihood of success.
f. In this context, we also comment on the relevance of the concept of 'no regrets' solutions.	Parts 4, 8 and 9 address 'no regrets' solutions.

QUESTION	WHERE CAN ANWER BE FOUND?
II. How much land/space is required, if wind/solar is used to deliver all required electricity by 2050, in The Netherlands and the Czech Republic?	Part 5 answers this question, Annex 1 provides further detail.
a. This question is answered based on a model that uses available, reliable estimates of the total energy demand in 2050 for the Czech Republic and The Netherlands, utilizing a reasonable range of potential increases or decreases in energy demand. A description of the model is included in this report.	Id.
b. We assume the current state of the technologies and proven capacities; we address any plausible future innovation (e.g. the latest wind turbines for installation in sea) in brief comments or, in some cases, in a short qualitative discussion. Our analysis includes wind at sea, wind on land, wind on surface waters (rivers, lakes, etc.), solar on land, and solar on roofs.	Id.
c. With respect to the land/space required, we reference the maximal surface of the land/space currently available for wind/solar power recognizing technical/regulatory restrictions, and indicate the extent to which this available space will be utilized or even exceeded.	Id.
d. In relation to the wind/solar power, our model is able to accommodate a range of estimated plausible land/space requirements, and expected energy production per km^2.	Id.
e. We indicate also how our estimates vary as a function of the degree of electrification, capacity factors, and other key parameters.	Id.
f. We provide a description of our model, explain how it works, and how it differs from other existing models.	Part 5 answers this question, Annexes I, IV, V, and VI provide further detail.
g. We do not analyze the issues and challenges related to the use of cross-border capacities and interconnections, and the import of electricity, and provide a qualitative analysis.	Id.
III. How much land/space is required, if nuclear power is used to produce all required electricity by 2050, in The Netherlands and the Czech Republic?	Part 5 answers this question, Annex I provides further detail.
a. This question is answered based on the same model as under II, above, using available, reliable estimates of the total energy demand in 2050 for the Czech Republic and The Netherlands as described under II. a, above; a range is stated.	Id.
b. We assume the current state of the technologies and proven capacities; in some instances, we briefly address plausible future innovations (e.g., small modular nuclear reactors) in a qualitative discussion and provide references for further reading.	Id.
c. With respect to the land/space required, we reference the surface of the land/space currently available for nuclear power recognizing technical restrictions, and indicate the extent to which this available space will be utilized or exceeded.	Id.
d. In relation to the nuclear power, we assume that state-of-the-art, well-performing, safe nuclear technology will be used. In the EU, as discussed in Part 2, above, there is extensive safety regulation of nuclear energy installations.	Id.
e. We identify the differences in land/space requirements between wind/solar and nuclear power, and add comments that are useful to understand these differences.	Id.
f. We conduct sensitivity analysis on the key model inputs, and explore land/space requirements for power mixes composed of wind/solar and nuclear power in various proportions. Given values for key inputs/parameters, we compute at which point there will insufficient land to meet power demand through a particular power technology (wind, solar, nuclear).	Id.

QUESTION	WHERE CAN ANWER BE FOUND?
IV. What is the cost of implementing the wind/solar option discussed under II, above, and the cost of the nuclear option discussed under III, above?	Part 6 answers this question, Annex II provides further detail.
a. Our cost estimates are based on a model that uses fully loaded costs, including capital expense, operational expense, and other expenses. This implies, for instance, that the costs of maintenance and decommissioning are included; for nuclear, it means, for instance, that the cost of the longer lead time are reflected. The fully loaded costs include costs such as the year-round operation safety, for both wind/solar and nuclear power, insofar as these are included in the numbers we used, which we cannot always verify. In any event, if not included in the quantitative model, these costs are addressed qualitatively in the discussion. However, the external cost necessary to ensure integration into the electricity system and other system-related costs (including transmission, system stability, etc.) are discussed separately (see Part 8, below).	Parts 6 and 7 answer this question. Annexes II and IX provide further detail.
b. We assume the current state of the technologies and proven capacities; any plausible future innovation is addressed in a qualitative discussion.	Id..
c. We assume that wind/power and nuclear power are treated as equal alternatives, without any priority or preference for one over the other.	Id.
d. In relation to the weighted average cost of capital, we use the lowest currently available market-based rates for wind/power and nuclear (correcting for status quo bias), respectively, and also a 0 (zero) % interest rate for both wind/solar and nuclear.	Id.
e. We conduct sensitivity analysis on the key model inputs, consider which are the main factors affecting the cost of wind/solar and nuclear, respectively. In addition, we consider how some of these factors could be favorably influenced in The Netherlands and The Czech Republic	Id.
f. As noted, our model does not incorporate integration and system-related costs, but we provide a qualitative discussion of the costs of integration of renewable power into the electricity system. We also comment on (the costs of) the adaptation of the electricity system (transmission, grid, etc.) that will be necessary, if renewable energy (wind, solar) supply all of the power required, no other power generation technology is deployed as back-up, and other technologies are deployed extensively to address the problem of intermittency of renewable power.	Part 6 and 7 answer this question. Annexes II and IX provide further detail.
V. Would a 50% nuclear – 50% wind and solar option have space or cost advantages over a 100% solution of either technologies?	Part 6 answers this question. Annex I provides further detail.
a. We assume an optimal location of wind/solar farms consistent with restrictions, and use numbers representative for currently operating wind/solar facilities, which have been built at attractive locations.	Annex I.
b. We consider briefly whether some other mix (e.g. 80/20%) might have further advantages.	Part 8 answers the question, Annex I provides further detail.
c. We assess the effects of the mixes we considered under b, above, on the costs of power in The Netherlands and The Czech Republic.	Part 8 answers this question.

Table 75.

Annex XII. Abbreviations

ARs	Assessment Reports (IPCC)
AR5	Fifth Assessment Report (IPCC)
Bn/bln	billion
BOE	Barrels of Oil Equivalent
°C	Celsius
CBS	Centraal Bureau voor de Statistiek (Dutch Central Bureau for Statistics)
CCGT	Combined Cycle Gas Turbines
CCS	Carbon Capture and Storage
Cf.	conferre (compare)
CFC	Chlorofluorocarbon
CH_4	methane
circ.	Circa
CMIP5	Coupled Model Intercomparison Project phase 5
CN	Climate Neutrality
CNS Study	Climate Neutral Scenario Study by Berenschot/Kalavasta
CO_2	carbon dioxide
CZK	Czech Koruna
DCCOE	Discounted Costs Cost of Electricity
DED	Decarbonized Energy Directive
DEFRA	Department for Environment, Food and Rural Affairs (United Kingdom (UK))
DFG	Decommissioning Funding Group
DMSR	Denatured Molten Salt Reactor
DSO	Distribution System Operator
ECR Group	European Conservatives and Reformists Group
Eds.	Editors
EEA	European Environment Agency
e.g.	example gratia (for example)
EGR	Emissions Gap Report
EJ	Exajoule (equal to 10^{18} joules, unit of energy)
EPR	European Pressurized Reactor
ERCOT	Electric Reliability Council of Texas
EROI	Energy return on investment
ESMS	Environmental and Social Management System
ESRL	Earth System Research Laboratories

et al.	et alia (and others)
etc.	et cetera (and so on)
ETM	Energy Transition Model
EU	European Union
EUR	Euro
EURATOM	European Atomic Energy Community
Eurostat	European Statistical Office
EV	Electric Vehicle
F-gases	fluorinated gases
FiP	Feed-in Premiums
FiT	Feed-in Tariffs
FOAK	First of a kind
GDP	Gross Domestic Product
GEN	Generation
GHG	Green House Gas
GMST	Global Main Surface Temperature
GT	Gigaton
GTC	Billion metric tons of carbon
GW	GigaWatt
GWh	GigaWatt hour
GWP	Global Warming Potential
H^2	Hydrogen
H/H	High/High
HER	Renewable Energy Scheme
HFCs	hydrofluorocarbons
hrs/yr	hours/year
IAEA	International Atomic Energy Agency
i.e.	id est (that is)
IIRC	International Integrated Reporting Council
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Association
JRC	Joint Research Centre
Kg	Kilogram
KPI	Key Performance Indicators
kWe	kiloWatt electrical
kWh	kiloWatt hour
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity
LNG	Liquefied/Liquid Natural Gas

LWR	Light-water reactor
MAGICC	Model for the Assessment of Greenhouse Gas induced Climate Change
M&O	Maintenance and Operation
MIT	Massachusetts Institute of Technology
MMBTU	Metric Million British Thermal Unit
Mn/mln	million
MSBR	Molton Salt Breeder Reactor
MTC	Million metric tons of carbon
Mtoe	Million tonnes of oil equivalent
MW	MegaWatt
MWe	MegaWatt electrical
MWh	MegaWatt hour
NDCs	Nationally Determined Contributions
NEA	Nuclear Energy Agency (OECD)
NECP	National Energy and Climate Plan
NF_3	nitrogen trifluoride
NICE Future	Nuclear Innovation: Clean Energy Future
N_2O	nitrous oxide
NOAA	National Oceanic and Atmospheric Administration
NOAK	Nth of a kind
NREL	National Renewable Energy Laboratory
NPV	Net Present Value
ODE	Opslag Duurzame Energie (Surcharge for Sustainable Energy)
OECD	Organisation for Economic Co-operation and Development
O&M cost	Operation and Maintenance cost
OPEC	Organization of Petroleum Exporting Countries
p.a.	per annum
PFCs	perfluorocarbons
PJ	PetaJoule (equal to 10^{15} joules, unit of energy)
PPM	Parts Per Million
PRTP	Pure rate of time preference
RCP8.5	Representative Concentration Pathway
R&D	Research and Development
RED-I	Renewable Energy Directive-I
RED-II	Renewable Energy Directive-II
RES	Renewable Energy Source
RES program	Regional Energy Strategy program
RoW	Rest of the World

SAR	Second Assessment Report (IPCC)
SCC	Social cost of carbon
SDGs	Sustainable Development Goals (United Nations)
SDE+	Sustainable Energy Production Incentive Scheme
SDS	Sustainable Development Scenario
SF_6	sulphur hexafluoride
Solar PV	Solar Photovoltaic
SPM	Summary for Policy Makers (IPCC)
STEPS	Stated Policies Scenario (IEA)
TCRE	Transient Climate Response to cumulative Emissions
TEG	Technical Expert Group
TES	Total Energy Supply
TRL	Technology Readiness Levels
TSO	Transmission System Operator
UN COP 25 CCC	United Nations Conference of the Parties 25 Climate Change Conference
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
USCPP	United States Clean Power Plan
USD	United States Dollar
VAT	Value Added Tax
VOL	Volume
VRE	Variable Renewable Energy
VVDE	Vereniging voor Duurzame Energie
WACC	Weighted Average Cost of Capital
WHO	World Health Organization
WNA	World Nuclear Association

Annex XIII. Glossary

Adaptation:
Adapting to climate change, rather than trying to prevent it, by anticipating the adverse effects of climate change and taking appropriate measures to remedy such adverse effects, or taking advantage of opportunities that may arise to prevent or minimize damage caused by climate change.

Average capacity factor:
The average of the capacity factors of two or more power-producing generators that use the same technology, which is used in this study for wind and solar energy.

Backup power generation facilities:
Power generation facilities that generate electricity to remedy (backup) the demand-unresponsiveness of intermittent power generation facilities (see also intermittency of renewable energy).

Balancing costs:
Costs associated with maintaining a balance between electricity supply and electricity use (demand). Balancing costs increase due to the intermittency (demand-unresponsiveness) and uncertain supply of power.

Baseload power:
The projected minimum demand for electricity based on reasonable expectations of customer requirements for electricity over a given period of time.

Better regulation:
An initiative of the EU aimed at improving the quality of EU interventions by designing and evaluating EU policies and laws transparently, backed-up by evidence, and informed by the views of citizens and stakeholders.

Capacity cost:
Costs arising from the fact that the output of power generation facilities is uncertain and intermittent (demand-unresponsive), and thus may not be able to meet demand for electricity at any point in time, in particular at times of peak demand, without additional compensatory facilities.

Capacity factor (or load factor):
The ratio of the actual power output of a power-generating unit over a given period of time to the maximum possible power output over that period, i.e. the actual output relative to the maximum output.

Capacity mechanism:
A system of payments made to power plants to be available for generating electricity when needed, irrespective of the amount of electricity actually produced, intended to ensure security of electricity supply.

Carbon:
CO_2 or carbon dioxide.

Carbon leakage:
The transfer of CO_2-emitting manufacturing and other facilities to other countries with laxer CO_2 emission constraints, which may occur if the costs imposed by climate policies make such transfer attractive from a financial or business viewpoint.

Carbon neutrality:
A balance between the emission of CO_2 from anthropogenic sources and the (net) removal or absorption of CO_2 from the atmosphere (often excluding absorption by carbon sinks, such as soil, forests and oceans).

Climate neutrality:
A state in which the emission and removal of greenhouse gases (GHG) produces a net zero result, i.e. as much GHG are emitted as are removed, so that there is no (further) temperature increasing effect arising from additional GHG. Note that there is a delay between the addition of GHG to the atmosphere and the resulting greenhouse (temperature-increasing) effect.

Climate neutral scenario's:
Scenario's developed by or for policy makers aimed at achieving an economy with net-zero greenhouse gas emissions (in the case of the EU, by 2050).

Cost model:
The model we use in this study to estimate the cost of electricity produced by various power generation technologies.

Cost of power:
The average cost of generating a given amount of electricity over a given period of time using a specific power generation technology (or a mix thereof), which can be fully loaded costs, including subsidies and quasi-subsidies and the cost of capital (determined based on the weighted average capital, see also WACC).

Cost of power at zero %:
The average cost of generating a given amount of power over a given period of time using a specific power generation technology, disregarding the cost of capital, i.e. assuming the interest rate is 0%.

Decommissioning of a power generation facility:
The administrative and technical process whereby a power plant at the end of life (or possibly even before end-of-life) is dismantled to the point that it no longer requires measures for protection and the site is available for reuse.

Demand response:
The modification by electricity end-users of their consumption patterns in response to incentives or restrictions imposed by grid operators or electricity companies, i.e. consuming more or less electricity in response to incentives or restrictions.

Distribution system operator (DSO):
The natural or legal person responsible for the operation, maintenance and, if necessary, development of the electricity distribution system in a given area and its interconnections with other systems. The DSO also ensures the system's long term ability to meet demand for the distribution of electricity.

Electricity mix:
The combination and relative share of the various electricity generation facilities in a given geographic region, also called power mix.

Electricity security of supply:

The over-all management of the electricity generation, transmission and distribution (delivery) systems to ensure that there always is sufficient electricity delivered to meet demand for electricity anywhere in a geographic area, including, but not limited to, the avoidance of black-outs. Security of supply can be enhanced by capacity payments to conventional or nuclear power plants in regions in which the share of intermittent renewable electricity is significant, by expanding interconnections, and a variety of other measures.

Energy independence:

The state of a country or other geographic area in which it produces sufficient energy within its borders to meet all energy needs, which can be enhanced by moving away from imports of fossil fuels and other energy sources, and increasing domestic production of fuels, electricity, and heat. The EU views energy dependence as a threat to the security of the energy supply, and strives for energy independence.

Energy poverty:

A situation in which a person has difficulties obtaining the energy necessary for adequate heating (or cooling) and lighting and to power appliances in his home to meet his basic needs, typically due to a lack of resources to pay for the energy required.

Energy transition model (ETM):

An open-source energy model that can be used to estimate total system costs, i.e. all costs related to the production and distribution of energy (e.g., electricity, heath, fuels such as hydrogen, etc.). The ETM can be used to model a large variety of power mixes, including wind/solar and nuclear energy. The ETM is said to be “independent, comprehensive and fact-based,” and is used in The Netherlands to model energy scenarios for government. In this study, the ETM is used to estimate the integration cost of renewable electricity relative to nuclear energy.

Externalities:

There are negative and positive externalities. Negative externalities are the uncompensated costs incurred, or damage suffered, by third parties as a result of an economic activity or transaction in which they do not participate. These costs are to be distinguished from private costs that are borne by the parties or beneficiaries of an activity. Positive externalities occur when third parties receive a benefit from an activity (see also free-riding).

Free-riding:

A person who benefits from something without expending effort or paying for it. The standard example is the passenger that does not pay for public transportation. In the context of power generation, an intermittent power generation facility rides for free on the capacity (and, as necessary, supply of power) provided by other non-intermittent sources.

Generation capacity:

This is the maximum power output when a power generator runs at full blast, measured in watts, typically megawatts (MW). This concept is relevant to understanding a generator’s ability to handle peak demands. Over longer periods of time, however, no power generator can constantly run at full speed; maintenance is a necessity, repairs may be required, etc. As a result, the actual power output differs from the generation (or name-plate) capacity (see also capacity factor).

Generator pays principle:

Policy principle pursuant to which all costs (including negative externalities) associated with an electricity generation technology (or a specific electricity generation facility) are internalized in its cost basis, so that the electricity produced by that technology or facility is costed at its full social cost.

Global warming potential (GWP):

Concept that enables comparison of the global warming impacts of different gases. The GWP of a gas refers to the total contribution of global warming resulting from the emission of one unit of that gas relative to one unit of the reference gas, CO_2, which is assigned a value of 1.

Greenhouse gases (GHG):

Gases that cause the 'greenhouse effect' and global warming, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), nitrogen trifluoride (NF3), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Water vapor (H2O) is also a GHG, but not regarded as such for policy purposes.

Integration cost:

The cost of integrating electricity generation facilities and the electricity produced by them into the electricity system, network, and grid. Integration costs comprise the following four cost categories (i) balancing costs; (ii) grid costs; (iii) capacity costs; and (iv) profile costs.

Intermittency of renewable energy:

A property of variable renewable energy (including wind and solar) that results in electricity being available in sufficient quantities only during some of the time (specifically, when the wind blows or the sun shines), and not being available at other times, irrespective of demand. Consequently, intermittent renewable energy, unlike conventional and nuclear energy, is not continuously available for conversion into electricity and may supply too much, too little or no electricity to the grid, leading to mismatches between electricity generation and consumer demand, i.e. it is demand-unresponsive. Backup power generation resources or other solutions, such as storage and conversion/reconversion, are necessary to address the intermittency of renewable energy, in particular as the penetration rate of renewable power increases.

Learning effect:

The increase in efficiency if the same or a similar task is performed multiple times, used in the context of the cost of constructing and operating electricity generation facilities. This effect is reflected in the difference between the cost of a 'first of a kind' (FOAK) and 'nth of a kind' (NOAK), whereby n is typically 5.

Levelized cost of electricity (LCOE):

The lifetime costs of energy generating facilities divided by the amount of energy produced, typically discounted to present value. LCOE considers only project-related cost, such as initial investments, operation costs and fuel costs during the facility's lifetime, and typically discounts the energy produced over a facility's lifetime, but not the intermittent energy produced by an intermittent power generation facility. To arrive at the total electricity system cost, the integration cost (including, but not limited to, profile cost) must be added to the LCOE. In this study, discounting of power is not the preferred method for calculating LCOE; instead, we use synchronized lifetime analysis (see further below).

Load dispatch:

The direction of the flow of electricity from power plants into the network to meet demand. Because the technical characteristics of power generation technologies vary, the process of load dispatch may vary.

Load factor:

See capacity factor.

Marginal cost:

The incremental cost incurred by producing one additional unit of a product or service (i.e. delta cost over delta quantity). Marginal costs occur when variable costs occur. The marginal cost of renewable power generation facilities (such as wind and solar) is low.

Merit order:

Concept describing the sequence in which power plants are designated to deliver (dispatch) power to the electricity system. This order can be based on the technological characteristics of power plants, or the price offered by electricity generating facilities (or electricity traders).

Merit order effect:

The effect on electricity prices that occurs if the dispatch of electricity to the network is determined solely on the basis of the (spot) price offered. Generally, it refers to a possible average electricity price-lowering effect of renewable energy due to its very low marginal cost of production.

Mitigation:

Any measure aimed at reducing the emission of anthropogenic greenhouse gases into the atmosphere to prevent global warming.

Nationally determined contributions (NDC):

Contributions to the temperature target set by the Paris Climate Change Agreement promised by states that are parties to it. NDCs are national climate action plans and constitute the main way in which the Paris goal of no more than a 2 or even 1.5 C increase in the average global atmospheric temperature by 2100 is pursued.

No regrets solution:

A measure that is worthwhile even if the risk the measure was intended to remedy does not materialize. In the context of climate change, no regrets solutions are policies that confer benefits, and do not cause adverse impacts and negative externalities, irrespective of any positive effects they may have on the problem of climate change. In other words, policies that provide economic, environmental, and other benefits, irrespective of their favorable effect on limiting global warming or preventing or remedying climate change.

Nuclear (or atomic) energy (or power):

The energy released during nuclear fission (or fusion), which is used in nuclear power plants to generate electricity. The amount of energy released by the nuclear fission of a given mass of uranium is more than a million times greater than that released by the combustion of an equal mass of carbon.

Outsourcing of emissions:

The emissions associated with imported goods and services that result in a nation’s domestic emissions being understated, if the import-related emissions are ignored. Developed nations may have low emissions due to the fact that the emissions associated with the goods they import and consume occur in developing nations that export to them.

Penetration rate:

The percentage of total power generation capacity provided by a particular power generation technology. For example, if the penetration rate of wind power is 20%, that means that wind power generation capacity makes up 20% of the total power generation capacity.

Power density:

The amount of electricity produced by a power plant on the surface it occupies expressed in GWh/km^2. This concept is also applied to electricity generation technologies, and measures the electricity output per surface unit.

Power generation technology:

Technology employed to generate electricity, including wind turbines, solar panels, and nuclear energy, through conversion of primary energy sources into electricity.

Power plant:

Facility that generates electricity for the public electricity network.

Power/surface ratio:

The ratio of power generated using a specific technology to the surface necessary to support the deployment of that technology (see also power density).

Profile costs:

Indirect costs, often not accounted for in integration costs, that are incurred by the electricity system due to the specific characteristics of power generation facilities. Specifically, profile costs are associated with intermittent electricity produced by renewable energy sources.

Renewable energy:

Energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas. Renewable energy does not include nuclear energy.

Sensitivity analysis:

A modelling tool used to determine how target (or output) variables are affected by changes in other variables known as input variables. It serves as a way to understand and better predict the range of possible outcomes of a decision given a certain range of variables.

Space Model:

The model we use in this study to estimate the area of land and space (sea) required by various power generation technologies.

Spatial requirement:

The surface area required by a power generation technology to produce a given amount of electricity.

State aid:

All benefits conferred on a selective basis to undertakings by national public authorities, including direct subsidies, tax exemptions, favorable regulatory treatment, etc. Certain forms of state aid are permissible under European Union law, while other forms of state aid are not.

Stated policies scenario (STEPS):

Scenario that incorporates existing energy policies as well as an assessment of the results likely to stem from the implementation of announced policy intentions.

Statistical dependence:

Phenomenon caused by positive correlation between the chance that one variable changes and the chance that another variable changes in the same or opposite direction. Statistical dependence may interfere with the workings of the law of the large numbers, thus reducing the accuracy of predictions of aggregate results.

Stochastic nature of renewable energy:

The random or poorly predictable variation of power production from intermittent renewable energy sources, such as wind and solar, due to the random nature of wind and clouds, which over time are predictable accurately only to limited extent.

Surface/power ratio:

The size of the surface required to generate a given amount of power using a specific electricity generating technology.

Sustainable finance:

Finance aimed at promoting sustainable development. The EU is boosting the role of finance to achieve a greener and more sustainable economy and prevent climate change.

Sustainable development scenario:

A scenario outlining an integrated approach to achieving internationally agreed or desired environmental, social and economic objectives, such as preventing climate change, promoting air quality, and universal access to modern energy.

Synchronized lifetime analysis:

The method used in this study to compare the cost of various power generating technologies, designed to avoid the distorting effects of discounting energy projects with different lifetimes or lead times.

Taxonomy:

A classification tool developed by the European Union aimed at investors, companies and financial institutions to define environmental and climate performance of economic activities across a wide range of industries, which sets requirements for companies and corporate activities to be considered sustainable.

Technology neutrality:

The idea that laws and regulations do not promote specific technologies or discriminate against one or more of them, but instead define objective performance or result-oriented requirements (such as carbon or climate neutrality), so that the market can decide which technologies best meet such requirements. In other words, the same regulatory principles apply regardless of the technology used. This concept allows EU member states to pursue different energy technologies within their territories.

Total surface demand:

The total surface required by a power generation technology to provide the total (or any defined part of the) power demand in a given country.

Total system costs:

Where used in relation to energy or electricity, the total of all costs related to the production and distribution of energy (e.g. electricity, gas, hydrogen, etc.) or electricity only.

Transmission system operator (TSO):

The operator responsible for the system that transmits electrical power from generation plants over the electrical grid to regional or local electricity distribution operators. The TSO is also responsible for ensuring the security of supply with a high level of reliability and quality.

Variable renewable energy:

Intermittent renewable energy sources that produce variable amounts of electricity not in response to demand, and, as a result, impose cost on the electricity system due to their fluctuating nature, such as wind and solar power.

Weighted Average Cost of Capital (WACC):

The weighted average cost of capital, which represents the weighted average of the expected returns to all investors (typically a combination of equity and debt) who invested in a project. The WACC is determined by three components: the cost of equity, the after-tax cost of debt (given that interest payments lower taxable profits in most jurisdictions), and the capital structure (i.e. the levels of debt and equity in the project).