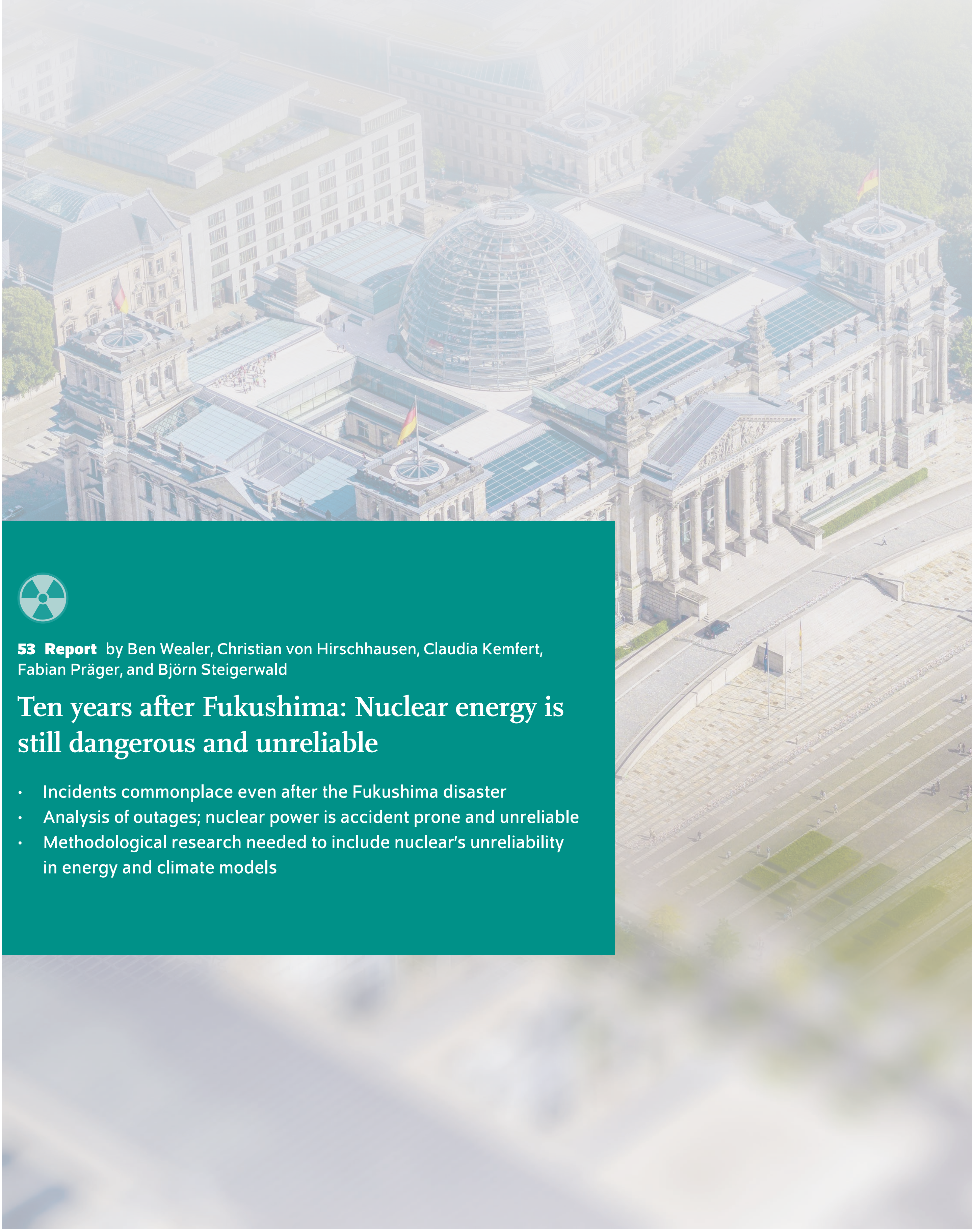
DIW Weekly Report

A policy bulletin from the German Institute for Economic Research

7+8 2021

Economy. Politics. Science.

DIW BERLIN



53 **Report** by Ben Wealer, Christian von Hirschhausen, Claudia Kemfert, Fabian Präger, and Björn Steigerwald

Ten years after Fukushima: Nuclear energy is still dangerous and unreliable

- Incidents commonplace even after the Fukushima disaster
- Analysis of outages; nuclear power is accident prone and unreliable
- Methodological research needed to include nuclear's unreliability in energy and climate models

LEGAL AND EDITORIAL DETAILS

DIW BERLIN

DIW Berlin — Deutsches Institut für Wirtschaftsforschung e. V.
Mohrenstraße 58, 10117 Berlin
www.diw.de
Phone: +49 30 897 89 – 0 Fax: – 200
Volume 11 March 1, 2021

Publishers
Prof. Dr. Tomaso Duso; Prof. Marcel Fratzscher, Ph.D.; Prof. Dr. Peter Haan; Prof. Dr. Claudia Kemfert; Prof. Dr. Alexander S. Kritikos; Prof. Dr. Alexander Kriwoluzky; Prof. Dr. Stefan Liebig; Prof. Dr. Lukas Menkhoff; Dr. Claus Michelsen; Prof. Karsten Neuhoff, Ph.D.; Prof. Dr. Carsten Schröder; Prof. Dr. C. Katharina Spieß; Dr. Katharina Wrohlich

Editors-in-chief
Dr. Gritje Hartmann; Dr. Anna Hammerschmid (Acting editor-in-chief)

Reviewer
Jan Stede

Editorial staff
Marten Brehmer; Rebecca Buhner; Claudia Cohnen-Beck; Kristina van Deuverden; Petra Jasper; Sebastian Kollmann; Sandra Tubik

Sale and distribution
DIW Berlin Leserservice, Postfach 74, 77649 Offenburg
leserservice@diw.de
Phone: +49 1806 14 00 50 25 (20 cents per phone call)

Layout
Roman Wilhelm, DIW Berlin

Cover design
© imageBROKER / Steffen Diemer

Composition
Satz-Rechen-Zentrum Hartmann + Heenemann GmbH & Co. KG, Berlin

ISSN 2568-7697

DIW Weekly Report 7+8 2021

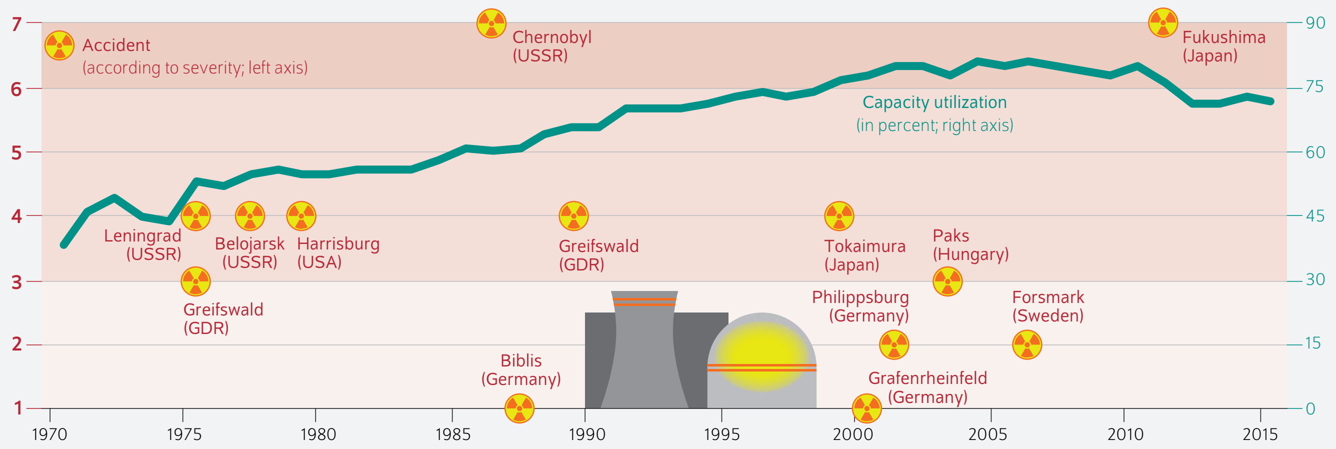
AT A GLANCE

Ten years after Fukushima: Nuclear energy is still dangerous and unreliable

By Ben Wealer, Christian von Hirschhausen, Claudia Kemfert, Fabian Präger, and Björn Steigerwald

- Analysis of global nuclear power developments, especially since the Fukushima major accident
- Since the beginning of the commercial use of nuclear power in the 1950s major incidents have repeatedly occurred
- Report investigates planned and unplanned outages; nuclear power is incident prone and unreliable
- Outages particularly frequent in France, but are a significant issue in Germany as well
- Methodological research needed to include nuclear's unreliability in energy and climate models

Numerous accidents over the past decades show the risks nuclear power poses; capacity utilization of nuclear power plants decreased after the Fukushima major accident



Source: Authors' own calculations based on PRIS and the following cited literature.

FROM THE AUTHORS

"Nuclear power has always been prone to incidents and accidents. This is evidenced not only by the major accidents, such as Fukushima and Chernobyl, but also the high outages during daily operation. Nuclear is a dangerous and unreliable energy source and therefore not promising from an economic standpoint either."
— Christian von Hischhausen —

MEDIA

Audio Interview with Ben Wealer (in German)
www.diw.de/mediathek

Ten years after Fukushima: Nuclear energy is still dangerous and unreliable

By Ben Wealer, Christian von Hirschhausen, Claudia Kemfert, Fabian Präger, and Björn Steigerwald

ABSTRACT

The catastrophic accident at the Fukushima Daiichi Nuclear Power Plant on March 11, 2011, revealed unexpected safety risks of nuclear energy once again. It also accelerated the decline of nuclear energy in the international energy sector: Nuclear energy's share of global electricity generation fell from 17 percent in 1996 to 13 percent in 2011 to approximately ten percent in 2019, with a share of primary energy from nuclear at only four percent. In addition to the regular occurrence of major nuclear accidents since 1945, nuclear power plants also experience considerable outages during normal operation: Only 66 percent of the global available capacity for nuclear power has been utilized since the 1970s. There have also been a number of incidents in Germany and its neighboring countries. Although the outages at German nuclear power plants are below the international average, they are nevertheless considerable even for the younger plants. Economic analyses have largely neglected the unreliable availability of nuclear power—so far, many energy and climate models still view nuclear power as an important source in the future. In Germany, the Fukushima major accident accelerated the nuclear phase-out, which is to occur by the end of 2022 in accordance with the Thirteenth Amendment to the Atomic Energy Act (July 2011).

March 11, 2021, is the 10th anniversary of the Fukushima Daiichi nuclear major accident an event that accelerated the decline of commercial nuclear energy's importance. In Germany, the major accident spurred on the already politically determined nuclear phase-out. After a tsunami hit the Fukushima Daiichi Nuclear Power Plant, three reactors experienced meltdowns that led to a leakage of large amounts of radioactivity, resulting in the subsequent long-term evacuation of hundreds of thousands of people. Fukushima is one in a long line of accidents and incidents at nuclear power plants (NPPs) and research reactors that began in 1945 and has continued systematically ever since (Figure 1).

Between 1965, the breakthrough of commercial NPPs, and 2019, about 93,040 terawatt-hours (TWh) were generated worldwide, 40 percent of which were produced in Europe and 35 percent in North America. Electricity generation from nuclear power plants first stabilized in the USA, and generation in Europe followed. Since the early 2000s, however, electricity generation has been stagnating in all regions except Asia. As of 2021, electricity generation from nuclear power plants has been increasing only in China.[1]

The importance of nuclear power in electricity generation has been declining worldwide. Since 2010, the year prior to the Fukushima major accident the share of nuclear power in electricity generation has fallen from 13 percent to just over ten percent in 2019 (Figure 2), equivalent to 2,796 TWh. This accelerated a downward trend that has continued since 1996, when the share was 17.5 percent. In terms of primary energy consumption, the share of nuclear power is even as low as four percent.[2] Construction of new nuclear power plants has been following a downward trend since 1978, even before major major accident such as Harrisburg (1979) in the United States and Chernobyl (1986) in Ukraine.[3] While the

1 All figures are taken from BP, *Statistical Review of World Energy* (available online; accessed on February 15, 2021. This applies to all other online sources in this report unless stated otherwise).

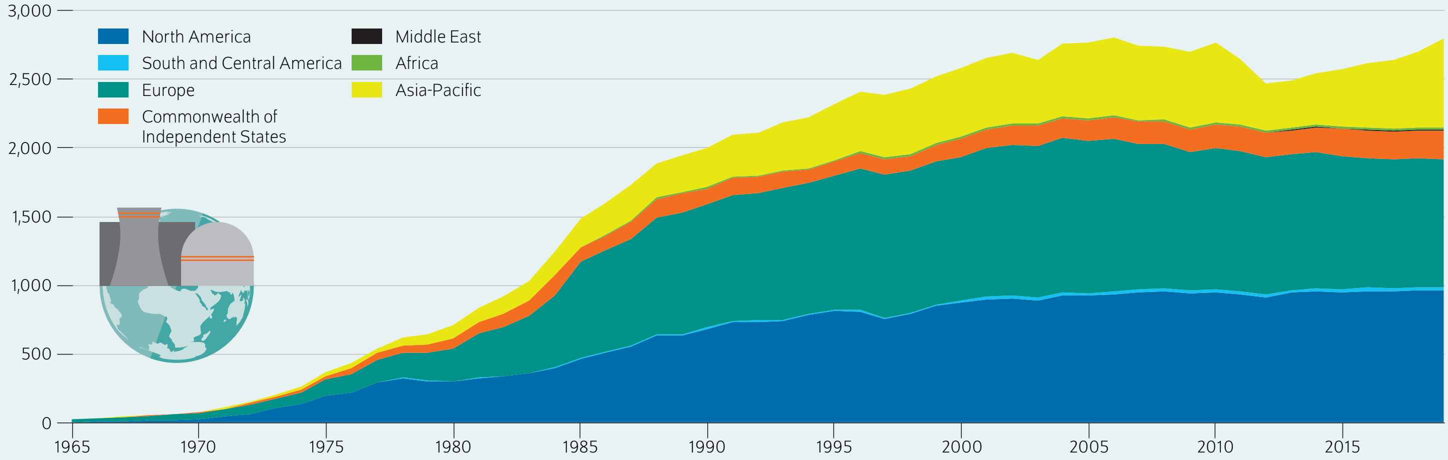
2 In contrast to other primary energy sources, nuclear power is mainly used for electricity production, but hardly for other uses, such as heat or transportation.

3 For a more detailed look at nuclear energy developments worldwide, see Ben Wealer et al., "Nuclear Power Reactors Worldwide – Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951–2017)," *Data Documentation* 93 (2018).

DOI: https://doi.org/10.18723/diw_dwr:2021-7-1

Figure 1

Nuclear power generation worldwide according to region (1965 to 2019)
In terawatt-hours



Source: BP (2020).

Nuclear power generation has been stagnating since the early 2000s.

number of new construction projects in the past years has slightly increased to a low level (especially in China), there is no nuclear energy renaissance to speak of.[4]

In 1998, Japan recorded the highest share of nuclear power in electricity generation at 31 percent. By 2010, it had declined to 25 percent. For a long time after the Fukushima major accident and continued shutdowns, the nuclear share was negligible. In 2014, all Japanese nuclear power plants were taken offline and as of 2021, nuclear power plays only a minor role in the country.

Catastrophic major accidents as well as the considerable outages during normal operation must be examined, as they are both relevant to safety and the energy supply. This Weekly Report discusses the frequency of incidents and accidents at nuclear power plants worldwide and puts the Fukushima major accident in context. In addition, the report provides insights into the significant outages at nuclear power plants, both globally and specifically in France and Germany. Nuclear energy is an unreliable source of energy, a fact that has been long underestimated, even in energy and climate economics.

Nuclear energy is dangerous: incidents are commonplace

Questions of reactor safety have been at the center of the critical approach to nuclear power since the beginning of its use. Large amounts of energy and radioactive radiation are created in nuclear reactors during the production process, which continues long after commercial use ends. Therefore, three safety objectives must be observed over very long periods of time:[5] confining radioactive fuel elements and other materials, monitoring reactivity, and removing the heat generated in the reactor cores and the cooling of the fuel elements.

Despite the apparent necessity to develop commercial nuclear power plants in tandem with safety aspects, questions of reactor safety and of commercial use were discussed separately at the beginning of the nuclear age.[6] In addition, fundamental questions about nuclear risks have been displaced by socializing accident risks. Both the energy and insurance industry assumed when commercial nuclear power was developed that society must bear these risks.[7] This fact still applies today: Risks stemming from nuclear energy are uninsurable, with nuclear power plant operators only bearing symbolic liability.[8]

Incidents and accidents have repeatedly occurred since the beginning of the nuclear age, sometimes significantly impacting people and the environment. While catastrophic

4 Cf. Lars Sorge et al., "Nuclear Power Worldwide: Development Plans in Newcomer Countries Negligible," DIW *Weekly Report* 11 (2020): 164–72 (available online).

5 Cf. Julia Mareike Neles and Christoph Pistner, "Kernenergie: eine Technik für die Zukunft?" *Technik im Fokus* (2012) (in German).

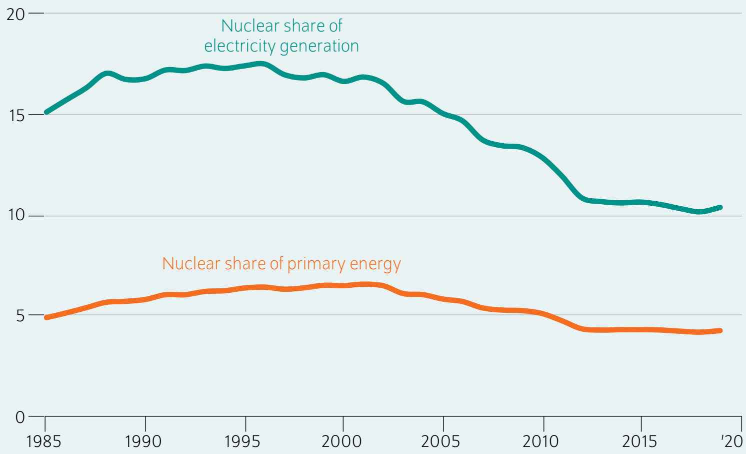
6 This also applied to Germany, where reactor safety comprised less than one percent of the federal budget's total spending on nuclear technology until the mid-1960s. Cf. Joachim Radkau, *Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975: Verdrängte Alternativen in der Kerntechnik und der Ursprung der nuklearen Kontroverse* (Reinbek bei Hamburg: Rowohlt, 1983) (in German), especially Chapter IV: "Die Enthüllung der Sicherheitsproblematik und die verspätete Reaktion der Gesellschaft."

7 Cf. Radkau, *Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975*, 389.

8 Also see Jochen Diekmann, "Verstärkte Haftung und Deckungsvorsorge für Schäden nuklearer Unfälle – Notwendige Schritte zur Internalisierung externer Effekte," *Zeitschrift für Umweltpolitik und Umweltrecht* 34, no. 2 (2011): 119–126 (in German).

Figure 2

Nuclear share of worldwide electricity generation and of primary energy (1985 to 2019)
In percent



Source: BP (2020).

The nuclear share is low and trending downwards.

major accident such as Fukushima or Chernobyl are rare, a large number of incidents and major accidents occur every decade (Figure 3).

Fatal accidents due to accidental exposure to radiation occurred in 1945 and 1946 during the development of the atomic bomb in Los Alamos, USA (The Manhattan Project).[9] Such accidents continued to occur at commercial nuclear energy and research reactors as development progressed over the 1950s: An accident due to a partial core meltdown in Chalk River, Canada, in 1952 had wider consequences.[10] In 1957, fuel cladding in the reactor core at the Windscale facility in Great Britain caught fire and took many days to be extinguished.[11] That same year, a tank with radioactive material exploded at the Mayak complex (near Chelyabinsk, Soviet Union), releasing a significant amount of radiation into the environment.[12]

In 1961, the SL-1 reactor, an experimental nuclear power reactor in Idaho Falls, USA, went prompt critical and exploded due to improper withdrawal of the central control rod.[13] Fermi 1, a fast breeder reactor, suffered a partial fuel meltdown due to cooling issues in 1966.[14] In 1975, the partial destruction of a reactor core at the Leningrad Nuclear Power Plant (Soviet Union) resulted in the release of radiation. Similarly, in 1977, a serious accident occurred at the Beloyarsk Nuclear Power Station (Soviet Union) due to a partial meltdown of the reactor.[15] Two main feed water pumps failed at the Three Mile Island Nuclear Power Plant in Harrisburg, Pennsylvania, USA, in 1979; operator errors in reactor cooling caused a partial core meltdown and the release of large quantities of radioactive gases.[16]

Both the Fukushima and Chernobyl major accident have been classified as “catastrophic” by the IAEA (INES Level 7). The Chernobyl major accident happened on April 26, 1986, when a drastic power increase occurred during a safety test, leading to the explosion of reactor No. 4 and subsequent long-lasting fires. Thousands of liquidators—civil and military personnel tasked with handling the immediate aftermath—were exposed to radiation during the rescue operations. A radioactive cloud spread across northern Ukraine and Belarus, reaching as far as Central and Western Europe.[17]

In 1999, an uncontrolled chain reaction occurred at the Tokaimura nuclear facility in Japan after workers filled a preparation tank with an over-enriched uranium mixture.[18] In April 2003, a “serious incident” (INES Level 3) occurred at the Paks-2 plant in Hungary when 30 fuel elements in a cleaning tank were severely damaged due to insufficient cooling.[19] In 2006, an electrical short circuit occurred at the Forsmark nuclear power plant in Sweden, causing two backup generators to fail.[20]

Methods of assessing nuclear accidents are controversial

The technical and socio-economic assessment of accidents remains controversial to this day, and there is still no uniform assessment scale for nuclear events. The International Atomic Energy Agency (IAEA) classifies events using the International Nuclear Event Scale (INES Scale), which ranges from 0 to 7.[21] The INES Scale has been criticized by both environmental organizations and the nuclear power industry.[22] After a statistical analysis of the data on nuclear accidents and incidents,

9 Cf. Edith C. T. Ruslow and Ralph Carlisle Smith, *Manhattan District History. Project Y.* (Los Alamos: The Los Alamos Project, 1947).

10 Cf. W. B. Lewis, "The accident to the NRX reactor on December 12, 1952," Canada (available online).

11 Cf. Walter C. Patterson, "Chernobyl: worst but not first," *Bulletin of the Atomic Scientists* 42, no. 7 (1986): 43–45.

12 Cf. Paul Josephson, "Minatom: Dreams of glory," *Bulletin of the Atomic Scientists* 58, no. 5 (2002): 40–47.

13 Cf. Patterson, "Chernobyl: worst but not first."

14 Cf. John G. Fuller, *We Almost Lost Detroit* (New York: 1978).

15 Cf. Minh Ha-Duong and V. Journé, "Calculating nuclear accident probabilities from empirical frequencies," *Environment Systems and Decisions* 34, no. 2 (2014): 249–258.

16 Cf. Samuel J. Walker, *Three Mile Island: A Nuclear Crisis in Historical Perspective* (Berkeley: 2005).

17 Cf. Adriana Petryna, "Chernobyl's survivors: Paralyzed by fatalism or overlooked by science?" *Bulletin of the Atomic Scientists* 67 no. 2 (2011): 30–37.

18 Cf. Edwin Lyman and Steven Dolley, "Accident prone," *Bulletin of the Atomic Scientists* 56 no. 2 (2000): 42–46.

19 World Nuclear Association, *Nuclear Power in Hungary* (2021) (available online).

20 Analysgroup, "The Forsmark incident 25th July 2006," (2007) (available online).

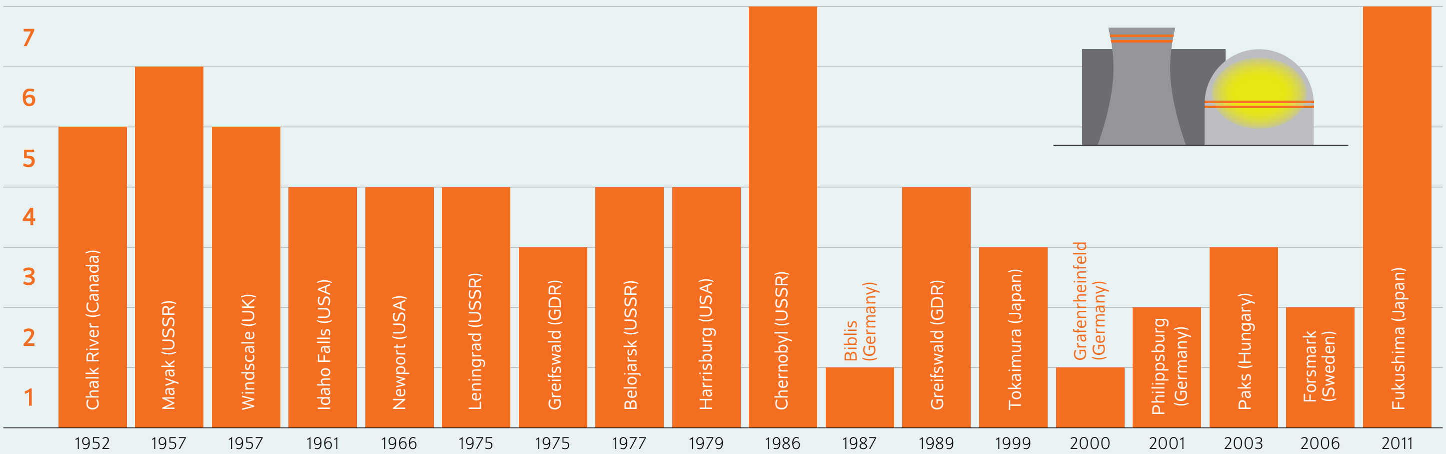
21 INES Scale: Level 0: Deviation, Level 1: Anomaly, Level 2: Incident, Level 3: Serious incident, Level 4: Accident with local consequences, Level 5: Accident with wider consequences, Level 6: Serious accident, and Level 7: Major accident. See the *Handbuch Reaktorsicherheit und Strahlenschutz – BASE*, page 4 (in German).

22 Cf. Declan Butler, "Nuclear Safety Chief Calls for Reform," *Nature* 472, no. 7,343 (2011): 274 (available online).

Figure 3

Timeline of nuclear events at nuclear power plants

According to the INES Scale



Source: Authors' own depiction according to cited literature.

Major accidents have been occurring regularly since the 1950s, even in Germany.

Wheatley et al., determined that the INES Scale is inconsistent and the scores provided by the IAEA are incomplete.[23]

Following the Fukushima major accident the IAEA—whose statutes state the organization has the task of promoting the use of nuclear power—was criticized for lacking the necessary impartiality to classify accidents.[24] One possible solution would be to use the Nuclear Accident Magnitude Scale of Radiation Release instead, which targets the radioactivity released and has no maximum upper level.[25] An economic scale using monetary assessments is also possible, but difficult to compare due to different monetization approaches.[26]

In a statistical analysis of 216 nuclear events, it was found that although they have been declining on average since the 1970s, there have been serious accidents every decade as well as smaller incidents with damages of up to 20 million USD, the expected value (occurrence) of which increases from year to year. Statistically speaking, an accident to the extent of the Fukushima major accident will occur every 60 to 150 years with 50 percent probability, and an incident such as Three Mile Island occurs every ten to 20 years.[27]

Nuclear power subject to fluctuations: NPPs have long outages and low capacity utilization

Notwithstanding the incidents, however, nuclear power is prone to failures even during normal operation and thus has low capacity utilization rates. The aggregated capital utilization factor[28] of all nuclear power plants since the 1970s is 66 percent, meaning over a third of the capacity has not been used to generate electricity, largely due to long outages.[29] The aggregated capacity utilization (Figure 4) shows that utilization was around 50 percent on average in the 1970s, the first decade of commercial nuclear power use. Thereafter, it began to rise continually. However, the highest capacity utilization values in the 2000s were only 80 percent, meaning a fifth of capacities could not be used. From the 2000s up until the Fukushima major accident capacity utilization was at around 80 percent; since 2012, it has decreased to 71 percent (Figure 4).

Numerous reasons for outages

The IAEA maintains very detailed statistics on all commercial nuclear reactors worldwide and their outages. Outages occur when the actual output power of a reactor unit is lower

23 For example, only 50 percent of the incidents in the database had INES scores. Furthermore, the authors concluded that the Chernobyl and Fukushima major accidents correspond to INES Level 10 and 11, respectively, above the highest level, Level 7. Also see Spencer Wheatley, Benjamin Sovacool, and Didier Sornette, "Of Disasters and Dragon Kings: A Statistical Analysis of Nuclear Power Incidents and Accidents," *Risk Analysis* 37, no. 1 (2017): 99–115.

24 Cf. David Smythe, "An Objective Nuclear Accident Magnitude Scale for Quantification of Severe and Catastrophic Events," *Physics Today* (2011).

25 Cf. Smythe, "An Objective Nuclear Accident Magnitude Scale."

26 Cf. Hans Jürgen Ewers and Klaus Rennings, *Abschätzung der monetären Schäden durch einen sogenannten Super-Gau* (Basel: 1992) (in German). Wheatley et al., "Of Disasters and Dragon Kings," as well as Rainer Friedrich and Alfred Voss, "External Costs of Electricity Generation," *Energy Policy* 21, no. 2 (1993): 114–122.

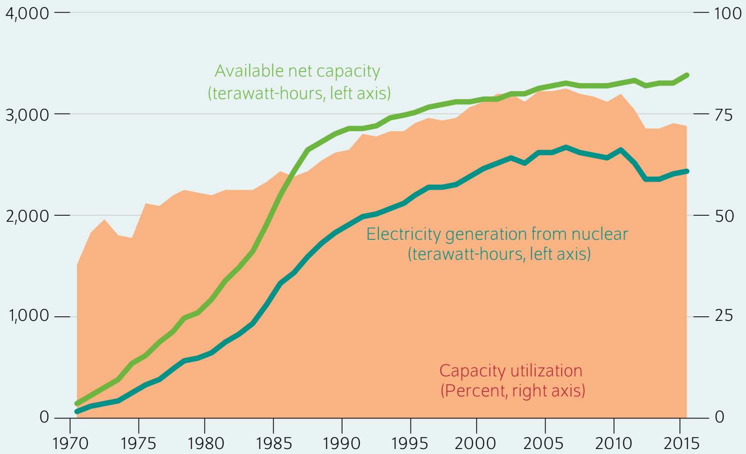
27 For a similar study, see Thomas Rose and Trevor Sweeting, "How safe is nuclear power? A statistical study suggests less than expected," *Bulletin of the Atomic Scientists* 72, no. 2 (2016): 112–115.

28 Quotient of electricity generation from nuclear energy and reference power of the plant multiplied by 8,760 hours.

29 Authors' own calculations using data from the IAEA PRIS database (available online).

Figure 4

Electricity generation from nuclear, available electricity capacity, and capacity utilization globally (1970 to 2015)
In terawatt-hours (left axis), percent (right axis)

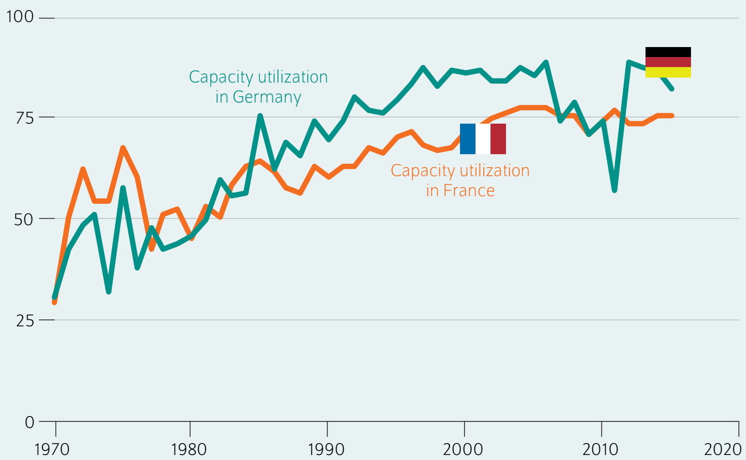


Source: Authors' own depiction based on PRIS.

Over a third of the nuclear capacity is not being used.

Figure 5

Comparison of capacity utilization of nuclear power plants in Germany and France (1970 to 2015)



Source: Authors' own depiction based on PRIS.

Capacity utilization is also relatively low in Germany.

than the reference power over a period of time.[30] There are three outage categories: 1) planned outage due to causes under control of operations management; 2) unplanned outage due to causes under control of operations management; and 3) unplanned outage due to causes outside of operations management's control (external events). Planned outages include the regular, necessary replacement of fuel assemblies as well as other periods that are not directly related to fuel assembly replacement. These unplanned outages primarily result from technical problems, tests, or human-related factors. The externally caused outages are primarily grouped in the "other" category.[31]

High outage rates in French nuclear power plants

Observing the developments in France is interesting due to its high share of nuclear energy in total power generation as well as the high number of reactors. With over 50 operational nuclear reactors and 70 percent of its power generated from nuclear energy, France is the second largest nuclear power producer. However, despite various attempts to standardize reactor construction and to use the relevant knowledge they had gained, the French nuclear power industry has not achieved an economic breakthrough. On the one hand, costs for constructing new generations of nuclear power plants are increasing instead of sinking as expected.[32] On the other hand, outages over the course of the years have not significantly declined. Observing historical operating times shows that at 69.3 percent, the load factor of French nuclear power plants is not significantly higher than the global value.[33] This means that over 30 percent of the invested nuclear power capacity is not being used (Figure 5).

Moreover, there are regular disruptions to the French energy system,[34] which is evident in the outages from 2016 to 2019. In summer 2016, over half of French nuclear power plants were out of service, causing a significant increase in the price of energy.[35] On August 25 and 26, 2018, 27 of the 58 reactors were out of service, leaving more than half of the installed capacity unavailable. At the peak of the outages in 2019, 24 reactors were simultaneously out of service. On 94 days, at least 20 reactors delivered no output over the course of one day. On 303 days (83 percent of the year), at least ten units were out at the same time. At least four reactors

30 According to this definition, outages include both power reduction and reactor shutdowns. An outage is considered significant if the loss of power generation is equivalent to at least ten hours of continuous operation at reference power. See IAEA, *Operating Experience with Nuclear Power Stations in Member States* (Vienna: 2020).

31 For more on the technical standards for analyzing reliability, see Roy Billinton and Ronald N. Allan, *Reliability Evaluation of Power Systems*, 2nd ed. (New York: Plenum Press, 1996).

32 Cf. Arnulf Grubler, "The Costs of the French Nuclear Scale-up: A Case of Negative Learning by Doing," *Energy Policy* 38, no. 9 (2010): 5174–88; Lina Escobar Rangel and François Lévêque, "Revisiting the Cost Escalation Curse of Nuclear Power: New Lessons from the French Experience," *Economics of Energy & Environmental Policy* 4, no. 2 (2015): 103–26.

33 Cf. Mycle Schneider et al., *World Nuclear Industry Status Report 2019* (Paris, Budapest: 2019).

34 The data in this section is from the World Nuclear Industry Status Report 2019 and 2020: Schneider et al., *World Nuclear Industry Status Report 2019*; Schneider et al., *World Nuclear Industry Status Report 2020*.

35 Cf. Joachim Moxon, *The French nuclear outages of 2016 : the backstory* (available online; accessed on February 15, 2021).

(4.8 gigawatts) were simultaneously out of order on every day of the year (zero production). In 2019, the total outage duration of the French reactor fleet reached 5,580 days, corresponding to an average of 96.2 days per reactor, or an outage rate of more than a quarter of the time.[36]

Even the outages described by the IAEA as "planned" are subject to considerable fluctuations, thus contributing to the unreliable power provision. In particular, it is common for "planned" outages to be extended due to unplanned delays, thus placing them in the "unplanned" category. For example, the outages reported as "planned" at France's 58 nuclear power plants were 44 percent (1,705 days) higher than those planned at the beginning of each outage.[37] At only one nuclear power plant (Dampierre-3) out of 58 did the actual outage correspond to the planned outage (82 days). The outages at Nogent-1 and the Fessenheim-1 and Fessenheim-2 reactors (shut down in 2020) were shorter than planned. In contrast, the outage was above the planned outages at 54 reactors.

The high frequency of outages thus significantly contributes to the commercial failure of French nuclear energy. This failure, due to cost increases and the lack of success in making better use of economies of scale and learning experiences, accelerated further after the opening of Europe's internal electricity market. *Électricité de France* (EdF), the domestic electric utility company, came under increasing pressure from lower-cost competitors on the internal market. EdF is heavily indebted, likely requiring a full nationalization of its debt to survive. It is unclear whether the Flamanville Nuclear Power Plant, which is currently under construction, will be completed or whether the expensive lifetime extensions for aging nuclear power plants can be implemented.[38]

Incidents also commonplace in Germany

Although there have not yet been major accidents in Germany, a large number of incidents have occurred and are also reported in the INES accident statistics (Figure 3). Additionally, there have been significant fluctuations in the availability of nuclear power in Germany since the beginning of commercial use in Kahl (West Germany, 1962) and Rheinsberg (East Germany, 1966). The Federal Office for the Safety of Nuclear Waste Management maintains a register of reportable events that began with the launch of the first German nuclear power plant. As of 2021, around 6,500 such events have been reported.[39] Since 1991, when reporting on the new and old federal states was merged, a total of 3,449 reportable events have been registered. Of those, 78 events are Level 1 and three are Level 2.[40] Two of the Level 2 events occurred in 2001 at the Philippsburg 2 NPP; the third occurred at the Unterweser NPP in 1998.

The most serious accident in a German nuclear reactor was classified as INES Level 3 by the IAEA: On December 7, 1975, a cable fire broke out in Unit 1 at the Greifswald NPP, severely damaging the reactor's coolant pumps.[41] One single pump attached to an external power source reportedly prevented a meltdown.[42]

Between 1971 and 1982, the AVR reactor in Jülich suffered a series of accidents that led to its closure.[43] In 1977, there was an incident at the Gundremmingen A NPP wherein the reactor was flooded, resulting in the loss of the reactor.[44] A hydrogen explosion at the Brunsbüttel NPP damaged a pipe and went unnoticed for two months in 2001.[45] A fire broke out at the Krümmel NPP in 2007, requiring the plant to be shut down; however, it was not officially taken offline until 2011.

German NPPs also experience a high number of outages

In Germany, too, commercial nuclear power plants suffer from high outages and fluctuating availability. Although the aggregated capacity factor (71 percent) has been greater than France's as well as the worldwide average since 1975 (Figure 5), a variety of causes also led to considerable downtime in Germany, with corresponding effects on availability and profitability.[46]

The 16 German nuclear power plants active at the beginning of 2011 experienced 1,116 outage hours per year on average over their lifespans. Particularly notable are the high outages of the older nuclear power plants Biblis A and Biblis B, Isar 1, Neckarwestheim, and Unterweser, which were taken offline in 2011. The Krümmel NPP stands out in particular with 2,179 average outage hours. While the nuclear power plants

36 Cf. Schneider, *World Nuclear Industry Status Report 2019*. The distribution of the outages was as follows: 16 NPPs up to 50 days; 18 NPPs 50–100 days; 15 NNPs 100–150 days; five NPPs 150–200 days; two NPPs 200–250 days; one NPP 250–300 days; and one NNP 365 days.

37 Cf. Schneider et al., *World Nuclear Industry Status Report 2020*, 141-2. This does not take into account load-dependent operation or other operating situations with reduced but above zero power, such as during heat waves and droughts.

38 Cf. Casimir Lorenz et al., "Atomkraft ist nicht wettbewerbsfähig: auch im Vereinigten Königreich und Frankreich ist Klimaschutz ohne Atomkraft möglich," *DIW Wochenbericht* 44 (2016): 2047–1054 (in German); Mario Kendziorski, Jan Paschke, Joris Kruckelmann, and Pao-Yu Oei, "Transition énergétique à la française – Dekarbonisierung mit oder ohne Atomumstieg?" *Energiewirtschaftliche Tagesfragen* 66, no. 11 (2016): 81–85 (in German); as well as Christian von Hirschhausen and Ben Wealer, "Restructuation inéluctable d'EDF et du nucléaire francais – La fin du rêve d'éléctricité nucléaire bon marché," (2021), submitted to *Le Monde Diplomatique* (in French).

39 BASE, Kernkraftwerke in Deutschland: Meldepflichtige Ereignisse seit Inbetriebnahme (in German; available online); incidents at East Germany's nuclear power plants, which were shut down following German reunification, have only been recorded since October 3, 1990.

40 INES Level 2 corresponds to an "incident." Beginning at this level, incidents must also be reported to the IAEA. The figures are based on the annual reports: BASE, *Jahresbericht zu meldepflichtigen Ereignissen* (in German; available online).

41 In 1990, an IAEA team investigated the causes and significance of the fire. According to reports, the fire caused the "degregation of important safety systems." Moreover, the fire reportedly damaged the cables for normal and emergency power supplies.

42 Cf. David A. V. Fischer, "Eastern Europe After Pax Sovietica," *Bulletin of the Atomic Scientists* 46, no. 6 (1990): 23–27.

43 Cf. Rainer Moormann, S*afety Re-Evaluation of the AVR Pebble Bed Reactor Operation and Its Consequences for Future HTR Concepts* (Forschungszentrum Jülich: 2008).

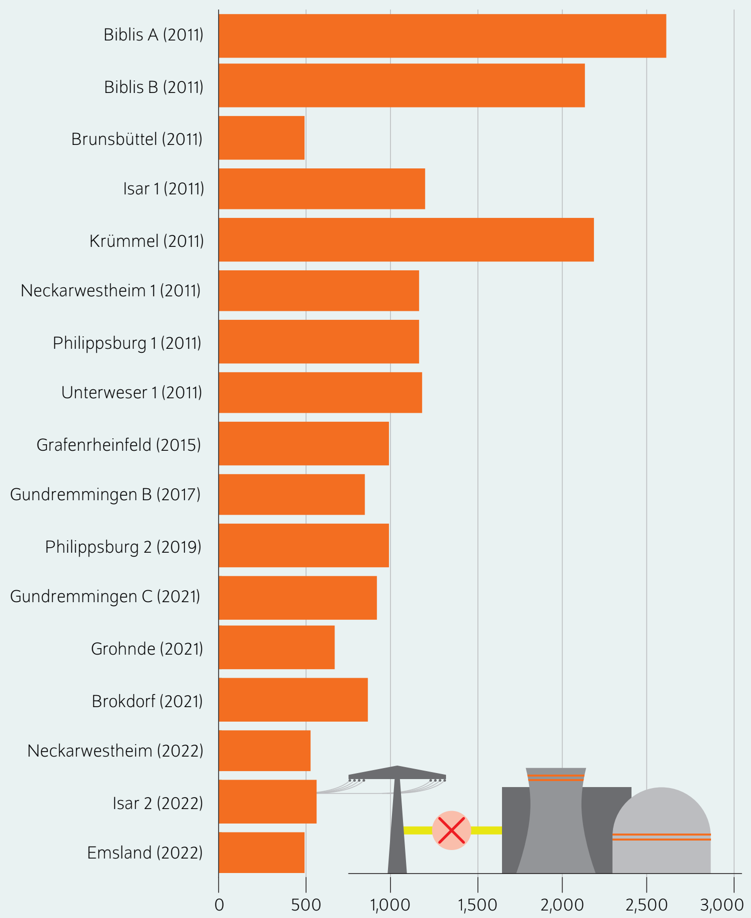
44 BR, *Historischer Störfall im Atomkraftwerk Gundremmingen* (2017) (in German; available online).

45 Tagesspiegel, *Explosion im Atomkraftwerk* (2002) (in German; available online).

46 For a deterministic analysis of availabilities and unavailabilities, see VGB, *Analyse der Nichtverfügbarkeit von Kraftwerken 2010–2019* (Essen: 2020) (in German) as well as VGB, *Verfügbarkeit von Kraftwerken 2010–2019* (Essen: VGB PowerTech e.V., 2020) (in German).

Figure 6

Average outage periods of German nuclear power plants
In hours per year, year taken offline in parentheses



Source: Authors' own depiction based on IAEA/PRIS.

Even nuclear power plants built more recently experience significant outages.

that continued to operate after the March 2011 moratorium have only triple-digit outages, it is still a considerable figure of 763 hours.

Fukushima and the nuclear phase-out in Germany

As after every major nuclear accident, Fukushima resulted in a reflective practice on the safety risks of nuclear power worldwide and in Germany. Three days after the major accident on March 14, 2011, the German Federal Government announced a three-month moratorium on extending nuclear power plant operations to reconsider its future nuclear policy. As a result, the seven oldest NPPs still operating were taken offline (Figure 6). On June 9, 2011, Chancellor Angela Merkel justified the decision in a government policy statement, pointing to the uncontrollable safety risks of nuclear power. A concrete phase-out plan has been determined for the remaining nine power plants. Since then, the Grafenrheinfeld (2015), Gundremmingen B (2017), and Philippsburg 2 (2019) NPPs have been taken offline. As a part of the phase out, the Brokdorf, Grohnde, and Gundremmingen C NPPs will go offline at the end of 2021, and the Neckarwestheim, Isar, and Emsland NPPs will join at the end of 2022.

Conclusion: put current energy and climate models to the test

The major accident at Fukushima was extreme in its extent but is still representative of 75 years of nuclear incidents and accidents. The risks that nuclear energy poses for humans and the environment are so high that no market in the world will insure them, thereby forcing society to bear the risks should a government decide to build nuclear power plants. This regulatory decision has supported both the rapid expansion of the unsafe technology since the 1950s as well as the low relative importance placed on reactor safety. Since the beginning of the nuclear age, not a single decade has gone by without major incidents. Statistically speaking, there will be another catastrophic accident on the scale of Fukushima within the next 60 to 150 years.

The international rules for assessing accidents were established by the nuclear power industry itself and at times are difficult to follow and inflexible. All major accidents should be evaluated using both the INES Scale and other indicators, such as the NAMS approach (Nuclear Accident Magnitude Scale of Radiation Release); this also applies retroactively to major accidents in the past for which such an assessment is not available.

Beyond the danger of accidents, nuclear power plants are prone to outages even during regular operation and are not permanently available. Historically, over one third of the available capacity has gone unused. Even in the 2000s, over one fifth of capacity was not used. France, a country with well over 50 reactors and the highest share of nuclear energy in total power generation is especially suffering due to the unreliable availability of nuclear power plants, which contributes to commercial failure. Again, the metrics of stochasticity established by the IAEA are inadequate: in particular, much of the planned downtime cannot in fact be planned, but is subject to unpredictable events that can extend downtime, sometimes significantly. A more exact depiction and quantification of uncertainty factors can contribute to a better understanding of this phenomenon. Due to low utilization days, especially as a result of planned and excessively long unplanned outages, nuclear power requires high backup capacity, further reducing its economic value.

There have also been a number of incidents in Germany since the 1960s, such as at the Greifswald, Unterweser, Philippsburg, and Krümmel nuclear power plants. Although the outages are lower than in other countries, they are still high, even in nuclear power plants more recently built that will be taken off the grid in 2021 and 2022.

The high safety risks and fluctuating operation of nuclear power plants has been largely neglected in economic analyses.

Accordingly, energy system models assign a special and, in some cases, even increasing importance to nuclear power in the future, thus contradicting the empirical observation of commercial nuclear power's economic decline. There is a need for methodological research to map the stochastic availability as well as the related additional reserve capacity. In particular, the Integrated Assessment Models (IAMs), which play an important advisory role in the Intergovernmental Panel on Climate Change, should be subjected to a critical analysis of their model assumptions regarding nuclear power. The impact of major accidents with low probability of occurrence, for example of the Fukushima type and the failure of the entire nuclear power plant fleet in Japan in 2011, should also be studied in more detail by applying robust modeling.

Ben Wealer is a guest researcher in the Energy, Transportation, Environment Department at DIW Berlin and a research associate at the Technical University of Berlin | bwealer@diw.de

Christian von Hirschhausen is Research Director at DIW Berlin | chirschhausen@diw.de

Claudia Kemfert is Head of the Energy, Transportation, Environment Department at DIW Berlin | sekretariat-evu@diw.de

Fabian Präger is a research associate at the Technical University of Berlin | fpr@wip.tu-berlin.de

Björn Steigerwald is a project staff at the Technical University of Berlin | bjoern.steigerwald@campus.tu-berlin.de

JEL: I51, L95, Q48

Keywords: nuclear power, outages, accidents, economics, Europe