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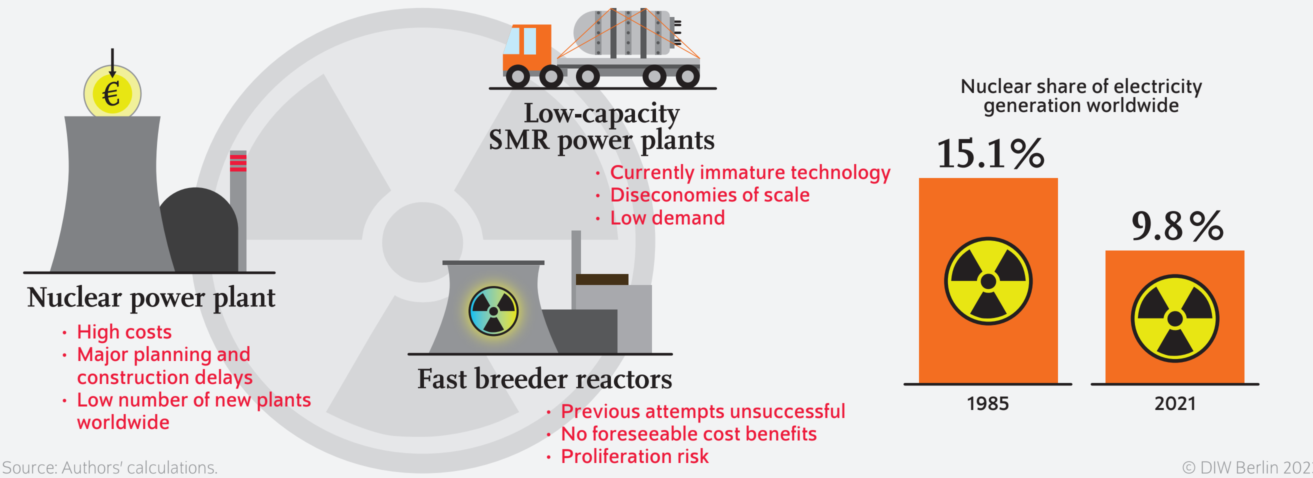
AT A GLANCE

# Plans for expanding nuclear power plants lack technological and economic foundations

By Alexander Wimmers, Fanny Böse, Claudia Kemfert, Björn Steigerwald, Christian von Hirschhausen, and Jens Weibezahn

- Study investigates the profitability and technological feasibility of reactor concepts worldwide
- Despite imminent nuclear phase-out, there are debates on new reactor concepts in Germany too
- Existing and planned power plant projects are uneconomical and no technological breakthroughs are expected
- A shift in energy system analysis toward renewable energy sources and away from nuclear energy has occurred
- Demands in Germany for research funding for constructing new nuclear plants are misguided

Nuclear power plant projects currently under discussion are not sustainable




Source: Authors' calculations.



FROM THE AUTHORS

*"Nuclear energy was, is, and remains unprofitable and technologically risky. Allegedly novel reactor concepts originating from the early days of nuclear energy in the 1950s and 60s do not change this."*

*— Alexander Wimmers —*

MEDIA

**Audio Interview** with Christian von Hirschhausen (in German)
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# Plans for expanding nuclear power plants lack technological and economic foundations

**By Alexander Wimmers, Fanny Böse, Claudia Kemfert, Björn Steigerwald, Christian von Hirschhausen, and Jens Weibezahn**


## ABSTRACT

In mid-April 2023, the final three nuclear power plants in Germany will be taken offline permanently. At the same time, the energy crisis resulting from the Russian invasion of Ukraine has fueled calls for the construction of new nuclear reactors in Germany. A similar debate is taking place in many other countries in the context of the climate crisis. Since the 1950s, nuclear power has been one of the most expensive energy sources and remains so to this day. It is also not a quick solution, as it takes decades to build reactors. Moreover, no significant technological breakthroughs are foreseeable in the development of cost-competitive reactors; this applies to both SMR concepts ("small module reactors") with lower capacity as well as for other types of reactors, such as fast breeder reactors. There is growing acceptance in the energy system modeling community, which previously predicted a substantial nuclear share while underestimating renewable energy sources due to overoptimistic assumptions, that there are no breakthroughs on the horizon.


On April 15, 2023, the final three nuclear power plants in Germany, Emsland in Niedersachsen, Isar-2 in Bavaria, and Neckwarestheim-2 in Baden-Württemberg, will be taken offline, thus ending the era of commercial nuclear power in Germany. Now, the focus will shift to decommissioning nuclear power plants and to the search for secure interim storage facilities and a final repository for highly radioactive waste. Germany and other countries have hoped to develop commercial nuclear power into a cost-effective and technologically innovative energy source since the 1950s, but this has never been realized. In fact, the original idea to develop a plutonium economy,[1] i.e., to produce an almost unlimited amount of inexpensive fissile material through a closed fuel cycle, has failed. In contrast, electricity generation from nuclear power plants is by far the most expensive way and has remained so since the beginning of the nuclear age in the 1950s. Nuclear power was and is not competitive compared to alternative energy generation technologies (previously coal, now renewable energy sources).[2] Furthermore, the economic questions that arise with decommissioning the nuclear power plants are unresolved. Worldwide, not a single repository is in operation yet.[3]

Nevertheless, the development of so-called "new" types of nuclear power reactors and the related construction of nuclear power plants are being intensively debated in some countries, in particular the nuclear-weapon states (USA, Russia, China, France, United Kingdom), but also in some countries that are only now planning to enter nuclear energy (Türkiye,

**1** Glen T. Seaborg, "The Plutonium Economy of the Future," (speech, Santa Fe, NM, 1970) (available online; accessed on February 23, 2023. This applies to all other online sources in this report unless stated otherwise).

**2** In 1957, one kWh of coal cost 0.87 US cents and one kWh of nuclear energy 5.19 US cents, cf. Fritz Baade, *Welt-Energiewirtschaft: Atomenergie – Sofortprogramm oder Zukunftsplanung* (Hamburg: Rowohlt, 1958) (in German). In 2010, these costs had increased to 7.40 USD for coal and 10.5 US cents for nuclear energy, cf. Lucas W. Davis, "Prospects for Nuclear Power," *Journal of Economic Perspectives* 16, no. 1 (2012): 49–66 (available online). Renewable energy sources have become nuclear's new competitor since the 2010s. In 2021, the costs for wind power were 3.80 US cents and 3.60 US cents per kWh for PV, while costs for nuclear energy had increased to 16.70 US cents per kWh, cf. Lazard, *Lazard's Levelized Cost of Energy Analysis* – Versions 4 to 15 (New York: LAZARD'S Levelized Costs of Energy Analysis, 2009–2021) (available online).

**3** The first is expected to open in Finland in 2024, cf. Achim Brunnengräber and Maria R. Di Nucci, *Conflicts, Participation and Acceptability in Nuclear Waste Governance: An International Comparison, vol. 3* (Wiesbaden: Springer VS, 2019) (available online).


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Egypt, Bangladesh) or have recently done so (Belarus, United Arab Emirates).

In Europe, the inclusion of nuclear energy in the EU taxonomy[4] has created new opportunities for the subsidization of new construction projects even more than before. However, the classification of nuclear power as a sustainable technology within the taxonomy is highly controversial among experts. In Germany and other European countries, there are currently political and societal calls to build new nuclear power plants as a longer-term solution in support of the energy transition and to step up the required research efforts.[5] However, the German energy industry has clearly rejected this perspective. Above all, it is unclear which technologies are even available for further developing nuclear energy and how they should become competitive in the foreseeable future.

## Nuclear share of electricity generation declining worldwide

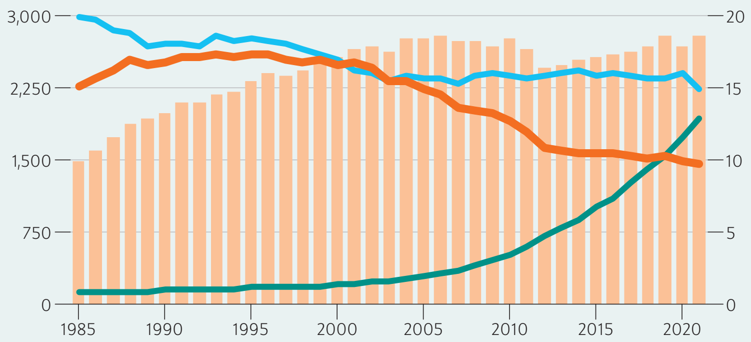
Worldwide, the expansion of nuclear power plants has largely stagnated following the construction boom of the 1970s and 80s. Since the 1990s, electricity generated by nuclear power plants has remained at around 2,600 terawatt hours per year.[6] Its share of total electricity generation, however, has been declining since its historic high of 17.6 percent in 1996. In 2021, the nuclear share was below ten percent for the first time in decades (Figure 1). In contrast, the share of renewable energy is continuously increasing.

The nuclear share of electricity generation will continue to decline. Over the next few years, a large number of nuclear power plants will be taken offline due to their advanced age.[7] These extensive shutdowns are offset by only 53 new construction projects (approximately 50 GW) currently underway. However, apart from 21 active expansion projects in China, development is proving to be protracted. Twenty-six of the current new construction projects are currently experiencing delays in planning, approval, or completion—in some cases by a significant amount of over ten years. On the other hand, the expansion of renewable energy sources is increasing continuously and will continue to reduce the nuclear share in the electricity mix, partially due to the expansion of electrification in the future.

Figure 1

**Worldwide development of electricity generation from nuclear energy, hydropower, and other renewable energy sources**

Annual generation in terawatt hours (left axis); shares in percent (right axis)




Sources: BP Statistical Review; authors' calculations.



For the first time, the share of worldwide electricity generated by nuclear energy is under ten percent; the renewable energy shares, in contrast, are becoming increasingly important.

## New construction plans are uncertain in terms of technology and economically questionable

In recent years, some countries have declared plans to build one or more new nuclear plants; in Europe, France and Great Britain in particular have ambitious expansion targets for nuclear plants.[8] Such discussions are also occurring in the Netherlands, Sweden, Poland, Hungary, Czechia, and even Germany. However, in most cases, it is unclear which reactor types would be used to realize these plans and how the reactors would be financed. This Weekly Report discusses this issue and looks at the three reactor types involved in the debate.

## Current generation of light-water reactors have major construction delays and are overpriced

Currently, the only realistic option for building nuclear power plants is to use existing technology, namely Generation III light-water reactors (LWR), which range from 600 to 1,600 megawatts (MW) of capacity. LWR reactors include the French European Pressurized Reactor (EPR; under construction in France and China); the American AP 1000 (manufactured by Westinghouse), and the Russian VVER 1200 (manufactured by the Russian state-owned enterprise Rosatom). The expansion of LWR reactors, especially water-cooled

**4** European Commission, *Taxonomy Complementary Climate Delegated Act* (Brussels: 2022) (available online).

**5** Roland Berger et al., "Wohlstand in Gefahr: Für eine neue Strategie in der Energiepolitik," *ifo Schnelldienst*, no. 12 (2022) (in German); ntv politik, "Gesamtmetall-Chef denkt über Bau neuer AKWs nach," August 1, 2022 (in German; available online); Achim Brunnengräber et al., "Monumentale Verdrängung: Die neue Pro-Atom-Troika," *Blätter für deutsche und internationale Politik*, no. 2 (2023): 9–12 (in German; available online).

**6** 1 TWh = 1 billion kWh.

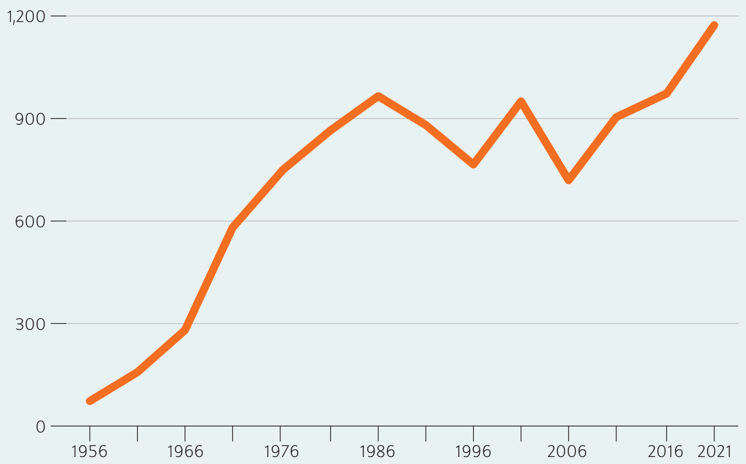
**7** According to current estimates, 84 GW (110 reactors) will go offline worldwide in the 2020s. In addition, between 2031 and 2040, 81 GW (95 reactors) and in the 2040s, 71 GW (72 reactors) will reach the end of their currently planned operating licenses, cf. Mycle Schneider et al., *World Nuclear Industry Status Report 2022* (Paris: Mycle Schneider Consulting, 2022) (available online)

**8** HM Government, *British Energy Security Strategy* (London: 2022) (available online); Ania Nussbaum and Francois De Beaupuy, "Macron Pledges New Nuclear Reactors—If He's Re-Elected," *Bloomberg*, February 10, 2022 (available online).

Figure 2

**Average capacity development of nuclear power plants**

Five-year average of electrical capacity in megawatts




Sources: Mycle Schneider Consulting; authors' depiction.



The capacity of new nuclear plants has grown rapidly from very low electrical capacity in the 1950s to over 1,000 megawatts in 2021.

thermal reactors, reached its peak in the 1970s and 80s. In the following decades, however, expansion worldwide, especially in the USA and Europe, experienced a sharp decline due to high costs and constant construction delays, among other issues.[9] Current cost analyses and comparisons with renewable energy technologies, whose electricity production costs are less than 100 USD per Megawatt hour, show that the currently massively high construction costs for nuclear power plants would need to be reduced by two-thirds to maintain a ten percent share of electricity production in a decarbonized European energy system.[10] Contrary to original expectations, the construction of nuclear power plants has not become more affordable over the decades, but rather has become continuously more expensive (per kilowatt of capacity). Moreover, it never became possible to leverage the standardization and mass production advantages achieved in other industries (such as for chip production and solar panels).[11]

## SMR concepts not fully developed and unavailable for the foreseeable future

One alternative to the ongoing construction projects could be to return to the lower capacities of the 1950s and 60s and to develop these reactors further based on established LWRs. This idea was suggested by US Secretary of Energy, Steven Chu, in 2010, who advertised SMRs as "America's new nuclear option."[12] Originally, SMR stood for "small and medium sized reactors,"[13] but later changed to "small modular reactors."[14] In this context, SMRs can be understood to be reactors with a capacity of up to 300 MW.

The term SMR has since found its way into energy and innovation policy debates.[15] However, the current hype around them is unfounded, as these are old reactor concepts that have not become established due to economic disadvantages resulting from the lower output (Box). Furthermore, they remain dangerous in terms of radiation, as the problems of transport and interim storage of radioactive waste would be multiplied.

The construction of low-capacity nuclear plants has been a possibility since the 1950s and the technology is thus no innovation. The first SMR developed in the USA was an S2W (Submarine Platform Second Generation Westinghouse Design) LWR for use in submarines. Following its installation in the first commercial nuclear power plant in Shippingport, Pennsylvania, in 1957, light-water technology triumphed.[16] However, these low-capacity reactors were merely used as a starting point to quickly move on to constructing larger-scale, higher-capacity plants. The search for economies of scale subsequently led to an increase in the average electrical capacity of nuclear power plants to 500 MW as early as the 1970s; today it exceeds 1,000 MW (Figure 2).

Despite decades of research, hardly any SMR nuclear power plant has been able to begin commercial operation. Rather, as with the nuclear power plants of higher power classes, the attempts are characterized by long development phases, short operating phases, and very long decommissioning phases (Figure 3). Many of the historical SMRs have not been finally disposed of as of 2023.

In addition to the historical prototypes, there are currently only six other SMRs in operation worldwide, such as the floating KLT-40S power plant with an electrical capacity of 64 MW in Pevek, Siberia, which began operating in 2020 after

**9** Ben Wealer et al., "Kernenergie und Klima," *Diskussionsbeiträge der Scientists for Future*, no. 9 (2021): 1–98 (in German; available online).

**10** Leonard Göke and Alexander Wimmers, "Economic Efficiency of Nuclear Power in Decarbonized Energy Systems," (speech, Vienna, Austria, February 16, 2022) (in German; available online).

**11** Chapter 4 in Christian von Hirschhausen, *Atomenergie: Geschichte und Zukunft einer riskanten Technologie*, 1st ed. (Munich: C.H. Beck, 2023).

**12** Steven Chu, "America's New Nuclear Option: Small Modular Reactors Will Expand the Ways We Use Atomic Power," *The Wall Street Journal*, March 23, 2010 (available online).

**13** IAEA, *Small and Medium Power Reactors – 1960* (Vienna: International Atomic Energy Agency, 1961); IAEA, *Small and Medium Power Reactors—1970* (Vienna: International Atomic Energy Agency, 1971).

**14** IAEA, *Advances in Small Modular Reactor Technology Developments* (Vienna: International Atomic Energy Agency, 2014) (available online) and IAEA, *Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS)* (Vienna: International Atomic Energy Agency, 2018).

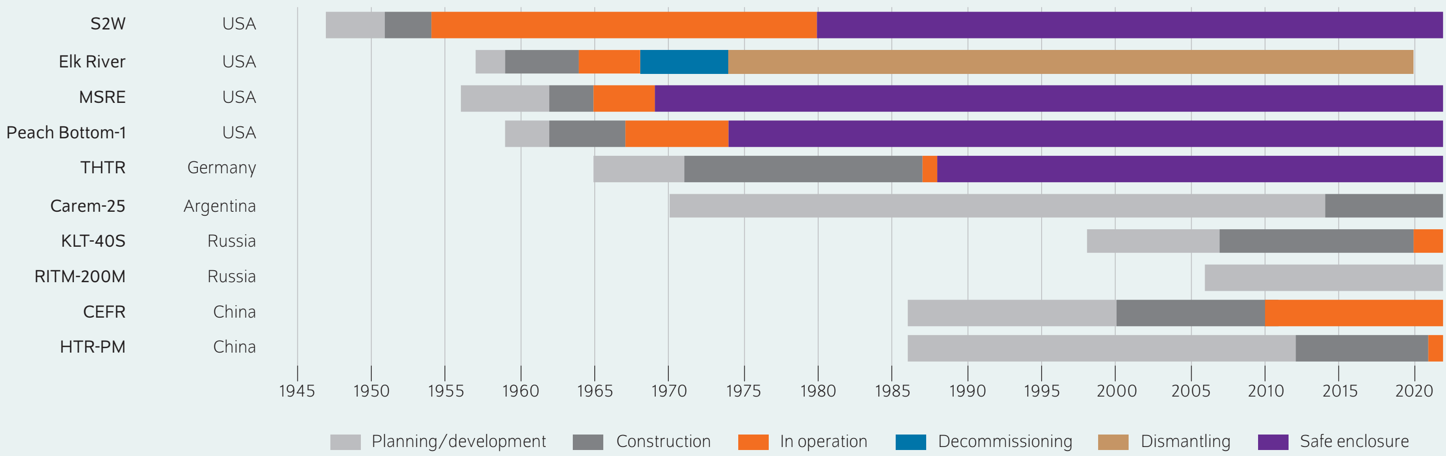
**15** Christoph Pistner et al, *Sicherheitstechnische Analyse und Risikobewertung einer Anwendung von SMR-Konzepten (Small Modular Reactors)* (Darmstadt: Öko-Institut e.V., 2021) (in German); Stephen Thomas and M. V. Ramana, "A Hopeless Pursuit? National Efforts to Promote Small Modular Reactors and Revive Nuclear Power," *WIREs Energy and Environment* (2022) (available online); IAEA, *Advances in Small Modular Reactor Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS)* (Vienna: International Atomic Energy Agency, 2022) (available online).

**16** Robin Cowan, "Nuclear Power Reactors: A Study in Technological Lock-In," *The Journal of Economic History* 50, no. 3 (1990): 541–567.

Figure 3

**Timeline of historical and current SMR concepts**

Planning and development, construction and operation periods, dismantling, and so-called safe enclosure




Sources: Pistner et al., Sicherheitstechnische Analyse; authors' depiction.



SMR concepts were developed, built, and operated in the 1950s. However, only a few remain in operation as of 2023.

13 years of construction.[17] The LWR project CAREM (*Central Argentina de Elementos Modulares*) in Argentina has been in progress since the 1980s, but commissioning has become a distant prospect due to the construction stop. In addition, there is a series of projects in the development or approval phases:[18] In the USA, for example, NuScale's VOYGR LWR design has received a standard design license for reactor construction.[19] However, there has been little demand and the costs have recently increased substantially. Other countries, too, such as Great Britain and Canada, are participating in the development of SMRs and expect to realize a demonstration reactor in the future.[20]

These projects are the first of their kind of the respective design. For such early prototypes or demonstration projects, reliable operation remains completely open, as well as the potential mass production of more reactors of the same design. However, these aspects are the prerequisite for the necessary cost degression. In particular, there is no prospect of overcompensating for the considerable diseconomies of scale via mass production. Optimistically, this would require the construction of several thousand identical nuclear power plants (Box). Yet mass production of reactors requires harmonization and standardization of designs and codes, which is unlikely to be feasible even in the medium term.[21]

Even under the optimistic framework conditions, it cannot be assumed that the offer is cost competitive. A current study involving DIW Berlin shows that in a simulation with random samples (Monte Carlo simulation) of SMR concepts, the expected average levelized costs of electricity for water-cooled concepts would be between 213 and 581 USD/MWh on average (Figure 4).[22] Thus, if ever built, they would be significantly more expensive than electricity from renewable energy sources from today's perspective. Furthermore, the problematic production of highly radioactive waste would continue.

## Fast breeder reactors and other non-LWR reactors neither available nor competitive for the foreseeable future

Beyond SMRs, there is debate about whether other reactor types could become available cost effectively on an industrial scale in the next few decades; development of these reactors was largely halted in the 1970s due to technical problems and a lack of competitiveness. Such other reactor types include non-light-water reactors with various cooling concepts and neutron spectra, referred to as Gen IV reactors in the nuclear industry. However, these non-light-water reactors are based on technology that had already been developed as early as

**17** World Nuclear News, "Russia connects floating plant to grid," December 19, 2019 (available online).

**18** Christoph Pistner et al, *Sicherheitstechnische Analyse und Risikobewertung*; IAEA, *Advances in Small Modular Reactor Developments.*

**19** IAEA, *Advances in Small Modular Reactor Developments.*

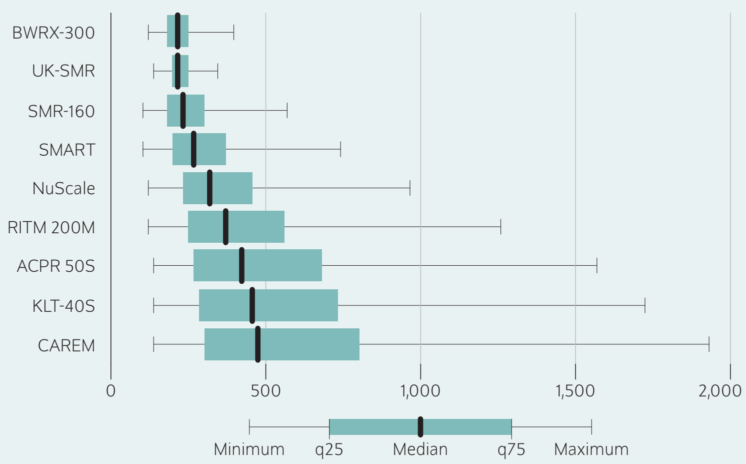
**20** Thomas and Ramana, "A Hopeless Pursuit?"

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

**22** Björn Steigerwald et al., "Estimating Production Costs of Future Nuclear Fission Reactors – The Effect of Parameter Choice and an Application to SMR Concepts under Development ('Small Modular Reactors')," (speech at the 43rd IAEE International Conference, Tokyo, Japan, August 2, 2022).

Figure 4

**Electricity generation costs of SMR concepts**
In USD per Megawatt hour




Note: Only light-water reactors are included.

Source: Steigerwald et al., "Estimating Production Costs of Future Nuclear Fission Reactors."



The expected costs of current SMR concepts are substantially higher than other energy sources.

Box

**Model calculation**

The return to constructing low-capacity reactors is tied to the hope of achieving cost benefits via modularization or mass production.[1] In the literature, however, it is initially assumed that specific construction costs either decrease as the size of the plant increases (capacity) or increase as output capacity decreases (economies of scale).[2]

A simplified model calculation from production theory shows that SMR concepts suffer from a strategic diseconomy of scale that could be eliminated only if production volumes were extremely high and unattainable from today's perspective: The cost disadvantage of an SMR reactor compared to light-water reactors with higher capacity could theoretically be compensated for by learning or mass production effects. Increases in the production quantity of a standardized product would thus lead to decreasing specific construction costs either through mass effects of a serial production or through higher labor productivity (learning effects).

The construction costs for a hypothetical mass produced reactor, i.e., the *n*-th reactor of a series ($C_{SMR,n}$), depend on the costs for the first of these reactors, the learning rate *x*, and the number of times the production output is doubled *d* (formula, left part). The cost of the first low-capacity reactor ($C_{SMR,1}$) can be represented by a comparison with a reactor of larger capacity (formula, right part). This stylized production cost calculation can be used to determine the number of SMR reactors that would compensate for the cost disadvantage created by economies of scale.[3]

**1** Giorgio Locatelli, Chris Bingham, and Mauro Mancini, "Small Modular Reactors: A Comprehensive Overview of Their Economics and Strategic Aspects," *Progress in Nuclear Energy* 73 (2014): 75–85 (available online).

**2** Geoffrey Rothwell, *Economics of Nuclear Power* (London: Routledge, 2016).

**3** Clara Lloyd, Robbie Lyons, and Tony Roulstone, "Expanding Nuclear's Contribution to Climate Change with SMRs," *Nuclear Future* 663 (2020).

the 1940s and led to prototypes in the 1950s. Fast breeder reactors, high temperature reactors, and molten salt reactors all failed to prevail over the light-water reactor technology.[23]

Since the early 2000s, new efforts have been underway to revive these reactor types. In addition, there are also efforts to realize concepts for better waste handling and increased fuel utilization as well as to reduce proliferation risks (the transfer of material that can be used in nuclear weapons).[24] With the establishment of the GenIV International Forum in 2001, 14 member states, including the USA, China, Russia, the EURATOM states, and the United Kingdom, have joined forces with the shared objective of further developing non-light-water reactor concepts.[25] However, these efforts have had little technological or commercial success so far.[26] The time frames by which functional demonstrators of the envisioned size classes (typically well over 300 MW) could be available are regularly pushed back by the Gen IV International Forum, most recently into the 2040s.

Low investment dynamics and a lack of implementation prospects in the non-light-water reactor developments can be illustrated by sodium-cooled reactors with a fast neutron spectrum, also known as "fast breeders."[27] This technology is considered to be the most advanced, with a pilot project

**23** Christoph Pistner and Matthias Englert, *Neue Reaktorkonzepte. Eine Analyse des aktuellen Forschungsstands* (Darmstadt: Öko-Institut e.V., 2017) (in German; available online); Cowan, "Nuclear Power Reactors"; Ben Wealer et al., "Nuclear Power Reactors Worldwide – Technology Developments, Diffusion Patterns, and Country-by-Country Analysis of Implementation (1951–2017)," *Data Documentation* 93 (2022).

**24** GenIV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems. Technology Roadmap GIF-002-00* (2002) (available online).

**25** GenIV International Forum, *Annual Report 2021* (2022) (available online).

**26** Edwin Lyman, *"Advanced" isn't Always Better: Assessing the Safety, Security, and Environmental Impacts of Non-Light-Water Nuclear Reactors* (Cambridge: Union of Concerned Scientists, 2021) (available online).

**27** Compared to thermal spectrum reactors, fast neutron spectrum reactors have higher fuel utilization because they breed fissile material. However, this material must be be laboriously reprocessed before it can be used again (as mixed oxide fuel or MOX). Reprocessing fuel is associated with very high costs, cf. Frank von Hippel, Masafumi Takubo, and Jungmin Kang, Plutonium: How Nuclear Power's Dream Fuel Became a Nightmare (Singapore: Springer, 2019) (available online). Currently, only a few countries are operating reprocessing plants, such as France, the UK, and Russia. Two such plants are currently under construction in China, cf. Matthew Bunn, Hui Zhang, and Li Kang, *The Cost of Reprocessing in China* (Cambridge: Belfer Center for Science and International Affairs Harvard Kennedy School, 2016) (available online).

Table

## Definitions of the calculation parameters

| Parameter | Definition |
|---|---|
| $C_{SMR,n}$ | Absolute construction costs for the nth of a small modular reactor ("*n*-th of a kind") [USD] |
| $C_{SMR,1}$ | Absolute construction costs for the construction of the first small modular reactor ("first of a kind") [USD] |
| x | Learning rate or factor of cost reduction after a d-fold doubling of the production quantity n. |
| d | Number of times the output amount n is doubled, meaning $n = 2^d$ |
| $C_{LR}$ | Absolute construction costs of a light-water reactor [USD] |
| $S_{SMR}$ | Electrical output of a small modular reactor [MW] |
| $S_{LR}$ | Electrical output of a light-water reactor [MW] |
| b | Economies of scale |

Source: Authors' own calculation.



$$C_{SMR,n} = C_{SMR,1} \times (1-x)^d = C_{LR} \times \left(\frac{S_{SMR}}{S_{LR}}\right)^b \times (1-x)^d$$

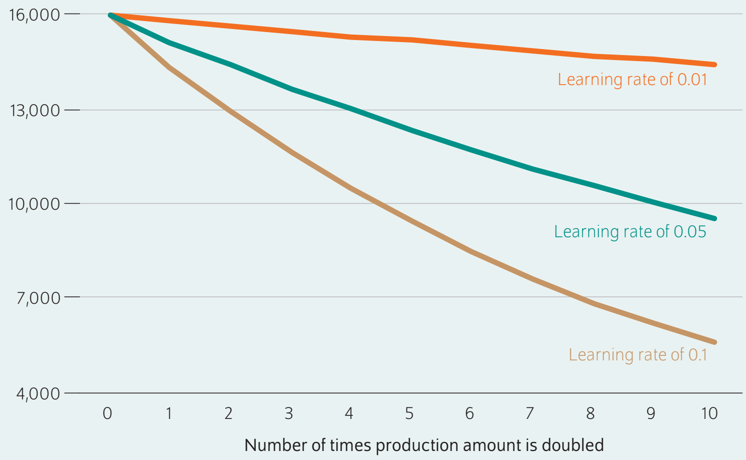
As an example calculation, two reactor designs (one low-capacity and one high-capacity) of the American company Westinghouse are used: an SMR design of a light-water reactor with a capacity of 225 MWe ($S_{SMR}$) and the AP1000, a light-water reactor with circa 1100 MWe ($S_{LR}$) of capacity. In the production calculation, this SMR design is expected to replace the specific construction cost of the AP1000 light-water design of 6000 USD/kW. Further, a learning rate of x = 0.06 (6 percent) and economies of scale of b = 0.55 are assumed. Under these circumstances, the specific construction costs of an SMR would not be lower than that of the AP1000 until approximately 3,000 reactors have been produced (i.e., d ≈ 11.55 doublings of production volume) (Table).[4]

**4** Pistner et al, *Sicherheitstechnische Analyse und Risikobewertung*; Steigerwald et al., "Estimating Production Costs of Future Nuclear Fission Reactors."

Figure

## Cost degression due to learning effects depending on the learning rate and doubling of production volumes

Specific construction costs for SMR in USD per kilowatt




Source: Authors' calculations.



SMR concepts have a structural cost disadvantage and could only approach the cost of current light-water reactors if production was in the several thousand range.

The figure shows a sensitivity analysis of this relationship: With higher learning rates *x*, a faster reduction of specific construction costs occurs. However, these learning rates for low-capacity nuclear power plants are likely to be far below the values achieved for other mass productions, for example microchips or solar cells. Furthermore, it must be taken into account that even the high-capacity light-water reactors could become somewhat cheaper through learning effects. And these costs are, as mentioned in the main text, even greater than those for renewable energy sources. Overall, therefore, the prospect of achieving cost advantages with SMR concepts is very small (Figure).

currently planned in the United States. Fast breeder reactors were developed in the 1950s, especially in Russia and the USA, but also in France, Germany, Japan, and, later, China.[28] In the early days of reactor development, it was assumed that all reactor development would lead to the fast breeder reactor and the plutonium economy.[29]

However, both technological and economic disillusionment began to spread in the many decades following the optimistic beginnings of the fast breeder reactor. Thus, its development has primarily been characterized by project cancellations. Initial demonstration projects in the USA were discontinued in the 1970s due to economic, technical, and proliferation risks (Table 1).[30] Moreover, technical problems such as coolant fires reoccurred because the coolant used, sodium, is

**28** Pistner and Englert, *Neue Reaktorkonzepte.*

**29** For more details on this, cf. Christian von Hirschhausen, "Nuclear Power in the Twenty-First Century (Part II) – The Economic Value of Plutonium," *DIW Berlin Discussion Paper* 2011 (2022) (available online).

**30** Thomas B. Cochran et al., *Fast Breeder Reactor Programs: History and Status. Research Report 8.* (Princeton: International Panel on Fissile Materials, 2010) (available online).

Table

**Historical examples of reactors with fast neutrons ("fast breeder reactors")**
Construction and operation periods

| Reactor concept | Country | Capacity (MWth) | Construction began in | Began operation in | Decommissioned in | Still active as of | Average capacity utilization |
|---|---|---|---|---|---|---|---|
| Experimental reactors | | | | | | | |
| Rhapsodie | France | 40 | 1962 | 1967 | 1983 | | n/a |
| KNK-II | Germany | 52 | 1975 | 1977 | 1991 | | 17.10 percent |
| DFR | United Kingdom | 60 | 1954 | 1959 | 1977 | | 33.80 percent |
| FBTR | India | 40 | 1972 | 1985 | | 2022 | n/a |
| PEC | Italy | 120 | 1974 | 2022 | | 2022 | n/a |
| JOYO | Japan | 140 | 1970 | 1977 | 2007 | | n/a |
| BR-10 | Soviet Union/Russia | 55 | 1956 | 1959 | 2002 | | n/a |
| BOR-60 | Soviet Union/Russia | 9 | 1958 | 1964 | | 2022 | n/a |
| EBR-I | USA | 1.2 | 1947 | 1951 | 1963 | | n/a |
| EBR-II | USA | 62.5 | 1958 | 1963 | 1994 | | n/a |
| Fermi | USA | 200 | 1956 | 1965 | 1972 | | n/a |
| FFTF | USA | 400 | 1970 | 1980 | 1992 | | n/a |
| CEFR | China | 65 | 2000 | 2010 | | | n/a |
| Demonstration reactors | | | | | | | |
| SNR-300 | Germany | 762 | 1973 | | 1991 | | Never began operation |
| Phoenix | France | 563 | 1968 | 1973 | 1983 | | Circa 50 percent |
| PFR | United Kingdom | 650 | 1966 | 1974 | 1994 | 2022 | 7 percent |
| PFBR | India | 1,250 | 2003 | 2012 | 2016 | | n/a |
| Monjou | Japan | 714 | 1985 | 1994 | 1999 | | From 1996 to 2010 out of service due to an accident |
| BN-350 | Soviet Union/Russia | 750 | 1964 | 1972 | | 2022 | 85 percent |
| BN-600 | Soviet Union/Russia | 1,470 | 1967 | 1980 | | 2022 | 74 percent (1982 to 2009) |
| BN-800 | Russia | 2,100 | 2006 | 2016 | 1983[1] | | 71 percent |
| CRBRP | USA | unknown | 1982 | | | | Never began operation |

1 While construction began in 1983, no construction activity took place between 1986 and 2006. It has restarted as of 2006.

Source: Authors' research.



highly reactive upon contact with water or air. There were also attempts to develop those reactor concepts, such as the fast breeder reactor in Kalkar near the Dutch border. However, it never began operation due to safety concerns and a lack of economic prospects.[31] Fast reactor technology also failed to take root in France. Russia is the only country still operating two fast reactors, located at the Beloyarsk nuclear power station near Zarechny; however, they have never been in commercial operation. China operates a research reactor near Beijing (Fangshan) and is currently constructing an initial demonstration reactor in the Fujian province.[32] Following the decommissioning of the fast neutron reactors, the US Department of Energy is again trying to build fast reactors in cooperation with the company TerraPower[33] using considerable government funding.[34]

The competitiveness of these reactors depends on three important parameters: the price of uranium, construction costs, and disposal costs. There is no foreseeable cost advantage for the fast reactors in any of these three parameters. A calculation of the break-even price of uranium shows the price at which a hypothetical fast reactor with reprocessing would be as expensive to operate as an LWR without reprocessing. Rough calculations suggest that the uranium price would have to be many times higher than the price observed on the market.[35] The construction costs for the planned pilot

**31** Today, the amusement park "Wunderlan Kalkar" is located on the site. Willy Marth, *Der Schnelle Brüter SNR 300 Im auf und ab seiner Geschichte* (Karlsruhe: Kernforschungszentrum Karlsruhe, 1992) (in German; available online); WDR, *Wunderland Kalkar hat neuen Eigentümer*, August 3, 2022 (in German; available online). Cf. for more on the history of German nuclear power plants Lena-Jülide Camurdas et al., *Einfach mal Abschalten, und dann? Wohin mit dem radioaktiven Abfall?* (München: oekom Verlag, 2023) (in German).

**32** IAEA, *Nuclear Power Reactors in the World* (Vienna: International Atomic Energy Agency, 2022) (available online).

**33** TerraPower is partly owned by Bill Gates, and the concept is being developed in collaboration with Lowell Wood, who formerly worked with Edmund Teller, considered the father of the hydrogen bomb.

**34** As one of two concepts, TerraPower received billions of dollars in grants from the US government, most recently topped up by the Biden administration's 2021 infrastructure bill. Cf. Office of Nuclear Energy, U.S. Department of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program (2020) (available online), and US Congress, *Infrastructure Investment and Jobs Act (IIJA) – Bipartisan Infrastructure Law* (2021) (available online).

**35** Matthew Bunn et al., "The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel. Project on Managing the Atom," *Nuclear Technology*, vol. 150 (2005) (available online); Christian von Hirschhausen, "Nuclear Power in the Twenty-First Century (Part II)."

projects in the United States are not foreseeable, but are likely to be significantly higher than the costs of the light-water technology, which itself is far more expensive than other energy sources. There is also no foreseeable benefit from the pilot project in terms of disposal costs.

## A change in energy system modeling has begun

The low potential of the nuclear industry to develop competitive reactor designs is now reflected in the energy system modeling and integrated assessment model (IAM) community. These experts had previously calculated very high nuclear shares in climate action scenarios in some cases. For example, until recently, nuclear energy was considered a low-carbon technology in climate scenarios, independent of its apparent lack of competitiveness.[36] On average, scenarios with an increasing nuclear share assume that by 2050, the annual volume of electricity generated from nuclear energy worldwide will be about 5,600 TWh, more than double the current volume. In these scenarios, the modelers previously assumed unrealistically low investment costs for nuclear power. At the same time, however, they assumed relatively high costs for renewable energy sources (especially solar) as well as excessive system integration costs while ignoring the system costs of nuclear energy.

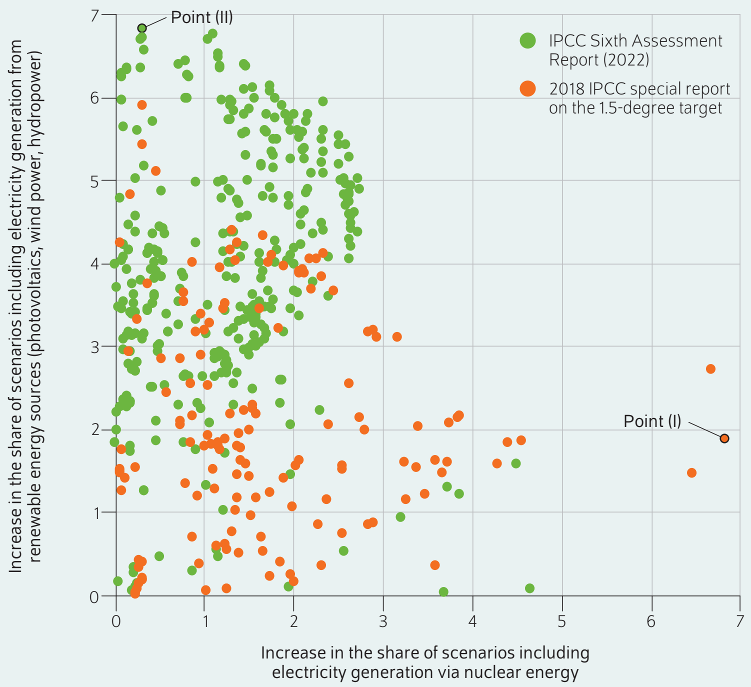
However, a few years ago, professionals began to rethink things, which has led to a weakening of the nuclear power modeling paradox[37] and gives way to modeling and underlying assumptions that are more strongly oriented toward real economic technical developments. This is characterized in particular by current cost assumptions for renewable energy sources, especially for photovoltaics and energy system integration costs.[38] A variety of models now identify renewable energy sources, rather than nuclear, as the driver of the future energy mix.

Comparing the energy scenarios in the 2018 and 2022 reports by the Intergovernmental Panel on Climate Change (IPCC) shows that the number of scenarios with an increase in nuclear energy (between 2020 and 2100) has decreased, while the number with a strong increase in renewable energy has grown (Figure 5). While the IPCC's 2018 special report on the 1.5-degree target focused on increasing shares of nuclear energy (orange dots), its 2022 report shifted toward increasing shares of renewable energy and decreasing shares of nuclear energy (green dots). The modelers at the Potsdam Institute for Climate Impact Research (PIK) also point out that nuclear energy would have to be largely replaced by renewable energy sources in the coming decades when following a cost-optimal decarbonization path.[39]

Figure 5

**Comparison of energy and climate scenarios in 1.5-degree report (2018) and the Sixth Assessment Report (2022)**

Increase in the share of electricity production from 2020 to 2100 in per mille




Legend: Orange point on the right (point (I)): Observation of the change in the percentage share of the respective technology of electricity generation between 2020 and 2100. A positive value means an increase in the respec-tive share over the observation period (increase in the share of nuclear energy (0.0068) | increase in the share of renewable energy sources (photovoltaics, wind power, hydropower) (0.0018)). Green point with the largest Y value (point (II)): (Increase in the share of nuclear energy (0.0003) | increase in the share of renewable energy sources (photovoltaics, wind power, and hydropower) (0.0068)).

Note: Only light-water reactors are included.

Source: Björn Steigerwald et al., "Nuclear Bias in Energy Scenarios: A Review and Results from an in-Depth Analy-sis of Long-Term Decarbonization Scenarios," (speech, Vienna, Austria, February 15, 2023).



In many energy scenarios, a shift away from nuclear energy and toward renewable energy sources is taking place.

## Conclusion: Expanding nuclear energy is neither technically nor economically feasible; focus should remain on disposal

Over the past decades, the nuclear industry has failed to produce competitive reactors. The current dynamics on the energy markets are resulting in hundreds of old nuclear power plants being taken offline. In Germany, as well as in the rest of Europe and worldwide, there are enough

**36** Son H. Kim, et al., "Nuclear Energy Response in the EMF27 Study," *Climatic Change* 123 (2014): 443–460. (available online)

**37** This contrast between the increasing importance of nuclear power despite its clear lack of operational competitiveness is also known as the nuclear power modeling paradox, cf. Christian von Hirschhausen, "Nuclear Power in the Twenty-first Century – An Assessment (Part I)," *DIW Discussion Paper*, no. 1700 (2017) (available online).

**38** Dmitrii Bogdanov et al., "Full Energy Sector Transition towards 100 % Renewable Energy Supply: Integrating Power, Heat, Transport and Industry Sectors Including Desalination," *Applied Energy* 283 (2021): 116273 (available online); Konstantin Löffler et al., "Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS)," *Energies* 10, no. 10 (2017): 1486 (available online).

**39** Gunnar Luderer et al., "Impact of Declining Renewable Energy Costs on Electrification in Low-Emission Scenarios," *Nature Energy* 7 (2021): 32–42 (available online).

cost-efficient renewable energy sources available for a climate-neutral and plutonium-neutral energy system.

Hopes for radical innovations and the expansion of reactor concepts that have not been tested at an industrial level seem unfounded in light of the experiences of the past decades. The idea of constructing low-capacity power plants was realized in the 1950s. However, it was quickly abandoned as a result of structural cost disadvantages. This, too, is why no improvements can be expected in SMRs as of 2023. Although some countries are attempting to revive non-light-water reactors, which have not been utilized to date, an industrial breakthrough in the coming decades is unlikely. Therefore, efforts should not be focused on researching allegedly new reactor concepts, but rather should focus exclusively on the challenges of decommissioning and storing radioactive waste. The nuclear phase-out, i.e., the end of all nuclear activities, will not be successful until its legacy—in the form of radioactive waste—has been disposed of as safely as possible in deep geological repositories.

The shift in energy system and integrated assessment modeling reflects the nuclear industry's meager prospects for competitive reactors. Although experts long shared the dream of a plutonium economy, this consensus has given way to a more realistic assessment of technology and cost developments. Taking into account current trends and data, nuclear energy remains far inferior to renewable energy sources in terms of costs.

The following implications can be derived from the analysis: In the context of research funding, policymakers should, in the future, focus on areas that can be expected to make substantial contributions to the energy transition, such as renewable energy sources, storage, and other flexibility options. Nuclear energy is not one of these areas. Policymakers should resolutely oppose efforts to label energy produced by nuclear power plants, such as hydrogen, as "green" or "sustainable." When designing the electricity sector in Germany and Europe, solutions aimed at subsidizing nuclear plants (as in France and Poland, for example) should be rejected.

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