ONE BILLION TONS

CO_2 Reductions and a Faster Coal Exit in Germany

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Key Findings and Policy Recommendations

About 60 million tons more CO_2 emissions annually

Today, in 2021, Germany has still six nuclear reactors in operation, producing around 65 terawatt-hours of electricity each year. If the same amount was produced using coal, there would be about 60 million tons more CO_2 emissions annually.

Saving roughly 3 billion euros per year

With the current prices of ~50 €/ton of CO_2, these reactors save roughly 3 billion euros per year in the European Emissions Trading System, compared to burning coal.

Cancelling the nuclear phaseout would protect the environment

Nuclear is very low-carbon and uses significantly less land and mineral resources, and therefore usually has a smaller overall environmental impact than other low-carbon energy sources. Cancelling the nuclear phaseout would protect the environment.

Cancelling the nuclear phaseout would protect the people from harm

Nuclear is among our safest ways of making energy. Contrary to popular belief, fewer people die from nuclear than from other energy sources. Cancelling the nuclear phaseout would protect the people from harm.

Half a billion tons of additional CO_2 emissions that could have been avoided

Up till 2020, the premature closures of German nuclear reactors – had coal production been closed instead – has caused roughly half a billion tons of additional CO_2 emissions that we could have avoided.

Around one billion tons of CO_2 emissions can be avoided

If the remaining six reactors are kept operational, and fossil fuel capacity (coal, and once there is no more coal generation, natural gas) is closed instead, around one billion tons of CO_2 emissions can be avoided by 2045. This is roughly a quarter of Germany's remaining carbon budget on a Paris-compatible emissions reduction pathway.[1]

Save thousands of lives and avoid millions of hours of lost productivity

Shutting down coal instead of nuclear will save thousands of lives and avoid millions of hours of lost productivity and work in the coming years and decades due to less air pollution.

Save multiple billions of euros each year

Keeping the nuclear plants operational would save the German people multiple billions of euros each year. These savings would come from lower electricity costs, lower health care costs, higher standard of health, and higher productivity.

Avoid almost one billion tons more of CO_2 emission by 2050

Suppose Germany starts a new program to build advanced heat sources that can efficiently replace natural gas and produce clean hydrogen and PtX fuels. In that case, it can avoid almost one billion tons more of CO_2 emission by 2050, in addition to the reductions already planned in the Agora Energiewende Carbon Neutral Germany 2050 scenario.

It can offer low-cost yet valuable services for an energy system

Nuclear, both current and especially advanced reactors with thermal storage systems, fits well with wind and solar. It can offer low-cost yet valuable services for an energy system with a high penetration of variable renewable energy sources.

1 See https://tinyurl.com/yev2fzlt

Foreword by Mark Lynas

"To shut down viable nuclear capacity in the midst of a climate change emergency (now, in other words), as Germany and Japan have done, is a refined form of madness, especially when at least some of that capacity is likely to be replaced by gas or coal, whose carbon emissions are much higher."

So wrote George Monbiot, the famous British writer and environmentalist, back in 2016. Since that time, the climate emergency has only gotten worse. Death Valley-style temperatures scorch Canada, while whole towns are wiped out by wildfires. Meanwhile, in Death Valley itself, another all-time Earth high temperature record is set at a sizzling 54.4 °C. The Arctic Sea ice coverage plummets every summer to new lows, while rain falls on the North Pole in winter.

Is the world in emergency mode to tackle the climate crisis? Not really. Since George complained about the "refined form of madness" of giving up zero-carbon nuclear power in the midst of an escalating climate emergency, this madness grips minds across Europe as strongly as ever. In Belgium, Green Party ministers fight tooth and nail to close nuclear plants, knowing full well that these will be replaced by fossil fuels like gas. In Germany, Greenpeace participates in a consensus pact to keep coal on the grid until 2038 – a betrayal of future generations so blatant it was later declared such by the nation's Supreme Court.

What is it about nuclear that makes committed environmentalists lose their minds and become as much of a danger to the climate as Exxon-Mobil?

What is it about nuclear that makes committed environmentalists lose their minds and become as much of a danger to the climate as Exxon-Mobil? How did this madness arise and why has it become so dominant, in Germany more than anywhere? As this report demonstrates – and as the European Union's own scientific advisers recently declared – there is no scientific evidence that nuclear power is uniquely dangerous. Indeed the contrary is the case – in terms of lives lost nuclear is orders of magnitude safer than all fossil fuels, and has carbon emissions comparable to onshore wind and lower than solar PV.

The price of anti-nuclear psychosis (for that is what it is) will be paid by vulnerable countries and future generations who suffer the escalating damages of climate breakdown. This report puts numbers on this price to be paid for the first time – a nice round number of a billion tonnes. That is the opportunity cost of closing down remaining nuclear early in Germany while keeping coal alive for nearly two more decades, as the anti-nuclear lobby demands. Islands will drown, coral reefs will die – but the anti-nuclear lobby must be appeased.

Fortunately there are people – even in Germany – who want to take an evidence-based approach, and put the climate first. Across the Europe a more pragmatic, pro-science environmentalism is rising, one which puts the joint climate and biodiversity emergencies at the top of the priority list, and is not trapped by ideological mindsets fixed in the 1970s. As the Fridays for Future movement rightly says, "Listen to the science". Whatever the issue, from Covid to climate, science is our beacon. Let us listen to what it says.

Mark Lynas, July 2021
Author of Our Final Warning: Six Degrees of Climate Emergency

Fortunately there are people – even in Germany – who want to take an evidence-based approach, and put the climate first.

CO_2

CLIMATE CHANGE

AWAKENING THOUGHTS

CO_2

An Action Plan for the Climate Emergency

Climate emergency is not just a buzzword. There is widespread consensus that man-made climate change requires urgent and effective action to prevent the most catastrophic consequences. In its ruling in April 2021, the German Federal Constitutional Court ordered the government to implement much greater CO_2 reductions before 2030 than had previously been planned. From current annual emissions of around 800 million tons CO_2 per year, Germany's emissions need to decrease by 30 to 35 million tons each year to keep Germany within its carbon budget compatible with the Paris Agreement targets. The current German climate protection law meets these goals only part of the way.

A New Approach

This report was commissioned by the environmental organization Ökomoderne e.V. But behind it is a much larger group calling for a completely new way of thinking about climate protection in Germany. We are a group of activists, scientists, energy industry professionals and regular citizens from across the political spectrum and from all age-groups.

Our new way to think about climate policy is evidence and science based, and it includes the tabooed and already abandoned nuclear energy in the mix, alongside the expansion of renewable energy sources. This report was commissioned to reveal the effects and consequences that this kind of inclusive climate policy would have. It would lead to a faster coal exit and less dependency on imported fossil gas.

Both renewables and nuclear are powerful climate protection technologies.

CO₂

CLIMATE CHANGE

We Have Lost a Lot of Time

There are several reasons why our country has not followed this climate-pragmatist path so far.

1 First is the lack of political courage and power to challenge the Merkel government's abrupt exit from nuclear energy which resulted from the Fukushima accident in 2011. As long as Merkel remained in office, even politicians who would view this as a mistake didn't want to start a political battle to get it revised. With each passing day, changes become harder and harder, as policy creates new path dependencies, and Germany sinks deeper into the hole she has dug for herself. With the ruling of the Federal Constitutional Court this has turned into a flight forward with an over installation of renewable capacity. But it is questionable if climate goals can be achieved in this manner - and within the stipulated time.

2 The situation is made worse by old political lines of conflict from back in the heyday of the antinuclear movement. These were transferred over into the climate debate, which led to stonewalling even though we all have to be on the same side . Any discussion or campaign quickly becomes a "fossil parties vs the green-left" or "industry vs the planet". The truth is climate is too big of an issue to be left in the fringe. We need all parties on board, no matter if they are conservative, liberal, left or green, no matter if they are attached to industry or ecological groups.

3 Climate change is too big of an issue to be made into a question of personal consumption choices or lifestyle shaming. This only leads to social delineation, preventing collective action on common interests. We need enormous amounts of clean energy already today, and even more during the next decades.

4 The German Energiewende's history of putting renewable energy against nuclear energy is unhelpful, even harmful. Both renewables and nuclear are powerful climate protection technologies. But a policy of mutual exclusion has turned their supporters against each other. This ensures we will be burning coal and other fossil fuels much farther into the future than we would have to. We can no longer afford this antagonism.

AWAKENING THOUGHTS

CO₂

"Everything" Means Truly Everything

We take Fridays for Future's often quoted instruction to act, "Everything for the climate," seriously. But when we say "everything," we truly mean everything. We mean the decarbonization of an industrial society using all available technologies. We simply cannot afford to lose or discriminate against any of them. We need both renewables and nuclear energy in the next ten years and beyond to achieve our climate goals.

But our first and foremost concern is the urgent rescue of the remaining six German nuclear power plants from being shut down. The SaveGER6-memorandum in July 2020 called for the suspension of the nuclear phase-out and instead advocated for a rapid decommissioning of a similar amount of coal production. It was sent to members of the German Bundestag and its coverage in the DIE ZEIT led to a still ongoing debate about the usefulness of the nuclear exit.

This report dives deeper into the consequences, providing many compelling arguments for keeping the six reactors running and closing down coal production instead. In addition, we present other scenarios that could conceivably be envisioned with the inclusion of nuclear energy use.

With this report, we would also like to appeal to the German climate movement, environmental NGOs and the Greens to join us and put aside old misgivings about the use of nuclear energy in favor of sober consideration. The climate emergency is simply too serious. As Fridays for Future says, we need everything, and that includes a thorough reconsideration of using nuclear energy to lower our emissions much faster than without.

We Must Act Quickly

At the end of 2021, three of Germany's remaining six nuclear power plants will be irreversibly taken off the grid. If we shut down lignite-fired power plants instead, we could prevent the emission of up to 65 Mt/a of CO_2. That is up to thirty times more savings than a 120 km/h speed limit would achieve. If we shut down the nuclear plants, 12% of our electricity production is lost, similar to demolishing all German solar PV plants, or 15,000 of our wind turbines. Actually, it is even worse, as nuclear plants provide valuable reliability for the electricity grid. No matter how much more renewable energy we are building, it will take many years to make up for the loss in low-carbon energy production.

This report gives decision-makers the arguments they need to take swift steps after the Bundestag elections for a climate emergency ordinance with suspension of the German nuclear phase-out by amending §7 of the Atomic Energy Act.

Such a step would also be a significant signal for those who have so far been less worried about the need to decarbonize. It would show that this is a serious matter – serious enough that politicians and the climate movement are prepared to not just demand significant lifestyle changes from everybody, but that they are also prepared to change their own behavior and priorities regarding nuclear energy, to help mitigate climate change. "Everything for the climate" must finally be taken at its word.

August 2021,

Anna Veronika Wendland, PhD,
nuclear technology historian

Rainer Moormann, PhD,
expert on reactor safety

Authors of the 2020 memorandum
"Why we still need the German nuclear power plants"

We need both renewables and nuclear energy in the next ten years and beyond to achieve our climate goals.

No matter how much more renewable energy we are building, it will take many years to make up for the loss in low-carbon energy production.

CO₂

CLIMATE CHANGE

AWAKENING THOUGHTS

CO_2

A lot has been written on the German Energiewende, "energy turnaround," so there is no point in trying to repeat all of that here. But a brief overview of the critical issues and events is required to give context for this report. There are many interpretations of the original purpose and aims of the Energiewende, but the following four key pillars should be a reasonable approximation of what was the original plan:[2]

1. Shifting Germany from a fossil-based society into a low-carbon society by 2050, with 80-95 percent lower emissions than 1990 levels. This goal has since been updated to be a carbon-neutral Germany by 2045.
2. Shifting Germany to a renewable energy-based economy, with 80% renewables by 2050, and fossil energy only as a backup. Given that Germany needs to be carbon neutral by 2045 (see constitutional court ruling below), this target will be updated accordingly.
3. Close the current nuclear fleet prematurely by 2022.
4. Increase demand flexibility and energy efficiency.

The first one is a target, while the three others are more of additional specifications and constraints on how the target needs to be achieved: with only renewable energy while closing low-carbon nuclear plants and increasing energy efficiency and demand flexibility.

During the roughly 20 years that the Energiewende has been in "full swing", there have been some changes and additions. For example, a few years ago, Germany decided to close down all of its coal plants by 2038. The German government has also introduced a national CO_2 emissions pricing for transportation and heating fuels, as the European emissions trading system, ETS, only includes power, district heating, and heavy industry. The goal of 80-95% lower emissions by 2050 has been redefined as carbon neutral by 2050, and so forth.

As a result of a 2021 constitutional court ruling,[3] the 2050 target of Germany saw a tightening of the timeline and addition of intermediate targets:

2 These pillars were taken from a presentation "Energiewende in Perspective", given by Dr. Leonard Birnbaum from World Energy Council in Finland, 2014.
3 https://www.bundesverfassungsgericht.de/SharedDocs/Pressemitteilungen/DE/2021/bvg21-031.html

- By 2030, Germany needs to reach a 65% reduction in emissions from 1990 levels (compared to 55% previously in the Climate Protection Act).
- By 2040, Germany needs to reach 88% reduction in emissions.
- By 2045, Germany needs to be climate neutral. This means that if there are emissions somewhere in the economy, there needs to be carbon sinks of similar size, either natural or artificial carbon capture and storage.

This, and the recent increase in the carbon emission prices in the European ETS, going from 5 euros per ton just a couple of years ago and then to 50 euros per ton in the first half of 2021, will likely make the "coal exit by 2038" obsolete. Meanwhile, in 2021, the EU also agreed to tighten its emissions reduction targets from previous 40% by 2030 to 55% by 2030 (from 1990 levels), which was arguably one reason for the recent price hike in emissions credits in the ETS.

In 1990, Germany's total emissions were 1,248 Mtons of CO_2-equivalent per year. In 2020, emissions were 739 Mtons, a reduction of 509 Mtons (40.8%) from 1990, or about 17 Mtons (1.36%) per year. This was achieved partly thanks to an over 8% reduction due to the COVID pandemic. According to the new 2030 target of 437 Mtons per year, there needs to be a reduction of roughly 30 Mtons per year for the next decade, almost double the speed of the previous 30 years. This is a lot to ask for the following reasons: The reduction in the last 30 years includes a global pandemic (a 70 Mton decrease in one year) as well as the one-time effect of the closure of inefficient East-German industries and power plants in the early 1990s (an over 110 Mton reduction in 4 years). Together these events, which were one-time occurrences that we really cannot repeat, accounted for roughly a third of the reductions in the last 30 years.

According to Boston Consulting Group's recent calculations,[4] the new targets mean at least the following needs to happen:

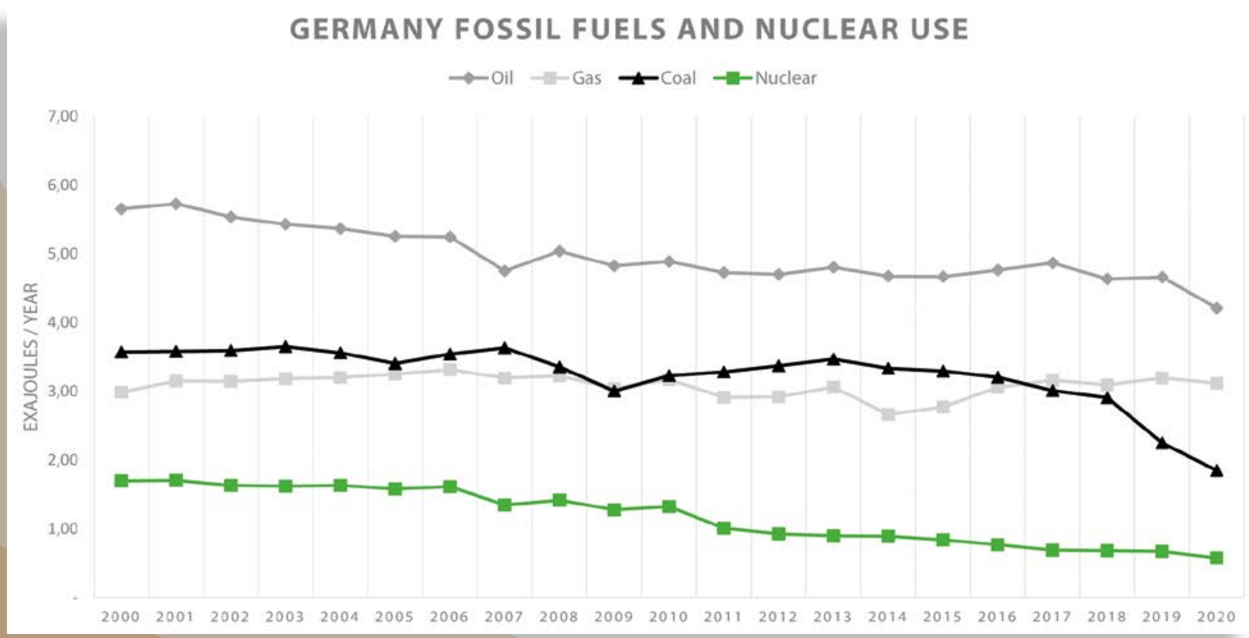
- Coal exit needs to happen sooner, perhaps by 2030.
- New buildings cannot have oil or gas heating installed after 2022.

4 See Handelsblatt: https://tinyurl.com/3xmvwdhd

- Existing buildings face massive energy efficiency investment needs.
- Registrations for new internal combustion engine cars need to stop by 2030.
- Wind and solar investments need to double.

So far, the results have not been great but can be described more as predictable. Germany has built a lot of wind, solar, and biomass-based energy production, which has been very expensive. Germany collects an EEG fee in electricity bills that is used to pay for the renewable energy feed-in-tariffs. This tariff has been around 24 billion euros per year or roughly 6.5 eurocents per kWh of electricity in consumer bills. If one divides that among all the renewable electricity (including wind, solar, bio, and hydro), the tariff is roughly 10 eurocents per kWh of renewable electricity. Indeed, one could have used that annual 24 billion euros to build three EPR (European Pressurized Reactor) reactors per year, assuming there would be no learning from the prototype. Expensive seems to be a relative concept.

Figure 1: Development of Germany's use of fossil fuels and nuclear. Source: BP Energy Statistics 2021.



Germany has closed nuclear power plants according to plan. In late 2010, Chancellor Angela Merkel did manage to postpone the closures from the original 2022 date, citing the need for emissions reductions as the main reason. A couple of months later, in the panic caused by the Fukushima accident, Germany closed eight of its older plants just three days after the tsunami and returned to the original closure plan for the remaining nine units.

And while coal has been on a slight decline, natural gas has been flat, or even increasing in electricity production. Certain types of gas turbines (called OCGT, of which Germany has roughly 20% of its gas turbines) are more flexible and can stabilize the electricity grid even with the higher fluctuations in wind and solar production. Oil, mainly used in transportation, has persistently remained at similar levels for a decade or more. Although fuel efficiency of new internal combustion engines has improved, there has been more driving and bigger cars.

Coal use has been declining sharply for the last couple of years. The main reasons are:

1. Warm weather in 2019-2020 winter, hence lower demand for heating.
2. Lower energy demand overall due to COVID hitting the economy in 2020.
3. The increase of CO_2 prices in the ETS market, which alters the order in which power plants are used.
4. The continued increase in renewable energy production.
5. Government mandates for premature coal plant closures.[5]

5 https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Kohleausstieg/kohleausstieg_node.html

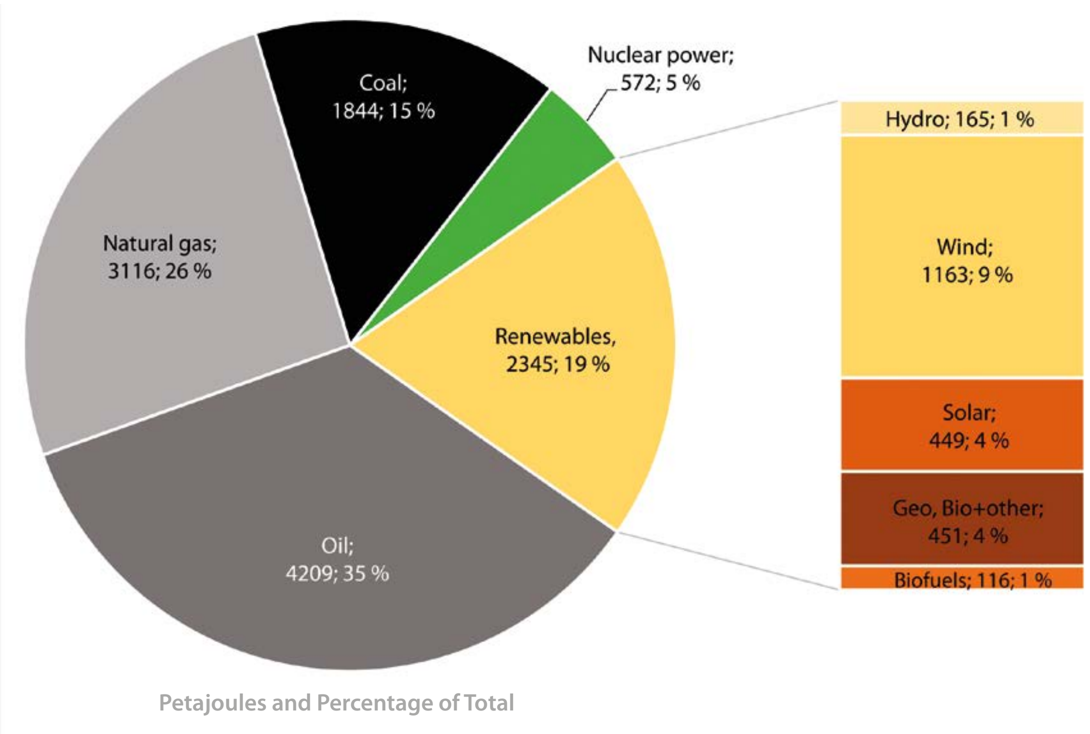
Coal use has been declining sharply for the last couple of years.

The snapshot in Figure 2 of the German energy use shows that there is a lot to do. After 20 years and hundreds of billions spent, renewable energy sources account for ~20% of total energy use. Including small scale wood burning and other uses not showing up in Figure 2 data, roughly half of it is from biomass, with a widely questioned sustainability.[6] Around 75 % of the overall energy mix is still fossil fuels.

Now, in another 20 years' time, Germany needs to increase that share some four or five times over while the job gets exponentially more challenging for several reasons. First, it becomes harder and more expensive to add more variable energy production (wind, solar) as their share increases (see Figure 3.) Secondly, countries have given up fossil fuels first in places where it has been the easiest and cheapest to do. It will tend to get progressively more demanding and more expensive in the future. Decarbonizing heating, industrial process heat, and transportation fuels will be much harder than

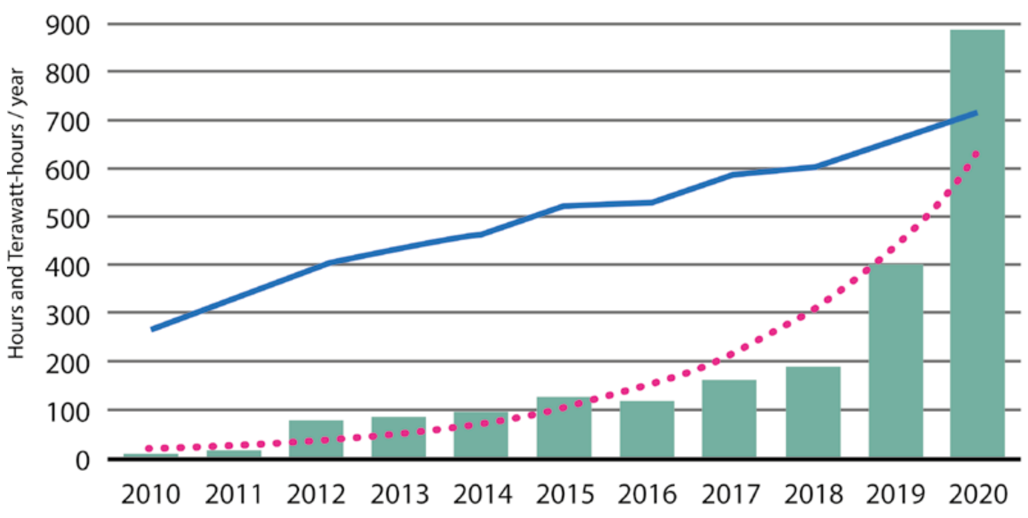
6 See https://ag-energiebilanzen.de/index.php?article_id=29&fileName=awt_2019_d.pdf

Figure 2: German primary energy mix in 2020



Introduction - Energiewende, Quo Vadis

Figure 3: The number of negatively priced hours in the European electricity market. Source: Platts Electricity Service and BP Energy Statistics 2021.



Blue line: Amount of renewable energy production in Europe
Green bar: Number of negatively priced hours in Europe per year
Red dotted line: Trend of negatively priced hours

electricity. Lastly, as Germany aims to close both nuclear and coal plants, it is likely to need to more than double its natural gas turbine capacity to ensure that peak demand can be met.

While the amount of renewable electricity in the European grid has grown linearly from 280 terawatt hours (TWh) per year to 710 TWh/year (blue line), the number of negatively priced hours in the electricity market has grown from almost zero in 2010 to nearly 900 in 2020 (green columns and the red dotted trendline). In 2020, the 50 TWh addition in renewable electricity was accompanied by more than double the amount of negative priced hours in Europe. Notably, the demand was impacted by the COVID-19 pandemic and warm winter weather decreasing the overall demand to a certain extent.

Lastly, as Germany aims to close both nuclear and coal plants, it is likely to need to more than double its natural gas turbine capacity to ensure that peak demand can be met.

Pricing Structure and Negative Prices

Negatively priced hours happen when there is too much production compared to demand. This tends to occur more frequently when the share of variable sources like wind and solar grow to a certain level in the total production.

As such, negative price hours are mainly a result of production subsidies such as feed-in-tariffs given for certain energy sources no matter what the energy demand and price at the market is. This makes investing in them worthwhile even at higher shares. If the grid's demand is 100 GW and there is 100 GW of wind power installed, that wind can meet all the demand when it's really windy. This tends to take the market prices for all electricity to zero. But because we also have less windy periods, this wind capacity will only end up producing some 30-40% of overall annual electricity demand, leaving the rest to be produced with something else[7]. If this "something else" does not get subsidies, it becomes less and less competitive due to the increased number of "worthless" hours. For example, due to the added electrification and closures of nuclear and coal in Germany, there is a growing need to install new natural gas turbines – some 100 GW by 2030 compared to the current capacity of 27 GW – to back up the increasing variability of the wind and solar production. These gas turbines will operate at very low capacity factors, making it infeasible to invest in them without some subsidies. This has led us to a situation where we are paying subsidies to install more of the fossil fuel infrastructure instead of getting rid of it.

Electrifying as much of the economy and activities as possible is one of the key strategies to achieving deep emissions reductions. However, this requires that electricity is cheap, preferably cheaper than the alternatives (fossil-based fuels), and not more expensive like in Germany. For the German consumer, electricity never gets cheap. Even if they buy electricity at the real-time spot market at zero cost, they would still pay a hefty sum for the kilowatt-hour in delivery, taxes, fees, and surcharges. So much so that even with an efficient heat pump, it would

7 This percentage is called capacity factor (CF) or load factor. For wind, it is often between 25 and 45%, depending on technology and location.

make more economic sense to heat with natural gas instead of electricity. High electricity costs make it harder and slower to electrify our society and decarbonize our energy use.

Germany faces a massive project in the next 10, 20, and 30 years, even without a nuclear phaseout. It is trying to do what has never been done before, basically with one hand tied behind its back[8]. While this might sound inspiring and uplifting, it is also needlessly adding risks and costs to a much more critical project than "taking a man to the moon and back safely within the decade" was, for example. It is likely that we get only one shot at this, and missing that shot can have civilization-threatening consequences[9]. Adding significant risk to this can only be seen as irresponsible.

Further, it has become clear that getting to net-zero emissions globally around mid-century is only the first step, if a big one. We already have too much CO_2 and other greenhouse gasses in the atmosphere and will need to find ways to reduce these concentrations to help stabilise our climate system. We need to get significant negative emissions, and this will likely use much more energy as we will need machines to capture carbon from the atmosphere, for example. In this report, we include all greenhouse gasses as CO_2-equivalents when we refer to CO_2 emissions.

This report discusses how Germany's Energiewende could be much more effective were nuclear included in the mix. The following section will discuss why nuclear energy is much better than its reputation in Germany would lead one to believe.

> We already have too much CO_2 and other greenhouse gasses in the atmosphere and will need to find ways to reduce these concentrations to help stabilise our climate system.

8 Given that another important technology, carbon capture and storage (CCS), is also largely left out in Germany, one could say that Germany has both hands tied behind its back.

9 See for example Mark Lynas' book "Our Final Warning: Six Degrees of Climate Emergency" (2020, HarperCollins)

A New Look at Nuclear

The analyses did not reveal any science-based evidence that nuclear energy does more harm to human health or to the environment than other electricity production technologies already included in the Taxonomy as activities supportin climate change mitigation.
– Joint Research Centre, 2021[10]

Nuclear has been proven safe and environmentally less harmful than most other energy sources time and time again. Yet, in Germany, it is considered common knowledge that nuclear is terrible and dangerous. It is a widespread belief in society. It is so widespread that questioning it rarely even comes to mind. And if questioning this does come to mind, the social pressure from everyone around makes sure that one rarely wants to speak about the topic publicly. There seems to be a big difference between what German people think and what they dare to say publicly because of what they think that others think. According to polls, most Germans would prefer to have nuclear instead of coal and would accept nuclear as a solution to mitigate climate change[11].

German media has also played its part, reinforcing and even leading fearmongering regarding nuclear[12]. And here, science and evidence have an uphill battle. There is little that a collection of statistical data and a library of scientific studies can do in the face of people's feelings, traditions, and long-held opinions.

Yet we must try. The stakes are too high. The German Energiewende, long a source of national pride and a public showcase of climate and environmental progressiveness, has severe problems in its foundations and priorities. It has been partly built on popular belief and prejudice instead of solid science and evidence. Nuclear has been put as the enemy number one and shutting it down as the priority number one.

10 https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/210329-jrc-report-nuclear-energy-assessment_en.pdf
11 https://nuklearia.de/2021/06/16/umfragen-mehrheit-der-deutschen-will-kernkraft-fuer-den-klimaschutz-2/
12 See for example Kepplinger 2015, https://www.tandfonline.com/doi/abs/10.1080/10584609.2015.1022240

Indeed, closing nuclear is the only one of Energiewende's goals that is succeeding. But succeeding in shutting down nuclear will come at the cost of failing what we know as the most crucial goal of the Energiewende: mitigating climate change by moving German society to net-zero emissions as fast as possible.

This chapter discusses why nuclear should not be seen as the enemy but as a valuable tool in achieving the important goal of reducing fossil fuel emissions. Much of what you have heard about nuclear is untrue, misleading, or lacks essential context and comparison. The prior quote from JRC is telling: Nuclear is as sustainable, safe, and environmentally benign as anything else we have labeled sustainable. In many cases, it is even more so.

The prior quote from JRC is telling: Nuclear is as sustainable, safe, and environmentally benign as anything else we have labeled sustainable. In many cases, it is even more so.

Nuclear, Climate and the Sustainable Development Goals

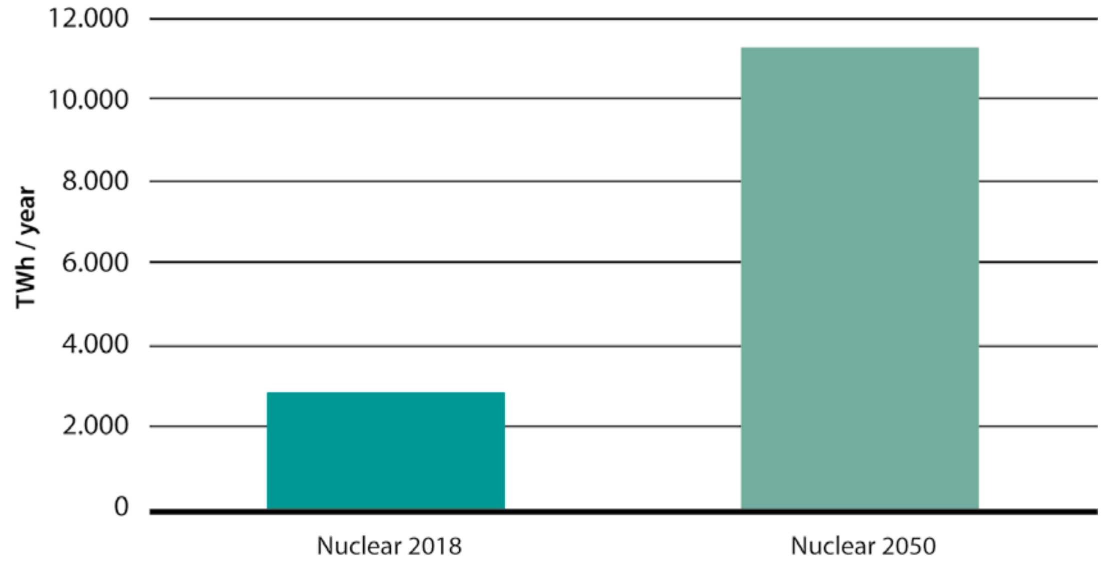
"Nuclear energy is an 'indispensable tool' for achieving the sustainable development goals (SDGs). It has a crucial role in providing affordable energy and climate change mitigation, as well as eliminating poverty, achieving zero hunger, providing clean water, economic growth, and industry innovation." – Expert Group on Resource Management of the United Nations Economic Commission for Europe (2021)

A recent report published by United Nations Economic Commission for Europe (UNECE) discusses how nuclear technology contributes to the 17 Sustainable Development Goals (SDGs) defined by the United Nations.[13] The report found that nuclear contributes at least somehow towards every single one of them, and for many, the contribution is substantial. Nuclear is a valuable tool for us to move towards greater sustainability and human wellbeing.

It is no wonder then that the Intergovernmental Panel on Climate Change (IPCC) had nuclear playing a significant role in its four main scenarios of the 2018 Special Report on Global Warming of 1.5°C.[14] As seen in Figure 4, the four main scenarios saw nuclear grow by more than four-fold by 2050 from 2018 levels, on average. These scenarios include assumptions of heroic increases in efficiency, solar deployment, wind additions, and even bioenergy expansion that does not seem sustainable from a biodiversity perspective. Carbon capture and storage also play a significant role in most of these scenarios, although it is still somewhat unproven as a scalable technology. Some of the scenarios even have energy usage drop significantly, even as the population will grow to 9 or 10 billion and developing countries will expand their economies along with their energy use – as they have been doing historically. This is a risky assumption, therefore we might face a situation where even more clean energy is needed.

13 See UNECE 2021, https://unece.org/sustainable-energy/publications/nuclear-entry-pathways
14 See https://www.ipcc.ch/sr15/

Figure 4: Nuclear generation in 2018 vs. 2050 (2050 is IPCC 2018 average of four main scenarios from the Summary for Policymakers). Nuclear 2018 data is from BP2020.



Source: IPCC (2018)

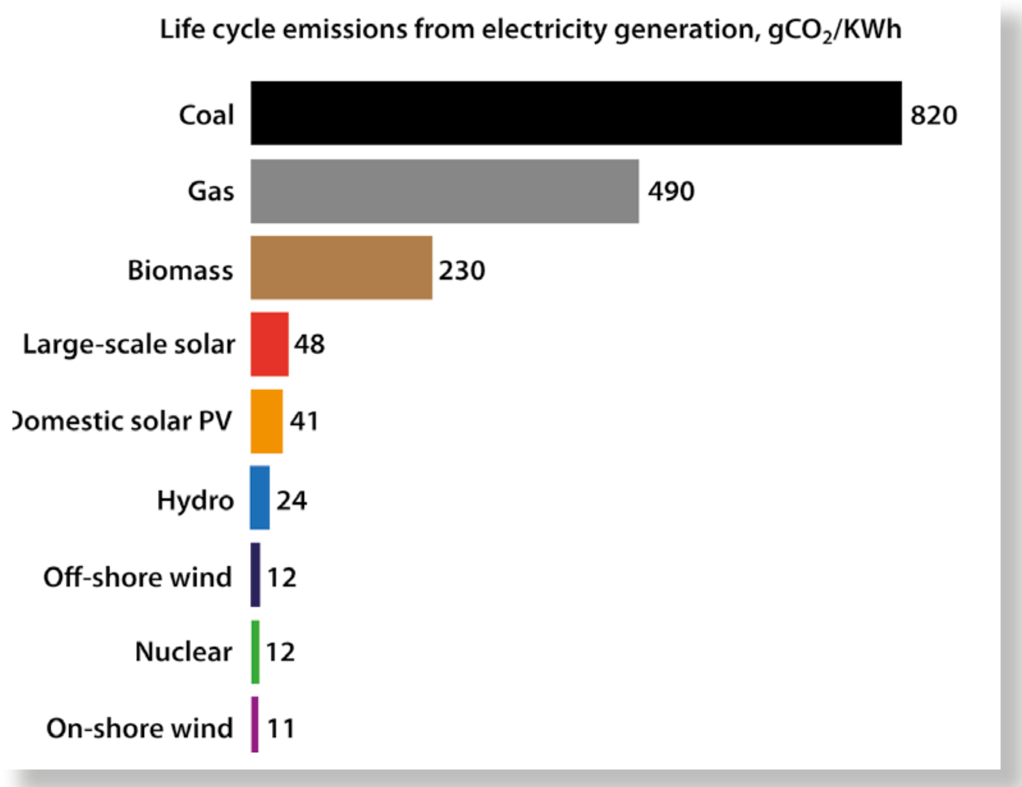
Nuclear Is Low Carbon

For a point that is as obvious as it is – an energy source that produces energy without burning any chemical fuels and is therefore considered low carbon – there is a lot of misinformation. Nuclear has one of the lowest emissions out of the energy sources that we have, even accounting for all the activities – construction, mining, transportation, enriching, decommissioning, waste management, and so forth. It is the lowest emissions pathway to provide society with reliable energy services. Other low carbon options are either not scalable (such as hydro and biomass) or need large amounts of support and back-up to offer an on-demand, reliable energy service (for example wind and solar). It is also important to consider the impacts of different energy production methods throughout their whole lifetime. The life-cycle climate impact of energy sources is often measured as grams of carbon dioxide per kilowatt-hour of electricity produced – or gCO_2/kWh. As seen on Figure 5 below, nuclear has a very low life-cycle carbon footprint.

Figure 5 is based on a meta-study (a review of the relevant scientific literature), so it gives a good approximation. The IPCC report came out in 2014, so the data in the studies it reviewed is even older than that, so the numbers have likely improved with technological advances we have seen in the last ten years. On the other hand, these are lifecycle emissions just for producing the energy, not for providing a reliable energy service, which is what we need. The variable production of wind and solar needs to be handled somehow, and the default choice for that is either hydroelectricity, if that is available, or natural gas. Currently, all the other options are still limited in scale or are expensive. An electricity grid with one third solar, one third wind, and one third natural gas would have, according to IPCC numbers above, emissions of roughly 180 gCO_2/kWh, which is at least four times too high to be considered low carbon.

Some studies have found higher numbers for nuclear as well, but they often rely on old and unreliable data and even biased assumptions. For example, all uranium enrichment today is done with centrifuge technology

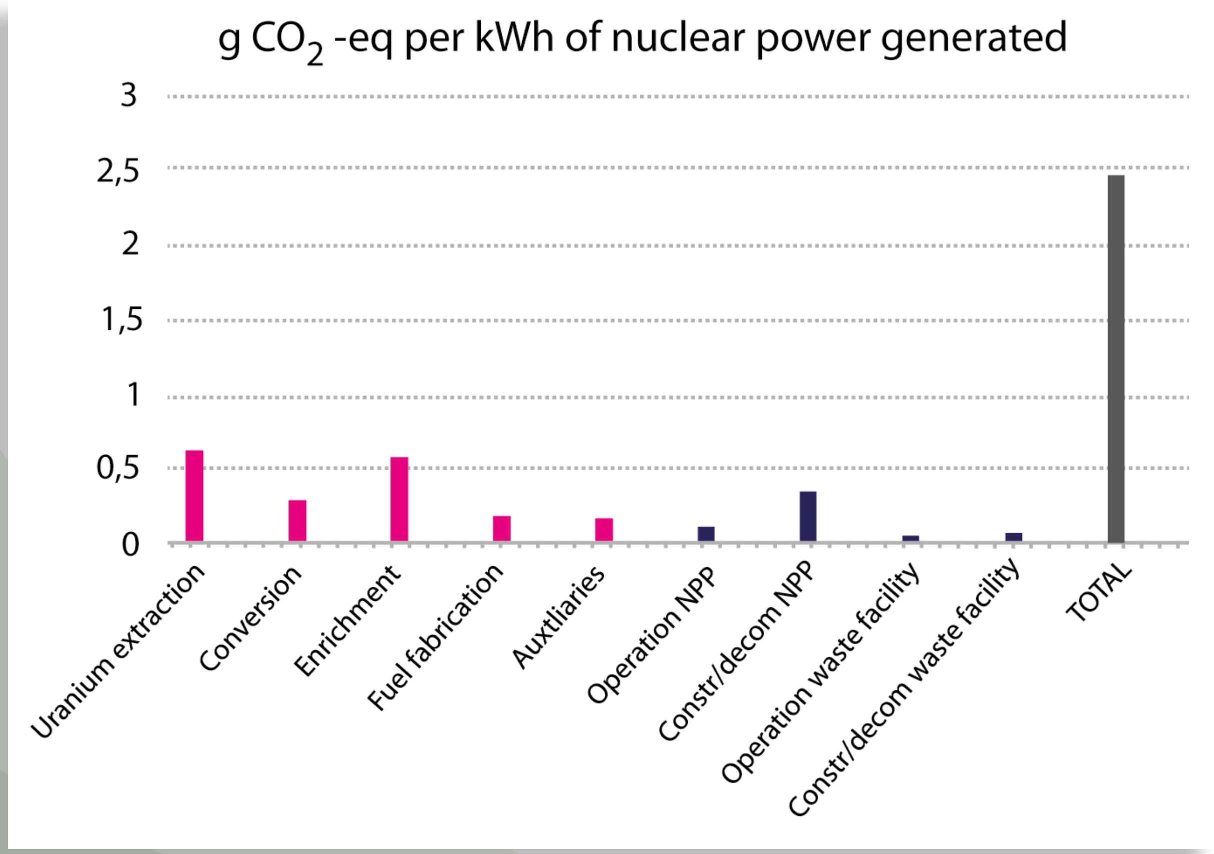
Figure 5: Median lifecycle emissions for electricity production according to IPCC 2014.



that is 50 times more energy-efficient than gaseous diffusion. Yet many of these studies that find higher numbers for nuclear assume that we use gaseous diffusion for enrichment. The most recent ISO-certified environmental assessment has Vattenfall's existing nuclear fleet at 2.5 gCO_2/kWh.[15] See Figure 6 below for how different steps share these emissions in the lifecycle. Nuclear energy is, quite conclusively, one of the lowest carbon energy sources we have.

15 https://www.environdec.com/library/epd923

Figure 6: Lifecycle emissions of the Vattenfall nuclear fleet, distributed by activity.



Nuclear Has a Low Environmental Footprint

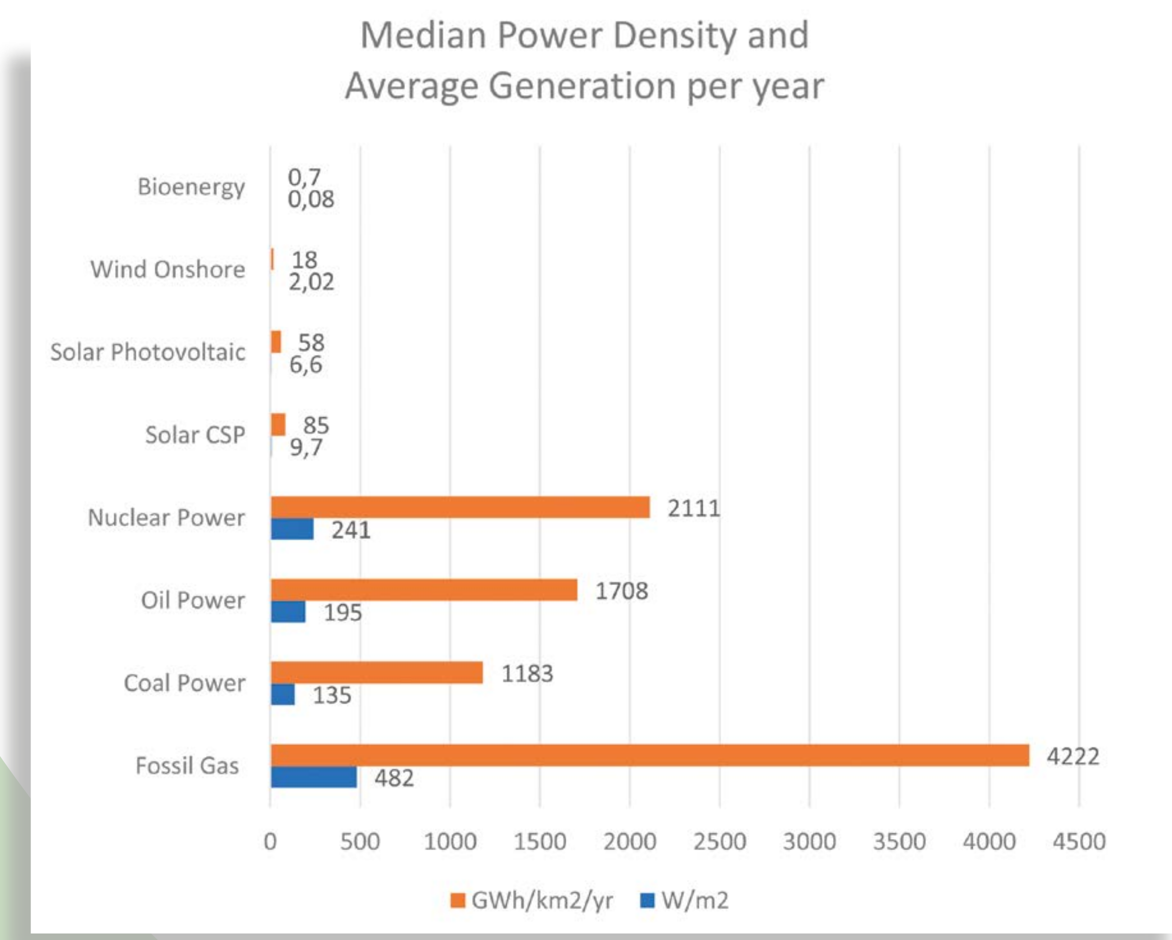
A nuclear power plant produces two valuable things: reliable power at any given moment that helps keep the power grid stable and a large amount of clean electricity over time. A single large reactor can produce over ten terawatt-hours of electricity per year – enough to supply millions of households,[16] and there can be multiple reactors at a single power plant. Even with a restricted zone around it, a 5 km² nuclear facility can have up to 10 gigawatts (GW) of power capacity, translating to 80 TWh of clean electricity produced over a year. This means that nuclear power plants can have a very high power density.

To help picture that, Germany uses roughly 600 TWh of electricity per year. Theoretically, this could be produced from a dozen large, multi-reactor power plants with a total area of some 60 km². Much of this land can (and does) act as a natural reserve, protecting species and adding to local biodiversity, given that human activities are limited inside the facility perimeters, and the buildings and roads take only a small portion of the total area. Similar is true with onshore wind; the park takes up a lot more of the total area than the turbines, powerlines, and access roads do. Nuclear sites usually have 2–4 reactors in the real world, so the median power density is lower than the theoretical maximum mentioned above.

According to a recent meta-analysis on power densities of different energy sources, nuclear power has the second-highest median power density of 241 W/m².[17] Renewables (including onshore wind, solar photovoltaic, solar CSP, and biomass) have a median power density of 0.23 W/m², three orders of magnitude lower than nuclear power has. Biomass has the lowest power density at 0.08 W/m² due to the low efficiency of photosynthesis. Solar PV and solar CSP have the highest median power densities of renewables at 6.6 W/m² and 9.7 W/m². Onshore wind is at 2 W/m². See average electricity generation by source in Figure 7.

16 This depends on assumed annual consumption of a "household", which can vary a lot.
17 Zalk et al 2018, https://doi.org/doi:10.1016/j.enpol.2018.08.023

Figure 7: Median power densities and average energy generation for various energy sources according to Zalk et al. 2018.



Wind Power: As a real-world example of offshore wind, we can look at the largest offshore project in the works, the Dogger Bank wind farm in the North Sea.[18] Dogger Bank has a planned capacity of 3.6 GW and an area spreading 1,674 km². Assuming an average annual capacity factor of 48% for the wind turbines, the whole Dogger Bank will produce a hair above 15 TWh per year. Copying a project like Dogger Bank repeatedly to supply Germany's demand of 600 TWh would require 40 such projects, taking an area of roughly 67,000 km². This gives Dogger Bank an energy production of approximately 9 GWh/km²/year, half of what onshore wind has in Figure 7.

Solar Power: Solar takes less space than wind but reserves that space all for itself. In places like rooftops and walls, this does not matter as there is no other use for the area, but rooftop solar is much more expensive than large-scale ground installations. On the other hand, bulldozing nature and covering it with solar panels is destructive for the local ecosystem. With the annual average production of 58 GWh/km²/year, it would take over 10,000 km² of solar panels to produce Germany's electricity demand of 600 TWh/year. For 83 million Germans, that means some 124 m² of solar panels each.

Bioenergy: With bioenergy, it would take roughly 850,000 km² to produce German electricity demand. German forest cover is around 114,000 km², so it would take almost eight times that area to supply German electricity consumption of 600 TWh or roughly 2.5 times German total land area.

To summarise, a mix of renewable energy can take roughly 100 times more space than nuclear power plants. This matters, as both people and nature get disturbed by our energy infrastructure, and the more land it takes, the greater the disturbance. Rooftop solar is a great idea, and so is harnessing the wind in areas where people and nature are not severely disturbed. But these areas are limited, and decarbonizing the whole energy mix, producing heat, hydrogen, and synthetic fuels at massive scales would mean the current wind and solar would need to cover areas an order of magnitude larger than today. Having a reliable backbone with nuclear power to supply some of the energy, this land use would be much smaller, which means fewer people and ecosystems are disturbed.

18 https://doggerbank.com/

Nuclear Is Our Most Reliable Energy Sources

Operating a nuclear reactor is highly regulated, and nuclear companies have every incentive to keep the plants in good shape and running as much of the time as possible, as any unnecessary downtime will mean financial losses. This is why nuclear power plants often run more than 90% of the time at full power. And even out of that 10%, by far the most significant share are periods of planned maintenance and refueling, which are usually done once per year, at times of low energy demand.

Reliability is extremely valuable for our society. Our high productivity and standard of living depend on the availability of energy services (power, heat, transportation, and other fuels) on demand. It is also something modern people take for granted because fossil fuels have provided us with reliable modern energy services for generations.

Wind and solar power are weather-dependent, which means that they are not "on-demand" in a similar way that most other energy sources are. Naturally, one can "create" reliability by adding extra capacity, demand flexibility, energy storage, and such, but this comes at an escalating cost – both financial, environmental, and material. The costs of creating a reliable energy system are called system costs. They depend on local circumstances and infrastructure, technology, neighboring countries and their circumstances, and so forth.

Reliable energy is extremely valuable for our society.

Nuclear Is One of Our Safest Energy Source

Given how much coverage the German media has given to the risks and dangers of nuclear power, one naturally finds it hard to believe that it is among our safest ways to generate energy. Indeed, even when nuclear goes horribly wrong, it doesn't cause nearly as many public health hazards as we assume. This can be observed from the accident in Fukushima. The Fukushima accident happened in horrible conditions, with much of the infrastructure, roads, buildings destroyed by the tsunami that was caused by the earthquake. This meant that all emergency work was extremely challenging. Mainly for this reason, Fukushima Daiichi nuclear power station had three reactors suffer the most severe type of accident that a light-water nuclear reactor can have: a core meltdown, where the uranium fuel gets so hot it melts and releases some of the radioactive materials within it into the environment.

This triple meltdown, combined with the wrecked infrastructure and the whole country of Japan in chaos, resulted in approximately zero deaths from radioactivity. Indeed, the most significant health hazards were caused by the fear of radioactivity, which caused hasty (and largely unnecessary) evacuations of hospitals and such in the area. Staying inside, closing doors and windows, and taking iodine pills would have been preferable for public health.

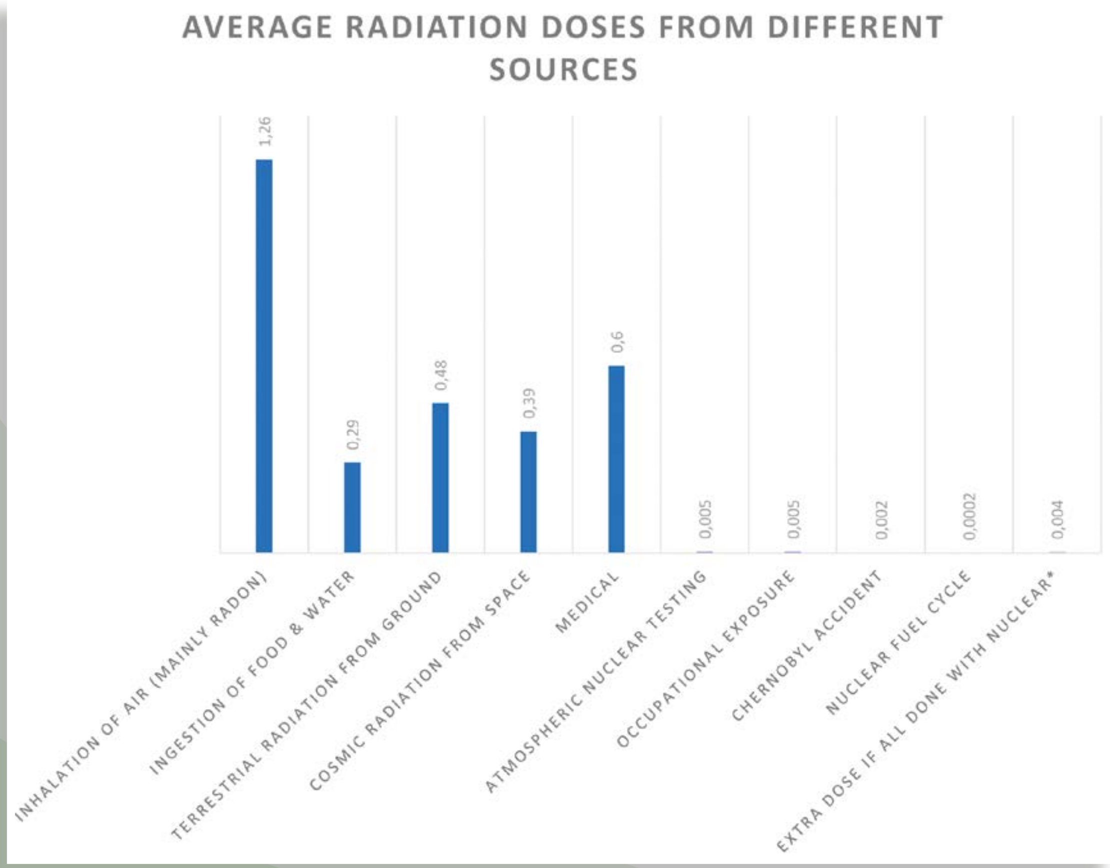
The most dangerous thing about nuclear and radioactivity might be our fear of it. It leads to nuclear being closed prematurely or not built in the first place, which means something else is built instead – often fossil fuels. These fossil fuels are several orders of magnitude more deadly and dangerous than modern nuclear power.

But what about Chernobyl? That accident did result in deaths due to radiation. Some 60 of those have been confirmed, and around 4,000 potential fatalities have been statistically modeled as possible.[19] But Chernobyl has nothing to do with modern, Western nuclear. Chernobyl's RBMK reactor design was never built in the West due

19 See United Nations Scientific Committee on the Effects of Atomic Radiation website for more up-to-date scientific information on Chernobyl: https://www.unscear.org/unscear/en/chernobyl.html

to the inherent safety issues in the design. These issues, combined with human error and poor safety culture in the Soviet Union, led to both the accident becoming a possibility and to the relatively large release of radioactive material the accident resulted in. Yet, even the health effects of Chernobyl will be so small that they will be impossible to see from the background noise of health statistics. Smoking, eating red meat, alcohol, burning coal for energy, and many other everyday things have orders of magnitude larger effects on our health than even the most catastrophic nuclear accident of our history.

Figure 8: The amount of radiation we get from the whole nuclear fuel cycle fits in a rounding error. The "fuel cycle" here includes all the activities involved, from mining to enriching, using, and storing fresh fuel and spent fuel. (*) *Assumes our electricity would all be done with French nuclear reactors for the next 80 years. Rabl A, J. V. Spadaro, M. Holland. 2014. How Much is Clean Air Worth: Calculating the Benefits of Pollution Control. Cambridge University Press. ISBN 978-1-10-704313-8*



Nuclear Waste and Radiation Are Not a Public Health Problem

Nuclear waste management is often pointed out as an "unsolved problem." The image most people have of nuclear waste is as vague as it is terrifying. The internet is full of scary pictures, but most of us do not know what spent fuel (highly radioactive nuclear waste) is, and even fewer of us have actually seen it, even in pictures. This lack of information has been filled in with terrifying images, misinformation, mistrust, and even conspiracy theories.

Yet civilian nuclear waste, during its 60+ years of existence, has never hurt practically anyone. There are many thorough studies on the amount of radiation that we get from nuclear power and related activities and the health effects of ionizing radiation overall.[20] Compared to all the worry and scaremongering, the truth is rather underwhelming. Or perhaps one could say it is inspiring.

Figure 8 shows the doses of radioactivity we humans get from different sources on average. Even the total average dose of roughly three millisieverts (mSv) is far from being harmful to one's health. Local variation in background radiation can be ten or even 100 times depending on where one is, and even then, there is not much statistical evidence of significant health effects. Everyday choices such as eating bacon or other red meat, smoking, or drinking alcohol pose a far gareater risk on one's health and increase the likelihood of getting cancer during one's lifetime. Indeed, in spas with "natural hot springs" that many people visit for health purposes the workers are exposed to a mean dose of 0.6 mSv, according to a 2021 study.[21] That is 3,000 times the dose people get from the whole nuclear fuel cycle on average.[22] To give us context, at annual doses below 100 mSv it is very hard to find any statistical effects on people's health, so

20 See for example United Nation Scientific Committee on the Effects of Atomic Radiation (2008), https://www.unscear.org/unscear/en/publications/2008_1.html and National Council on Radiation Protection and Measurements https://ncrponline.org/publications/reports/ncrp-report-160-2/ (with an overview at the US Environmental Protection Agency website here: https://www.epa.gov/radiation/radiation-sources-and-doses)

21 Nugraha, E.D., et al, Radon Activity Concentrations in Natural Hot Spring Water: Dose Assessment and Health Perspective. Int. J. Environ. Res. Public Health 2021, 18, 920. https://doi.org/10.3390/ijerph18030920

22 Dose and millisievert (mSv), are used to describe the estimated health effect of ionizing radiation.

visiting natural hot springs for relaxation and recreation is perfectly ok.

The final repository now under construction in Finland has been thoroughly studied and analyzed. The results show that it has a safety margin of at least 1:1,000,000. That is if the absolute worst case occurs such that both the copper and the bentonite clay surrounding a waste canister mysteriously disappears after just 1,000 years and a person lives her whole life on the most contaminated square meter, drinking only the groundwater from this spot, and eating only food grown there (never mind that this is not possible), what would the maximum dose for this person be?[23] It is 0.00018 mSv, roughly equivalent to eating a couple of bananas or sleeping next to another person – as both are activities we get radioactivity from.

It is abundantly clear that we have good solutions for dealing with spent nuclear fuel in the long term. The "unsolvable problem" has mainly been due to two reasons. First, we have not needed a final repository facility to be operational yet as the spent fuel is still cooling off. Second, our politicians have failed to make a decision and allow a repository to be built. The Finnish example offers some lessons on how to do it, given that in the process, two municipalities ended up competing to get the repository.

How can our image of nuclear waste be so different from reality? That is a good question, and answers can be different depending on the country and person in question. During the years and decades, societies have slowly built a common story on nuclear energy and waste. The Cold War information and propaganda campaigns caused a strong mental association between nuclear technologies and violence, even if the modern nuclear energy facilities can actually dismantle nuclear armaments and make energy from them. The "Megatons to Megawatts" program helped dismantle some 20,000 nuclear warheads' worth of weapons material and made clean, low carbon energy from it.[24] Nuclear power plants are among the best ways to get rid of nuclear weapons material and make something useful from them.

23 The text refers to scenario PD-BC on page 137 in the report: Hjerpe, T., Ikonen, A. T. K., Broed, R. (2010). Biosphere Assessment Report 2009. Posiva 2010-03, ISBN: 978-951-652-174-2. Another, more recent paper with even smaller doses predicted is Posiva (2013), Safety Case for the Disposal of Spent Nuclear Fuel at Olkiluoto–Biosphere Assessment 2012. Posiva 2012-10, ISBN: 978-951-652-191-9.

24 See https://www.centrusenergy.com/who-we-are/history/megatons-to-megawatts/

Nuclear Is Low Cost

Existing nuclear reactors that have amortized their capital investments are an extremely low-cost way of producing clean and reliable electricity. The cost includes operations, maintenance, fuel, and decommissioning/waste fund. It comes in around 20 euros per megawatt-hour – while simultaneously offering lots of well-paying union jobs for the local community. For comparison, the German household pays roughly 300 euros per megawatt hour for their electricity, although that includes many transmission fees, surcharges, and taxes. From an economic perspective, shutting down existing, well-running nuclear power plants is madness. From a climate perspective, it is downright criminal.

Nuclear power plants are built in a way that pretty much all the parts can be exchanged for new ones as they wear down. This means that water-cooled nuclear reactors built in the 1970s to 1980s can usually be maintained and safely operated for 60 or even 80 years. Some have already been licensed for that. Even longer might be possible, but we will only find out when we get there. According to a recent study by IEA, this Long-Term-Operation (LTO) of nuclear reactors is the lowest cost way to "add" low-carbon energy production. The report recommends that countries and utilities seek to maximize their safe usage.[25]

Even newbuild nuclear is usually not that high cost, although, in Western Europe and North America, the costs of recent projects have skyrocketed, and schedules missed. Current prices of nuclear power capacity vary from the European cost level of $5,500/kW to the Chinese cost level of $3,500/kW. The extensive study done on the cost drivers of nuclear projects found out what the main reasons for the price differences are as follows:[26]

- Building first-of-a-kind or first-in-a-gene-ration power plants. Europe stopped building nuclear power plants in the 1990s, so it is sno wonder that rebuilding the expertise, validating

25 See https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system
26 https://es.catapult.org.uk/reports/nuclear-cost-drivers/

the supply chains, and getting into the routine takes time and money.

- Starting with unfinished designs. The French EPR was only halfway designed when construction began in Finland and France. This led to a lot of rework and expensive back-and-forth with the design team, construction crew, and the regulator. The US AP1000 was less than half-designed when construction started.
- Building multiple reactors of the same type at a single site in succession instead of single reactors at a site as one-off projects.

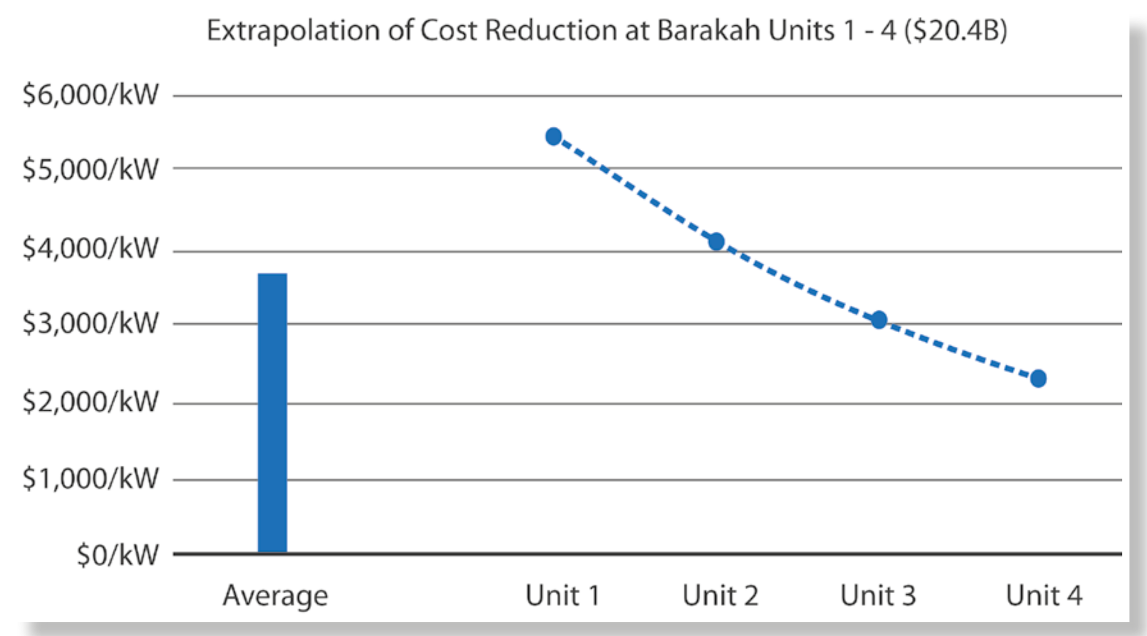
Meanwhile, the Barakah nuclear power plant project in the United Arab Emirates used a finished design that had already been built multiple times. It had experienced project management and work-crew for the four reactors that were built at single-site in succession. The average cost for the reactors ended up much lower than the cost of the first of the four reactors.[27]

In Figure 9, we see that the cost between the first, second, third, and fourth reactors got progressively lower, with the fourth one having less than half the capital cost of the first reactor.

The surest way to make nuclear, or pretty much anything really, expensive is to only do it once in a generation, starting and then stopping, building, and then dismantling all the expertise and networks along the way every time. The best way to bring the cost down is to lock in a design and then build many of these reactors, learning by repeating.

27 Also see Lovering et al, 2016, Historical construction costs of global nuclear power reactors, Energy Policy, https://doi.org/10.1016/j.enpol.2016.01.011

Figure 9: The cost reductions from one reactor to the next were significant at the UAE's Barakah nuclear power plant project.



The best way to bring the cost down is to lock in a design and then build many of these reactors, learning by repeating.

Nuclear Is Fast to Deploy

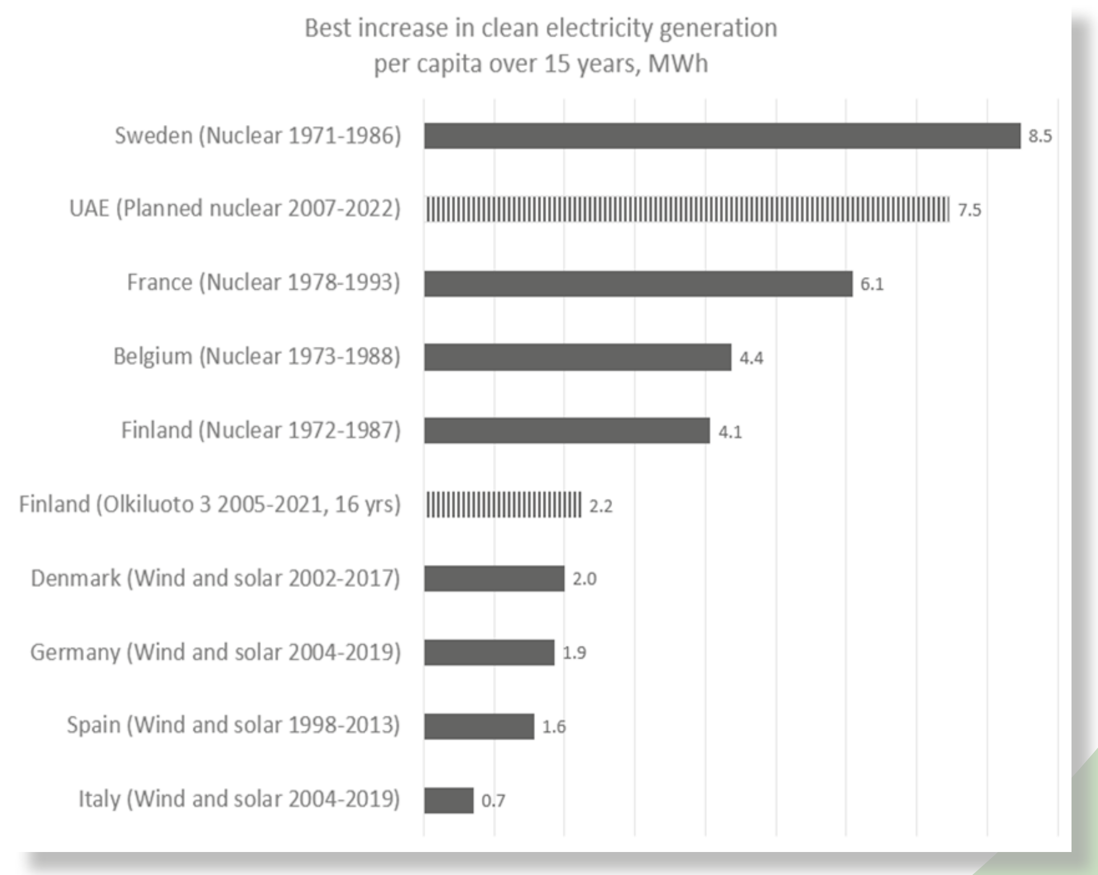
Nuclear power plants can take a long time to build, but the reason for that is mainly their size. They are big. It takes time to build big things, especially given the tight regulation that nuclear construction has. In the West, the delays of the handful of new projects (Flamanville, Olkiluoto, Vogtle) have other reasons as well, discussed in the chapter above. The average global construction time of new nuclear plants is around seven years.[28] The fastest ever built large nuclear reactor is Japan's Kashiwazaki-Kariwa reactor-unit 6, a 1315 MW advanced boiling water reactor which took just over three years from first concrete to first criticality.

But even the failed nuclear projects are not particularly slow. As seen in the graph below, even Olkiluoto 3 as a single project, which took 16 years from start to finish, has been faster on a per capita basis than wind and solar combined in any nation in a similar time. So while it can take many years to build a nuclear reactor from start to finish, the payoff is enormous and well worth the wait.

Of course, we should also build wind and solar. Those technologies have been gathering speed as they have matured, so their installation speeds are getting better and costs lower. But claiming nuclear power is somehow "too slow" means that wind and solar are even slower. They are faster to set up, but if a single facility is perhaps a thousand times smaller than a large nuclear reactor, thousand times more facilities need to be built to get the same energy output. Indeed, nothing is stopping us from building multiple nuclear reactors at the same time as well.

28 https://www.statista.com/statistics/712841/median-construction-time-for-reactors-since-1981/

Figure 10: The fastest ways of adding low carbon electricity production have been done with nuclear power programs. Hydro is excluded as it cannot be significantly expanded from current levels in OECD countries. Energy data: BP 2021.



The Future of Nuclear is Full of Opportunities

The nuclear industry today is developing rapidly. New types and sizes of reactors are developed by dozens of start-ups and large state-owned nuclear corporations worldwide. These new designs offer many exciting properties, such as producing high-temperature steam for industrial process use (now done almost 100% by fuel combustion) or operating at atmospheric pressures, making heavy and expensive pressure vessels unnecessary. There are designs based on helium gas, molten salt, or liquid metal as the coolant or fuel. Some of these can have sizeable high-temperature energy storage for added flexibility. Some designs even use our current "spent fuel" (which has roughly 95% of the usable nuclear energy still in it) to make much more energy, destroying many of the long-lived radioactive elements in the process.

Some reactors are "micro-size," offering remote off-grid communities such as mining towns or islands a lower-cost, cleaner, and more reliable energy source than the diesel generators used today. Some can make low-cost and low-carbon synthetic fuels for uses like aviation, long-haul trucking, and marine transportation. Some are designed to safely and automatically operate themselves, not even requiring human operators.

But nuclear technology is not just about energy. Nuclear medicine has saved millions of people by diagnosing and treating diseases and continues to do so every day. Industrial facilities routinely use radioactive materials to detect micro-fractures in pipelines and containers before they become an issue. These uses are possible because radioactivity is extremely easy to detect with simple equipment. This also makes it easy to detect any problems at nuclear power plants long before they escalate into real issues, which plays a big part in nuclear safety. We also have reactor designs for space use, and there are concepts even for nuclear rocketry suitable for eventual inter-planetary travel. The use-cases and opportunities for peaceful uses of nuclear are tremendous, and they are expanding further by the day.

German people need to ask themselves do they really want to forego all the benefits that nuclear technology offers modern society just because many are unaware of the facts regarding nuclear. Nuclear technology around the world is developing at great speed and can be used to solve many of our current and future problems. It can work together with clean, renewable energy sources, offering us a future of clean, safe, and reliable energy at a lower cost. There are dozens of newcomer countries planning or already building their first reactors, and only a handful of countries are planning to shut down their nuclear industry. Some of them, such as The Netherlands and Sweden, have even been reversing that position in recent years as the math on climate mitigation has become more apparent. So, much of the rest of the world is going nuclear, with or without Germany. Does Germany really want to exclude itself from the international nuclear community in the future?

Nuclear technology around the world is developing at great speed and can be used to solve many of our current and future problems. It can work together with clean, renewable energy sources, offering us a future of clean, safe, and reliable energy at a lower cost.

Scenarios

This part of the report describes and discusses the scenarios and findings. We use Agora Energiewende's (AEW) Carbon Neutral Germany 2050 scenario as the baseline. It aims to get a truly carbon-neutral society in Germany by 2050. We note that a more recent scenario, Carbon Neutral Germany 2045, has come out. At the time of preparing this report, the detailed data was not yet available. Our main scenario keeps the current six reactors operational and assumes they replace fossil coal and fossil gas. This assumption and most emissions reductions hold even when compared to the AEW 2045 scenario, because that still assumes nuclear is closed. Our scenario gets lower emissions, lower cost and lower risk of failure than the Carbon Neutral Germany 2045 scenario from Agora Energiewende.

Scenario Introductions

First, we will discuss the main scenario of keeping the current fleet of 6 large reactors operational and closing similar amounts of fossil coal and gas instead. What would be the effect on annual and cumulative emissions? How much faster could Germany close its coal plants, and how much faster could Germany reduce its dependency on (Russian) natural gas?

Then we take another step into decreasing emissions faster and more efficiently by building a new fleet of advanced reactors starting in the early 2030s. These flexible "advanced heat sources" will be used to replace remaining fossil fuels, ensuring that there is enough clean energy available and preventing Germany from becoming reliant on significant imports of clean hydrogen and synthetic fuels from its neighbors. They will have their own hands full and might want to import clean energy and hydrogen from their neighbors as well.

Lastly, we include an "Energy Abundance Instead of Scarcity" -scenario, given that the radical decrease in energy demand presented in the AEW Carbon Neutral Germany 2050 -base-scenario is a risky proposition as nothing similar has been seen anywhere throughout history. Instead of dropping by half as it does in the AEW scenario, our scenario only drops energy consumption by a quarter by 2050, reducing risk of failure. We take a cue from IPCC's Special Report on Global Warming of 1.5 Degrees summary for policymakers, which sees a significant need to increase global nuclear production, roughly doubling in the next ten years and growing 4-fold by 2050. In this scenario, Germany would do all that it plans with renewables. In addition, it would expand its nuclear fleet to be four times the level of 2010 by 2050 by introducing a national program to build advanced heat sources in serial production.

In the appendix, we also include a "what if…" scenario called Time Machine. It takes us back 10+ years and looks at what might have happened had Germany decided not to panic and shut down much of their reactor fleet after the Fukushima accident but instead had shut down coal plants. Taking it a bit further, we also speculate what could have happened had Germany decided to use a similar amount of money it has collected from its people and companies as EEG payments to build nuclear reactors with that money. What would emissions look like today, and how much CO_2 would have been avoided in the ten years that have passed?

Our scenario gets lower emissions, lower cost and lower risk of failure than the Carbon Neutral Germany 2045 scenario from Agora Energiewende.

CARBON NEUTRAL

CLIMATE CHANGE

CO_2

What About the Reactors Already Shut Down?

Germany has a handful of reactors that have been shut down, have had their fuel removed, but no significant decommissioning has started yet.[29] Would it be possible to bring some of them back online? Under current law, this is forbidden, but laws can be changed. What is the point of no return, and what are the legal and regulatory hurdles of bringing a "cold" reactor safely back online? And further, what are the potential benefits and lessons one could get from such a program? These are hard questions to answer with confidence, as this is largely uncharted territory. Our interviews with industry experts concluded that "it is hard to say, as we have minimal experience in this kind of matters, but it would likely take 2-6 years of work per reactor even if it were possible." Some of the advantages include existing infrastructure and cooling, pre-existing site permits, and public acceptance and expertise in the area.

As a recommendation, we propose that Germany, together with the international community (IAEA, NEA, and others), starts a thorough review to study these hurdles from all relevant aspects – technical, safety, regulatory and legal, economic, and human capital (expertise). Such a study might conclude that none of the reactors is worth bringing back on, but it would tell us what the reasons for that are and what can be seen as "the point of no return." It would also provide the global community with precious information. It would help future politicians and utilities make more informed decisions regarding how to treat their nuclear fleets, both from a policy, regulatory, and operational perspective.

For example, utilities have specific deadlines by which they need to decide whether to invest in long-term operations in their operational fleet. These deadlines can be hard or soft, depending on the case, but the reasoning behind them is often complex for non-experts like policymakers to understand. Yet, these policymakers make critical decisions regarding the matter. Most of us do not intuitively understand that what happens to a fleet of reactors 5 or 10, or even 20 years from today, is strongly dependent on the path we choose today. For example, what kind of maintenance is done this year or five years from now? What kind of programs are initiated to ensure skilled operators are available when current operators retire? What kind of measures are taken to ensure the availability of licensed spare parts and fuel in the future? Is the fleet in a condition to apply for a long-term operation license in 5- or 10-years' time? The nuclear industry is unlike many other sectors due to its stringent regulations and very long time horizons for projects and operations.

To be conservative, we are not assuming any of the reactors to be re-started in our scenarios. If it was found out to be feasible and safe, re-starting some of the cold reactors even after the mid-2020s would provide a valuable bridge for skilled operators and for training new professionals. This would help bring the new fleet of advanced reactors online in Germany in the early 2030s for our advanced heat sources scenario.

Germany should initiate an international study on the conditions and possibilities of bringing now-closed nuclear reactors back online. It would provide useful information even if restart was not found feasible.

29 At least from the information we were able to gather from third party sources at the time of writing.

Scenarios

General Assumptions and Justifications

All scenario models get results that depend on the assumptions made. This report is not meant to be a complex or academic modeling exercise but an alternative scenario that is easy to understand. We use relatively simple models and straightforward assumptions behind them. This appendix lists our key assumptions and explains the justifications behind them.

Coal, Natural Gas and Nuclear 1:1

Coal and nuclear power plants play quite similar roles in the electricity system. Both provide mostly stable baseload power and spinning reserves (which helps with stability) for the grid with only some flexibility and load following. It does bear noting that nuclear in Germany provides flexibility services for the grid, ramping production up and down as required, within limits. With these things in mind, we assume that everything else remaining the same, nuclear replaces coal 1:1, and vice versa – as long as there is something to replace. If a nuclear plant is closed, a similar amount of coal production cannot be closed simultaneously, and if nuclear is kept running, the same amount of coal production can be shut down. In the case of fossil gas, we assume that current nuclear reactors can replace natural gas use 1:1 to the maximum degree of around one-third of annual natural gas use by 2040.

In the Advanced Heat Sources and Abundance Instead of Scarcity (IPCC 1.5 C) -scenarios, we use new smaller and more advanced nuclear reactors that can be designed to play a similar role to gas turbines in the power system. They can, for example, have double or triple the power generation capacity compared to the nuclear reactor output, and coupled with thermal storage such as molten salts, they can ramp their power output between 0 and 300% of the reactor output level. They can also produce direct process steam for industry. To keep it simple, we assume they can replace natural gas 1:1.

Power-to-X, PtX

We assume that any nuclear power left over from replacing coal and natural gas can be turned into synthetic low-carbon PtX fuels at an overall efficiency of 60% (from electricity to fuel). This somewhat high efficiency is due to the more efficient high-temperature steam electrolysis (HTSE) enabled with advanced heat sources such as next-generation nuclear reactors. HTSE can reach an efficiency of over 90% in turning electricity into hydrogen, which can then be turned into other synthetic fuels such as ammonia, methane, methanol, and others. We assume that PtX in the original base scenario is imported (as it is positioned as a net energy source for Germany).

Lifecycle Emissions

Replacing coal emissions, we assume a rough mix of 2/3 lignite (at ~1,100 gCO_2/kWh) and 1/3 of hard coal (~800 gCO_2 in modern coal plants), giving us avoided emissions of **1,000 gCO_2/kWh.** This is a close approximation of the generation mix between these types of coal in Germany in recent years. For nuclear (12 gCO_2/kWh) and natural gas (490 gCO_2/kWh), we use IPCC 2014 median lifecycle emission values. Natural gas emits less than that when burned at highly efficient turbines. Still, methane also leaks at all stages of production, transporting, storing, and using, so the lifecycle emission is higher. These numbers are unlikely to be exactly right for any single power plant or mine. Still, they are also unlikely to be wrong by a significant amount, and for nuclear, the number is likely to be conservatively high. For example, a recent ISO-certified environmental product declaration from Vattenfall has their existing nuclear fleet at 2.5 gCO_2/kWh.[30]

Pre-shutdown Nuclear Production

To get a baseline number for the German nuclear fleet production before shutdowns in 2011, we calculated the average production between 2000 and 2010 from BP Statistical Energy Review 2020. We came up with 157.6 TWh/year.

Fatalities from Energy Production

To compare coal and nuclear health effects, we used data from the Our World in Data -website.[31] According to it, coal causes 24.6 premature fatalities per one TWh of energy. Nuclear causes 0.07 fatalities per TWh, including all the accidents. With light-water reactors such as those in Germany, the number for nuclear is even closer to zero. We also included global fatalities by 2100 due to increased heat, which are 226 per million tons of CO2 released, according to a recent paper published in Nature Communications on the mortality cost of carbon.[32]

30 https://portal.environdec.com/api/api/v1/EPDLibrary/Files/8371d0c5-faa0-47e9-aafd-61fdd1b0dc81/Data
31 https://ourworldindata.org/safest-sources-of-energy also lists the publications and reasoning behind their numbers.
32 R. Daniel Bressler, (2021), https://doi.org/10.1038/s41467-021-24487-w

Main Scenario – One Billion Tons

We use the Agora Energiewende carbon-neutral Germany 2050 as our baseline for the future. The main difference is that in our main scenario, we refrain from closing down further nuclear and assume the following:

- Instead of nuclear power plants, a similar amount of coal-fired energy production is closed.
- Once there is no coal capacity left, natural gas-fired production is closed.

Historically Germany has reduced its emissions by 17 Mton per year since 1990. A lot of that happened during the few years after unification, as Germany closed down the less efficient and more polluting energy and industrial infrastructure in former East Germany. To reach the new target of carbon neutrality by 2045, emissions would need to be reduced by 30 Mton per year, according to Agora Energiewende. The average reduction speed in the 2000s will need to double or more, and given that the easier reductions have been made first, these reductions will get progressively more challenging each year.

Currently, Germany is planning to shut down the six remaining nuclear reactors at the end of 2021 and the end of 2022, three each year. Not shutting down the remaining nuclear capacity and reducing coal production by a similar amount instead would help significantly with the emissions reductions. Indeed, there would be a double benefit, as instead of needing to build more renewables first to replace the closed nuclear plants and then build even more to shut down a similar amount of coal, one could just keep the nuclear running and use it to shut down coal. Notably, the recent constitutional court ruling stated that Germany's emissions reductions are weighed too heavily in the 2030s and after, and more should be done already in the 2020s. One straightforward way to reduce emissions significantly in the 2020s would be to keep the current nuclear fleet operational instead of prematurely closing it.

The current remaining six nuclear reactors produce roughly 65 TWh of clean, low-carbon electricity each year. Replacing a similar amount of coal combustion, these reactors prevent approximately 64 million tons

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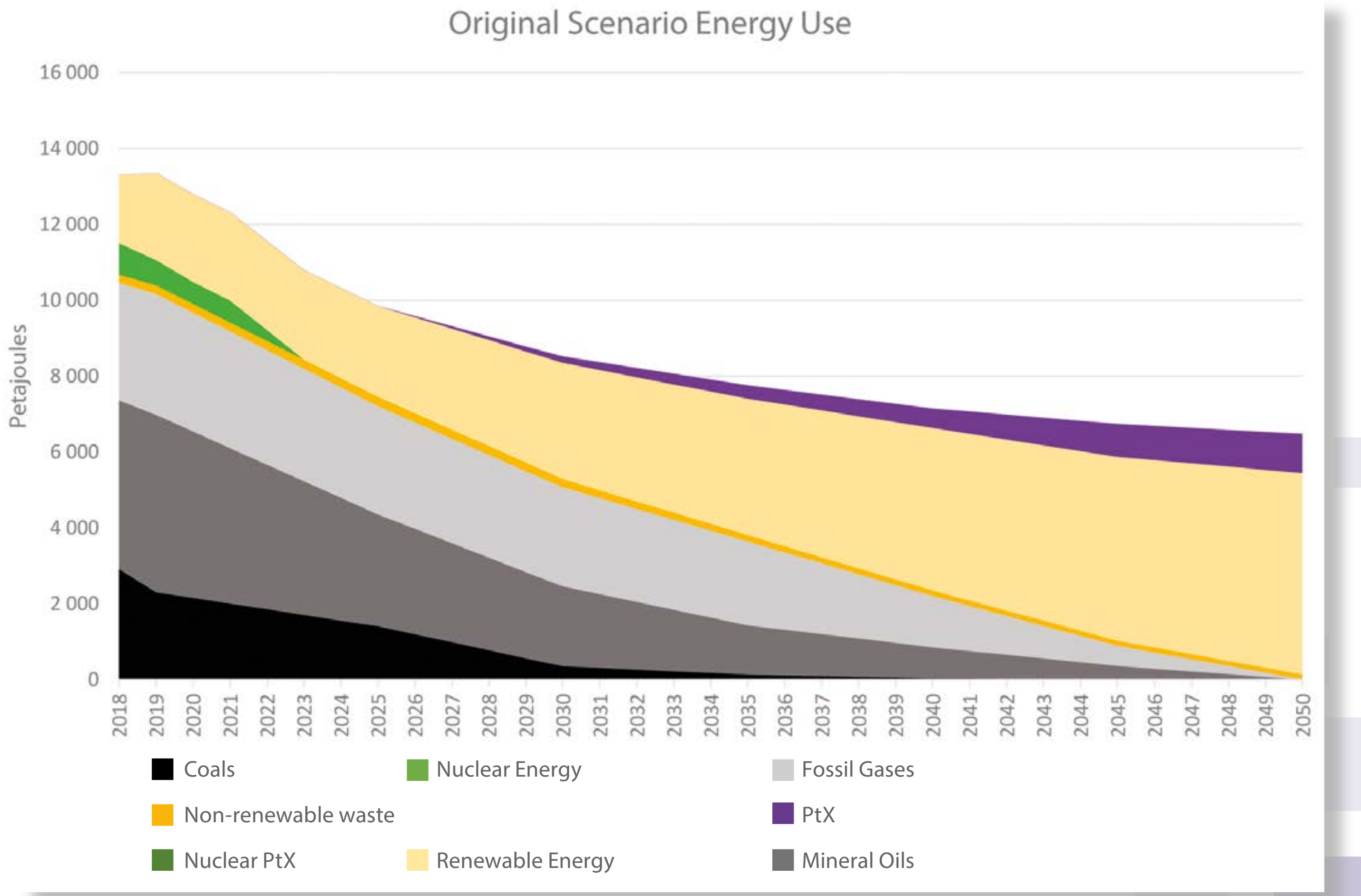
Figure 11: The energy use by source in the original Carbon Neutral Germany 2050 scenario by Agora Energiewende.



One straightforward way to reduce emissions significantly in the 2020s would be to keep the current nuclear fleet operational instead of prematurely closing it.

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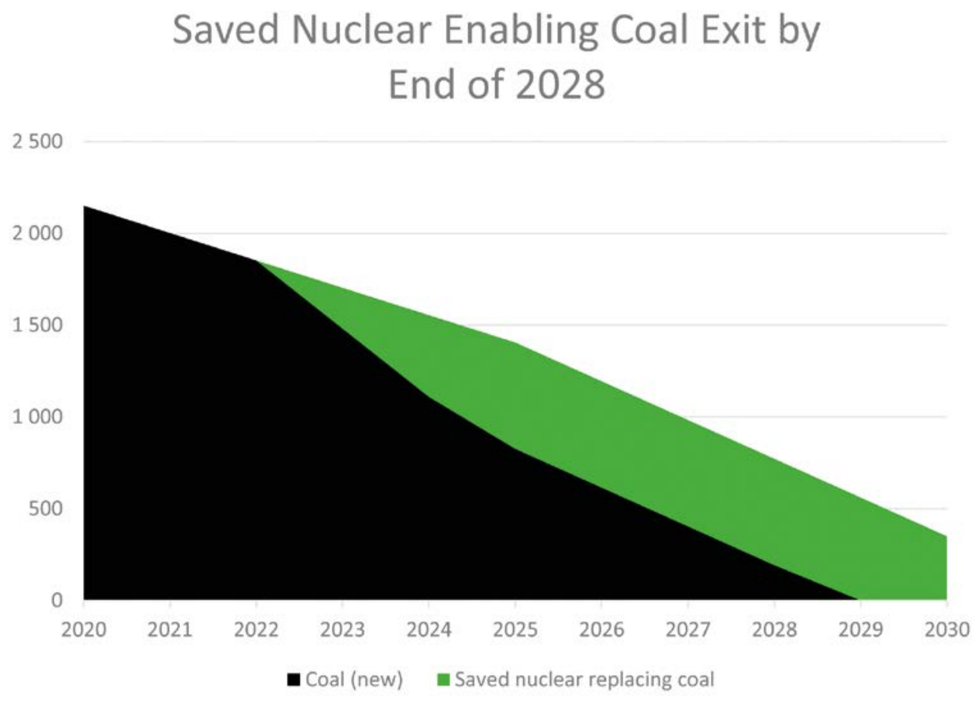
Table 1: Remaining nuclear fleet in Germany is made of larger, more recently built units.
Source: https://world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx

Plant	Type	MWe(net)	First power	Operator	2010 agreed shutdown	Planned close (post-Fukushima accident)
Gundremmingen C	BWR	1288	11/1984	RWE	2030	2021
Grohnde	PWR	1360	9/1984	E.ON	2031	2021
Brokdorf	PWR	1410	10/1986	E.ON	2033	2021
Isar 2	PWR	1410	1/1988	E.ON	2034	2022
Emsland	PWR	1335	4/1988	RWE	2035	2022
Neckarwestheim 2	PWR	1310	1/1989	EnBW	2036	2022
Total operating (6)		**8113**				

Figure 12: Saved nuclear enables Germany to exit coal by the end of 2028.



of CO_2 emissions each year.[33] For example Greenpeace has a published list of lignite coal plants with proposed shut-down dates.[34] As Germany's coal plants get phased out, nuclear reactors can start to replace natural gas in electricity production. Natural gas has lower emissions than coal, but its emissions are still significant.

In the base Carbon Neutral Germany 2050 -scenario from Agora Energiewende, coal use for energy production continues into the 2030s, although only in small quantities after 2030. If we would keep nuclear power plants operational, a complete coal exit can be done in 2028. All other energy sources are assumed to stay the same, so Figure 12 only shows coal and nuclear that replaces coal.

After coal has been shut down, the reactors can continue providing extremely valuable, reliable, and flexible electricity to the grid. German nuclear reactor fleet is already operated in a flexible way. In 2029, when coal has been pushed out entirely by renewables and nuclear, there is still a lot of natural gas in the energy system, and that can be replaced partly by keeping the remaining nuclear fleet in operation. Starting in 2029, nuclear starts to replace natural gas, which will result in roughly one-third less gas use in 2040.

33 Roughly half of German coal is actually lignite, which has much higher emissions than the IPCC 2014 median we use here, so in reality the savings could be even higher.
34 See https://www.greenpeace.de/sites/www.greenpeace.de/files/publications/kohleausstiegsgesetz-abschaltliste-kohlekraftwerke.pdf

The current remaining six nuclear reactors produce roughly 65 TWh of clean, low-carbon electricity each year. Replacing a similar amount of coal combustion, these reactors prevent approximately 64 million tons of CO_2 emissions each year. [31]

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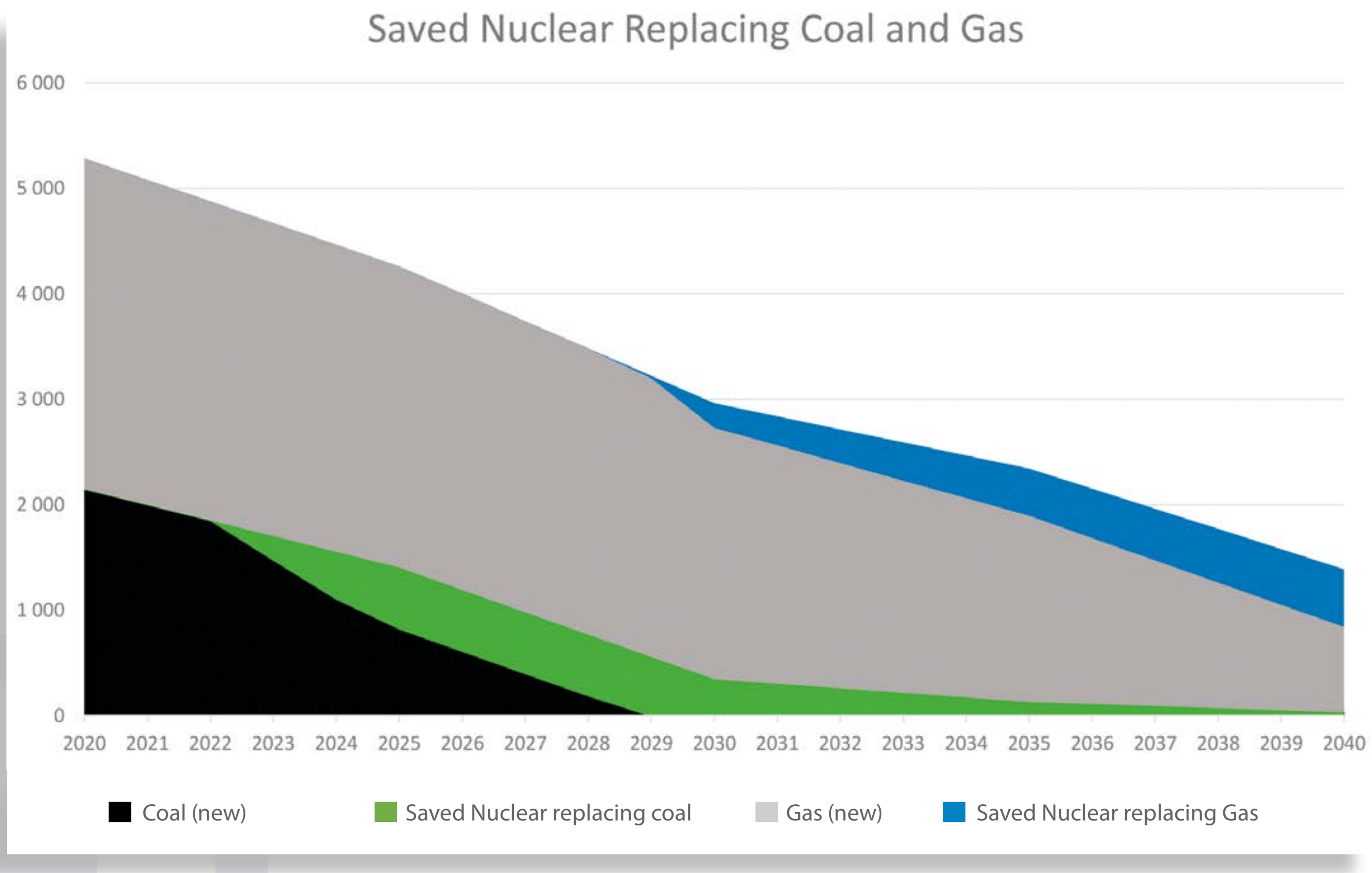
Figure 13: In addition to coal exit, the saved nuclear fleet can reduce German natural gas use starting in 2029.



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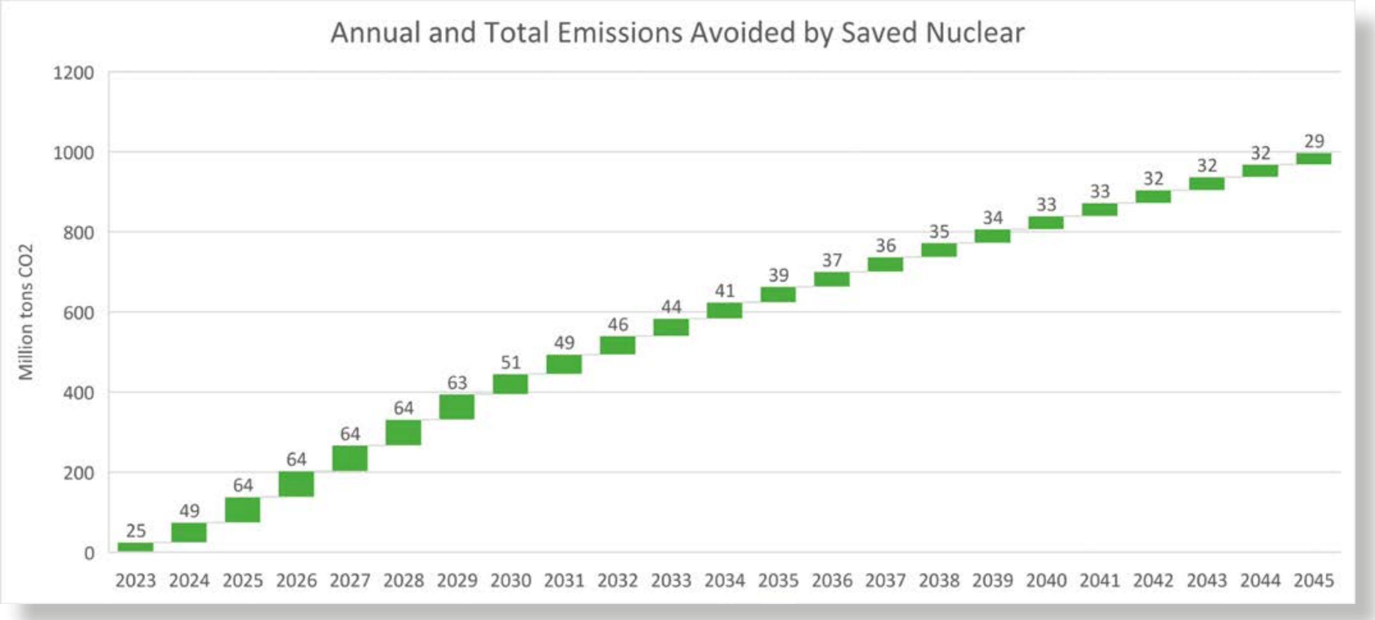
Scenarios

Figure 14: Cumulatively, the saved nuclear fleet will avoid around one billion tons of CO_2 emissions by 2045.



As seen in Figure 14, roughly **one billion tons of CO_2** emissions can be avoided in total by continuing operating the remaining six reactors until 2045. This emissions reduction corresponds roughly to removing 10 million internal combustion engine cars from the roads for the same period. Refurbishing the reactors to run another 20-30 years will surely cost money, but at the same time, it is likely by far the cheapest way for Germany to reduce emissions.

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Public Health Effects

As discussed earlier, nuclear is an extremely safe energy source. In this section, we discuss some of the implications of that. Solid fuels, such as coal and biomass and liquid fuels such as gasoline and diesel oil, release small particulate matter when burned, and we know that these are harmful to our health. These health effects can be modelled statistically, which gives us an estimate on the preliminary fatalities we will give with a certain amount of air pollution.

Maintaining the operations of the existing six nuclear reactors in Germany while closing coal plants instead would prevent roughly 1,800 premature fatalities in the nation from particulate pollution due to coal combustion each year. Operating these reactors for another 25 years, with agreement from the safety regulator, will save 18 to 35 thousand German and European lives from being lost prematurely due to respiratory diseases caused by air pollution.[35]

But that is only a small part of the public health picture. Another, larger part is the mortality cost of carbon through increased temperatures. As mentioned earlier, a recent study in Nature Communications came up with an estimate of 226 additional premature deaths by 2100 per million tons of CO_2 released. So, as the six remaining reactors would avoid roughly one billion tons of CO_2 emissions by mid-century, we can calculate they would also avoid roughly 226,000 premature fatalities from happening by 2100.

While we can and should mitigate the direct health effects of additional heating to a point, for example with adding air conditioning, the number presented does not include many of the indirect health effects of a warming world. These include the effects of crop failures caused by climate change, local unrest and violence due to those crop failures and the resulting hunger, disease, starvation and destabilisation of governments, mass migration caused by these, and so forth.

35 See https://ourworldindata.org/grapher/death-rates-from-energy-production-per-twh

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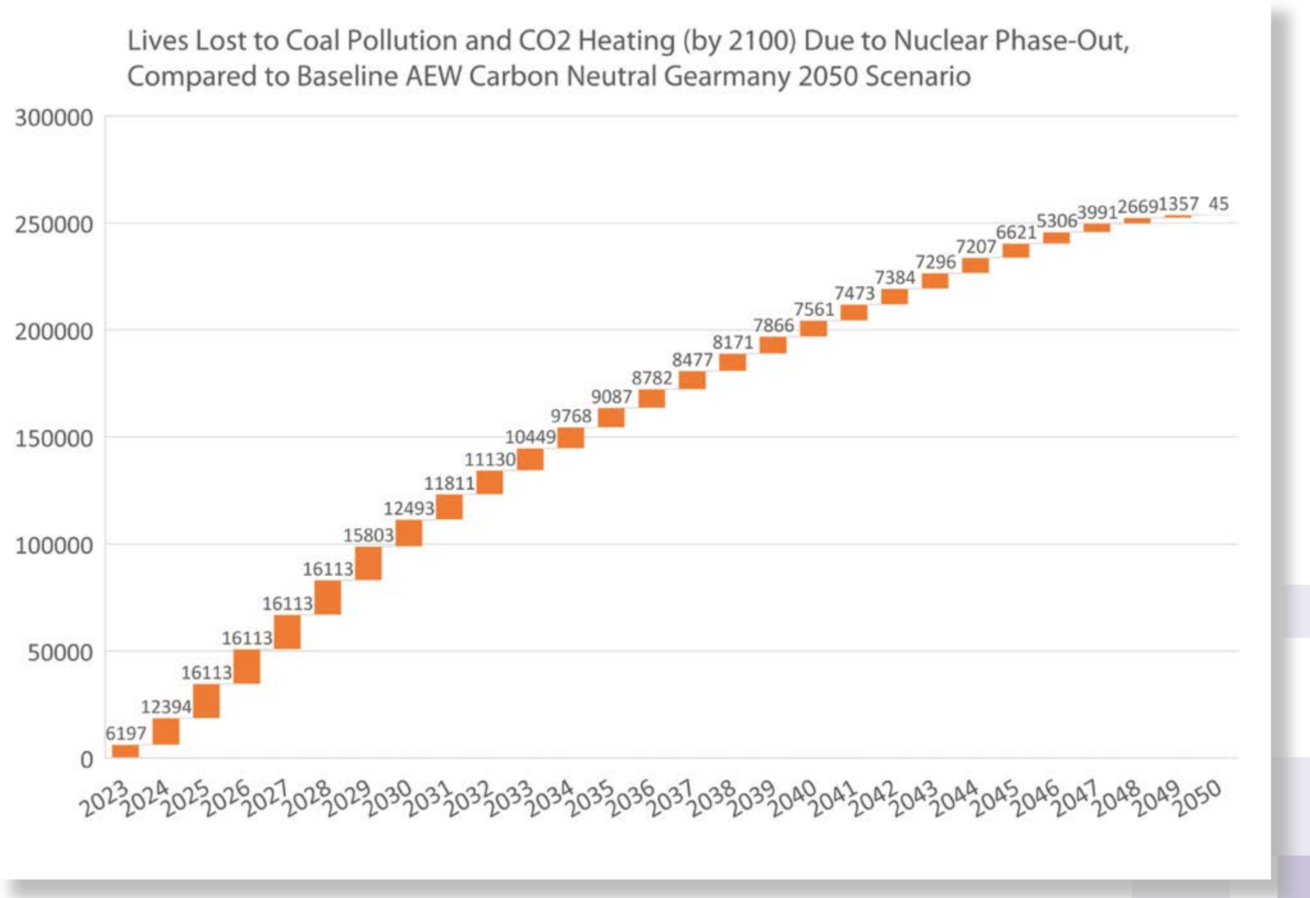
Figure 15: Lives lost between now and 2100 because of the closures of the six remaining reactors in Germany. It should be noted that had the whole fleet stayed operational since 2011 and kept operational until 2050 while replacing fossil fuels, the total number of prevented mortality would be much higher still.



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Environmental Implications

The current fleet of six nuclear reactors produces 65,000 GWh of electricity per year. To do that, it occupies a relatively small area of land, perhaps a couple dozen km². Let us assume we would use a mix of 20% forest-based biomass, 40% solar and 40% wind to replace those nuclear power plants.

	GWh	GWh/km2	Area needed, km2
Wind	26,000	18	1,440 km2
Solar	26,000	58	450 km2
Biomass	13,000	0,7	18,570 km2
TOTAL	65,000		20,460 km2

With these assumptions, it would take 20,000 square kilometers (2,000,000 ha) to produce the same electricity as what is produced at the current nuclear sites. The Agora Energiewende 2050 projection sees renewables more than doubling from current levels in Germany. It remains to be seen how easily local populations and environmentalists accept this expanding energy sprawl, given that the communities´ opposition to local energy infrastructure projects has already been growing in Germany. This risk analysis is something that most scenarios, such as those by Agora Energiewende, lacks.

Economics of Not Phasing Out Nuclear

As discussed earlier, lifetime extension for existing nuclear power plants is the most cost-effective way to add clean, reliable energy supply. Depending on the case, the cost is between 33-45 €/MWh (40-55 USD/MWh), according to International Energy Agency.[36] The nuclear plants in Germany have been operating with a known closure date, so the cost is likely in the upper end of the range. But it would still be of great value to keep them operational. Today, the EEG surcharge, used to pay for renewable feed-in-tariffs, is well above 100€/MWh of renewable electricity produced. This is more than double the likely cost of refurbishing and extending the operations of the current nuclear fleet. In the German electricity futures market, the cost of electricity is over 70 or even 80 €/MWh.[37]

Another aspect is carbon price at the emissions trading system (ETS). The cost per ton of CO_2 emissions has been increasing sharply during the last couple of years and is around 50 €/ton in summer 2021. This means that the existing nuclear fleet would save Germans some 3 billion euros per year just from the ETS carbon prices, were they to replace coal production. The ETS prices will only go up in the coming years as Europe sets its policies more in line with the Paris Accord it has signed. Indeed, this saving in CO_2 prices would by itself pay for the lifetime extension and refurbishment costs of the nuclear power plants.

Further, the savings in health costs (lost working hours, premature fatalities, health care costs, and other social costs of pollution) would likely be in the ten billion per year -range. Quoting a recent paper: "The social cost of this shift from nuclear to coal is approximately $12 billion per year. Over 70% of this cost comes from the increased mortality risk associated with exposure to the local air pollution emitted when burning fossil fuels."[38] This statement refers to the authors' models and calculations on the effects of the 2011 closures of several nuclear power plants in Germany. These costs are much higher than even the most generous estimates on nuclear risks and waste disposal.

The savings, both direct and indirect, of keeping the nuclear fleet operational for another 30 years would be very significant, likely in the tens of billions of euros per year.

Summary

There is no denying that extending the life of the current reactor fleet will be challenging and will require a firm push both politically and technically, and significant investments into the nuclear plants. It will likely require substantial refurbishments and other arrangements, and the reactors will need to be shut down for a year or two to do all this. Skilled operators will also need to be secured, and that is not likely to be cheap.

But it also needs to be noted that managing this is at least an order of magnitude easier to do than Energiewende without nuclear power would be – building an energy system almost entirely dependent on variable renewable energy. Keeping reactors open for 30 more years might be challenging, but it is a walk in the park compared to what needs to be done without nuclear. Having nuclear play its part will make decarbonization significantly faster, lower risk and lower cost, with lesser environmental impact and social cost – all highly desirable outcomes.

36 https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

37 At the time of writing in June 2021. See current prices at: https://www.eex.com/de/marktdaten/strom/futures#%7B%22snippetpicker%22%3A%22EEX%20German%20Power%20Future%22%7D

38 https://www.nber.org/system/files/working_papers/w26598/w26598.pdf

Scenario – Advanced Heat Sources

The goal of the Advanced Heat Sources -scenario is to show how to replace natural gas in its many uses and enable more cost-effective hydrogen production to replace the hydrogen imports in the baseline Agora Energiewende Carbon Neutral Germany 2050 (or 2045) scenario. This scenario does not replace any of the renewables in the AEW Carbon Neutral Germany 2050 -scenario. It simply adds a supplementary building program for technology that is very well suited to replace natural gas as a flexible energy source and produce hydrogen and synthetic fuels (PtX).

The scenario assumes no changes in the renewable energy production build-out. Notably, there will be a lot of demand to build wind and solar, as the current fleet will need to be rebuilt by 2050 at least once, and the renewables fleet more than doubles from today. Indeed, Germany will need to build more than their current renewable energy production equivalent every decade and do most of it with wind and solar as hydro and biomass cannot be sustainably expanded from current levels.

There is a lot of R&D on various types of advanced heat sources done around the world. The ones furthest down the road are already starting up (such as the HTR-PM in China), while many others plan to have First-of-a-Kind facilities come online sometime during this decade, with a full-scale commercial roll-out soon after that. The main product of these systems is not so much electricity as it is the other energy services we will likely be needing going into the 2030s. These include:

- Increased flexibility and firming services for the power grids (acting as a low-carbon alternative to natural gas turbines).
- Reliable, affordable high-temperature steam for industrial processes.
- Combined production of power and (lower quality) heat which can be used for district heating/cooling or seawater desalination.
- Flexible and more efficient production of clean hydrogen through High-Temperature Steam electrolysis which can combine high-temperature heat form the heat source with surplus renewable electricity from the grid.

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These are all extremely valuable for our future energy system. And the more there is variable renewable energy like wind and solar in the system, the more valuable many of these services become. There are many (indeed, dozens) technological pathways, configurations, and options that these advanced heat sources can have, and going through all of them is not in the scope of this report. Yet, it is helpful to mention some of the leading technology pathways and the benefits and options they include. See Table 2.

This scenario shows how Germany could become a genuinely leading country for effective decarbonization and combining variable renewable energy with advanced heat sources in a low-cost, low-carbon, and reliable energy system. This is the very thing we all want and need as fast as possible.

Table 2: Various types of advanced reactor technologies and some of their properties.

	Light water	Molten salt	Liquid metal	Gas
Medium Temp (sub 300°C)	Yes	Yes	Yes	Yes
High Temp (sub 600°C)	No	Yes	Yes	Yes
V.High Temp (over 600°C)	No	Sometimes	No	Sometimes
High-Pressure Vessel needed	Yes	No	No	Yes
Flexible Operation	Yes	Yes	Yes	Yes
Heat Storage for Added Flexibility	Possible	Often	Possible	Possible
Inherent / Passive Safety	Sometimes	Yes	Yes	Yes
Can Use "Spent Fuel" as Fuel	No	Sometimes	Often	No

This scenario shows how Germany could become a genuinely leading country for effective decarbonization and combining variable renewable energy with advanced heat sources in a low-cost, low-carbon, and reliable energy system.

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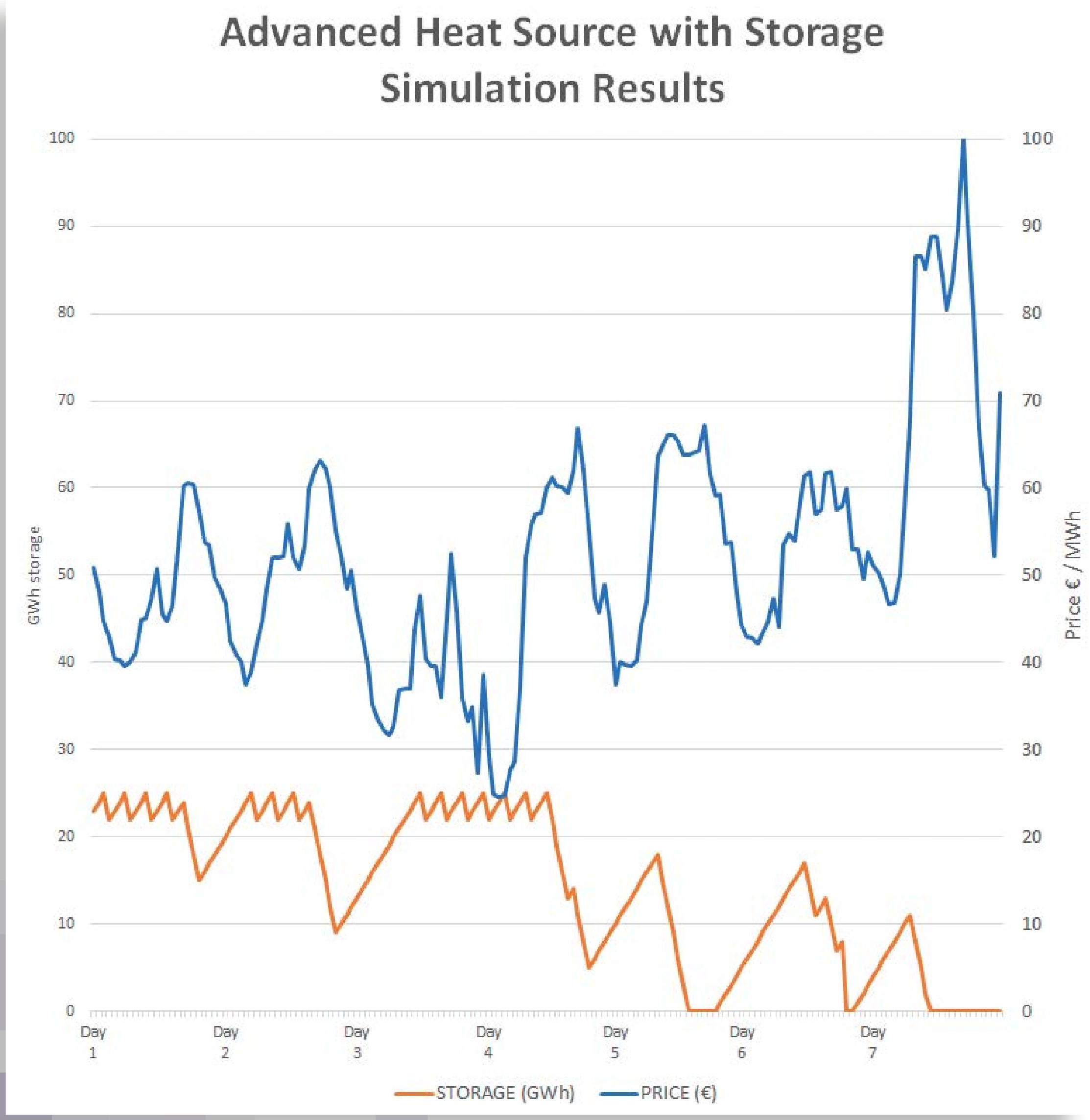
Figure 16: A local high-temperature energy storage is attached to an advanced heat source. The energy storage, in turn, has a turbine generator attached to it. The energy storage is either charged or discharged depending on the price of electricity at any given moment.



Flexibility of Advanced Heat Sources

To demonstrate, Figure 16 shows a 1 GW advanced heat source coupled with a local high-temperature heat storage system and additional turbine capacity (at 3 GW) following the load by charging the 24 GWh storage when power price is low and discharging it (producing power) when prices are higher. The 24 GWh storage corresponds to the turbine running at full power for 8 hours. This, in effect, can follow the daily changes in solar and wind production and changes in demand. As this kind of high-temperature thermal storage is reasonably low-cost, it can be an affordable way to increase the shares of variable renewable energy production in the energy system. As seen on the Figure, power is produced (storage discharges) in the afternoons, when demand spikes and solar goes down and the market price is the highest. During night-time, when prices and demand are lower, the storage is charged. Further optimization could be done if the day 7 price peak can be foreseen a day or two earlier.

Assumptions

The scenario assumes that the current fleet of reactors will be kept online and will replace coal and some natural gas. It also assumes that in 2030, Germany brings the first 500 MW, in 2031 another 1,000 MW, and then from 2032 onwards 1,500 MW (electric, roughly 4,000 MW of thermal capacity) worth of advanced heat sources online each year in serial and parallel projects. These would primarily be located in current nuclear power plant sites to simplify licensing and zoning and utilize the infrastructure and transmissions already at the site and the local population's expertise and experience. Perhaps some might be sited at offshore platforms.[39] In this scenario, we do not separate different technologies or assume anything about the sizes of individual advanced heat sources. As this scenario goes all the way to 2050, thus starting in 2046, the added capacity will also replace the current reactor fleet as it retires during the 2040s.

Due to their added flexibility and the possibility of local high-temperature thermal energy storage, these advanced heat sources

39 See for example https://www.lucidcatalyst.com/hydrogen-report for more info on offshore platforms.

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replace natural gas 1:1 in the scenario. In contrast, the ability of current nuclear to replace natural gas is more limited. After there is no more gas or coal to replace, they start to replace Power-to-X imports, increasing energy security and enabling Germany's neighbors to use their domestic PtX production to decarbonize their energy mix faster. Nuclear electricity is turned into PtX with a 60% average efficiency.

Cumulatively, this scenario would avoid almost 2 billion tons of CO_2 emissions by 2050.

Results

As was the case in the main scenario of keeping the current fleet operational, coal has a phaseout by the end of 2028, ten years faster than the current target of 2038. Thanks to the added advanced heat sources, fossil gas will see a phaseout by the end of 2039, instead of by 2050 as in the baseline AEW scenario. In addition, German-made nuclear PtX fuels start to replace imported fuels in 2040, and by 2045, Germany becomes a net exporter of PtX fuels.

Cumulatively, this scenario would avoid almost 2 billion tons of CO_2 emissions by 2050.

In the first decade, emissions savings come from mainly offsetting coal burning by the saved nuclear fleet. In the second decade, savings come from saved nuclear and advanced heat sources replacing natural gas. Towards the end of the 2030s and in the 2040s, most avoided emissions come from clean PtX fuels replacing fossil-based fuels (natural gas and liquid fuels). **These emissions reductions are added to the significant cuts already in the baseline Carbon Neutral Germany 2050 scenario.**

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Figure 17: Saved nuclear and advanced heat sources replace all fossil fuels by 2040 and nuclear PtX replaces PtX imports by 2045.

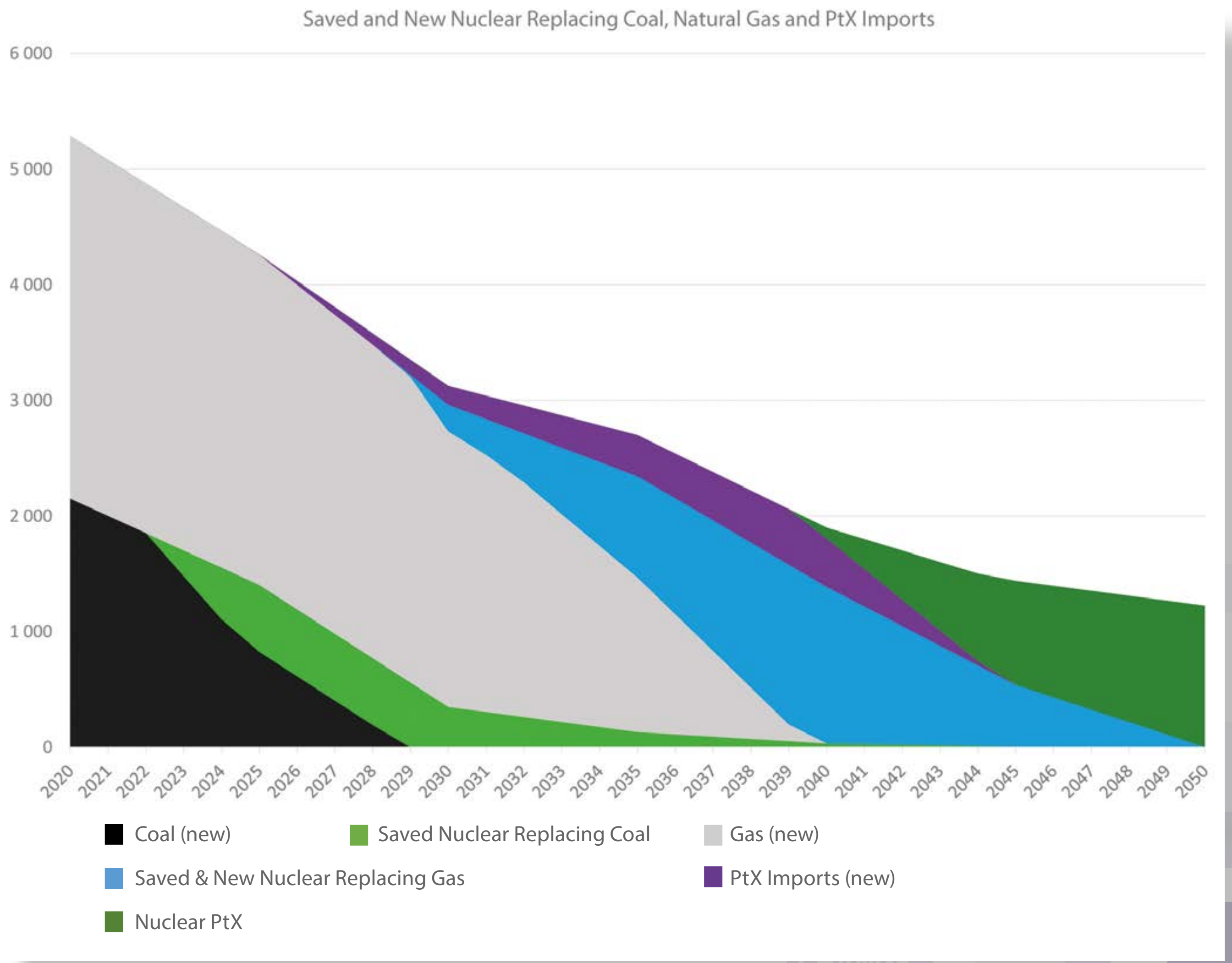


Figure 18: Annual and total avoided emissions with saved nuclear fleet and a program of building flexible advanced heat sources.

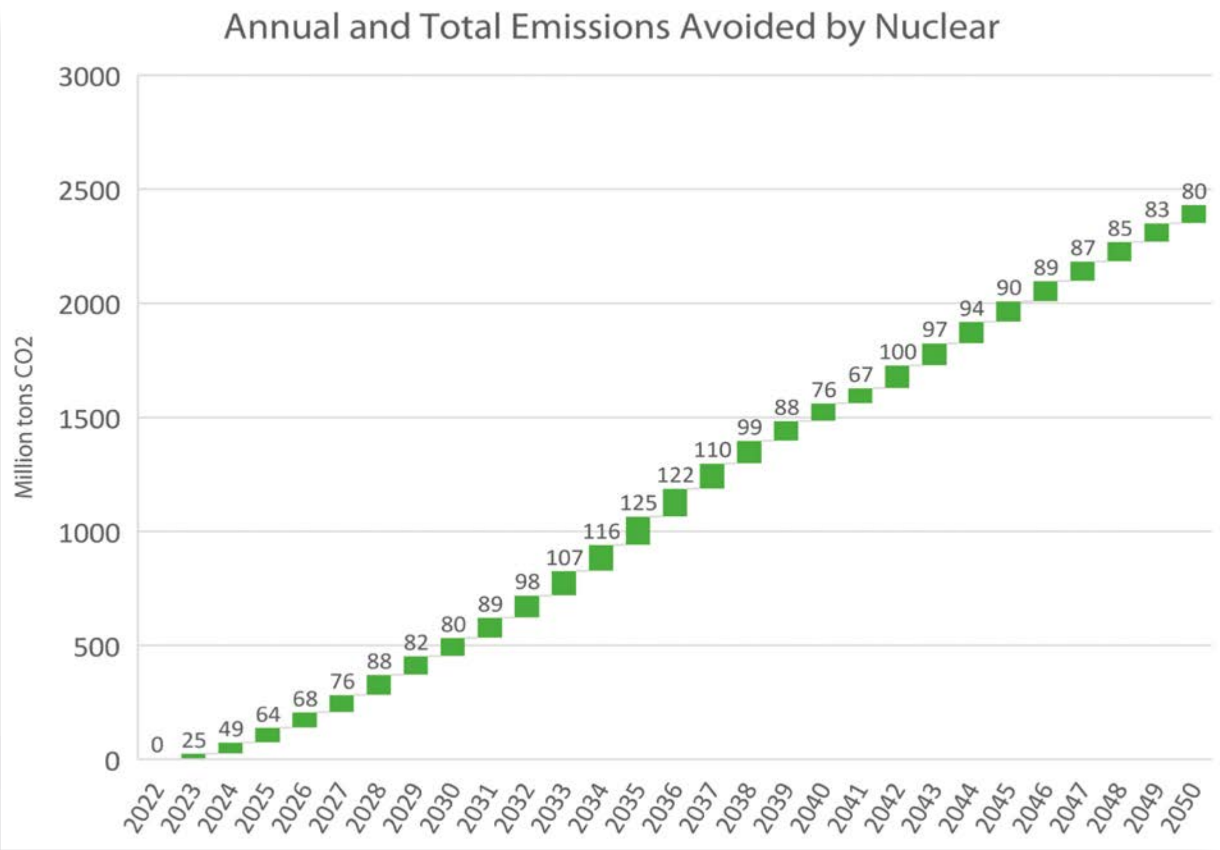
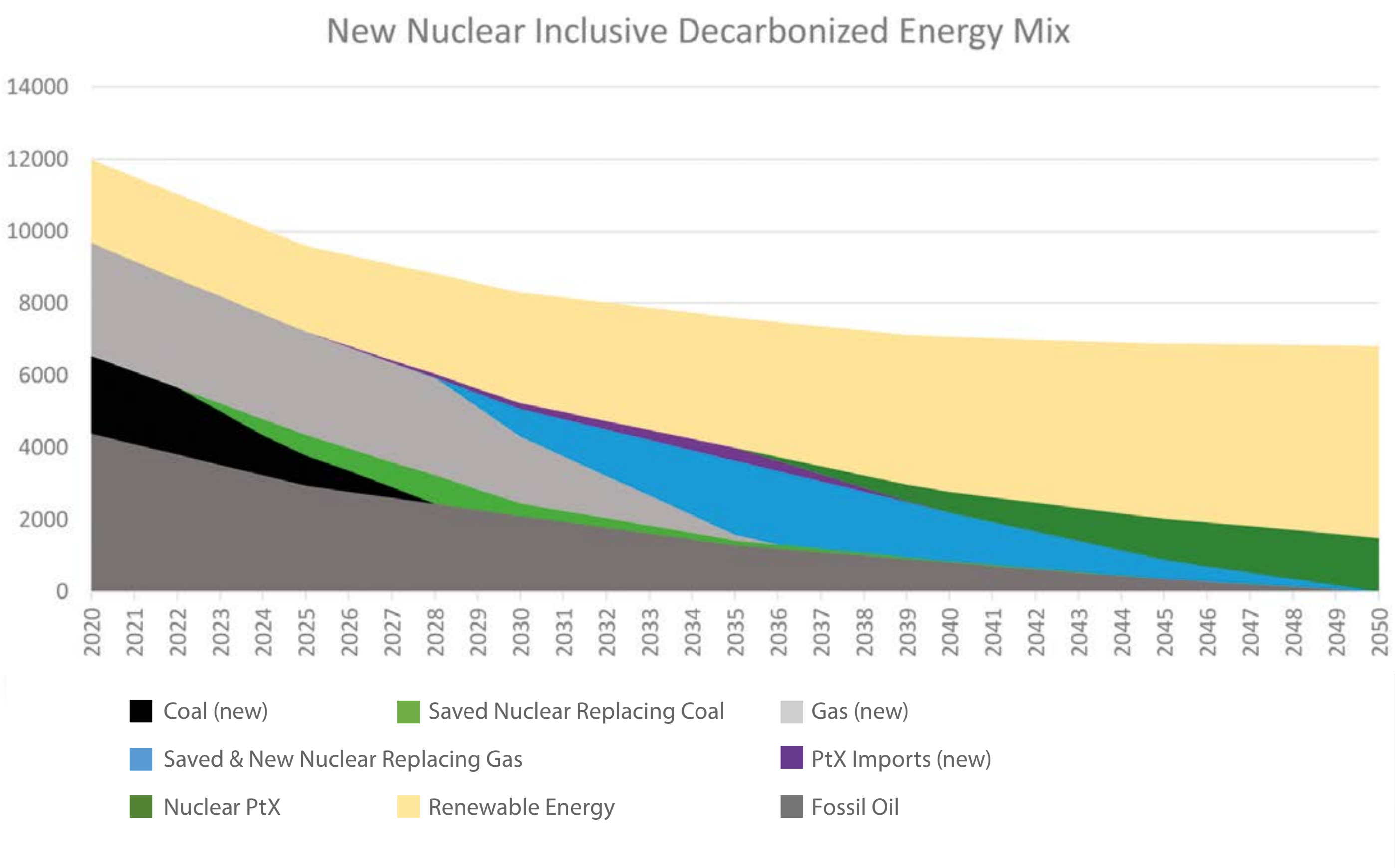


Figure 19: Energy mix, where fossil fuels and PtX imports get replaced by renewable energy, current nuclear fleet, and advanced heat sources.



Scenario: Energy Abundance Instead of Scarcity

Our final scenario addresses two concerns. First, the rapid decline in energy use that the AEW base scenario assumes might be a risky assumption, considering that people might not willingly lower their standards of living significantly and efficiency improvements of the economy have their limits. Second, the IPCC Special Report on Global Warming of 1.5°C sees nuclear growing very significantly globally (in Summary for Policymakers the four main scenarios see nuclear growing 4-fold by 2050 on average). Combining these two, we assume that on top of building renewables and saving their current nuclear fleet, Germany starts a program to ingrease their nuclear fleet roughly four times 2010 levels by 2050, in line with the global average required by the IPCC's scenarios.

Will Energy Use Decrease by Half?

While we used Agora Energiewende's Carbon Neutral Germany 2050 scenario "as is," we do need to discuss the amount of total energy use and its rapid decline in the scenario. While there are some reasons to assume that our energy use can decrease, there are also multiple reasons to believe it won't, at least not so fast and not without dire consequences for the German people and businesses.

Economic activity happens when energy is used. This can be calories eaten by laborers or work animals or external energy carriers (fuels, electricity, steam) used by machinery and processes that produce goods and services. Economic growth is mainly born from productivity growth and population growth. Productivity growth means that per workhour, more goods and services are produced. This happens primarily through the use of machinery and industrial equipment, which in turn use external energy. To simplify the chain of events: to grow the economy, productivity needs to grow, and to grow productivity, energy use needs to grow.

The value (euros, GDP) produced per unit of external energy used results from the energy efficiency of the economy, measured as € of GDP/kWh (or gigajoule). This efficiency has been improving steadily throughout the decades at roughly 2% per year (+/- 1%).[40] This means that if the economy is assumed to grow by 2% per year per capita, and if the economy's energy efficiency improves at a similar rate of 2% per year, then the energy consumption of the economy (if the population remains the same) will stay the same level. To reach the roughly 50% reduction in the 29 years we have until 2050, the primary energy use of the economy would need to fall at approximately 2% per year on average. So either economy will not grow (something the structure of our current society cannot handle), or we find and invest in new ways to improve energy efficiency much faster than it has traditionally done. We also need to realize those efficiency improvements as savings instead of producing more at that higher efficiency (the rebound effect).

Practically the whole history since the Industrial Revolution has been a history of improving efficiency that has led to faster economic growth and even more energy and materials used. Reversing this rebound is possible, at least to a degree. Still, we do not know to what degree it can be done, as nobody has done it sustainably over more extended periods at a national scale.

So while decreasing energy use by half might be within the realm of possibility, it is by no means certain, nor might it even be likely – at least according to the lack of historical evidence of anything like that ever happening. Assuming that this can and will be done is a risky strategy. It could prove to be irresponsible as well. If those efficien-cy targets are not met, the planned actions and investments might be much too small in scale compared to the energy demand we will end up having. This can lead to the increased use of fossil fuels, given that they are readily available and quick to set up and use. This, in turn, would mean accele-rating climate change and missing emissions reductions targets.

Further, we must ask how much of our decrease in energy use and emissions has been a result of moving industrial production from Europe into other countries and then importing the goods from there. Global emissions have been increasing despite our efforts to reduce national emissions, so we need to be honest and transparent about the possibility that we have "exported" part of our emissions into developing countries.

The rapid decline in energy use that the AEW base scenario assumes might be a risky assumption.

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40 https://www.iea.org/reports/energy-efficiency-2020

IPCC and 1.5°C

In its 2018 Special Report on Global Warming of 1.5°C, IPCC's four main scenarios assume, on average, that global final energy demand will increase slightly (8.75%) by 2050 from 2010 levels and stay roughly the same compared to 2018 levels.[41] Most of this growth will come from developing nations consuming more.

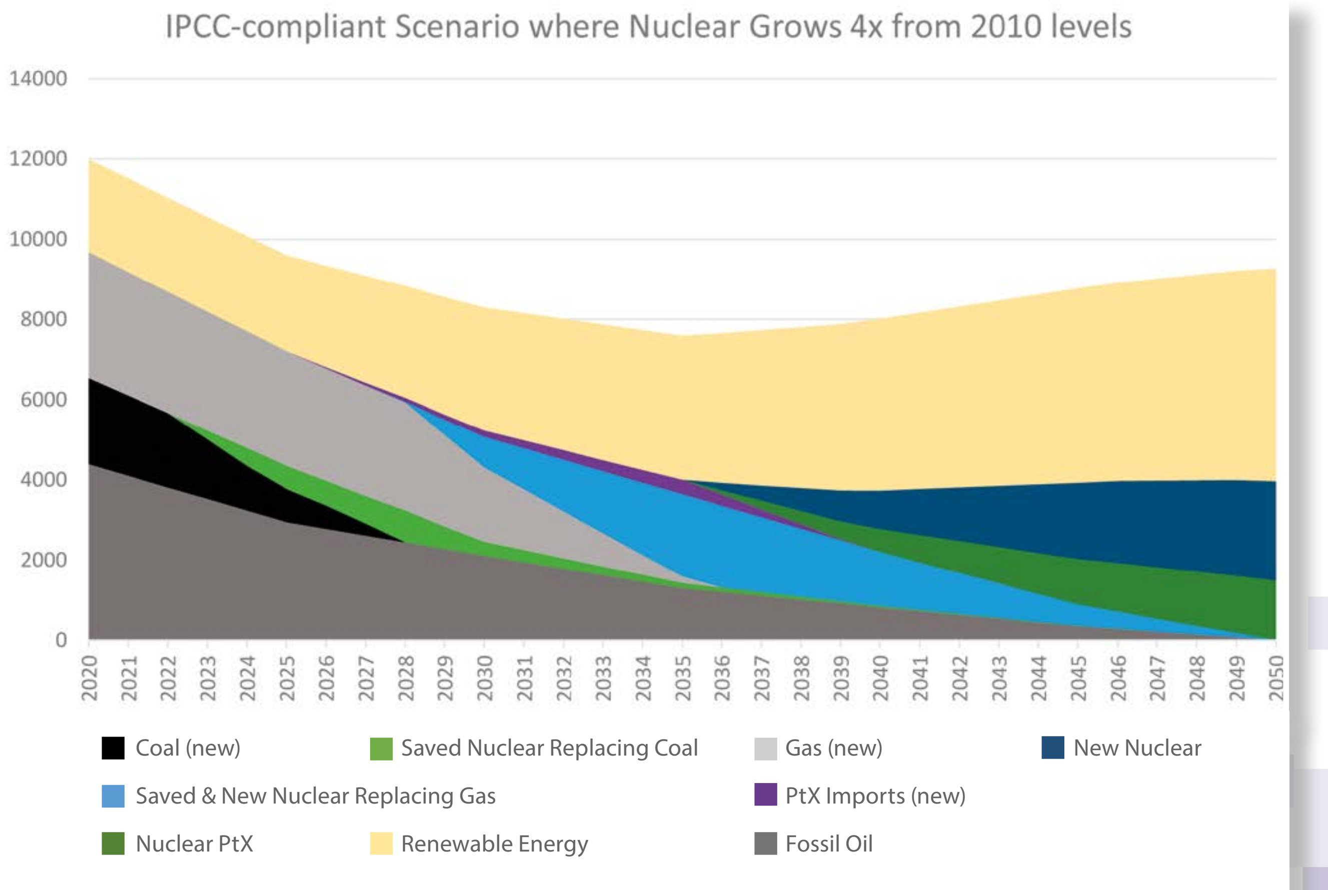
In this sensitivity analysis scenario, we assume Germany does with nuclear what the IPCC Special Report on Global Warming of 1.5°C four main scenarios assumed on average in its Summary for Policymakers. That means growing nuclear production by 4-fold by 2050 from 2010 levels. This is in addition to increasing non-biomass renewables over 11-fold from 2010 levels.

Global demand is different from German demand, so the comparison is not without its issues. But it is a helpful exercise to help realize the needed scale of both RE and nuclear scale-up and the reality that Germany's perhaps most progressive climate scenario is ignoring a significant growth needed from nuclear globally to stay at roughly 1.5°C of warming. One can debate how realistic these decarbonization scenarios of the IPCC's report are to happen. Still, they are much less realistic through the German Energiewende -style project, which chooses to leave out essential nuclear and carbon capture and storage technologies. If a seemingly dedicated nation like Germany cannot do it, how can we assume that any other country can? And if not, it is clear that we need to either shift how we see nuclear or shift our expectations of what can be done without it. This means accepting a much higher degree of global warming and the harmful climate impacts it means for both us and for future generations.

Growing German nuclear 4-fold from 2010 levels is challenging given that Germany has been moving in the wrong direction regarding nuclear. To get there, Germany would need something like the nuclear program shown in Figure 20, where Germany starts a new build -program around the mid-2020s and quickly grows its annual additions of new nuclear to a level of around 3 GWe (adding ~24 TWh of new production each year). This scenario, given that renewable

41 https://www.ipcc.ch/sr15/

Figure 20: The scenario which assumes Germany grows nuclear in line with IPCC (2018) four main scenarios average and only reduces its energy demand by a quarter by 2050, instead of halving it.



additions are kept the same as in the original Agora Energiewende -scenario we used as the base, has the added benefit of not needing a halving of German primary energy use as discussed earlier. Total demand still decreases (and there is an ominous slump in the 2030s), but only by a quarter by 2050, not by half. If Germany somehow manages to drop domestic demand by half anyway, the extra energy can be exported to its neighbors, or the building program toned down.

This is ambitious, but it is also based on what IPCC's four main scenarios required as happening by 2050. Mitigating climate change in time requires us to do ambitious things, and that goes for renewable energy, energy efficiency, and nuclear power. For so long, our progress, Germany included, has been much too slow. Globally we have not even managed to slow down the annual increase in atmospheric CO_2, despite 30 years of negotiations, policies, and actions. This inability to get moving means that we need to get moving much faster now. One of the fastest ways to "get moving" is not to prematurely close any low-carbon electricity production.

Mitigating climate change in time requires us to do ambitious things, and that goes for renewable energy, energy efficiency, and nuclear power.

CARBON NEUTRAL

As we can see, a technology-inclusive approach is by far the most effective way to solve the climate problem. In the case of Germany, the energy sector could be carbon-neutral decades faster with nuclear than without it. Given that we need to act very fast and reduce emissions significantly in the 2020s, keeping the currently operating nuclear plants open is the quickest and surest way to do that. It could avoid roughly one billion tons of CO_2 emissions. Changing Germany's position on nuclear energy will be challenging, but it is not impossible. Solving the climate challenge in the timeframe and scale needed without one of the most capable technologies we have at our disposal might well prove to be practically impossible and politically infeasible. At the very least, it is highly risky and irresponsible towards future generations. But it is something that only German people and politicians can decide on – we merely hope this decision is made with as much factual information as possible, instead of the misinformation now prevalent in German society.

Even more worrying is Germany's recent tendency to force its energy policy and views on other nations, both directly and indirectly. Whether Germany ends up giving nuclear up or not, it has no right to bully other countries into following suit. It is undermining other nation's sovereignty, the founding documents of the European Union, and global progress in mitigating climate change and eradicating poverty. If Germany wants to leave the growing group of nuclear nations, that is her choice to make. But it would do well to let other nations make their choices for themselves, for all our sake.

We recommend and hope that perhaps with this report's help, Germany can start a new public discussion regarding its relationship with nuclear technology and its potential role in mitigating climate change and preventing air pollution today and in the future. We hope that science and evidence will prevail, and humanity can face our shared future together with Germany, with its talented scientists and exceptionally skilled engineers working for the best of humanity – also in the field of nuclear technology and its many applications.

In the case of Germany, the energy sector could be carbon-neutral decades faster with nuclear than without it.

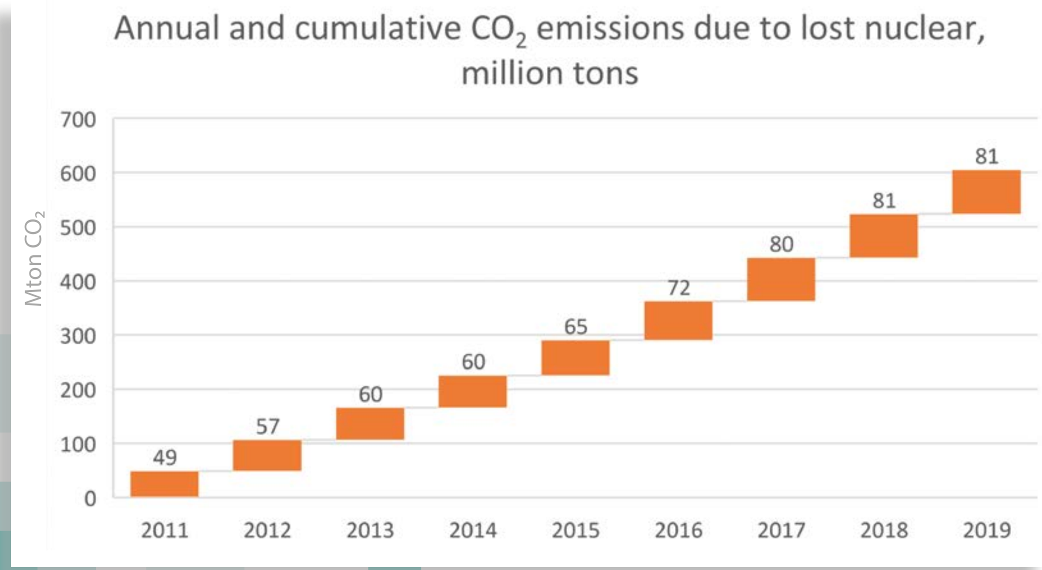
Suppose Germany had taken a deep breath and decided to shut down coal plants instead of nuclear plants after the Fukushima accident in 2011. In that case, all else remaining the same, those nuclear plants shut down since (up to the end of 2019) would have saved 495 million tons of CO_2 emissions between 2011 and 2019. That is 55 million tons per year, more than the total annual emissions of Sweden.

As shown in Figure 22, German energy emissions would be roughly 10% lower had they closed coal capacity instead of nuclear. That is not insignificant. Indeed, it is relatively close to the difference between Germany achieving its emissions reduction targets and Germany not reaching them. Germany is, quite literally, sacrificing climate to shut down nuclear.

Human Lives Matter

Further, by replacing the harmful particulate pollution and NO_2 coal plants release, some 15,000 lives would not have been prematurely lost between 2011 and 2019 in Germany and neighboring countries. Thousands of children would not have gotten asthma during those years. Millions of workdays would not have been lost due to sickness and lower productivity. Because

Figure 21: Annual and cumulative CO2 emissions caused by closing nuclear power plants after 2011.



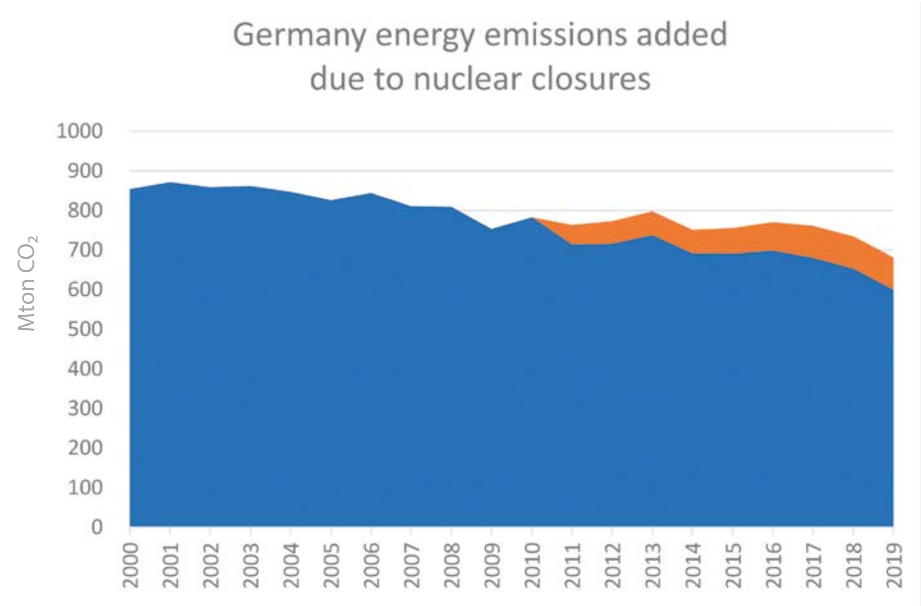


Figure 22: Germany has closed some of its nuclear capacity after the Fukushima accident took place in 2011. This graph shows how much emissions that capacity would have saved had Germany reduced coal capacity instead.

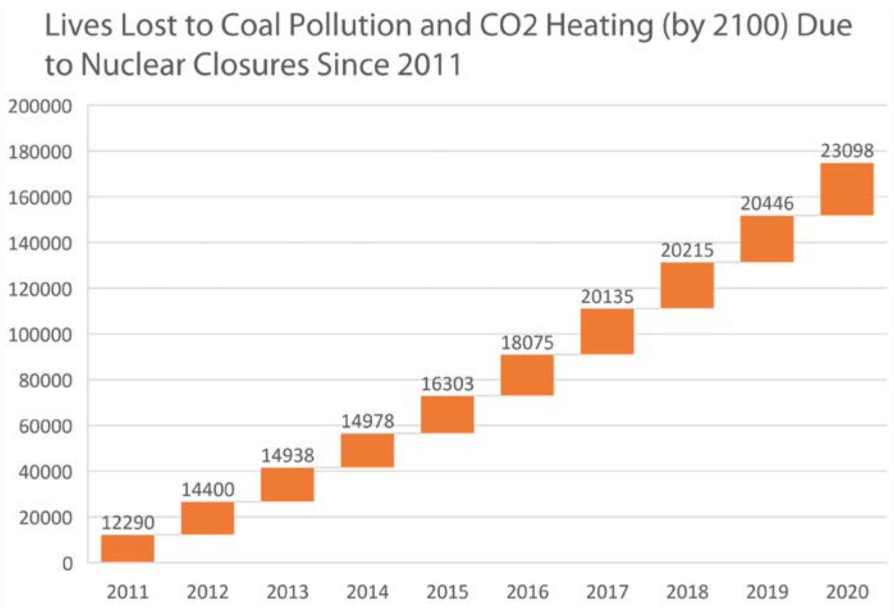


Figure 23: Human lives lost prematurely due to Germany closing nuclear instead of coal since 2011.

nuclear energy is one of our safest energy sources, practically nobody would have died (or would die in the future) prematurely because of nuclear.

When we add the mortality cost of carbon discussed earlier in the report, we see that the phase-out decision has already, by end of 2020, caused and locked in the premature deaths of almost 180,000 people globally due to pollution and increased heat by 2100. And, as discussed earlier, this in only one aspect of global warming's health effects.

The past is the past and cannot be changed. But still, it is worthwhile to analyze the consequences of decisions made in the past to better inform us about the decisions we are making in the present. For climate change and people's safety and health, the decision to close nuclear in Germany has been a disastrous one.

Opportunity Costs – Building More Nuclear?

In our Time Machine-scenario above, we discussed the consequences of the political nuclear closures that have taken place during the last ten years in Germany. To illustrate the concept of "alternative cost" and its importance, we ask one more "what if" question. Germany has spent and is spending billions of euros each year to pay for the feed-in-tariffs of installed wind, solar, and biomass production. This feed-in tariff is like a guaranteed price that the producers get for their output, no matter what the price on the market is. Essentially, this can be used to incentivize investments into certain technologies, as the guaranteed price ensures profits and removes market and technology risks for the investor. It can arguably be called a "blunt instrument" to drive a market in a specific direction. In Germany, that direction has been towards more renewable energy and away from nuclear.

As a blunt instrument, it has done the job. Germany has an 19% share of renewable energy, and this share has been growing. But as mechanisms go, feed-in-tariffs are pretty expensive and do not effectively promote technological advancement. And when it comes to spending public money, one should always think about alternative costs. What else can one do with that same money?

Let's see what would have happened had the Energiewende taken a similar amount

CARBON NEUTRAL

For climate change and people's safety and health, the decision to close nuclear in Germany has been a disastrous one.

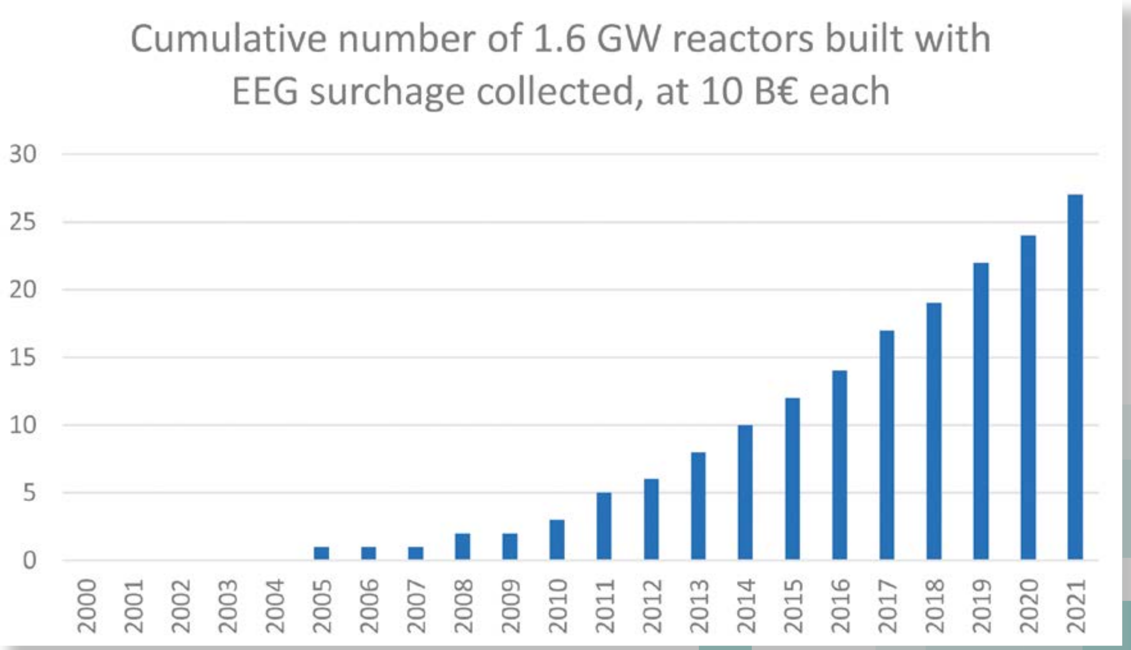
of money it has now collected through the EEG surcharge to pay for renewable feed-in-tariffs and decided to build nuclear with that money. This is not an apples-to-apples comparison, but we make this comparison here to make a certain point.

In this particular scenario, we assume Germany would have started building 1.6 GW reactors that would have cost €10 billion each. For simplicity's sake, we are also assuming that each time the cumulative EEG collected reaches €10 billion, a reactor comes online.[42]

In 2021, Germany would have built 27 new reactors, with two new reactors coming online every year through the 20+ billion in collected EEG surcharges. One other thing to note is that the wind and solar capacity these EEG payments support today will be mostly gone by 2050 due to the limited operational lifetime of the facilities. Indeed, Germany is already facing a growing situation where new

42 EEG sums from: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/eeg-in-zahlen-xls.html

Figure 24: How much nuclear could have been built by using the EEG surcharge collected to pay for renewable energy feed-in-tariffs.



CO_2

wind and solar installations are increasingly used to replace retiring wind turbines and degraded solar panels.

Adding the older fleet of 17 reactors we discussed earlier, Figure 25 shows the amount of clean electricity that the nuclear fleet would produce in total, compared to the historical achievement done with renewables.

At this rate, it would take nuclear until 2025 to surpass the 600 TWh/year power generation level that Germany currently has. This would have been nothing short of climate heroism.

As we can see, from a climate and human health perspective, holding on to existing nuclear and building more would have been much more effective than the path that Germany chose with its Energiewende. Now the question is, will Germany acknowledge this and change, or will it continue despite the increasing costs.

Figure 25: How nuclear energy would have grown if a similar sum was used to build reactors that was collected as EEG.

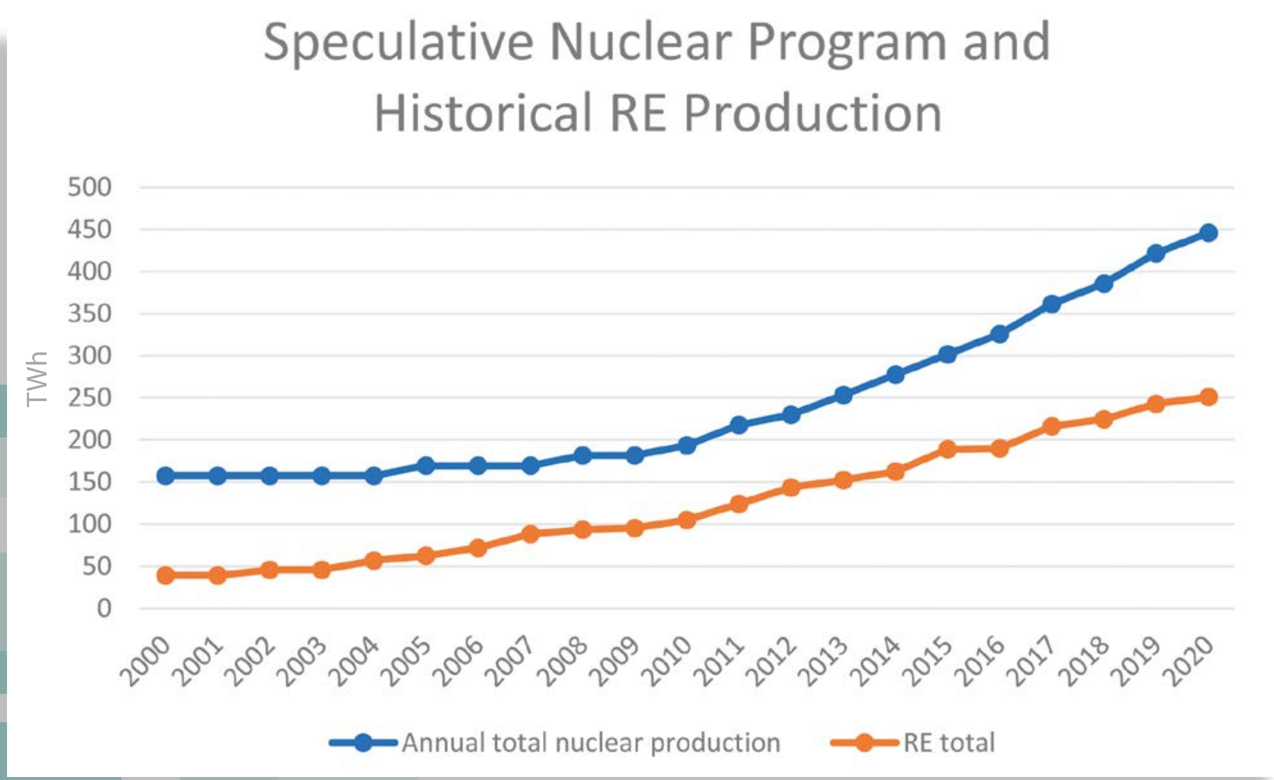
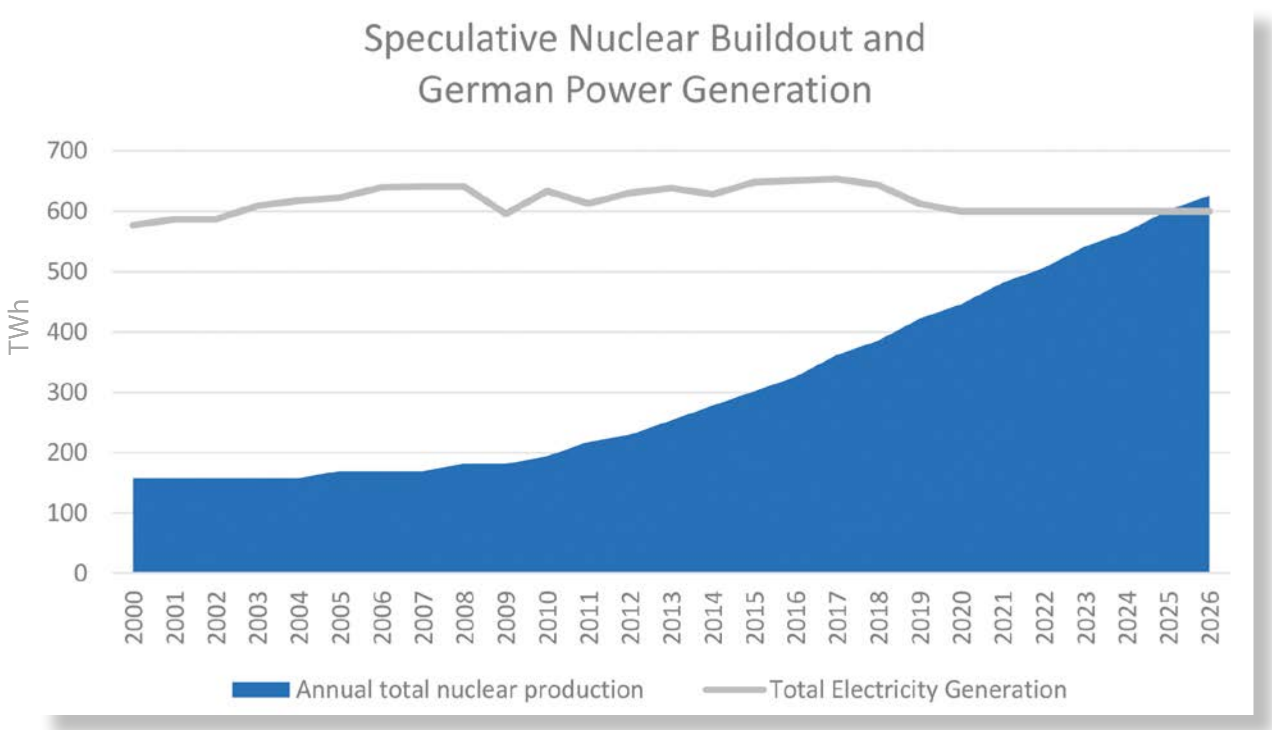


Figure 26: A nuclear program would have decarbonized the German grid by 2025.



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CLIMATE CHANGE

CO_2

Rauli Partanen

Rauli Partanen is an independent, award-winning science writer and communicator who lives in Finland with his wife and three kids. He started studying and writing about energy and the environment over ten years ago, first through his blog and then through books, articles and studies.

His first book **"Finland After Oil"** (2013) got shortlisted for both of the two biggest non-fiction book awards in Finland and was since published in English by Routledge **(World After Cheap oil, 2014)** and got also translated into German as "**Die Welt nach dem billigen Öl**". In 2015, he and his co-author Janne M. Korhonen published "**Climate Gamble – Is Anti-Nuclear Activism Endangering Our Future**", which has since been published in 7 languages. Rauli and Janne also wrote "**Musta Hevonen – Ydinvoima ja Ilmastonmuutos**", published in 2016, which was translated and published in English in 2020 as "**The Dark Horse – Nuclear Power and Climate Change**". In 2017, Rauli and Aki Suokko wrote "**Energian Aika – Avain talouskasvuun, hyvinvointiin ja ilmastonmuutokseen**", or "**The Age of Energy**" which won the Science Book of the Year award in Finland and will soon be published in English as well.

Rauli has written multiple studies and reports on energy and climate, and dozens of articles in multiple national and international publications. He is a frequent speaker in climate and energy seminars and conferences, and as one of the co-founders of The Ecomodernist Society of Finland, has organized a few international seminars himself as well. In 2018 he co-founded Think Atom (thinkatom.net), an independent and non-profit think tank, which he has been the head of since then.

Olli Soppela

Olli Soppela has a BSc in Environmental Engineering and MSc in Electrical Engineering, focusing on the study and research of advanced energy systems. Olli has just finished his Master's Thesis in Aalto University on the topic of "**Possibilities of hydropower to balance Nordic electricity markets**" where system impacts of increasing VRES generation and hydropower demand are modelled.

His professional background includes international resource-efficiency engineering projects and construction management of infrastructure projects while the interest is starting to lean more and more towards advancing the use of nuclear generation technologies.

One Billion Tons

CO_2 Reductions and a Faster Coal Exit in Germany

Germany can avoid a staggering 60 million tons of CO_2 emissions each year. How? By keeping its remaining 6 nuclear reactors open and closing down coal and lignite production instead.

Despite all the ambitions and promises, Germany is falling short in meeting its own climate goals. This is no wonder as the country has closed down low-carbon nuclear power plants, with the last ones scheduled to permanently shut down in 2022. However, the remaining six reactors could operate for an additional 20 years or longer, well into the 2040s. This would avoid up to One Billion Tons of CO_2 emissions. This report shows the data and rationale for cutting CO_2 emissions with nuclear power.

"This report puts numbers on this price to be paid for the first time - a nice round number of a billion tons. That is opportunity cost of closing down remaining nuclear early in Germany while keeping coal alive for nearly two more decades, as the anti-nuclear lobby demands. Islands will drown, coral reefs will die - but the anti-nuclear lobby must be appeased."

From the Foreword by Mark Lynas,
Author of Our Final Warning: *Six Degrees of Climate Emergency*

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