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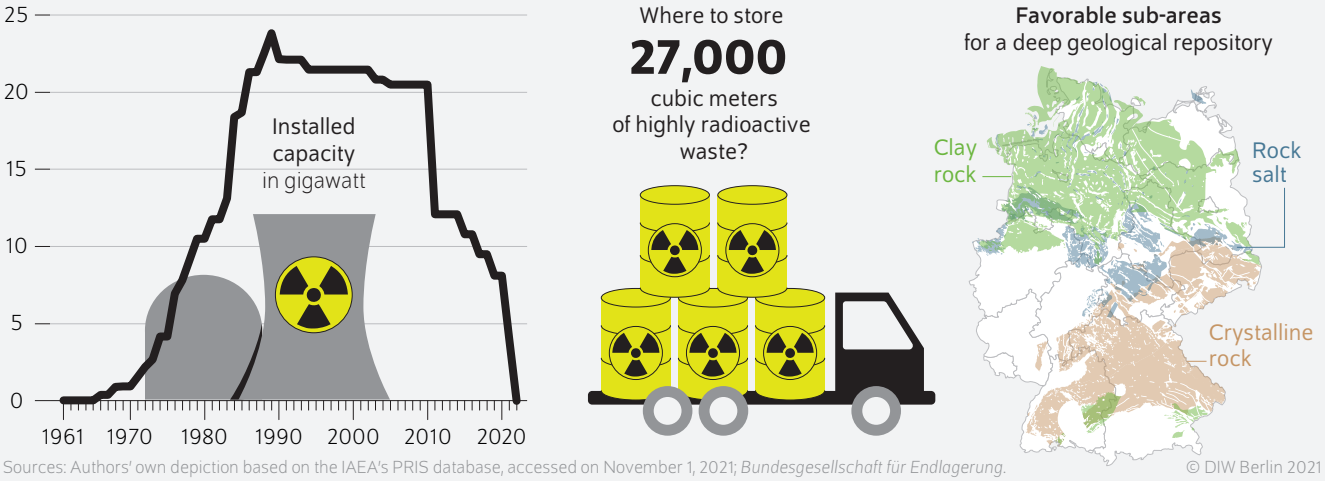
AT A GLANCE

Nuclear turn: Closing down nuclear power plants opens up prospects for the final repository site search

By Mario Kendziorski, Claudia Kemfert, Fabian Präger, Christian von Hirschhausen, Robin Sogalla, Björn Steigerwald, Ben Wealer, Richard Weinhold, and Christoph Weyhing

- The closure of the six remaining nuclear power plants in Germany is unproblematic for the energy sector
- There is sufficient capacity in the short and medium term; supply security is guaranteed
- An increase in carbon emissions is expected, which can be combated by accelerating renewable energy expansion
- The closures are necessary for successfully selecting a final repository site for highly radioactive waste
- Subsidies for nuclear power should be ended and not reintroduced elsewhere in Europe

Nuclear turn: final repository site search is the next step after shutting down nuclear power plants



Sources: Authors' own depiction based on the IAEA's PRIS database, accessed on November 1, 2021; *Bundesgesellschaft für Endlagerung.*

FROM THE AUTHORS

"The shutdown of the final six nuclear power plants is the end of a historic attempt to use a dangerous and expensive energy source in Germany. Supply security should not be threatened. We now need to focus on the next steps of the nuclear turn, especially safely disposing of radioactive waste."

— Christian von Hirschhausen —

MEDIA

Audio Interview with Christian von Hirschhausen (in German)
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Nuclear turn: Closing down nuclear power plants opens up prospects for the final repository site search

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ABSTRACT

With the closure of the final six nuclear power plants, the commercial use of nuclear energy for electricity generation in Germany will come to an end in 2022. Due to the German power system's sufficient capacities—in 2020, the sector exported 20 terawatt hours (TWh), or about four percent of its electricity production—and its integration into the European electricity system, there is no reason to fear a lack of supply security. According to model calculations, the impact on electricity flows and local supply and demand situations will remain minimal. This closure is also necessary to gain societal acceptability for a final repository site for radioactive waste. Following several unsuccessful attempts, the search is now concretely on the agenda with the Repository Site Selection Act of 2017, and a site is to be decided upon by 2031. However, the nuclear turn goes beyond closures and the disposal of radioactive waste: Existing nuclear subsidies must be eliminated as well, and new ones avoided.

According to the Thirteenth Amendment to the Atomic Energy Act of 2011, the Brokdorf, Grohnde, and Gundremmingen C nuclear power plants, with a total of around four gigawatts (GW) of net capacity, will be closed down by the end of 2021.[1] At the end of 2022, the closure of the final three remaining plants—Neckarwestheim, Isar 2, and Emsland, also with a total of around four GW net capacity—will follow. Overall, these six power plants have a total of around eight GW net capacity and generated 11.3 percent of German electricity in 2020.[2]

Nuclear power was developed during the postwar period. Initially, there were hopes of utilizing it for electricity generation in addition to its military uses.[3] However, nuclear power failed to become economically competitive.[4] In particular, the transition to fast breeder technology, on which the original hopes for commercial use were based, did not occur.[5] Therefore, following an initial phase of excitement, the construction of nuclear power plants in Germany came to a standstill in the 1980s (Figure 1). Following considerable controversy and a brief lifespan extension, the 2002 nuclear consensus, an agreement on ending the commercial use of nuclear power, was confirmed in 2011 and specific closure dates for nuclear power plants were specified.

Closing down nuclear power plants in Germany has had no significant impact on the electricity flows and supply

1 "Thirteenth Amendment to the Atomic Energy Act of 2011", *Federal Law Gazette* part 1, no. 43, G5702 (Bonn: Deutscher Bundestag, 2011) (in German; available online. Accessed on November 3, 2021. This applies to all other online sources in this report unless stated otherwise.).

2 See AG Energiebilanzen, *Stromerzeugung nach Energieträgern 1990 – 2020* (2021) (in German; available online).

3 Joachim Radkau and Lothar Hahn, "*Aufstieg und Fall der deutschen Atomwirtschaft*", (Munich: Oekom Verlag, 2013) (in German).

4 See the analyses by Fritz Baade, *Welt-Energiewirtschaft: Atomenergie – Sofortprogramm oder Zukunftsplanung* (Hamburg: Rowohlt, 1958); Lucas W. Davis, "Prospects for Nuclear Power", *Journal of Economic Perspectives* 26, no. 1 (2012): 49–66, (available online); as well as Ben Wealer et al., "Investing into third generation nuclear power plants – Review of recent trends and analysis of future investments using Monte Carlo Simulation", *Renewable and Sustainable Energy Reviews* 143 (2021) (available online).

5 Joachim Radkau, "*Aufstieg und Krise der deutschen Atomwirtschaft 1945-1975: Verdrängte Alternativen in der Kerntechnik und der Ursprung der nuklearen Kontroverse*", (Reinbek bei Hamburg: Rowohlt, 1983) (in German).

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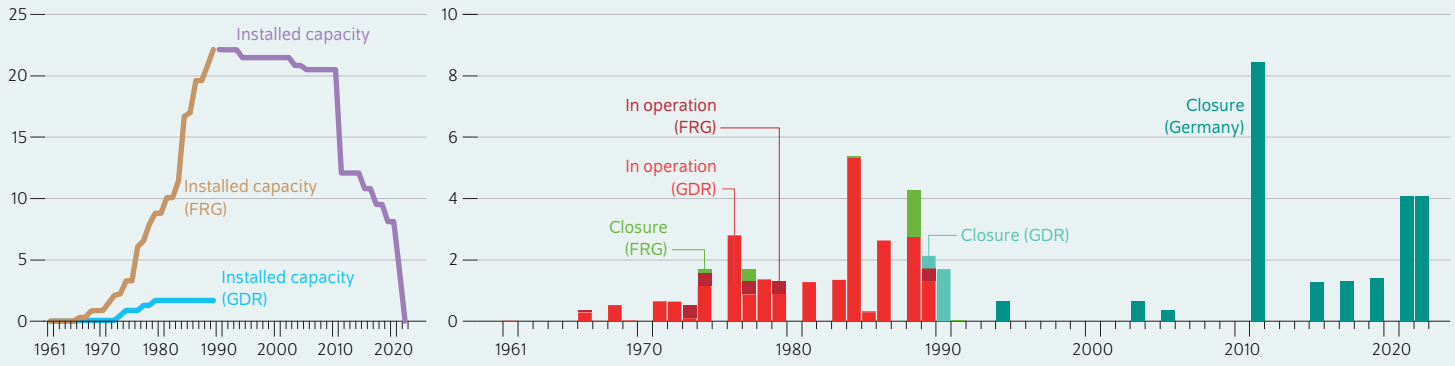
Figure 1

Development of nuclear power in Germany (1961–2022)
In GWe



Sources: Authors' own calculations based on IAEA's PRIS database, accessed on November 1, 2021.

There was a stark increase in nuclear power plant construction in the 1970s and 80s. Since 2011, there has been a sharp decline.

security in the past.[6] This was even the case when six older plants were closed down in March 2011, as the price of electricity returned to its original level after only a brief increase of a few euros per megawatt hour (MWh). Moreover, recent studies show that renewable energy expansion is more cost effective than nuclear energy expansion.[7] One reason for this is nuclear power plants' lack of reliability; they are forced to interrupt operations regularly for fuel changes or due to technical problems.[8]

Closing the remaining six nuclear power plants reduces the risks this technology poses to people and the environment in Germany. However, the nuclear phase-out is far from finished. There are still nuclear risks that require further, systematic steps in Germany, in Europe, and worldwide. The Federal Ministry for Environment, Nature Conservation, and Nuclear Safety (*Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit*, BMU) has outlined these steps in the form of 12 specific actions to be taken.[9] Above all, com-

6 See the study by Friedrich Kunz et al., "Security of Supply and Electricity Network Flows after a Phase-out of Germany's Nuclear Plants: Any Trouble ahead?", RSCAS Working Papers (2011) (available online); Friedrich Kunz and Hannes Weigt, "Germany's Nuclear Phase Out – A Survey of the Impact since 2011 and Outlook to 2023", *Economics of Energy & Environmental Policy* 3, no. 2 (2014) (available online). For a discussion on supply security, see Kunz et al., "Mittelfristige Strombedarfsdeckung durch Kraftwerke und Netze nicht gefährdet", DIW Wochenbericht, no. 48 (2013): 25-37 (in German; available online). For a discussion on the effects of shutting down the KKW Grafenrheinfeld in 2015, see Christian von Hirschhausen et al., "Atomausstieg geht in die nächste Phase: Stromversorgung bleibt sicher – Große Herausforderungen und hohe Kosten bei Rückbau und Endlagerung", *DIW Wochenbericht*, no. 22 (2015): 523-531 (in German; available online).

7 See Behrang Shirizadeh and Philippe Quirion, "Low-Carbon Options for the French Power Sector: What Role for Renewables, Nuclear Energy and Carbon Capture and Storage?", *Energy Economics* 95 (2021): 105004 (available online).

8 See Ben Wealer et al., "Ten years after Fukushima: Nuclear energy is still dangerous and unreliable", *DIW Weekly Report*, no. 7/8 (2021): 53-61 (available online).

9 See Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, "12 Punkte für die Vollendung des Atomausstiegs – die Position des Bundesumweltministeriums". Position Paper (2021) (in German; availabe online).

Box

Power Market Tool (POMATO)

On an hourly basis, the POMATO[1] energy market model finds the minimum-cost combination of generation capacity to serve electricity demand. The resulting power plant input must additionally meet technical constraints. In particular, storage utilization, heat demand, energy exchanges with neighboring countries, and the varying availability of renewable energy is considered in great detail.

In line with real market conditions, the model calculations consist of two steps. In the first step, the supply is determined according to the demand, with the power generation capacities outside of Germany being aggregated to individual nodes. Only transport capacities (net transfer capacities) between neighboring market areas are taken into account. In the second step, congestion management takes place, which adjusts power plant use so that all electricity flows are within the parameters allowed for secure grid operation. Unlike in the actual congestion management process, renewable energy is considered simultaneously, which tends to lead to underestimating the necessary adjustments.

The electricity market and congestion management are modeled in hourly resolution for an entire year. 2019 serves as the weather year for load and availabilities of wind and PV power generation.

1 Richard Weinhold and Robert Mieth, *Power Market Tool (POMATO) for the Analysis of Zonal Electricity Markets* (2020) (available online); as well as Richard Weinhold, *Evaluating Policy Implications on the Restrictiveness of Flow-based Market Coupling with High Shares of Intermittent Generation: A Case Study for Central Western Europe* (2021) (available online).

Figure 2

Regional distribution of the remaining six nuclear power plants in Germany

Source: Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety.

Three of the remaining six nuclear power plants are located in the northwest of Germany and three are in the south.

mercial nuclear power must be ended to achieve the societal acceptability necessary for the disposal of highly radioactive waste. Following the Repository Site Selection Act (*Standortauswahlgesetz*), a decision on a final repository site is to be made by 2021. It is in the interest of the entire population, especially of those who live in the vicinity of current interim storage facilities, that the decision is rapidly implemented once it has been made.[10]

Few short-term effects on the energy sector

For the short-term analysis, a simultaneous closing of all six remaining nuclear power plants is assumed for simplicity (Figure 2) and it is investigated which electricity flows are expected to be covered by which other energy sources. For this purpose, the electricity market and network model POMATO (Power Market Modeling Tool) is used, which maps the German and European electricity markets in great detail (Box).

In the reference scenario, the six remaining power plants are still in operation. In the nuclear-free scenario, they are closed completely. By comparing both scenarios, the effects on electricity flows and market results become clear.

Nuclear energy primarily replaced by fossil fuels in the short term

Following the closure of the remaining nuclear power plants, there will be sufficient capacities from fossil fuels and renewable energy to meet the annual peak load of almost 80 GW.[11] In 2019, nuclear power plants generated 71.0 terawatt hours (TWh) of electricity net, or 85 percent of capacity.[12] This amount must be absorbed by another energy source or imports.

The respective production costs for additional electricity (incremental costs) as well as the existing capacities influence which energy sources are used on the electricity market (Figure 3). Because renewable energy has lower incremental costs than nuclear, it is barely affected by the closure of nuclear power plants. Nuclear energy will mainly be replaced by fossil fuels and more imports, which will increase by around 15 TWh.

Overall, this will result in an increase in carbon emissions of about 40 million tons in Germany. This estimate represents the upper limit, as the model calculations do not take further changes in the electricity system into account.[13]

Power grid congestion management increasing slightly

The closure will result in different electricity flows due to changes in the use of fossil fuels and additional imports. To maintain stable grid operation, nuclear power plant feed-ins must be regionally lowered or increased (congestion management). In the reference scenario, 14 TWh of electrical energy is spent on congestion management, which is close to the value estimated by the Federal Network Agency in

10 "Gesetz zur Fortentwicklung des Gesetzes zur Suche und Auswahl eines Standortes für ein Endlager für Wärme entwickelnde radioaktive Abfälle und anderer Gesetze", *Federal Law Gazette* part 1, no. 26, G5702 (Bonn: Deutscher Bundestag, 2017) (in German; available online).

11 The installed capacity data are based on Federal Network Agency, "*Installierte Erzeugungsleistung. SMARD Strommarktdaten*" (2021) (in German). The peak load data are based on Bundesverband der Energie- und Wasserwirtschaft, "*Jahresvolllaststunden 2019/2020* (2020)" (in German; available online).

12 See AG Energiebilanzen, "*Stromerzeugung nach Energieträgern 1990 – 2020*" (in German; available online).

13 Robin Sogalla et.al., "The effect of Germany's nuclear phaseout on CO_2 emissions: A theoretical decomposition analysis", (2021) (mimeo).

2019 (see Figure 4).[14] Between 2016 and 2020, the value fluctuated between 11 TWh and the maximum of 18 TWh. In the nuclear-free scenario, the value rises to 18 TWh, which is at the upper end of the fluctuation range of recent years.[15]

Measures to manage congestion differ regionally. In the reference scenario, nuclear power plants in the west and south of Germany must increase their output while plants in the east must decrease output in order to maintain stable grid operation. In the scenario without nuclear power plants, capacity in the west must be increased while it must be decreased in the east (see Figure 5).

Supply security also guaranteed in the long term with the expansion of renewable energy

In the long term—beyond 2030—supply security is guaranteed by forward-looking network and electricity generation planning. Germany has committed to achieving a carbon-neutral energy supply by 2045, with renewable energy expansion and the phasing out of fossil fuels and nuclear energy at the core of this transition.[16] The transition also entails extensively electrifying the transport and heating sectors as well as industry in the long term (often referred to as sector coupling) so that electricity consumption increases. Efficiency strategies can partially counteract this trend. Multiple current studies show that a completely renewable energy system is possible and can cover the increasing electricity.[17]

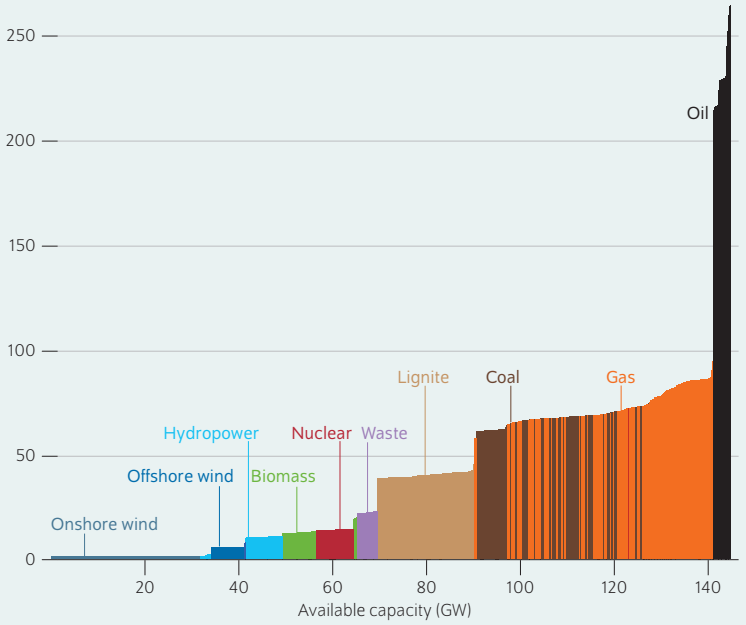
Some calculations using the AnyMOD modeling framework, which enables an hourly representation of the electricity sector and simultaneous optimization of the operational planning in other energy sectors, show that supply security is still guaranteed in the 2030s if renewable energy is expanded (Figure 6).[18]

By 2030, the use of coal-fired electricity will have declined almost completely. Throughout the same decade, the use of fossil fuels will decline sharply. In contrast, the amount of electricity generated by both on and offshore wind turbines as well as from photovoltaics will increase starkly until the target year of 2040, when the energy sector will be completely renewable.

Figure 3

Available generation capacity for one hour during the night along the variable generation costs

Cost structure of the German electricity market, marginal generation costs (euro/MWh)



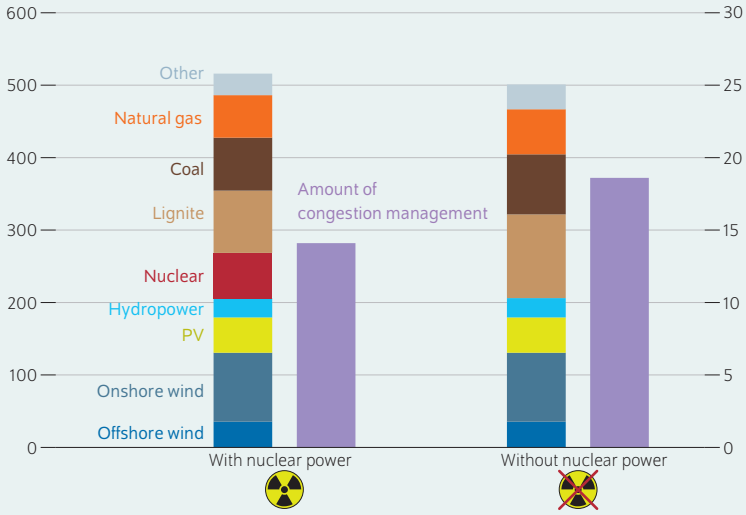
Source: Authors' own depiction.

The nuclear power plant capacity used will be shifted.

Figure 4

Generation volume per technology and scenario aggregated for 2021

In terawatt hours, the second axis measures congestion management for the corresponding scenario



Source: Authors' own calculations.

By closing the nuclear power plants, the amount of power generated by lignite and coal plants will increase, as will the amount of imports.

14 See Federal Network Agency, *Monitoringbericht 2019* (Bonn: 2020) (in German; available online).

15 See Federal Network Agency, *Monitoringbericht 2019*.

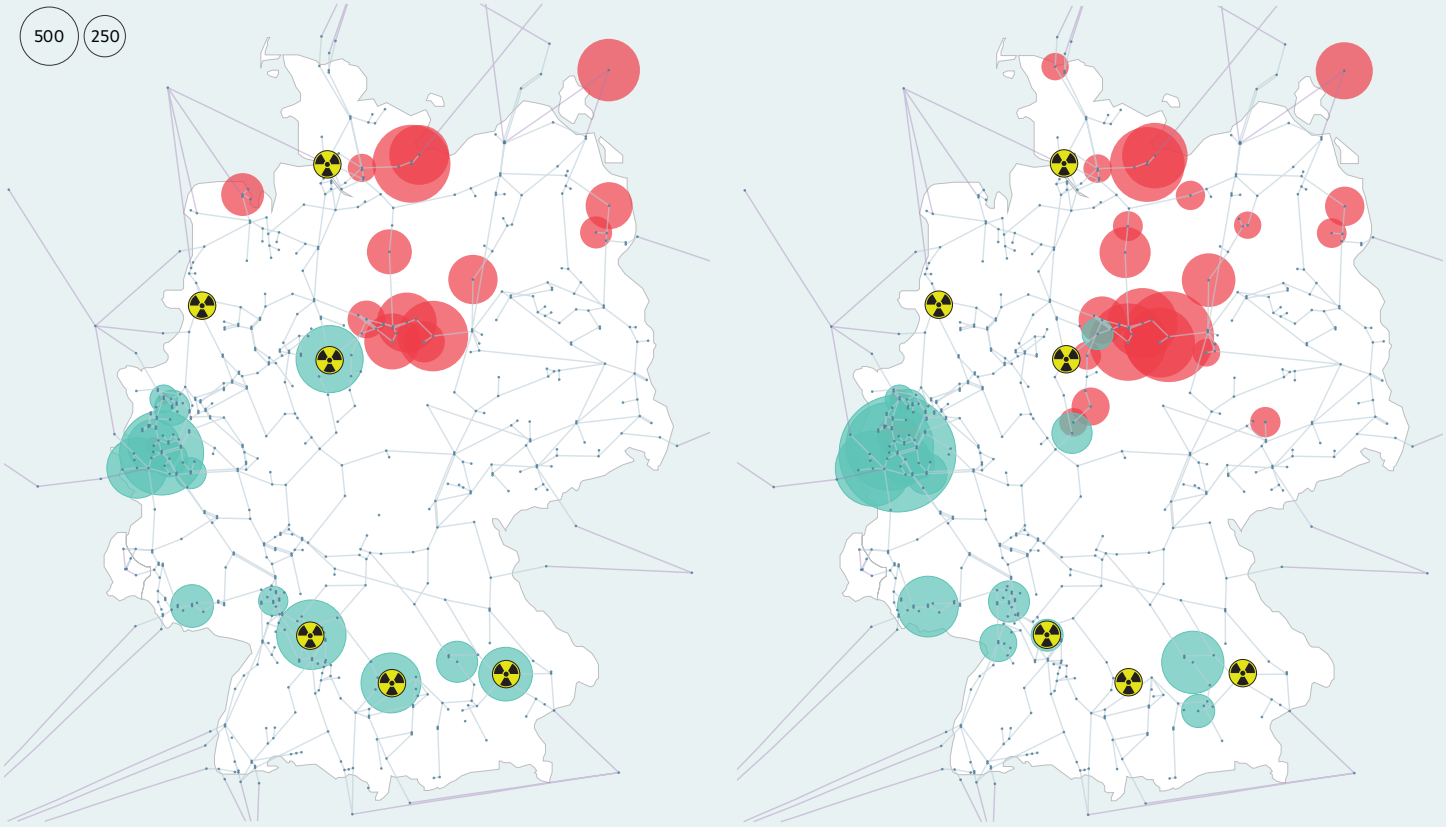
16 Deutscher Bundestag, "Entwurf eines Ersten Gesetzes zur Änderung des Bundes-Klimaschutzgesetzes", *Bundestags-Drucksache* 19/30230 (2021) (in German; available online).

17 Wuppertal Institute, *"CO2-neutral bis 2035: Eckpunkte eines deutschen Beitrags zur Einhaltung der 1,5-°C-Grenze"* (Wuppertal: 2020) (in German; available online); Prognos, Öko-Institut, and Wuppertal Institute, *Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann* (2021) (in German; available online).

18 Based on Mario Kendziorski et.al., "The economics of NPP lifetime extensions – Conceptual approach and lessons from electricity sector modeling in the US, France, and Germany. IAEE Paris 2021 (available online).

Figure 5

Adjustment measures to maintain the power grid
Start up of power plants in green, closure of nuclear power plants in red, with locations of nuclear power plants in blue



Source: Authors' own depiction.

Structural congestion in the power grid will still exist after the nuclear power plants are closing down, but it will not be caused by the closure.

Search for final repository site is the next step

The end of the commercial use of nuclear energy is also a necessary pre-condition for a successful radioactive waste disposal process. Ending its use limits the amount of radioactive waste, which enables concrete logistics planning and the planning of repository formations.

The search for a suitable disposal site for 27,000 cubic meters of highly radioactive waste by 2031 and the subsequent construction of a repository is a complex problem with considerable socio-technical challenges.[19] The repository site must be designed to store nuclear waste safely for more than one million years. Especially in the site selection process, transparency and public participation are important for avoiding societal conflicts in the future and finding an acceptable site. For this purpose, the *Endlagerkommission* (Final Storage Site Commission) has developed key recommendations which were included in the Amendment to the Repository Site Selection Act in 2017.[20] Accordingly, the site selection process is to be carried out "in an open-ended, transparent manner, according to legally defined technical criteria and with the participation of the public."[21] Public participation is the responsibility of the Federal Office for the Safety of Nuclear Waste Management (*Bundesamt für die Sicherheit der nuklearen Entsorgung*, BASE), which monitors the site selection procedure. By the end of 2021, the sub-areas conference (*Fachkonferenz Teilgebiete*) was held by BASE,[22] which is to

19 See Achim Brunnengräber, *"Ewigkeitslasten: die „Endlagerung" radioaktiver Abfälle als soziales, politisches und wissenschaftliches Projekt: eine Einführung."*, Vol. 2 (Baden-Baden: Nomos, 2019) (in German).

20 See Kommission Lagerung hoch radioaktiver Abfallstoffe, *"Abschlussbericht der Kommission zur Lagerung hochradioaktiver Abfälle"* (Berlin: 2016) (online verfügbar) Berlin (2016) (in German; available online).

21 See Federal Office for the Safety of Nuclear Waste Management, information platform on the final repository site search (in German; available online).

22 For an overview of the *Fachkonferenzen* results, see Fachkonferenz Teilgebiete, *"Bericht der Fachkonferenz Teilgebiete"* (2021) (in German; available online) and for a scientific monitoring of the process, Dörte Themann et al., "Alles falsch gemacht? Machtasymmetrien in der Öffentlichkeitsbeteiligung bei der Standortsuche für ein Endlager", *Forschungsjournal soziale Bewegungen* 1 no. 34 (2021) (in German; available online).

be followed by further procedural steps until the repository site is determined by the *Bundestag* in 2031.

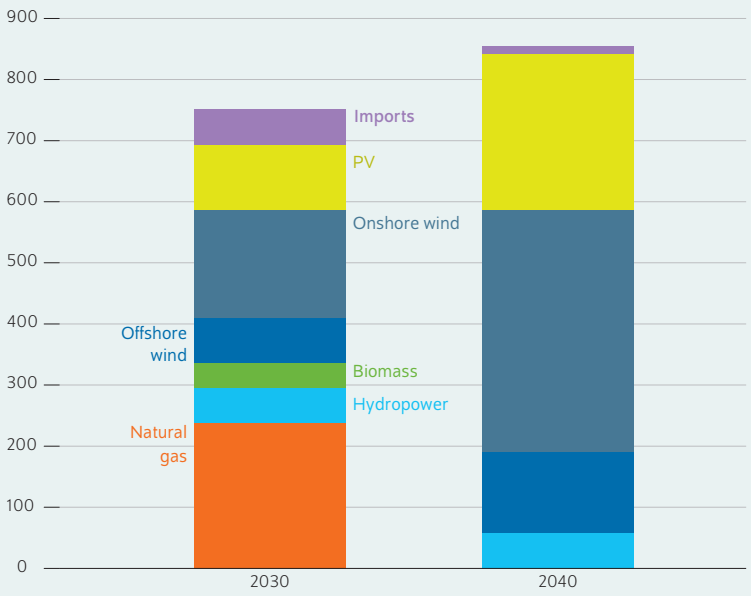
Societal acceptability for the construction of a repository will only come if the end of commercial use of nuclear energy, as has been decided politically and made law, continues. The Federal Office for Radiation Protection (*Bundesamt für Strahlenschutz*) identified this nexus 20 years ago when a new attempt was made to find a final repository site.[23] BASE, which is also the regulatory authority for the repository site search, has also recently highlighted this nexus.[24]

Further steps necessary until the end of commercial nuclear power

In the public discussion, it is often implied that the upcoming closure will be the end of the nuclear turn. However, that is not the case: The closure is just another step in the phase-out, which is only one part of the transformation to a 100 percent renewable energy system. Further steps in the nuclear power phase-out will be more highly prioritized in the future, such as the closures of the remaining fuel fabrication facility in Lingen and the uranium enrichment facility in Gronau.[25] A systematic nuclear power phase-out also includes Germany's commitment against lifetime extensions as well as against investments in new nuclear power plants, both in the European and international context.[26] This implies that, in the context of EU taxonomy discussions, Germany must continue to work to ensure that no public money flows into nuclear energy. Furthermore, the points made by the BMU in its position paper, including that nuclear energy is not a viable option for combating climate change or for meeting climate targets, should be implemented[27]: It is "too expensive, too dangerous, and too slow to expand to meet a substantial share of the worldwide primary energy consumption" and poses the unsolved, global problem of final repository sites for highly radioactive waste.[28]

Figure 6

Long-term electricity generation in Germany
Annual generation in TWh



Sources: Authors' own calculations based on Hainsch et al. (2020) and Kendziorski et al. (2021).

Long-term energy supply is guaranteed even without nuclear power and with sharply declining carbon emissions.

Conclusion

With the closure of the last remaining nuclear power plants in Germany, a period characterized by technical risks, high costs, and unsolved conflicts regarding the interim and final storage of radioactive waste is coming to an end. Following the largely event-free closures of older nuclear power plants since 2011, it is expected that the new shutdowns will have little impact on the energy system in the two years following. In particular, regional electricity flows will not change significantly, and grid congestion is likely to intensify only slightly, if at all. In the short term, an increase in carbon emissions from the energy sector is to be expected in 2022 and 2023, which should be able to be rapidly reduced by accelerating the expansion of renewable energy. Supply security is also not endangered in the medium term as long as the German energy system rapidly switches to renewable energy for energy storage and flexibility options. Its integration into the European energy system remains significant for efficiency and coordination reasons.

The closure of the remaining nuclear power plants is necessary to gain societal acceptability for a repository site selection process and for the process to succeed. A renewed debate about this endangers the already fragile public participation process. Moreover, a systematic nuclear power phase-out requires the closures of the uranium enrichment facility in Gronau and the fuel fabrication facility in Lingen as well as an increase in security and radiation protection from power

23 In Wolfram König, "Atommüll und sozialer Friede – Strategien der Standortsuche für nukleare Endlager". Speach at the conference of the Evangelischen Akademie Loccum. 9th of February 2003 (in German; available online).

24 See BASE, "*Der Ausstieg aus der Nutzung der Kernenergie ist zentrale Voraussetzung für eine erfolgreiche Suche nach einem Endlager*" (in German; available online).

25 Urenco, a British-Dutch-German firm, enriches uranium in Gonrau. In Lingen, a subsidary of the French firm Framatome produces fuel elements for use in nuclear power plants worldwide, including the new Finnish power plant Olkiluoto-3.

26 See the expert opinion of BASE on the Joint Research Center (in German) *Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 Taxonomy Regulation (2021)* (available online) ; as well as Christoph Pistner, Matthias Engler and Ben Wealer, "Sustainable at risk – A critical analysis of the EU Joint Research Centre technical assessment of nuclear energy with respect to the "do no significant harm" criteria of the EU Taxonomy Regulation". Brüssel 2021 (available online).

27 Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, *12 Punkte für die Vollendung des Atomausstiegs – die Position des Bundesumweltministeriums* (in German; available online).

28 Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, *12 Punkte für die Vollendung des Atomausstiegs.*

plants near the German border. To monitor the nuclear power phase-out process, systematic "nuclear power phase-out monitoring" should be developed and carried out regularly.

Currently, a group of EU countries, led by France, is attempting to have nuclear energy included in the taxonomy, thus giving it a sustainability label.[29] In this context, the outgoing and incoming German federal governments must prevent nuclear energy from being included in the EU taxonomy as an equally "sustainable" technology. To this end, Germany should strengthen its alliance with other important countries and emphasize the socio-technical advantages of an energy system without nuclear power. By preventing the greenwashing of nuclear energy at a European level, the Federal Government is increasing the welfare of both Germany and the EU.

29 For example, ministers from ten countries heavily reliant on nuclear power, including France, Bulgaria, Finland, Romania, Slovakia, Croatia, the Czech Republic, Hungary, and Poland, have called for nuclear energy to be included in the taxonomy. See Kira Taylor, "EU-Länder machen Druck, um Kernenergie als „grüne" Investition auszuzeichnen", *Euractiv* (2021) (in German; available online).

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