DIW Weekly Report

30 2019

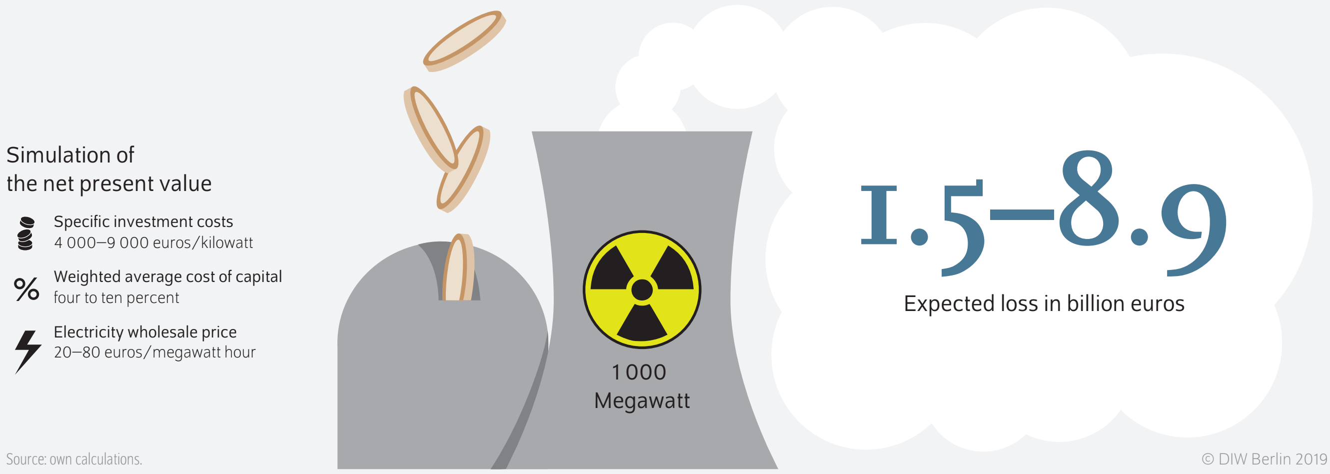
AT A GLANCE

High-priced and dangerous: nuclear power is not an option for the climate-friendly energy mix

By Ben Wealer, Simon Bauer, Leonard Göke, Christian von Hirschhausen, and Claudia Kemfert

- Analysis of the historical, current, and future profitability of nuclear power plants
- Consideration in terms of economic history and financial examination of net present values of investments in nuclear power
- Private economy investment was unprofitable in the past, and this also applies to new investment
- Due to danger of radioactive emissions and proliferation, nuclear energy technology is high-risk
- Policy makers should reject nuclear energy as an option for sustainably supplying energy

Investing in a nuclear power plant is uneconomical. This holds for all plausible ranges of specific investment costs, weighted average cost of capital, and wholesale electricity prices



Source: own calculations.

FROM THE AUTHORS

"Nuclear power was never designed for commercial electricity generation; it was aimed at nuclear weapons. That is why nuclear electricity has been and will continue to be uneconomical. Further, nuclear energy is by no means 'clean.' Its radioactivity will endanger humans and the natural world for over one million years."
— Christian von Hirschhausen, Coauthor of the present study —

MEDIA

Audio Interview with Christian von Hirschhausen (in German)
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ABSTRACT

The debate on effective climate protection is heating up in Germany and the rest of the world. Nuclear energy is being touted as "clean" energy. Given the circumstances, the present study analyzed the historical, current, and future costs and risks of nuclear energy. The findings show that nuclear energy can by no means be called "clean" due to radioactive emissions, which will endanger humans and the natural environment for over one million years. And it harbors the high risk of proliferation. An empirical survey of the 674 nuclear power plants that have ever been built showed that private economic motives never played a role. Instead military interests have always been the driving force behind their construction. Even ignoring the expense of dismantling nuclear power plants and the long-term storage of nuclear waste, private economy-only investment in nuclear power plant would result in high losses—an average of five billion euros per nuclear power plant, as one financial simulation revealed. In countries such as China and Russia, where nuclear power plants are still being built, private investment does not play a role either. Nuclear power is too expensive and dangerous; therefore it should not be part of the climate-friendly energy mix of the future.

The debate on effective climate protection is heating up, and various sides are bringing nuclear energy into the mix under the guise of "clean" energy. More and more people think that in the spirit of climate protection, Germany should extend the service life of existing nuclear power plants.[1] On the European level, the Clean Energy Package—the continuation of the long-term EU climate protection strategy—not only contains significant service life extensions but also recommends building over 100 new nuclear power plants by 2050.[2] A recent study by the International Energy Agency (IEA) is also calling for *nuclear energy in a clean energy system*, arguing that nuclear energy should be supported by large subsidies for both energy suppliers and new technologies.[3]

The "nuclear power for climate protection" narrative is hardly new. Nuclear physicist and inventor Alvin Weinberg, who was highly involved in the development of pressurized water reactors from the 1950s on,[4] warned about the global consequences of the rise in electricity generated by fossil fuels in the 1970s. He believed that nuclear power was the best answer to the sharp increase in energy consumption.[5] And Tony Blair, the former British prime minister, linked the effort to protect the climate with a demand to expand nuclear power. As a result, nuclear energy was highlighted as a key option for climate protection in the *Stern Review*, a climate protection study by Nicholas Stern that Blair commissioned.[6]

Accordingly, the present study critically examines whether or not nuclear energy would be a clean, economical option for the sustainable energy mix of the future. To accomplish this from the perspective of economic history, the authors looked at the political and institutional conditions and costs

1 See for example Henrik Mortsiefer et al., "VW-Chef fordert radikalere Klimapolitik," *Der Tagesspiegel Online*, June 1, 2019 (in German; available online, accessed July 8, 2019; this applies to all other online sources in this report unless stated otherwise).

2 European Commission, A Clean Planet for All—A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy (2018) (available online).

3 International Energy Agency, Nuclear Power in a Clean Energy System (2019).

4 Alvin M. Weinberg, "Some Thoughts on Reactors," *Bulletin of the Atomic Scientists*, 15 (3), (1959): 132–137 (available online).

5 Alvin M. Weinberg, "Global Effects of Man's Production of Energy," *Science*, 186 (4160) (1974): 205 (available online).

6 Nicholas Stern, The Economics Climate Change: The Stern Review (2007) (available online).

DOI: https://doi.org/10.18723/diw_dwr:2019-30-1

at which nuclear power plants were constructed worldwide. From the business perspective, they also present detailed simulation calculations of the expected net present value of investments made today. The findings show that nuclear energy has never been a clean economical energy source and will not be in the future.

The economic history perspective: in the private economy, there has never been a basis for commercial nuclear energy

The commercial use of nuclear energy—sometimes also called "civil" use—is a byproduct of the military development of nuclear power in the 1940s, particularly the accelerated search for atom bombs in the final phase of World War II.[7] Contrary to the initial optimism regarding the potentially lower cost of nuclear energy ("too cheap to meter"),[8] by the end of the 1950s it was clear that nuclear energy would not be able to compete in the free market.[9] In the U.S. and later in other countries, the armament and energy industries grew comfortable with nuclear power only after they had received significant subsidies. Further, since the 1960s the construction of new nuclear power plants has not led to a reduction in fixed unit costs. Instead, the cost per kilowatt (kW) of nuclear power plant output has steadily risen.[10]

Over several decades, these findings have regularly been confirmed for the U.S. They also apply to France[11] and "third generation" reactors.[12] Two campus-wide studies by MIT (2003) and the University of Chicago (2004) concur that in the first decade of this century, nuclear energy was not competitive with coal or natural gas.[13] In recent years, further studies have confirmed that nuclear energy is not competitive.[14]

Nuclear reactor construction based on military-related political and institutional conditions

To better understand the phenomenon, at the German Institute for Economic Research (DIW Berlin) the authors carried out a descriptive empirical analysis of all 674 nuclear reactors used to produce electricity that have been built since 1951.[15] Research reactors were excluded. Investment activity in the sector was analyzed alongside the political and institutional conditions under which the reactors were built. Four development phases were identified; competitive private-economy investment did not play a role in any of them.[16]

1) The early phase of commercial use of nuclear energy in the post-war era (1945 until the 1950s) was marked by the advent of the Cold War between the U.S. and its partner countries on the one side, and the Soviet Union along with its satellites on the other side. The further development of nuclear weapons and other military applications was the focus. Nuclear power plants were primarily designed to be "plutonium factories with appended electricity production."[17]

2) The second phase began in the 1950s with the spread of nuclear reactors. It was also marked by the geopolitics of the Cold War. The failure of the U.S. effort to control the flow of military-grade fissile nuclear materials by setting up an international authority (Atoms for Peace, later the International Atomic Energy Agency, IAEA) triggered a race with the Soviet Union to spread nuclear power plant technology in the countries of the respective block. In a few countries, the U.S. and Germany for example, massive subsidies were applied to acquiring private-economy energy suppliers to develop and operate nuclear power plants. But competitive, non-state-guaranteed money was not invested anywhere.[18] At the same time, states such as India, Pakistan, and Israel, which were not tied to any block, developed their own nuclear programs.

3) The 1980s and 1990s saw the transition from a bipolar to a global, multipolar nuclear arms race. As a result, at least ten countries gained possession of the technology and knowledge required for nuclear weapons.[19] Alongside the U.S., the United Kingdom, France, and the Soviet Union, the list comprises China, India, Pakistan, North Korea, Israel, and South Africa. None of the ten uses nuclear energy commercially via private, non-state-supported investment.[20]

7 François Lévêque, The Economics and Uncertainties of Nuclear Power (2012) (available online).

8 Lewis Strauss, Remarks prepared by Lewis L. Strauss, Chairman, United States Atomic Energy Commission, for delivery at the Founders' Day Dinner, National Association of Science Writers, on September 16, 1954, New York (available online).

9 See the detailed techno-historical reappraisals in Joachim Radkau, *Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975: Verdrängte Alternativen in der Kerntechnik und der Ursprung der nukleearen Kontroverse* (Reinbek bei Hamburg: Rowohlt Verlag, 1983); Joachim Radkau and Lothar Hahn, *Aufstieg und Fall der deutschen Atomwirtschaft*, (Munich: oekom verlag, 2013); and Joachim Radkau, *Geschichte der Zukunft: Prognosen, Visionen, Irrungen in Deutschland von 1945 bis heute*, (Munich: Carl Hanser Verlag, 2017).

10 The specific investments for nuclear power plants whose construction started in 1966 and 1967 was around 700 U.S. dollars per kW. In 1974–1975, the value was around 3,100 U.S. dollars per kW. (Both figures refer to the U.S. dollar exchange rate in effect in 1982). See Energy Information Administration, An Analysis of Nuclear Power Plant Construction Costs (1986) (available online).

11 Arnulf Grubler, "The Costs of the French Nuclear Scale-up: A case of negative learning by doing," *Energy Policy* 38 (9) (2010): 5147–5188 (available online); and Lina E. Rangel and Francois Lévêque, "Revisiting the cost escalation curse of nuclear power: new lessons from the French experience," *Economics of Energy & Environmental Policy*, 4 (2) (2015): 103–126 (available online).

12 See Mycle Schneider et al, World Nuclear Industry Status Report 2016 (2016) (available online).

13 See Massachusetts Institute of Technology, "The Future of Nuclear Power," (PDF, Massachusetts Institute of Technology, Cambridge, 2003) (available online); and University of Chicago, "The Economic Future of Nuclear Power," (PDF, University of Chicago, Chicago, 2004) (available online).

14 Paul L. Joskow and John E. Parsons, "The Future of Nuclear Power After Fukushima," *Economics of Energy & Environmental Policy* 1(2) (2012): 99–113 (available online); and William D. D'haeseleer, "Final Report: Synthesis on the Economics of Nuclear Energy—Study for the European Commission," (PDF, European Commission, Leuven, 2013) (available online).

15 See Ben Wealer et al., "Nuclear Power Reactors Worldwide—Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951–2017)," *DIW Berlin Data Documentation* 93 (2018) (available online).

16 See Ben Wealer et al., "Nuclear Power Reactors Worldwide."

17 See the presentation by Joachim Radkau, "Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975," 53, on the development of the first nuclear reactor in the United Kingdom in Calder Hall, 1956.

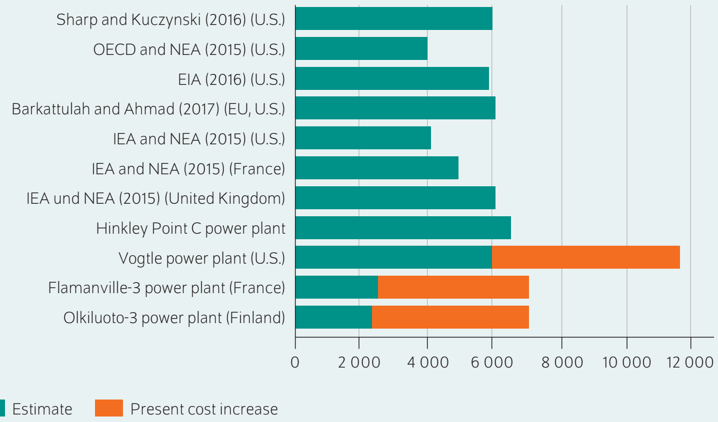
18 See Joachim Radkau, "Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975."

19 Strategy researcher Paul Bracken writes about the transition from the first to the second nuclear age. See Paul Bracken, *The Second Nuclear Age—Strategy, Danger, and the New Power Politics*, (New York: Macmillan USA, 2012).

20 See Ben Wealer et al., "Nuclear Power Reactors Worldwide."

Figure 1

Current overnight construction cost estimates for reactors in Europe and the U.S. as well as for ongoing new-build projects
In U.S. dollars (as of 2017) per kilowatt



Sources: Ben Wealer et al., "Cost Estimates and Economics of Nuclear Power Plant Newbuild: Literature Survey and Some Modelling Analysis," *IAEE Energy Forum Groningen Special Issue 2018*, (2018): 43–45 (available online); Phil Sharp and Stephen Kuczynski, "The Future of Nuclear Power in the United States. Washington, D.C.," (PDF, 2016) (available online); OECD and NEA, "Nuclear New Build: Insights into Financing and Project Management," (PDF, 2015) (available online); EIA, "Capital Cost Estimates for Utility Scale Electricity Generating Plants," (PDF, 2016) (available online); Nadira Barkatullah and Ali Ahmad, "Current Status and Emerging Trends in Financing Nuclear Power Projects", *Energy Strategy Reviews*, 18 (2017):, 127–140 (available online); IEA and NEA, "Projected Costs of Generating Electricity 2015 Edition," (PDF, 2015) (available online).

Current costs considerably exceed estimates from the literature.

4) The present phase has been shaped by the rhetoric of the "nuclear energy renaissance," but in reality is characterized by the decline of its commercial use in Western market economies (see Box 1). Particularly of note in this context are the bankruptcy of major nuclear power plant construction companies Westinghouse (U.S.)[21] and Framatome (formerly Areva, France)[22] and the efforts of energy suppliers to shut down unprofitable nuclear power plants as quickly as possible or shift the financial responsibility to the state. The market for electricity has become increasingly liberalized since the 1990s, and there is little incentive for private investment in nuclear power plants. The development of nuclear energy has been left to other non-market systems, in which countries insist on developing their nuclear capability for reasons of policy, military strategy, etc.—above all, nuclear powers China and Russia.

An examination of economic history confirmed that electricity has primarily been used as a coproduct of nuclear power generation. The driving force was military developments and interests, primarily generating weapons-grade plutonium and, especially in the U.S. in the 1950s, developing pressurized water reactor technology to drive submarines.[23]

Still no reasons for the private economy to invest in commercial nuclear power today

The low investment being made in nuclear power plants in Europe and OECD countries today yields foreseeably ubiquitous losses in the two-digit billions.[24] For example, the cost of the Olkiluoto-3 nuclear power plant in Finland has risen from the original estimate of three billion euros (1995) to more than 11 billion euros. This is equal to around 7,200 euros per kW (as of 2018). In France, in the wake of extensive cost increases and regular reports of substandard reactor safety, the entire nuclear expansion program of energy giant Electricité de France (EdF) is being critically examined. Further, the corporation's high level of debt—over 40 billion euros—is likely to lead to complete nationalization if bankruptcy is to be avoided.[25] One of the two investment projects in the U.S. was canceled after its cost doubled (UC Summers, Virginia). At the second project (Vogtle, Georgia), costs increased from the original 14 billion U.S. dollars (equal to around 6,200 U.S. dollars per kW) in 2013 to an estimated 29 billion U.S. dollars in 2017 (equal to around 9,400 U.S. dollars per kW) (see Figure 1).

Monte Carlo analysis turns up lack of financial basis for investment in nuclear power plants

From a purely private economy perspective, the authors examined the profitability of a nuclear plant under a variety of energy sector conditions that are key influencing factors. They did not include external costs such as those incurred for the permanent storage of nuclear waste.

The model includes a large number of possible variations of several variables: first, the wholesale price of electricity, which was assumed to range between 20 and 80 euros per megawatt hour (MWh) in reflection of the current situation in Europe and as a conservative estimate of the medium-term price trend.[26] Second, based on current estimates or cost trends, the variable of specific investments, or overnight construction costs, was included within the range of 4,000 to 9,000 euros per kW (see Figure 1), and, third, the weighted average cost of capital (WACC) was varied in the

21 Westinghouse's cost overruns on the Vogtle and Summer construction projects in the U.S. are one of the main reasons for the company's losses of 6.2 billion dollars and its filing for bankruptcy protection in March 2017. See Mycle Schneider et al., World Nuclear Industry Status Report 2017 (2017) (available online).

22 In 2018, Areva NP sold most of its reactor division to state-controlled EdF for 1.9 billion euros and renamed it Framatome. EdF already owned 75.5 percent of the company's shares. See Mycle Schneider et al., World Nuclear Industry Status Report 2018 (2018) (available online).

23 See Alvin M. Weinberg, "Today's Revolution," *Bulletin of the Atomic Scientists*, 12 (8) (1956): 299–302.

24 See Ben Wealer et al., "Cost Estimates and Economics of Nuclear Power Plant Newbuild: Literature Survey and Some Modelling Analysis," *IAEE Energy Forum Special Issue 2018*, (2018): 43–45 (available online); and Casimir Lorenz et al., "Nuclear power is uncompetitive—climate protection without nuclear power also viable in UK and France," *DIW Wochenbericht* 44 (2016): 2047–1054 (available online).

25 See Par Pierre Le Hir and Nabil Wakim, "Après le nouveau retard de l'EPR de Flamanville, la filière nucléaire dans l'impasse," *Le Monde*, June 20, 2019 (in French; available online).

26 Long-term price forecasts in electricity markets are difficult to make because fundamental aspects such as market design are subject to change. The price for baseload futures in Germany is an indicator. In July 2019, it was around 50 euros per MWh for the 2020 to 2023 period. See the data on the European Energy Exchange website (in German; available online). This means that market participants anticipate a price on that level. On the other hand, prices below the 30-euro range have been observed in recent years. In this spirit, our range of 20 to 80 euros per MWh is conservative, because it includes higher prices and in turn, higher revenue for power plant operators.

four to ten percent range.[27] Around 90 euros per kW and year were taken into account for maintenance and 12 euros per MWh were included for operation and nuclear fuel.[28] A service life of 40 years was imputed to the reactors themselves. The analysis assumes an exemplary nuclear plant with an electrical nameplate capacity of 1000 megawatts (MW).

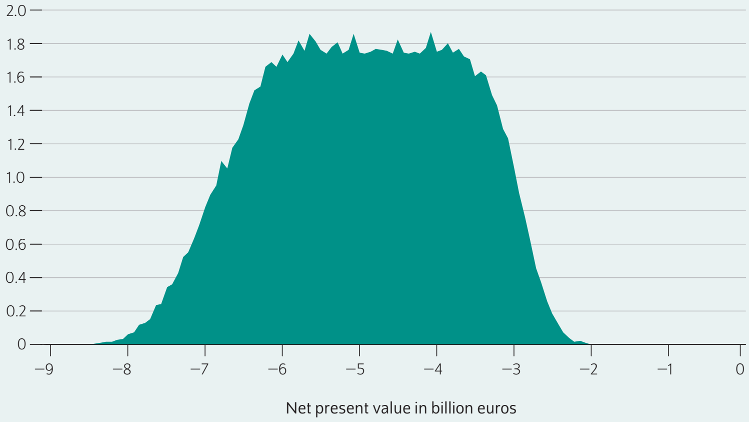
A Monte Carlo simulation determined net present value for a great number of combinations of the uncertain variables. In the process, a random draw of each uncertain variable was selected from a continuous uniform distribution within the specified bounds and inserted into the formula for net present value. This step was repeated 100,000 times. Net present value compares future revenue streams to present and future costs. Because both variables are discounted to the present, it indicates the present value of an investment. The higher the net present value, the more profitable the investment from the business perspective. If the net present value is negative, the investment will yield an expected loss. By simulating a number of possible combinations of uncertain influencing variables, the possible event space can be estimated with acceptable accuracy.

The results showed that in all cases, an investment would generate significant financial losses (see Figure 2). The (weighted) average net present value was around minus 4.8 billion euros. Even in the best case, the net present value was approximately minus 1.5 billion euros. The authors included conservative assumptions with high electricity prices, low capital costs, and specific investment. Considering all assumptions regarding the uncertain parameters, nuclear energy is never profitable.

Figure 2

Results of the Monte Carlo simulation for the net present value of an exemplaric nuclear plant with 1000 megawatts

Probability density in percent



Source: own calculations.

All combinations of the uncertain variables (electricity price, specific investments, weighted averaged costs of capital) lead to a substantially negative net present value for a nuclear plant.

External costs: simply no insurance for nuclear energy

Expanding the perspective to include macroeconomic considerations, it becomes obvious that above and beyond high private economy costs, high external costs and risks would be incurred along the value creation chain. They include: the radiation emitted when uranium is mined, possible radiation emission during operation, the complex and technically demanding dismantling process, the unanswered issue of how to store nuclear waste, and the risk of proliferation (see Box 2). Society will be asked to bear a very large proportion of these costs. The fact that nuclear power plant operators are not insured against the risk of accidents makes this abundantly clear. Worldwide, there are no financial service organizations that offer insurance to them.[29]

In the U.S., the Price-Anderson Law limits the liability of the domestic nuclear industry to 9.1 billion U.S. dollars in case of accident. This is less than two percent of the up to 560 billion U.S. dollars-worth of damage that a nuclear catastrophe could cause.[30] The remaining 98 percent of the cost would have to be borne by the general public. The Price-Anderson Law has been the blueprint for nuclear accident legislation in most countries with nuclear reactors and for international treaties. It stipulates sole liability for the plant operator in the case of a reactor accident. This reduces the cost of constructing reactors, since it relieves all suppliers of the possible risks involved with the defective plant components that may later be found to have caused the accident.[31]

A study by Versicherungsforen Leipzig has determined the potential premium for adequate accident insurance for nuclear power plant operators.[32] It was between four and 67 euros per kilowatt hour. To compare: the current end consumer price for electricity is approximately 0.30 euros per kWh, lower by a factor of ten to 200.

27 The weighted average cost of capital (WACC) is a company's average total capital cost rate. WACC is equal to the arithmetic average of equity and dept cost rates weighted by equity and dept capital as the respective proportions of total capital.

28 See Nadira Barkatullah and Ali Ahmad, "Current Status and Emerging Trends in Financing Nuclear Power Projects," *Energy Strategy Reviews*, 18 (2017): 127–140 (available online).

29 See Jochen Diekmann, "Verstärkte Haftung und Deckungsvorsorge für Schäden nuklearer Unfälle – Notwendige Schritte zur Internalisierung externer Effekte," *Zeitschrift für Umweltpolitik und Umweltrecht*, 34 (2) (2011): 111-132.

30 See NIRS and WISE, "Nuclear Power: No Solution to Climate Change," Nuclear Monitor, 621/622 (2005) (available online).

31 See Tomas Kaberger, "Economic Management of Future Nuclear Accidents," in *The Technological and Economic Future of Nuclear Power*, eds. Reinhard Haas, Lutz Mez, and Amela Ajanovic (Wiesbaden: Springer Nature, 2019) (available online).

32 See Versicherungsforen Leipzig, Berechnung einer risikoadäquaten Versicherungsprämie zur Deckung der Haftpflichtrisiken, die aus dem Betrieb von Kernkraftwerken resultieren. Eine Studie im Auftrag des Bundesverband Erneuerbare Energie e.V. (BEE) (2011) (in German; available online).

"New" technology concepts do not change the outlook

Those in favor of nuclear energy like to point out the ongoing technological developments that could lead to it growing more efficient in the future. They include "fourth generation" nuclear power plants and mini-nuclear power plants (small modular reactors, SMRs). Anything but new, both concepts have their roots in the early phase of nuclear power in the 1950s.[33] Then as now, there was no hope that the technologies would become economical and established.

The majority of fourth generation reactors are "fast breeders" that facilitate the more efficient use of nuclear fuel but have never been economically profitable and technologically hardly controllable.[34] Most of the larger fast breeders that were developed in the 1970s have already been decommissioned.[35] Further, these reactor types encourage the proliferation of highly enriched, weapons-grade uranium or plutonium in the context of reprocessing fuel. This provides direct access to the material for military purposes.[36] Nor can we expect any technological or economic breakthroughs from other types of fourth generation reactors.[37]

SMRs (sometimes called "backyard nuclear reactors") are based on developments in the 1950s, particularly the military's attempt to use nuclear power to drive submarines. But even more modern approaches toward developing SMRs are not suitable as replacements for larger plants. On the one hand, as in the case of all nuclear power plants, the question of safety remains unanswered. Since reactor standardization is a key parameter for manufacturing SMRs, the worldwide specifications would have to be harmonized, which on the other hand would be difficult or even impossible in the short to medium term.[38]

Conclusions

The economic history and financial analyses carried out at DIW Berlin show that nuclear energy has always been unprofitable in the private economy and will remain so in the future.

Between 1951 and 2017, none of the 674 nuclear reactors built was done so with private capital under competitive

33 See Alvin M. Weinberg, "Today's Revolution."

34 See Amory B. Lovins, "The Case against the Fast Breeder Reactor: An Anti-Nuclear Establishment View," *Bulletin of the Atomic Scientists*, 29 (3) (1973): 29–35 (available online); and Thomas B. Cochran et al., "It's Time to Give Up on Breeder Reactors. *Bulletin of the Atomic Scientists*, 66 (3) (2010): 50–56 (available online).

35 Among them are Superphénix in France and Monju in Japan. Kalkar, the German fast breeder reactor project, never made it to the implementation phase. Instead, it was converted into an amusement park, Wunderland Kalkar.

36 Amory B. Lovins, L. Hunter Lovins, and Leonard Ross, "Nuclear Power and Nuclear Bombs."

37 See M.V. Ramana, "The checkered operational history of high-temperature gas-cooled reactors," *Bulletin of the Atomic Scientists*, 72 (3) (2016): 171–179 (available online); and Benjamin K. Sovacool and M.V. Ramana, "Back to the Future: Small Modular Reactors, Nuclear Fantasies, and Symbolic Convergence," *Science, Technology, & Human Values*, 40 (1) (2015): 96–125 (available online).

38 Tristano Sainati, Giorgio Locatelli, and Naomi Brookes, "Small Modular Reactors: Licensing Constraints and the Way Forward," *Energy 82*, (2015): 1092–1095 (available online).

Box 1

Decline of nuclear power in Germany, Europe, and the U.S.

In Germany, recent calls to extend the service life of nuclear power plants have been rejected by operator companies.[1] The remaining seven German nuclear power plants (9.5 GW capacity) are being disconnected from the grid according to plan. The plant in Philippsburg will be disconnected at the end of 2019, the blocks in Brokdorf, Gundremmingen-C, and Grohnde will be retired at the end of 2021, and Isar-2, Emsland, and Neckarwestheim-2 will go dark in 2022 (see Figure 1).

On the European level as well, the economic criteria speak against building new nuclear power plants and extending the service life of existing ones. Doing without nuclear energy is not expected to limit Europe's security of supply.[2] Without service life extensions and taking the technical service life of 40 years into account, the installed power would drop sharply anyway (see Figure 2).[3] As early as 2025, installed power would decrease by 50 percent to 54 GW. And ten years later, nuclear energy would feed only around 14 GW into the European grid. The remaining nuclear power plant operators would primarily be located in Eastern Europe: the Czech Republic, Romania, and Slovakia. The reactors there contain technology designed to run for 30 years and some of them do not even have containment structures.[4]

And although it has almost 100 reactors from the world's largest nuclear energy producer, the U.S. nuclear industry has never been able to interest private investors in a competitive environment.[5] Many reactors are subject to cost-plus regulation that guarantees their operators a fair financial return. The regulation's costs are grafted onto the price of electricity. As in Europe, not only investment in nuclear power plants is a loss-making activity; in many cases, their operation is as well. According to an MIT study, 35 nuclear power plants

1 See Jacob Schlandt, "Die Nutzung der Kernenergie hat sich erledigt," *Der Tagesspiegel Online*, June 5, 2019 (available online).

2 See Claudia Kemfert et al., "European Climate Targets Achievable without Nuclear Power," *DIW Wochenbericht* 45 (2015): 1063–1070 (in German; available online).

3 The current shutdown dates of nuclear power plants that were connected to the grid after 1978, and are therefore over 40 years old, were considered. Belgium: Doel-3 in 2022, Tihange-2 in 2023, Doel-1/2/4, and Tihange-1/3 in 2025. Netherlands: Borssele in 2033. Sweden: Ringhals-2 in 2019, Ringhals-1 in 2020. The UK: Hinkley-Point B-2, Hunterston B-1, Hunterston B-2 and Hinkley-Point B-1 in 2023, Hartlepool A-1/2, Heysham A-1/2 in 2024, Dungeness B-1/2 in 2028, Torness-1/2, Heysham B-1/2 in 2030, and Sizewell B in 2035. Finland: Loviisa in 2021. Germany: by 2022 (2019/21/22).

4 See Thomas Halverson, "Ticking Time Bombs: East Bloc Reactors," *Bulletin of the Atomic Scientists*, 49 (6), (1993): 43–48 (available online).

5 See Ben Wealer et al., "Nuclear Energy Policy in the United States: Between Rocks and Hard Places," *IAEE Energy Forum*, second quarter 2017 (2017): 25–29.

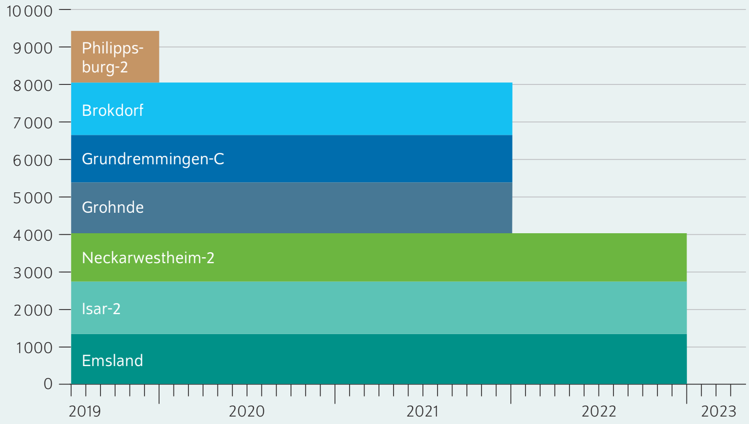
with a total capacity of 58 GW are unprofitable today.[6] The situation is leading to nationwide shutdown plans. Between 2013 and 2018, seven plants (5.3 GW capacity) exited the grid. Further decommissioning plans involve nine reactors with a total capacity of 8.7 GW. At the same time, a wave of demands for subsidies has hit. It has already been successful in the states of New York and Illinois. The centerpiece is the zero emission credits (ZEC) instrument. After ZECs were implemented in New York and Illinois, former nuclear giant Exelon withdrew the shutdowns it had just announced (power plants Clinton, Quad Cities, Ginna).[7]

6 Of this, 14 GW are located in deregulated electricity markets and 44 GW in regulated markets. See Geoffrey Haratyk, "Early Nuclear Retirements in Deregulated U.S. Markets: Causes, Implications and Policy Options," *Energy Policy*, 110 (2017): 150–166 (available online).

7 See Mycle Schneider et al., "World Nuclear Industry Status Report 2018."

Figure 1

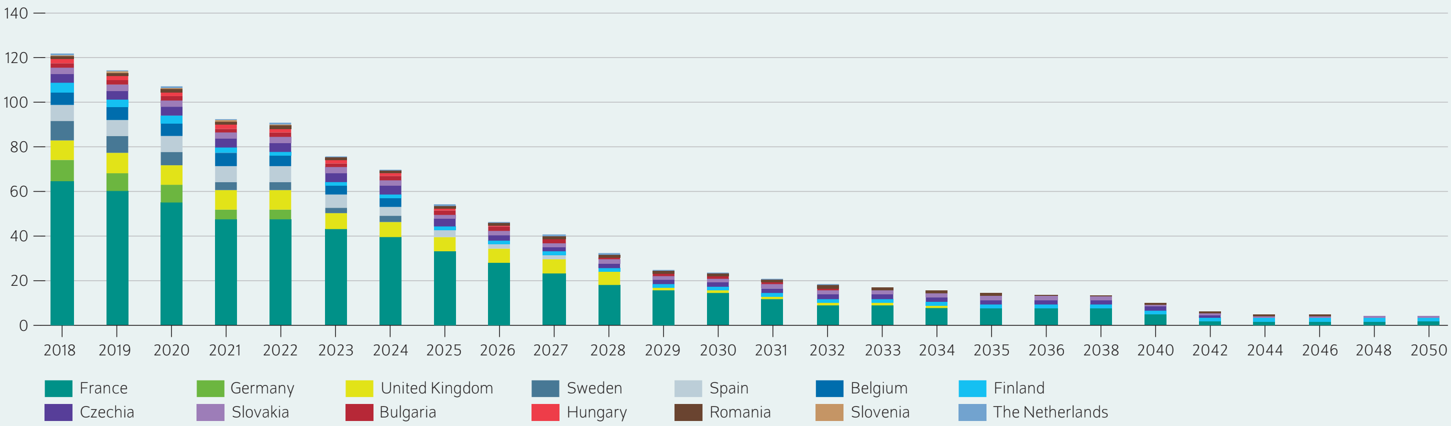
Total installed capacity of German nuclear plants until 2022
In megawatts



From 2023 on, there will be no nuclear plants connected to the German grid any more.

Figure 2

Installed capacity of nuclear plants in EU-28 given the scheduled shutdowns and end of life dates
In gigawatts



Source: own illustration based on Ben Wealer et al. (2018): Nuclear Power Reactors Worldwide - Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951–2017). DIW Berlin Data Documentation 93 (available online).

Due to retirements, almost all nuclear plants would go offline until 2050.

Box 2

Nuclear energy is not clean

Due to nuclear energy's intense, long-lasting radioactivity and the associated risks to human life and the natural world, it cannot be designated a clean source of energy. This applies to its entire value creation chain. Mining for uranium ore generates large quantities of radioactive waste that has made giant swathes of land unusable.[1] Splitting uranium and plutonium during electricity production causes radioactive emissions in the form of particle radiation, which is a potential hazard to human health. A number of studies have established a correlation between building and operating nuclear power plants and the risk of children in the vicinity contracting cancer or leukemia.[2]

After such plants no longer produce energy, their systems and buildings may contain radioactive contamination, leading to significant risks when nuclear power plants are dismantled. The technical complexity and financial assessment of the risks have consistently been dramatically underestimated and virtually ignored in discussions of energy policy. Seventy years after the beginning of the commercial use of nuclear power plants as a source of electricity, only 19 of 173 disconnected plants have been completely dismantled (as of 2018). Early, high-capacity nuclear energy countries such as Great Britain, Canada, and France have still not dismantled any of their reactors. Calder Hall, the first commercial nuclear power plant in Great Britain, was commissioned in 1953. It will not be completely dismantled until well into the 21st century. Chinon-A, a French nuclear power plant, is not likely to be dismantled until 2056—more than 100 years after construction began.[3]

The challenges of the long-term storage of nuclear waste have been basically ignored, to the extent that today there are no long-term storage facilities for highly radioactive waste in operation. In countries such as Germany, the United Kingdom, and the U.S., the search for a suitable location has gone on for decades.[4] Finland was the first country to issue a construction permit for a long-term storage facility, which will be commissioned in the 2020s. In Germany, a new, more comprehensive attempt was made in 2016 with the new Choice of Location Act (*Standortauswahlgesetz*, StandAG). However, if it is adopted, the process will take several decades until completion. Until then, the interim storage of highly radioactive waste poses a high risk in a large number of locations.

Although serious reactor accidents are rare, the consequences are catastrophic. One year after the Fukushima disaster, scientists at the Max Planck Society determined that similar accidents could happen every ten to 20 years, 200 times more often than previously assumed.[5] Such near-misses, or harbingers of possible core meltdowns, occur much more frequently than the nuclear industry claims.[6] Older reactors are particularly at risk. The world is debating an extension of the service life of older reactors from 40 to 50 or even 80 years.[7] Since nuclear power plants are designed for a service life of 30 or 40 years, waiting to pull their plugs would lead to significant material stress and wear, increasing the likelihood of accidents.[8] The troubled reactors in Tihange (Belgium) and Fessenheim (France), both of which are located in close proximity to Germany, are good examples. The Dukovany power plant in Slovakia, 100 km north of Vienna, is also a source of concern. First, like many earlier Soviet reactors, it was built without a containment structure and is therefore particularly high-risk.[9] Second, the risk of accidents was increased by the unlimited service life extension of Block 1, which was originally scheduled to shut down in 2025 after a 40-year service life.

Proliferation is another important risk in the context of nuclear energy. In 1946, the Acheson-Lilienthal Report confirmed that the value creation chains for developing nuclear energy for peaceful purposes and nuclear weapons are basically interchangeable and interdependent.[10] In recent years, studies have returned to these findings.[11] The generation of electricity from nuclear power is the most important driver of proliferation: the spread of nuclear weapons and radioactive material.[12] Some countries such as India, Pakistan, North Korea, and Israel have procured nuclear weapons under the guise of the "civil" application of nuclear power.[13] If a

1 Examples include uranium mining in the GDR (Aue region), and in France and Niger, where the French public corporation Orano has mined uranium for 40 years. See Gabrielle Hecht, "Being Nuclear: Africans and the Global Uranium Trade," (Cambridge, London: The MIT Press, 2017).

2 See Peter Kaatsch et al., Epidemiologische Studie zu Kinderkrebs in der Umgebung von Kernkraftwerken (KiKK-Studie) (2007) (in German; available online).

3 Mycle Schneider et al., "World Nuclear Industry Status Report 2018." In Germany there are two large, extensively dismantled nuclear power plants: Gundremmingen-A and Würgassen. Buildings on the sites are still being used as interim storage depots or packaging for nuclear waste. As a result, the buildings have not been exempted from nuclear legislation. See Ben Wealer, Jan Paul Seidel, and Christian von Hirschhausen, "Decommissioning of Nuclear Power Plants and Storage of Nuclear Waste: Experiences from Germany, France, and the UK," in eds. Reinhard Haas, Lutz Mez, and Amela Ajanovic, *The Technological and Economic Future of Nuclear Power*, (Wiesbaden Springer Nature, 2019) (available online).

4 See Achim Brunnengräber and Mirands Schreurs, "Nuclear Energy and Nuclear Waste Governance Perspectives after the Fukushima Nuclear Disaster," in eds. Achim Brunnengräber et al. *Nuclear Waste Governance. An International Comparison*, (Wiesbaden: VS Verlag für Sozialwissenschaften, 2015); and Maria Rosaria Di Nucci et al., "The Technical, Political and Socio-Economic Challenges of Governing Nuclear Waste," in eds. Achim Brunnengräber et al. *Challenges of Nuclear Waste Governance. An International Comparison Volume II*, (Wiesbaden: Springer Fachmedien Wiesbaden GmbH, 2018).

5 See J. Lelieveld, D. Kunkel, and M.G. Lawrence, "Global Risk of Radioactive Fallout after Major Nuclear Reactor Accidents," *Atmospheric Chemistry and Physics*, 12 (9) (2012): 4245–4258 (available online).

6 The Nuclear Regulatory Commission (NRC) in the U.S. documented 61 incidents and 102 states that could cause the system to break down and eventually lead to a core meltdown for the 2006–2016 period. Independent experts reached a different conclusion. The NRC not only neglected to register the three riskiest near-misses of the last decade, but also left out an additional 100 close calls. See Jim Riccio, Nuclear Near Misses: A Decade of Accident Precursors at U.S. Nuclear Plants, (2016) (available online).

7 See Steve Clemmer et al., The Nuclear Power Dilemma. Declining Profits, Plant Closures, and the Threat of Rising Carbon Emissions, (2018) (available online); and Jan Haverkamp, ed., Lifetime extension of ageing nuclear power plants: Entering a new era of risk (2014) (available online).

8 See Jan Haverkamp, "Lifetime extension," 10.

9 A containment structure is the airtight reinforced steel or lead structure enclosing a nuclear reactor. Depending on reactor technology, it also includes coolant loops and secondary systems. Its purpose is to prevent radioactive substances from leaking into the environment after an incident.

10 See Chester I. Barnard et al., A Report on the International Control of Atomic Energy (1946) (available online).

11 See Andy Stirling and Phil Johnstone, "A Global Picture of Industrial Interdependencies Between Civil and Military Nuclear Infrastructures," (2018) (available online).

12 Amory B. Lovins, L. Hunter Lovins, and Leonard Ross, "Nuclear Power and Nuclear Bombs," *Foreign Affairs*, 58 (5) (2018): 1137–1177 (available online).

13 Lutz Mez, "Nuclear Energy–Any Solution for Sustainability and Climate Protection?" *Energy Policy*, 48 (2012): 56–63 (available online).

nuclear infrastructure exists – and the material for weapons is produced in enrichment or reprocessing plants, military reactors, "dual-use" reactors, or fast breeders – the decision of whether or not to build nuclear weapons is only a matter of political will.

And last but not least, when the entire life cycle is considered (construction, operation, plant dismantling, and the nuclear fuel cycle), nuclear energy can by no means be called a carbon-free technology. One meta study determined an average value of 66 grams of CO_2 equivalents per kWh for the greenhouse gas emissions of nuclear power plants. This is around 20 percent of the emissions of a gas-fired power plant.[14]

14 Benjamin K. Sovacool, "Valuing the greenhouse gas emissions from nuclear power: A critical survey," *Energy Policy* 36 (2008): 2950–2963 (available online).

conditions. Large state subsidies were used in the cases where private capital flowed into financing the nuclear industry. The post-war period did not witness a transition from the military nuclear industry to commercial use, and the boom in state-financed nuclear power plants soon fizzled out in the 1960s. Financial investment calculations confirmed the trend: investing in a new nuclear power plant leads to average losses of around five billion euros. The lack of economic efficiency goes hand in hand with a high risk with regard to the proliferation of weapons-grade materials and the release of radioactivity, as shown by the accidents in Harrisburg (1977), Chernobyl (1986), and Fukushima (2011). For all these reasons, nuclear energy is not a relevant option for supplying economical, climate-friendly, and sustainable energy in the future.

Energy, climate, and industrial policy should therefore target a quick withdrawal from nuclear energy. Subsidies and special tariffs for service life extensions are not recommended because they are life-support systems for the risky, uneconomical nuclear industry. This is even more true for new construction. Budgets for researching new reactor types should be cut.

"Nuclear energy for climate protection" is an old narrative that is as inaccurate today as it was in the 1970s. Describing nuclear energy as "clean" ignores the significant environmental risks and radioactive emissions it engenders along the process chain and beyond. The German federal government would be well advised to counteract the narrative in the EU and other organizations in which Germany is involved.

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JEL: L51, L95, Q48

Keywords: nuclear power, net present value, profitability, economic history

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 9 July 24, 2019

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