Road to EU Climate Neutrality by 2050

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

Extensive summary of a Peer-Reviewed Publication for ECR Group and Renew Europe, Brussels, Belgium

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

Brussels, January 2021

Road to EU Climate Neutrality by 2050

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

Extensive summary of a Peer-Reviewed Publication for ECR Group and Renew Europe, Brussels, Belgium

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

Brussels, January 2021

This publication has been prepared for ECR Group and Renew Europe.

- 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/

Table of Contents

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 a summary of the results of a study[1] 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.

While we invite the interested reader to read the full study, this illustrated Extensive Summary follows each main step in our analysis, so that the reader can discern the structure of our reasoning. We also added a glossary and list of abbreviations as annexes to assist the reader.

Authors and Contributors of the study

The authors of the 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. These peer reviewers include 2018 Nobel Laureate in Economics **Professor William Nordhaus, Dr. Joeri Rogelj, Dr. Fabien Roques and many more distinguished scholars**[2].

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.

1 Cf. Katinka M. Brouwer, Dr. Lucas Bergkamp, Road to Climate Neutrality By 2050: Spatial Requirements of Wind/ Solar and Nuclear Energy and Their Respective Costs, Brussels, 2021

2 The list of these peer reviewers is attached to the full report as Annex XIV.

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.[3] 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"[4] 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.[5]

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.

3 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

4 "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/

5 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."[6]

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.

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 summary will be widely distributed and read.[7] The people of Europe deserve it and the energy transition needs it.

Brussels, December 2020

6 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

7 The full study report can be found at [insert].

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 (assuming estimates are accurate).[8]
- Electricity-generating technologies therefore should be evaluated for the degree to which they constitute 'no regrets' solutions.

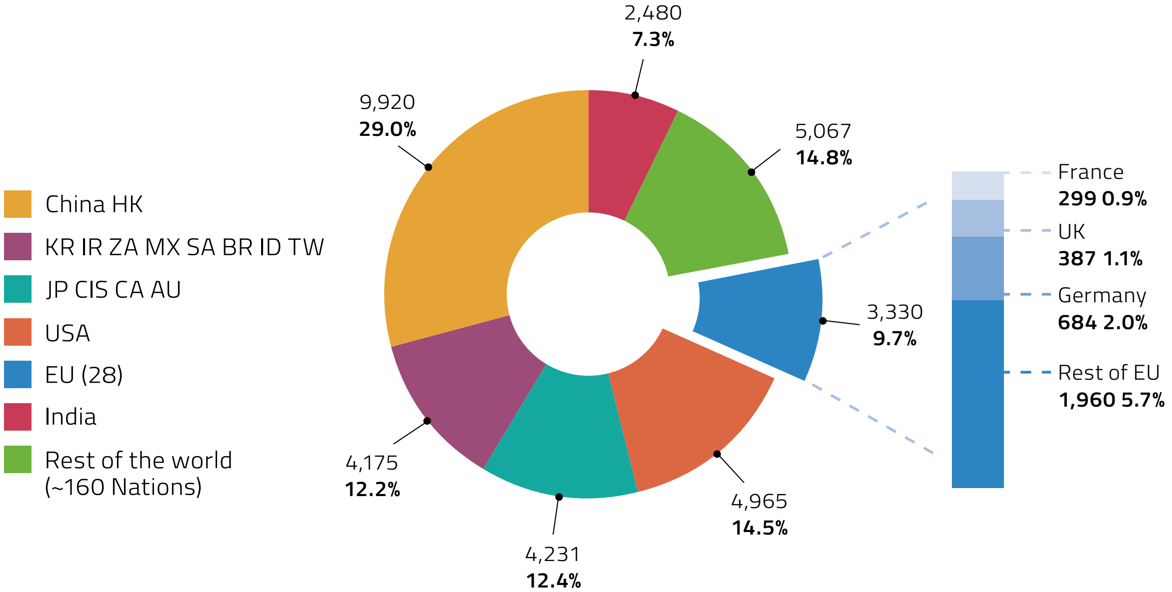
a. The EU's plan to become the first climate-neutral continent in 2050 is merely aspirational; there is **no proven pathway** that will lead to this result.[9] Much depends on factors that the EU does not control, such as technological breakthroughs, demand for energy, the cost of moving towards climate 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 of the full study report	0.02°C	0.05°C
Rogelj (2016) [7] – number derived from author's numbers; for methodology see Annex VII of the full study report	0.06°C	0.15°C

8 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).

9 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.

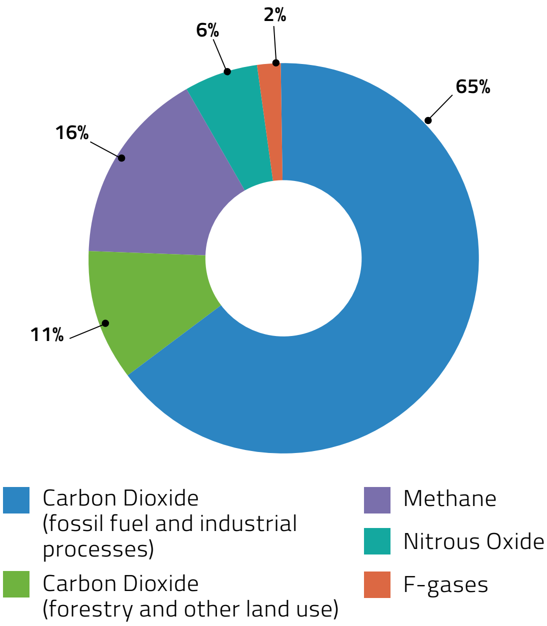


Annual CO_2 emissions 2019: in million tonnes - % global output *BP data 2020.*

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]:



Global Greenhouse Gas Emissions by Gas.

Global greenhouse gas emissions by gas and source [14]

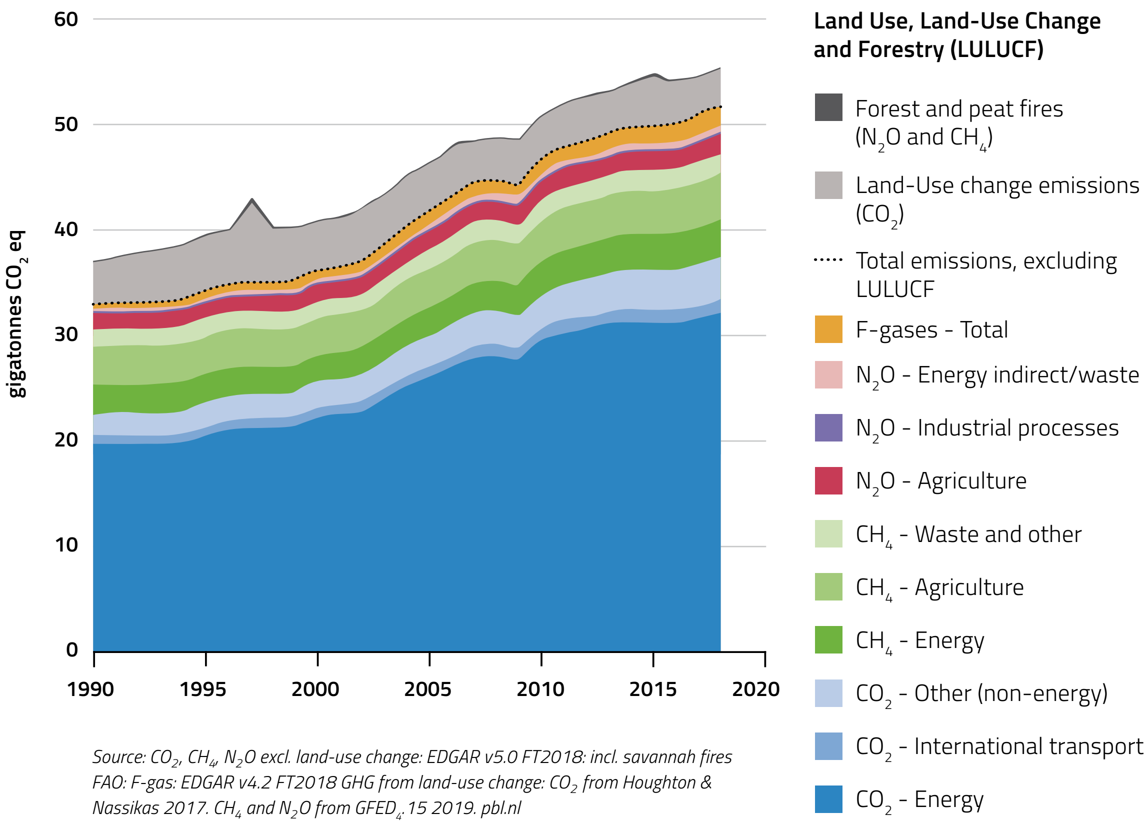
d. **Growth in global GHG emissions** (excluding those from land use change) in 2018 was the **highest since 2011, increasing at a rate of 2.0%**, reaching 51.8 gigatonnes of CO_2 equivalent (GTCO_2 eq), with the **developing world steadily increasing**. [14]

   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.

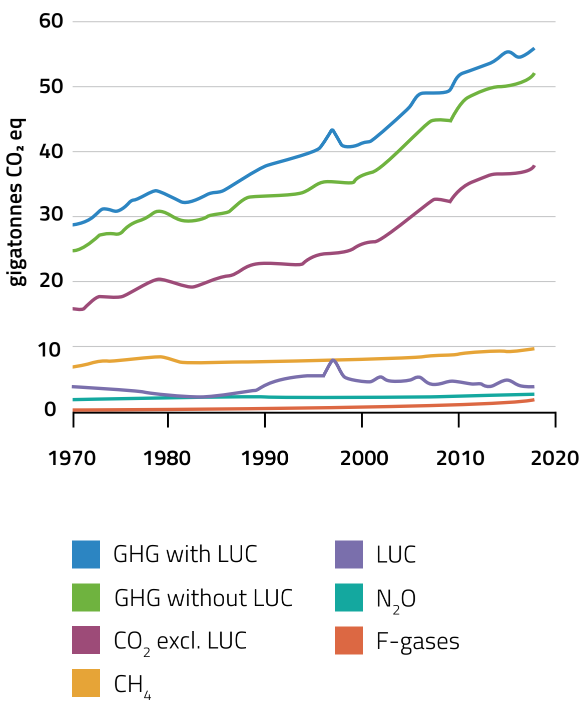
   iii. **Global consumption of oil products and natural gas continued to increase, by 1.2% and 5.3% in 2018**, led by increased consumption in China, the US, and Russia.

   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.



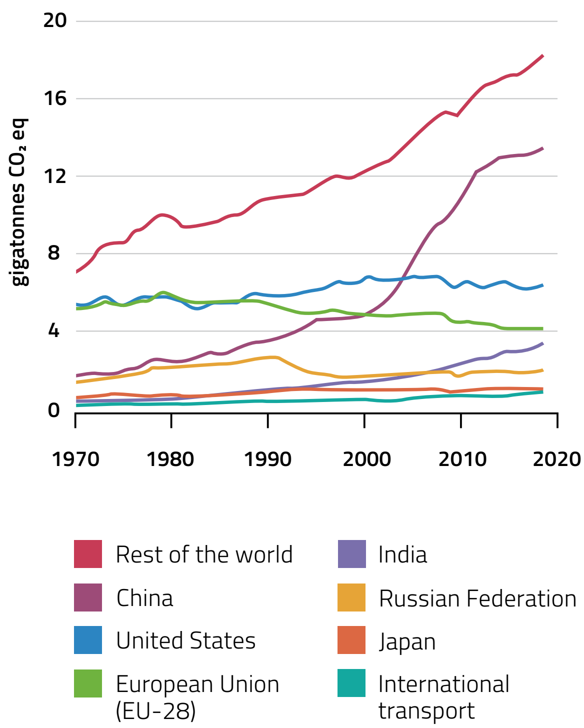
Source: CO_2, CH_4, N_2O excl. land-use change: EDGAR v5.0 FT2018: incl. savannah fires FAO: F-gas: EDGAR v4.2 FT2018 GHG from land-use change: CO_2 from Houghton & Nassikas 2017. CH_4 and N_2O from GFED$_4$.15 2019. pbl.nl

Figure 2.1. 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

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.

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

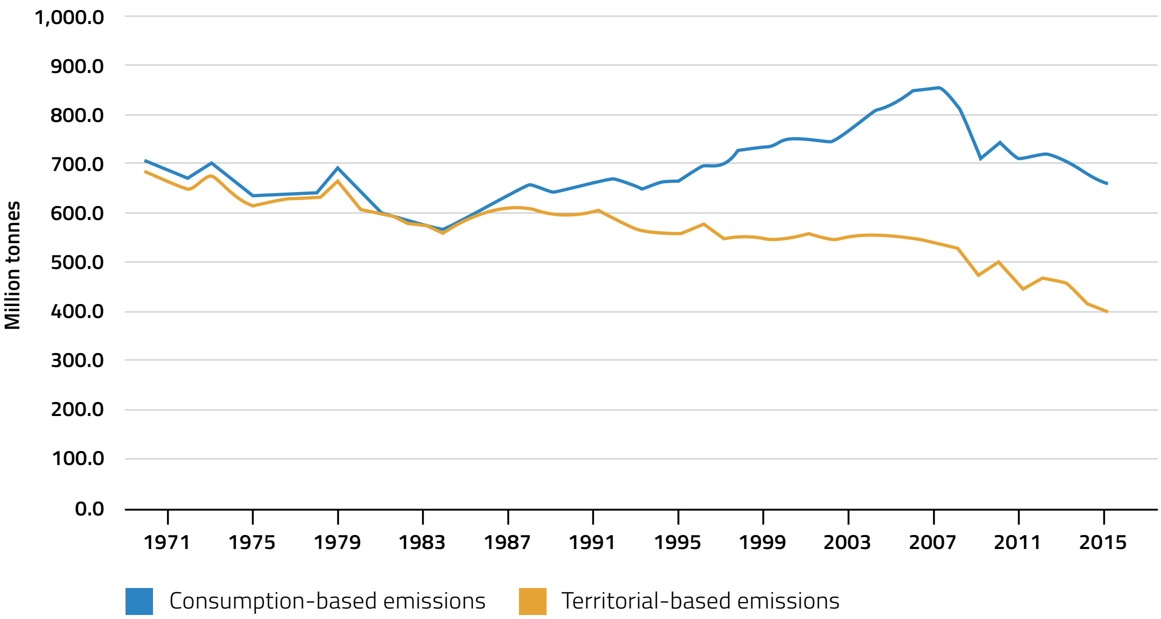
Global GHG emissions by type of gas and country [14]

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.

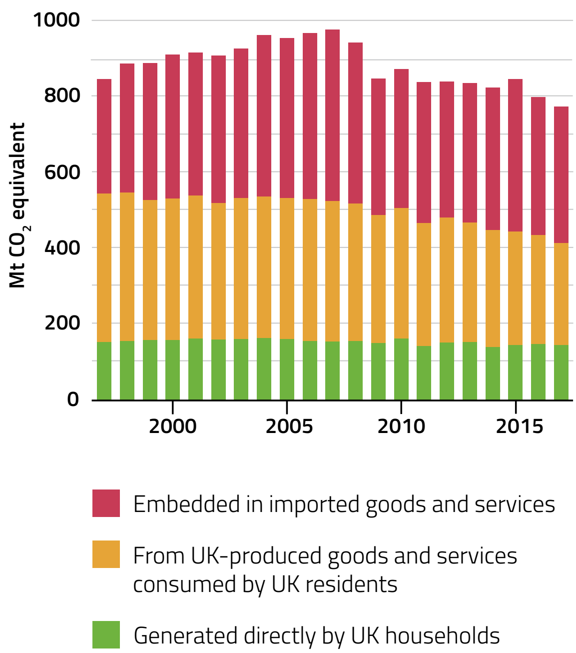
Decoupling of GDP per head from CO_2 emissions seems to have happened at the expense of outsourcing manufacturing [2]



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

Total GHG emissions associated with UK consumption [3]

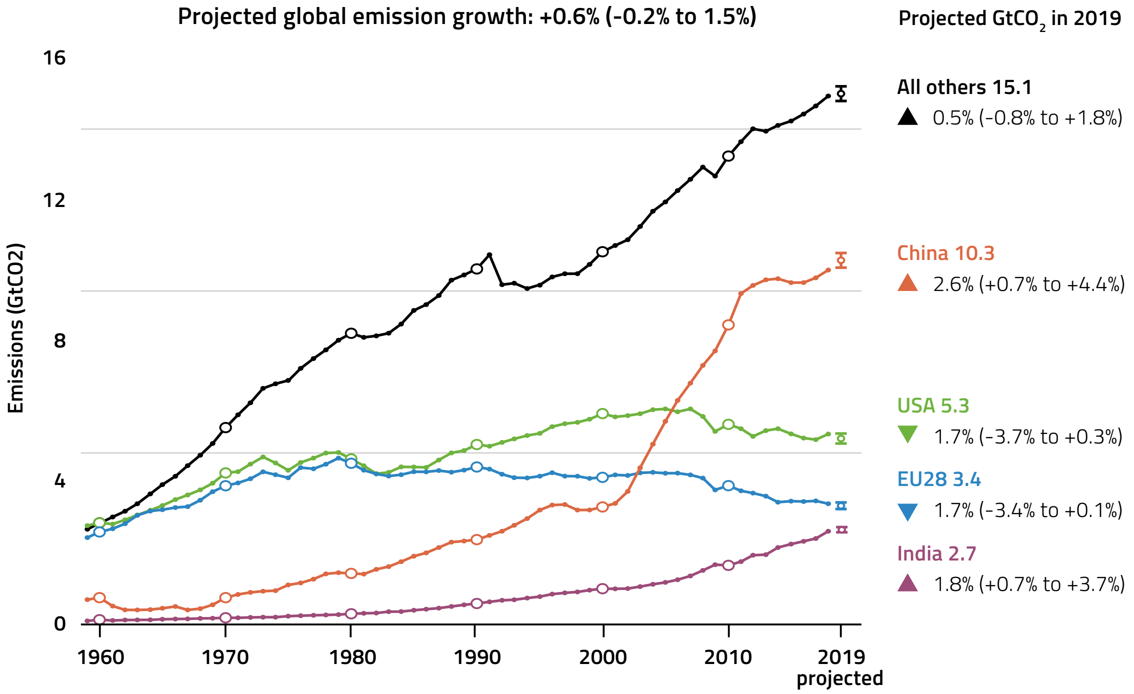
g. In 2019, global carbon emissions from energy use increased by at least 0.5%, despite a decrease in the EU.[10] According to JRC, the global emissions growth continued in 2019 with global anthropogenic fossil CO_2 emissions increasing by 0.9% compared to 2018, reaching 38.0 Gt CO_2. [13] The increase 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]



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

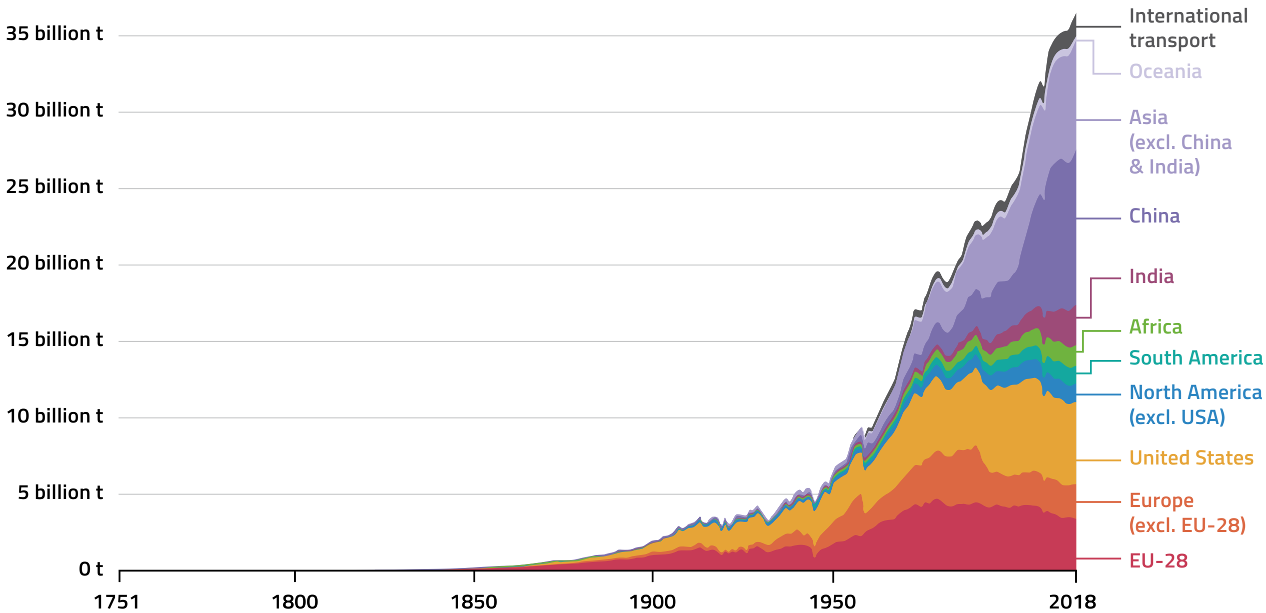
10 We do not discuss 2020 and the COVID-19, which has created an exceptional situation.

Annual Fossil CO_2 emissions 2019 [4]



Annual fossil CO_2 emissions and 2019 projections

Annual Total CO_2 Emissions [8]

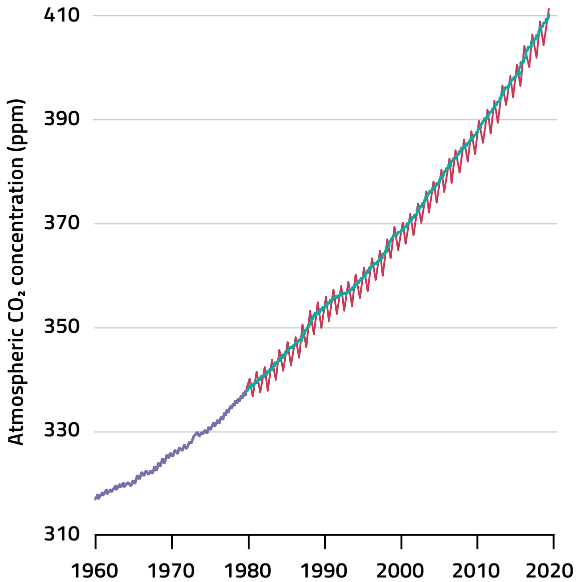


Annual total CO_2 emissions, by world region

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

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.[11]

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

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 ***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**.

---

11 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.

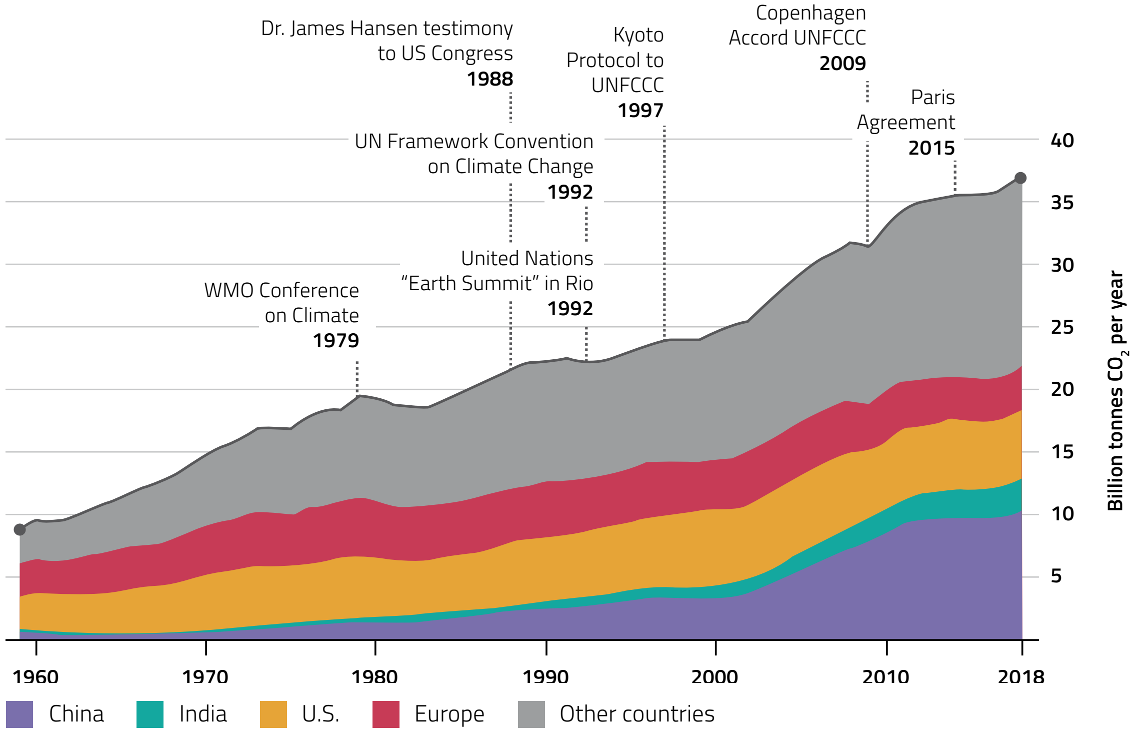
ii. The EU and national policies have produced modest reductions in carbon emissions thus far, and emissions from the rest world continue to increase, with **no sustained evidence of a peak, let alone of the necessary decrease.**[12] Thus, there is a substantial risk that the EU's efforts, even if successful, 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;



Global Carbon Emissions

Source: Global Carbon Budget 2018 ▪ Get the data

12 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 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.[13]

iii. To prevent carbon emissions in the rest of the world with a high degree of certainty,[14] over the period from now to 2050, the EU could **buy up all fossil fuels (oil, gas, coal/lignite) and retire them definitively**.

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

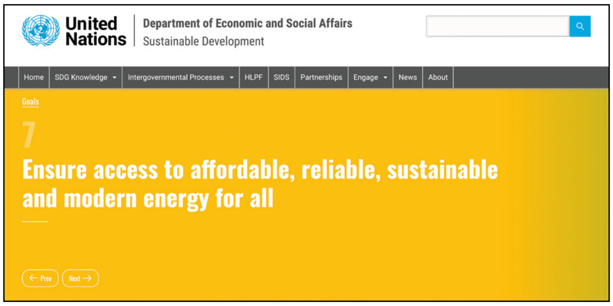
14 Adverse substitution effects may occur, if, instead of fossil fuels, wood and other biomass are combusted for energy. If this results in deforestation, carbon dioxide will be added to the atmosphere, but not subsequently removed.

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 approximately **7 times the entire EU's annual GDP** and equal to €560,000 per EU household.[15]

v. Assuming the buying will be linear over 30 years, the E**U 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**"[16] and **industrialization**.[17] All of these goals are ranked higher than the fight against climate change.[18]



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.

---

15 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.

16 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.'

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

18 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

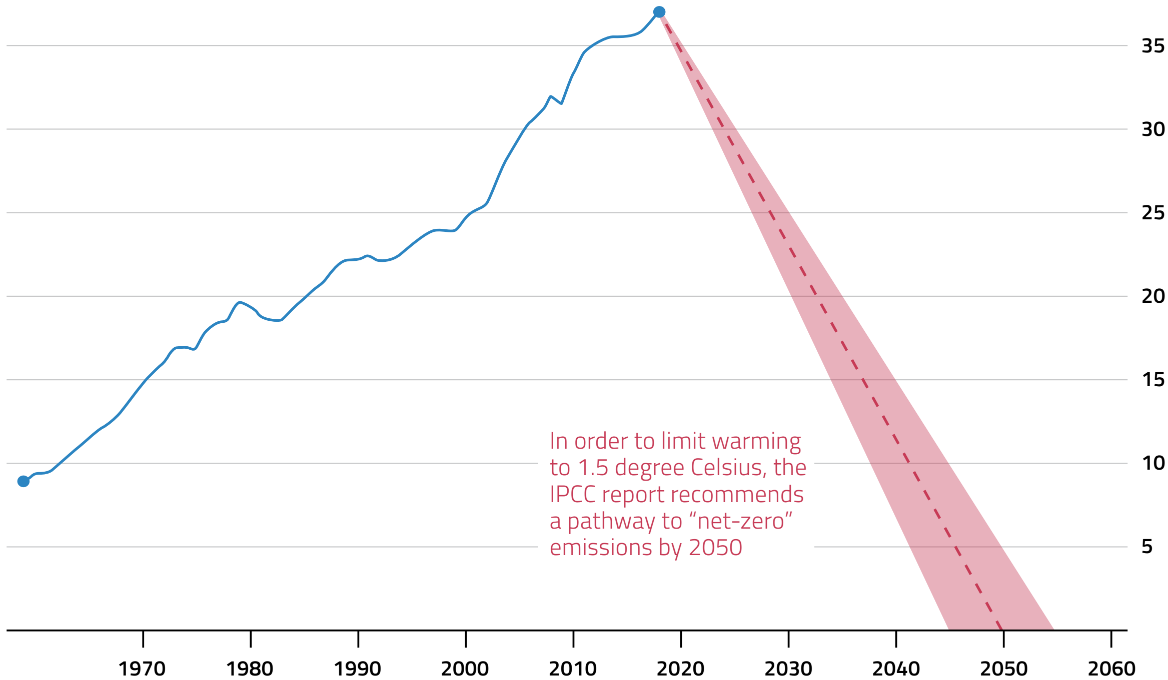
A failure to recognize the factors behind continued emissions growth could limit the world's ability to shift to a pathway consistent with 1.5 °C or 2 °C of global warming. Continued support for low-carbon technologies needs to be combined with policies directed at phasing out the use of fossil fuels.

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).

NATURE CLIMATE CHANGE | VOL 10 | JANUARY 2020 | 2–10 | www.nature.com/natureclimatechange 3

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 **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.
- There is **no plausible, feasible plan or pathway** to achieve global climate neutrality by 2050, however. It is merely an aspiration.



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

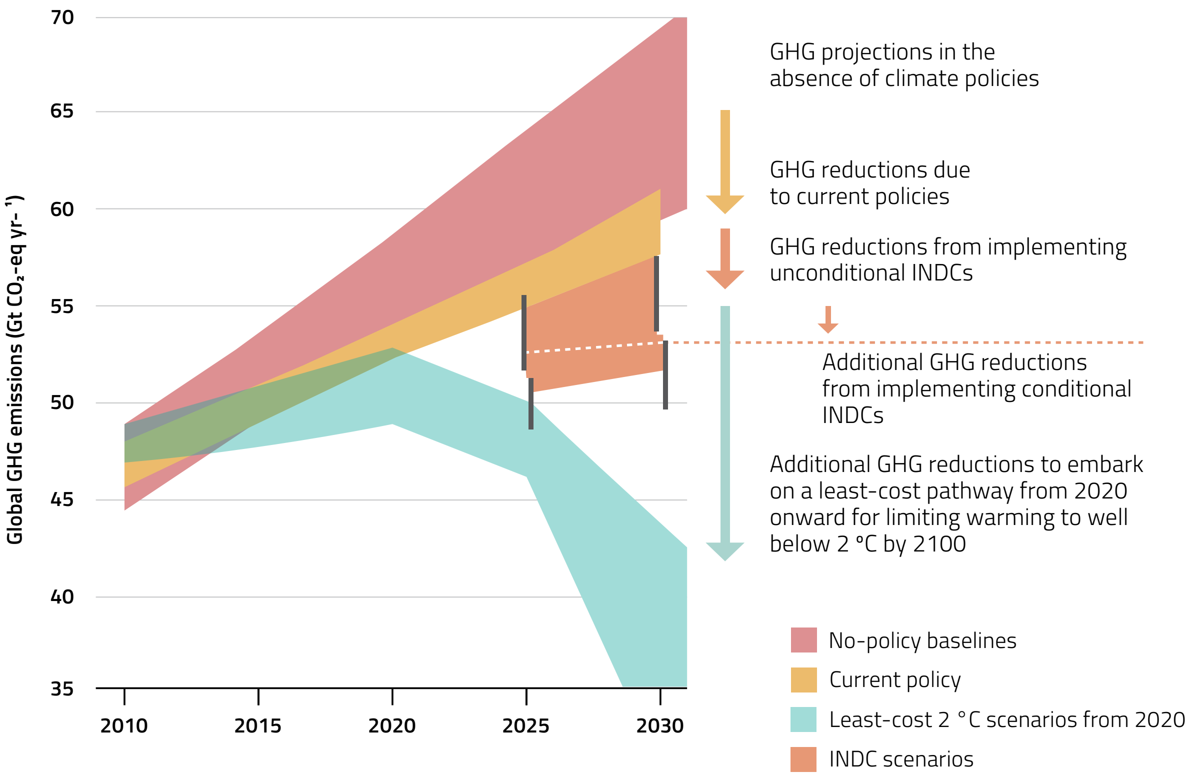
IPCC Special Report -- Limiting warming to 1.5 degrees C requires dramatic emission reductions by 2030 and carbon neutrality by around 2050. This would entail unprecedented transformations of energy, land, urban, and industrial systems, including measures to achieve "negative emissions" by removing carbon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

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



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 would have to retired every day. All **new, additional energy use would have to be carbon-free**. Reality is entirely at odds with these requirements.

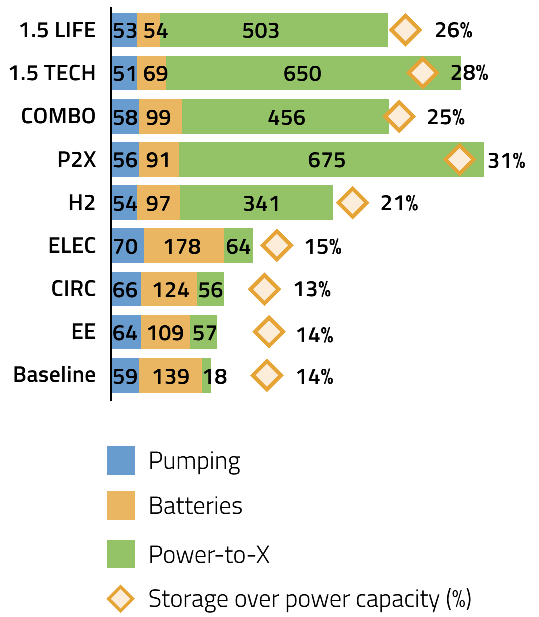
xiv. Thus, the **EU is not likely to achieve climate neutrality by 2050**. There is **no well-defined plan to get there**. No cost/benefit-analysis has been done on alternative policy options; not all policy options have been carefully considered, some viable options, most notably, nuclear power, are 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 renewable energy and emissions reductions, and financial incentives for research and development, which d**o 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 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**.



Source: PRIMES model.

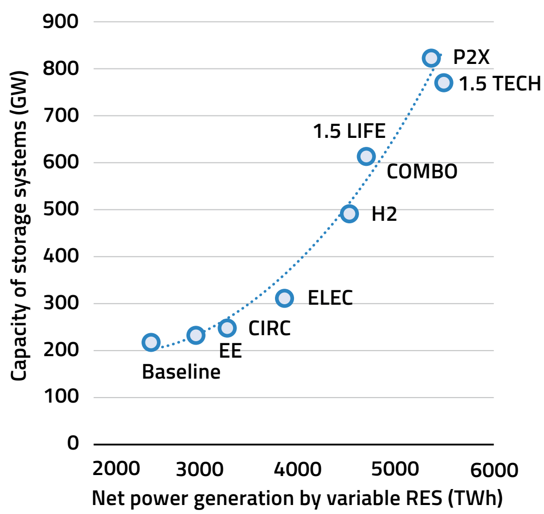


Fig. 6. EU storage systems capacity (GW), share of total power capacity and correlation of power storage with variable RES generation. In these graphs, the abbreviations 'P2X', '1.5TECH', '1.5LIFE', 'COMBO, etc. refer to scenarios of energy mixes with a decreasing percentage of variable renewable energy.

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 of the full study report.

xvii. **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).

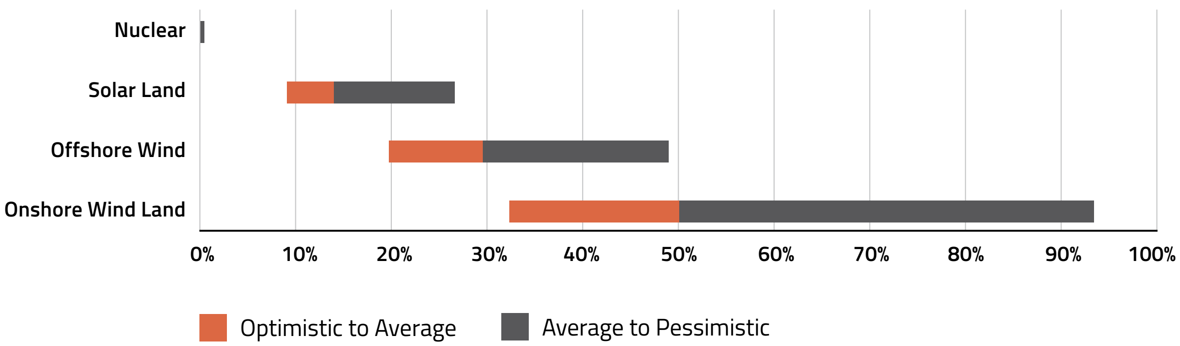
a. Depending on variables such as electricity demand and capacity factors, in realistic scenarios, there is **not enough land to meet all power demand** if the Czech Republic and The Netherlands were to rely solely or predominantly on wind and solar power. In the Czech case, it is even **out of the question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



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

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%

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).

Energy Demand (PJ)	% of Energy Demand Supplied by Renewables								
	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%

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

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.[19] 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

The Netherlands

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

The Czech Republic

a. While the above table 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 andconversion (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

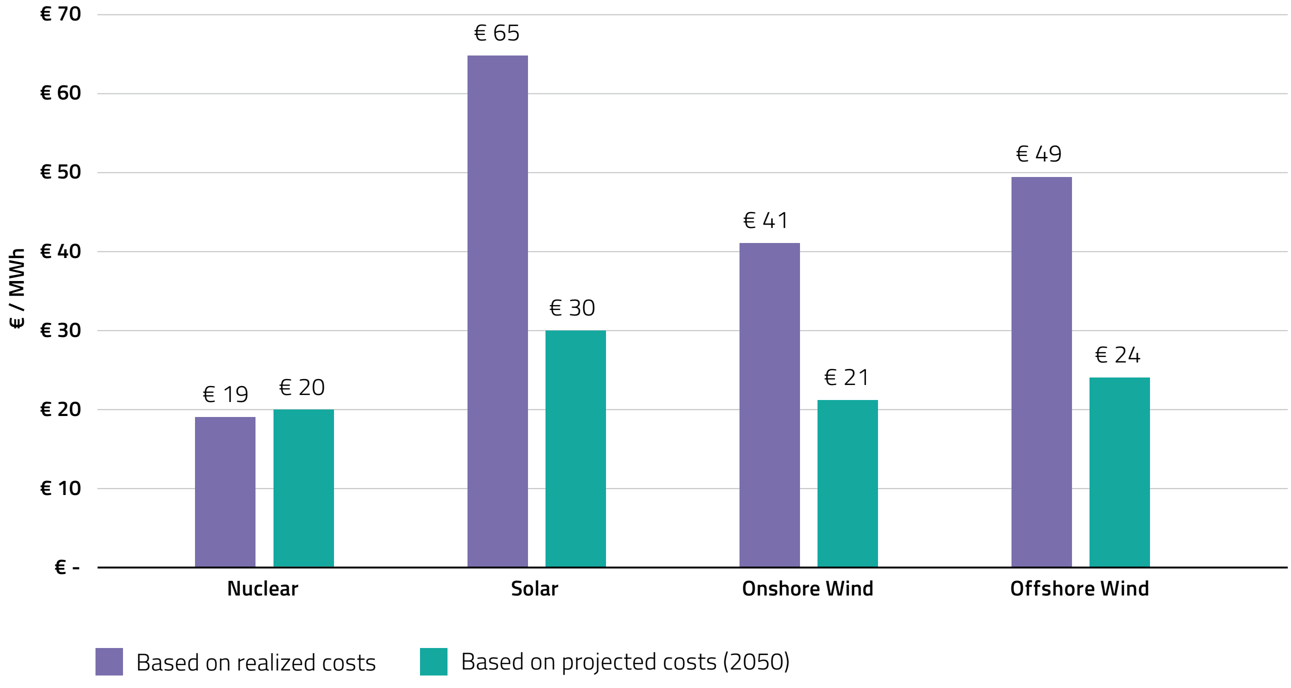
The **WACC is the most influential**, but also the most controversial factor. Based on thorough analysis of this debate, our approach estimates the WACC for policy makers by **separating government risk** (which policy makers control) from **project risk** (which operators control to a great extent). In standard LCOE calculations, non-intermittent nuclear electricity is discounted more heavily than intermittent renewable electricity, even though electricity is fungible and the economic value of intermittent electricity is lower. Our method avoids this practice, but does not discount intermittent renewable electricity to account for its lesser economic value.

19 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.

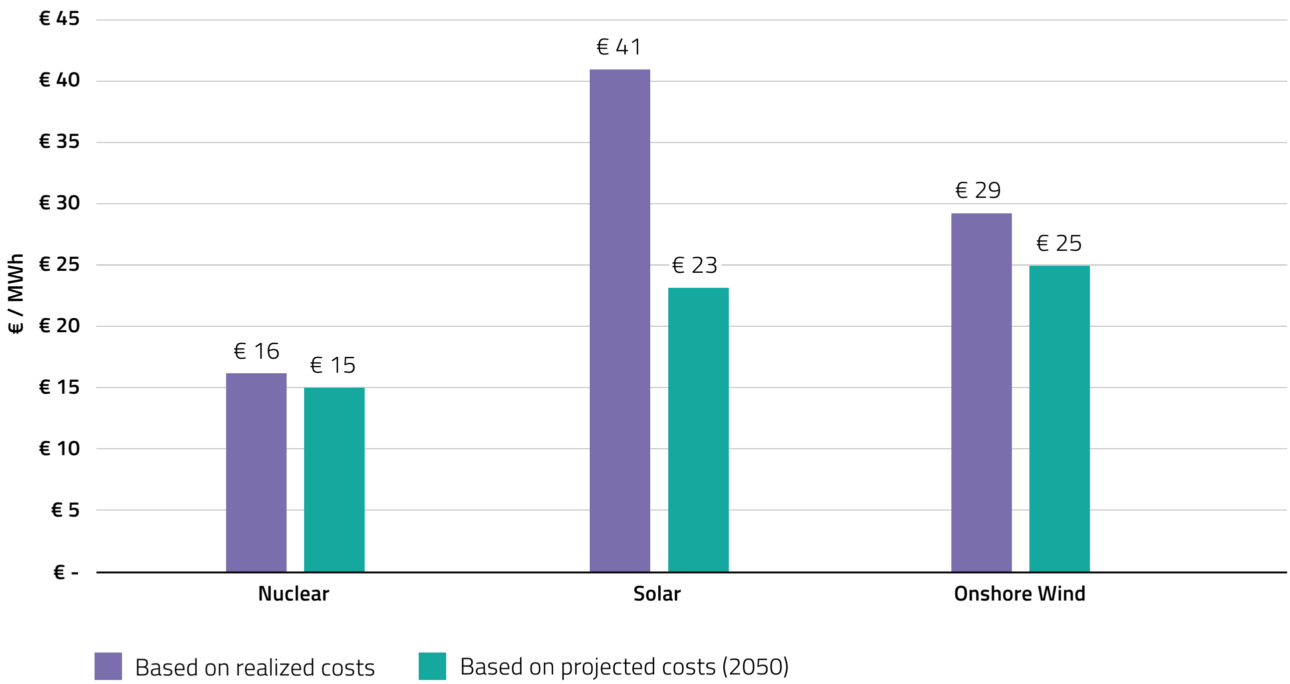
3. In part because the WACC is also used as discount rate, the WACC to be applied in planning decisions is not a given for policy makers. The choice of a WACC/discount rate is a value-laden decision, not a technical matter to be decided by experts. Deciding the appropriate discount rate for policy purposes 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 LCEO 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 the Czech Republic and The Netherlands, even before integration- and systemrelated 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).



The Netherlands: LCOE Analysis



The Czech Republic: LCOE Analysis

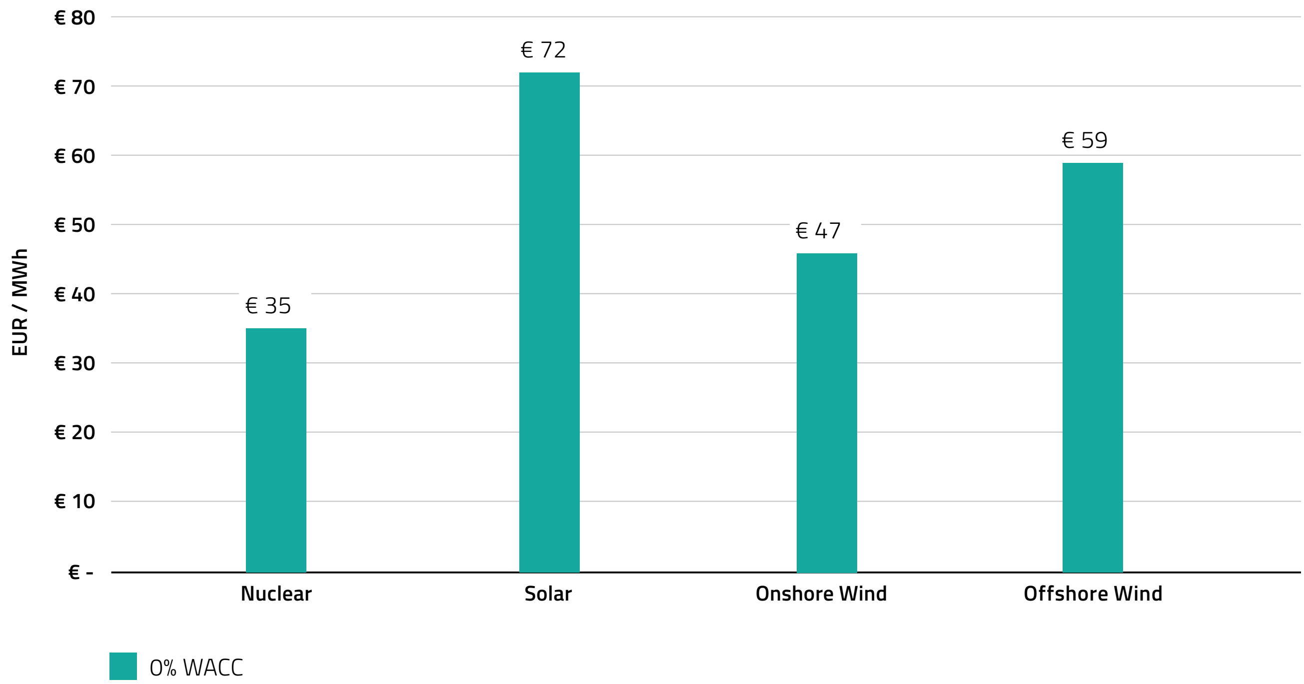
4. We further **adapted the LCEO method** by developing a **synchronized lifetime analysis** as an additional point of reference. A synchronized lifetime analysis is the preferred method for comparing various power generating technologies, because it avoids the distorting effects of discounting projects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

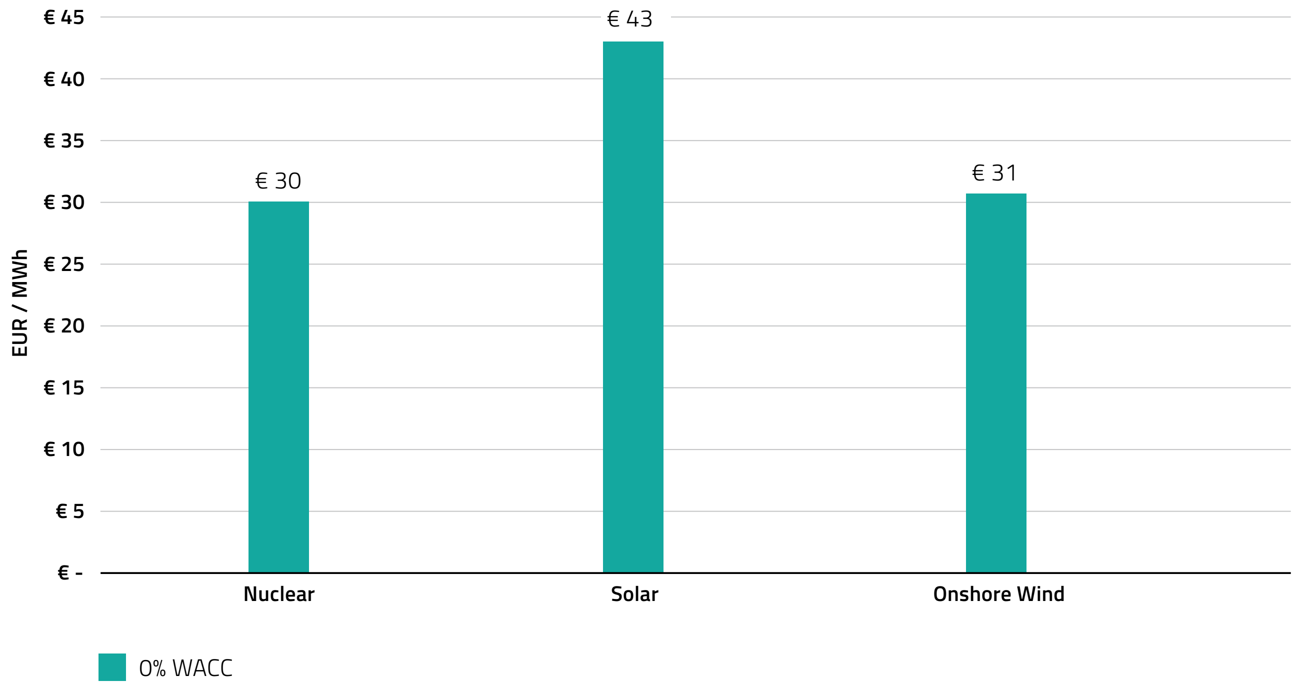
Note: The time periods under consideration for The Netherlands and the Czech Republic are different due to different technical lifetimes of the renewable power technologies.

	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

The Netherlands - Synchronized Lifetime Analysis



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



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

	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

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.

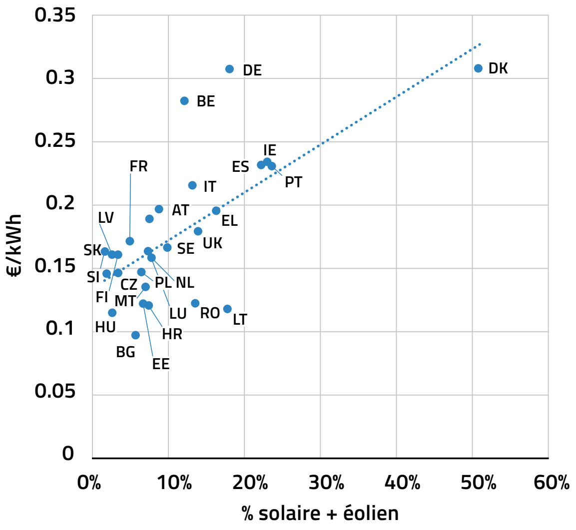
   b. **Integration- and system-related costs are high for wind and solar power, because this power is intermittent (no constant output) and it is incapable of producing power on demand (stochastic, no flexibility)**. As renewable energy displaces conventional energy sources, integration- and system-related 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.

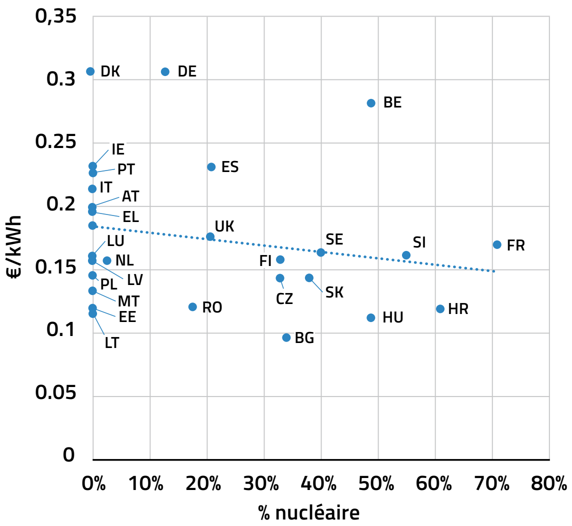
24 Jan 2020, 14:00 | Ellen Thalman, Benjamin Wehrmann

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]





Price of electricity (household)

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

Source: Eurostat (Dec 2018)

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%.

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 below 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 damag**e (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.

References:

1. BP Statistical Review of World Energy 2019, https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
2. 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
3. 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
4. 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.
5. Pierre Friedlingstein et al., Global Carbon Budget 2019, Earth Syst. Sci. Data, 11, 2019, pp. 1783–1838.
6. Bjorn Lomborg, Impact of Current Climate Proposals, Global Policy, Volume 7, Issue 1, February 2016, pp. 109-116.
7. 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).
8. Global emissions have not yet peaked, Our World in Data, https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions
9. United Nations Framework Convention on Climate Change, https://unfccc.int/resource/docs/convkp/conveng.pdf
10. 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
11. 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.
12. Sepulveda, N.A. (2016), Decarbonization of Power Systems: Analyzing Different technological Pathways, Master Degree Thesis, Massachusetts, Institute of Technology (MIT).
13. 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.
14. 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.
15. 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.
16. 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
17. 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

Annexes

Annex I. Abbreviations

°C	Celsius
Cf.	conferre (compare)
CH_4	methane
CO_2	carbon dioxide
DED	Decarbonized Energy Directive
DEFRA	Department for Environment, Food and Rural Affairs (United Kingdom (UK))
DSO	Distribution System Operator
ECR Group	European Conservatives and Reformists Group
Eds.	Editors
EGR	Emissions Gap Report
EJ	Exajoule (equal to 10^{18} joules, unit of energy)
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
F-gases	fluorinated gases
GDP	Gross Domestic Product
GEN	Generation
GHG	Green House Gas
GT	Gigaton
GTC	Billion metric tons of carbon
GW	GigaWatt
GWh	GigaWatt hour
GWP	Global Warming Potential
H^2	Hydrogen
HFCs	hydrofluorocarbons
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
kWh	kiloWatt hour
LCOE	Levelized Cost of Electricity
MW	MegaWatt

MWh	MegaWatt hour
NDCs	Nationally Determined Contributions
NECP	National Energy and Climate Plan
NF^3	nitrogen trifluoride
O&M cost	Operation and Maintenance cost
PFCs	perfluorocarbons
PJ	PetaJoule (equal to 10^{15} joules, unit of energy)
SDGs	Sustainable Development Goals (United Nations)
SF_6	sulphur hexafluoride
SPM	Summary for Policy Makers (IPCC)
UNFCCC	United Nations Framework Convention on Climate Change
WACC	Weighted Average Cost of Capital

Annex II. Glossary

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.

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.

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.

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).

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.

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.

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.

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.

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.

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.

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.

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 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).