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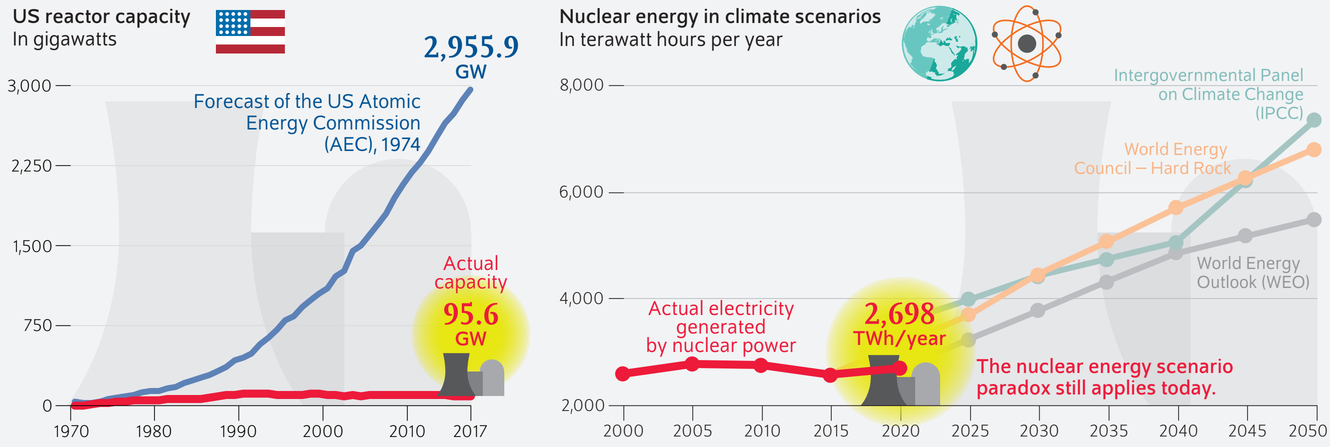
AT A GLANCE

Energy and climate scenarios paradoxically assume considerable nuclear energy growth

By Christian von Hirschhausen, Björn Steigerwald, Franziska Hoffart, Claudia Kemfert, Jens Weibezahn, and Alexander Wimmers

- Study investigates the importance given to nuclear energy in long-term energy and climate scenarios
- Despite a lack of innovation and economic competitiveness, most scenarios assume a considerable increase in nuclear energy
- Contradiction between overly optimistic scenarios and reality is deemed the nuclear energy scenario paradox
- Paradox reflects long-term hopes of a plutonium economy, which were unrealistic in 1945 and remain so in 2023
- There is a risk of investing significant funds in the development of nuclear energy technologies although other technologies are more cost-efficient and carry less risk

Most energy scenarios include considerable reactor capacity growth, which contradicts reality



Source: Authors' depiction based on Frank von Hippel, Masafumi Takubo, and Jungmin Kang (2019); IAEA.

FROM THE AUTHORS

> *"If politicians and the energy industry base their planning on false interpretations of climate scenarios, a lot of money in the future will go to projects that rely on nuclear energy instead of renewable energy. This is money that will then not be available for a sustainable and cost-effective energy transformation."*
> *— Christian von Hirschhausen —*

MEDIA

Audio Interview with Christian von Hirschhausen (in German)
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Energy and climate scenarios paradoxically assume considerable nuclear energy growth

By Christian von Hirschhausen, Björn Steigerwald, Franziska Hoffart, Claudia Kemfert, Jens Weibezahn, and Alexander Wimmers

ABSTRACT

Most climate and energy scenarios created by international organizations and researchers include a considerable expansion of nuclear energy. In the IPCC Sixth Assessment Report, for example, nuclear energy increases from a current 3,000 terawatt hours on average to over 6,000 terawatt hours in 2050 and to over 12,000 terawatt hours in 2100. This doubling and quadrupling of nuclear energy production by 2050 and 2100 is contradictory to the technical and economic realities: At no point have newly built nuclear energy plants ever been competitive, nor will they become so in the foreseeable future. This contradiction, referred to here as the nuclear energy scenario paradox, can be explained by a series of politico-economic, institutional, and geopolitical factors. In particular, the close relationship between the military and commercial uses of nuclear energy as well as the interest of the nuclear industry and its organizations in self-preservation play a role. The assumptions and model logic of the scenarios must be critically scrutinized. There is the risk that considerable public and private funds will be invested in developing technologies for the commercial use of nuclear energy despite the fact that other technologies are expected to offer a significantly better cost-performance ratio with fewer economic, technical, and military risks. In light of the urgency of climate change mitigation, continuing to channel personnel and financial resources into nuclear energy is problematic.

Phasing out fossil fuels such as coal, natural gas, and petroleum in addition to the rapid expansion of renewable energy sources is key to establishing a sustainable energy supply. The role of nuclear energy in this transformation is being discussed increasingly, such as in the debates on an industrial power tariff or a taxonomy of sustainable investments. Different organizations' climate scenarios play an important role in the discussion on various transformation pathways, but also in legitimizing measures.[1] Industrial, political, and scientific actors are competing with one another to have the most influential models and scenarios. Generally, this process is far too complicated for the general public to evaluate it.[2] In addition to the quantitative development of scenarios, qualitive scenarios can help illuminate the underlying assumptions and thus review the scenarios in terms of their consistency and plausibility.[3]

Current climate scenarios focus on a reduction of greenhouse gas emissions, often referred to as net zero emissions. Germany has committed to achieving climate neutrality by 2045, the European Union (EU) by 2050, and most countries worldwide are preparing climate-neutral scenarios.[4] Nuclear energy has a large and often increasing role in these scenarios, despite the fact that the long-awaited technical innovations have never materialized and that to this day, nuclear

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[1] Leonard Göke, Jens Weibezahn, and Christian von Hirschhausen, "A Collective Blueprint, Not a Crystal Ball: How Expectations and Participation Shape Long-Term Energy Scenarios," *Energy Research & Social Science* (2023) (available online; accessed on October 10, 2023. This applies to all other online sources in this report unless stated otherwise).

[2] Arnulf Grubler, "Energy transitions research: Insights and cautionary tales," *Energy Policy* 50 (2012): 8–16 (available online); Franziska M. Hoffart, Elias-Johannes Schmitt, and Michael Roos, "Rethinking Economic Energy Policy Research – Developing Qualitative Scenarios to Identify Feasible Energy Policies," *Journal of Sustainable Development of Energy* 9 (2021): 1–28 (available online); Frank W. Geels, "Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective," *Energy Research & Social Science* 37 (2018): 224–231 (available online).

[3] Hoffart, Schmitt, and Roos, "Rethinking Economic Energy Policy Research;" Franziska M. Hoffart, "What Is a Feasible and 1.5°C-Aligned Hydrogen Infrastructure for Germany? A Multi-Criteria Economic Study Based on Socio-Technical Energy Scenario," *Ruhr Economic Papers* 97 (2022) (available online).

[4] Fernanda Ballesteros et al., "On the Way to Climate Neutrality: Scenarios Can Facilitate the Transition of Companies and the Financial Sector," *DIW Weekly Report*, no. 25 (2023): 183–190 (available online).

DOI: https://doi.org/10.18723/diw_dwr:2023-45-1

energy has never become competitive.[5] A good example of this is the International Energy Agency's (IEA) Net Zero Emissions by 2050 Scenario.[6] Although the IEA explicitly lists nuclear energy as one of the most expensive energy sources, its scenario assumes that worldwide, electricity generated from nuclear energy will increase from 2,700 terawatt hours in 2020 to over 5,000 terawatt hours in 2050 (Figure 1).

Nuclear energy has been playing an important role in energy scenarios since 1945. After the first nuclear bomb was dropped, it was assumed that nuclear energy would not only be used for weapons production, but could also one day be used to generate commercial electricity and heat. However, still to this day, there is not enough focus on the resulting radioactive waste that must be stored long term, the risks of nuclear accidents, and the potential proliferation of fissile materials.[7]

Over a decade of research from DIW Berlin shows that nuclear energy is not competitive, lacks innovation, and entails long construction times with significant technical risks.[8] This contradiction between the strong increase in nuclear energy in scenarios and its clear lack of economic competitiveness is referred to here as the nuclear energy scenario paradox.[9] This Weekly Report presents this paradox and scrutinizes it, looking at the past, present, and future.

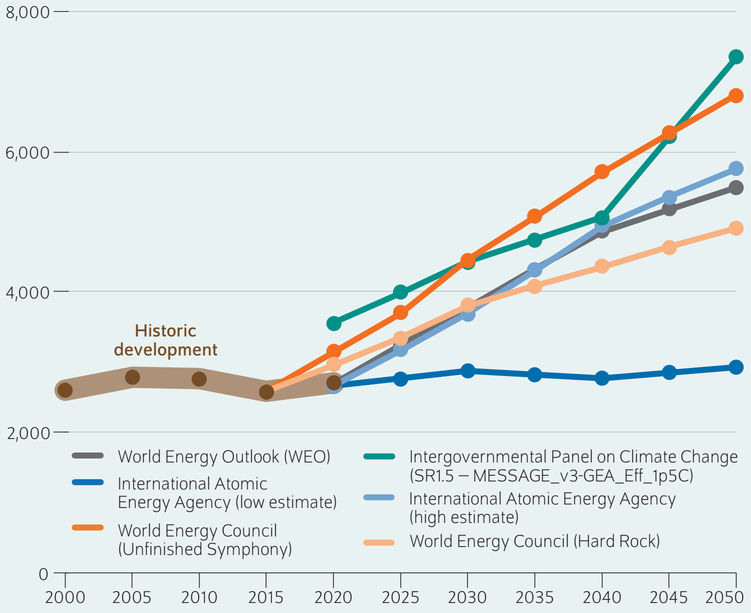
From 1945 and onward, energy scenarios are too optimistic and unrealistic about nuclear energy

There have been attempts to develop nuclear energy for commercial use in electricity and heating since 1945, but there have not been any decisive breakthroughs in profitability as of 2023.[10] It has also been assumed since 1945 that using plutonium instead of uranium, especially in fast-breeder reactors, would increase the profitability of nuclear energy. Due to the fast-breeder process, plutonium can utilize nuclear energy 60 times better than uranium-235.[11] In 1945, the limited availability of natural uranium deposits was the main reason the plutonium fuel cycle was used to generate energy. Nuclear physicist Leo Szilard, who discovered the nuclear chain reaction in 1933, believed it would be possible to import 400 tons of natural uranium per year after World War II. However, this would have only been sufficient for the operation of two light-water reactors with an electric capacity of 1,000 MW.[12] Therefore, the first nuclear programs in the United States, and later in other countries were planned with plutonium breeder reactors. In Germany, Werner Heisenberg contributed to the narrative of the plutonium economy by declaring to Konrad Adenauer and the public in 1953 that the issue of

Figure 1

Development of nuclear energy in selected climate scenarios

In terawatt hours



Note: Scenarios of electricity generated by nuclear energy are shown.

Sources: IEA, IAEA, WEC, and IPCC.

Most climate scenarios predict considerable growth in electricity generated by nuclear energy.

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[5] Ben Wealer et al., "Investing into third generation nuclear power plants – Review of recent trends and analysis of future investments using Monte Carlo Simulation," *Renewable and Sustainable Energy Reviews* 143 (2021): 110836 (available online); Björn Steigerwald et al., "Uncertainties in Estimating Production Costs of Future Nuclear Technologies: A Model-based Analysis of Small Modular Reactors," *Energy* 281 (2023) (available online).

[6] International Energy Agency, *Net Zero by 2050: A Roadmap for the Global Energy Sector* (2021) (available online).

[7] Ben Wealer et al., "Ten years after Fukushima: Nuclear power is still dangerous and unreliable," *DIW Weekly Report*, no. 7/8 (2021) (available online); Spencer Wheatley et al., "Reassessing the safety of nuclear power," *Energy Research & Social Science* 15 (2016): 96–100 (available online); Mariliis Lehtveer and Fredrik Hedenus, "Nuclear power as a climate mitigation strategy – technology and proliferation risk," *Journal of Risk Research* 18 (2015): 273–290 (available online).

[8] Cf. the section of the DIW Berlin website on nuclear power (in German; available online).

[9] Christian von Hirschhausen, "Nuclear Power in the Twenty-first Century – An Assessment (Part I)," *DIW Discussion Paper* 1700 (2017): 25–28 (available online); Björn Steigerwald et al., "Nuclear Bias in Energy Scenarios: A Review and Results from an in-Depth Analysis of Long-Term Decarbonization Scenarios," presented at the 17th European IAEE Conference (Athens, Greece: 2022).

[10] Lucas W. Davis, "Prospects for Nuclear Power," *Journal of Economic Perspectives* 26 (2012): 49–66 (available online); Geoffrey Rothwell, "Projected Electricity Costs in International Nuclear Power Markets," *Energy Policy* 164 (2022): 112905 (available online); Ben Wealer et al., "High-Priced and Dangerous: Nuclear Power Is Not an Option for the Climate-Friendly Energy Mix ," *DIW Weekly Report* no. 30 (2019): 235–243 (available online).

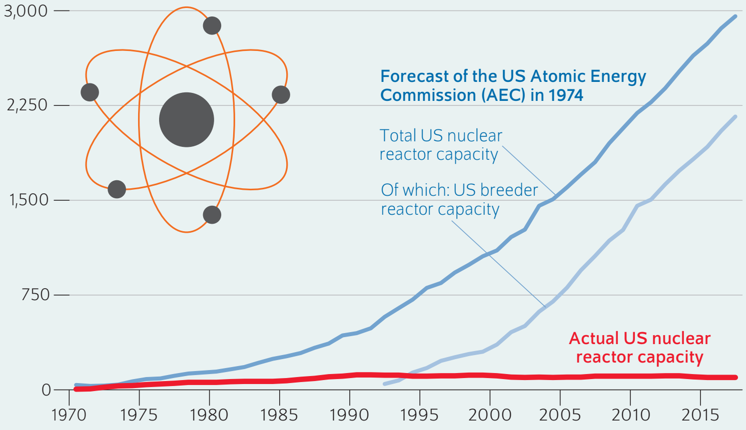
[11] By breeding additional fissile material in plutonium fast-breeder reactors, fissile (weapons-grade) plutonium can even be created from the non-fissile portion of uranium, uranium-238, so the process would be like a perpetual motion machine: the more it is used, the more energy can theoretically be provided. See Christoph Pistner, "Kernenergie: eine Technik für die Zukunft?" in *Kernenergie*, eds. Julia Mareike Neles and Christoph Pistner (Berlin: 2012): 37–38 (in German; available online).

[12] Leo Szilard, "Atomic Energy, a Source of Power or a Source of Trouble," speech given April 23, 1947 in Spokane, WA (UC San Diego: Leo Szilard Papers, MSS 32, Special Collections & Archives) (available online). Cf. von Hirschhausen, "Nuclear Power in the Twenty-first Century – An Assessment (Part I)," 18–25 for more on the data; OECD/NEA, *Uranium Resources, Production and Demand* (Paris, Vienna, Organization for Economic Co-Operation and Development and the Nuclear Power Agency: 2022) (available online).

Figure 2

Expected and actual development of reactor capacity in the United States (1974)

In gigawatts



Note: Contrary to the forecast, there are only light-water reactors in operation in the United States and no breeder reactors.

Source: Frank von Hippel, Masafumi Takubo, and Jungmin Kang, *Plutonium* (Singapur, 2019): 33.

The US Atomic Energy Commission (AEC) expected a breakthrough in the plutonium economy in the 1970s, but it never occurred.

Box

Reactor technologies

Reactor technologies can primarily be divided into reactors using a thermal neutron spectrum and a fast neutron spectrum. Thermal-neutron reactors include light-water reactors, which make up 80 percent of the reactors currently on the network. Light water is used as a moderator in these reactors to conduct nuclear fission of uranium-235. The use of uranium-235 as a fuel requires a number of complex processes, such as the enrichment of natural uranium. Reactors with a fast-neutron spectrum use other decay processes that could breed plutonium-239 from uranium-238 and theoretically make upstream processes from fuel fabrication for light-water reactors obsolete. For this reason, these reactors are also known as "fast-breeder reactors." Worldwide, only a handful of such reactors are in operation. Commercial breakthroughs have yet to materialize.[1]

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[1] More information on how these reactors function can be found in Frank von Hippel, Masafumi Takubo, and Jungmin Kang, *Plutonium* (Singapore, 2019) as well as Man-Sung Yum, *Radioactive Waste Management: Science, Technology, and Policy. Lecture Notes in Energy* (Springer, 2022) (available online).

the fast-breeder reactor had been solved.[13] The first reactor development program in Germany in 1957 (Eltville program) was equipped accordingly with plutonium breeder reactors.

Despite the failure of the first generation of plutonium breeder reactors in the 1950s in places such as Detroit (USA), Majak (Soviet Union), and Windscale (UK), the narrative of the plutonium economy of the future remained in the energy scenarios. As chairman of the US Atomic Energy Commission, American nuclear chemist Glenn T. Seaborg, who won the Nobel Prize for Chemistry in 1951 for isolating plutonium in 1940, later advocated for "plutonium as the energy cornerstone of our future economy," the so-called plutonium economy.[14] According to Seaborg, skyrocketing growth in nuclear energy would occur almost entirely due to plutonium breeder reactors following a transition phase (Figure 2). Thus, according to the 1974 forecast, around 100 gigawatts of plutonium breeder reactors would allegedly be built annually between 1995 and 2015. This expected annual increase would be greater than the current total capacity of nuclear energy plants in the United States.

Another attempt to conjure up plutonium breeder reactors in energy scenarios occurred in the 1970s and 1980s in the context of the International Institute for Applied Systems Analysis (IIASA) energy system analyses, in which German nuclear physicist Wolf Häfele was a significant participant.[15] A boom in nuclear energy, especially plutonium breeder technology, was forecast for individual countries as well as worldwide. For example, the share of nuclear energy in electricity generation was predicted to increase considerably in the 1990s and the uranium light-water reactor was to be gradually replaced by the plutonium breeder reactor starting around 2010 (Figure 3, left part). However, researchers Midttun and Baumgartner quickly demonstrated that these were "negotiated nuclear energy futures" that had been determined by IIASA and other research groups together with industry and policymakers and that they were not robust with respect to economic assumptions, for example. Thus, the slightest change in input parameters led to different results, especially in regards to nuclear energy (Figure 3, right part): In the case of the United States, not even the uranium light-water reactor can remain in the energy mix as soon as the assumed costs increase by 16 percent.[16] In reality, very few new uranium light-water reactors have been built since the 1980s and the share of plutonium breeder reactors has remained negligibly low to this day, both in the USA and worldwide.[17]

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[13] Joachim Radkau, *Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975: Verdrängte Alternativen in der Kerntechnik und der Ursprung der nuklearen Kontroverse* (Reinbek bei Hamburg: 1983): 65 (in German).

[14] Glenn T. Seaborg, "The Plutonium Economy of the Future," speech held at the Fourth International Conference on Plutonium and Other Actinides (1970) (available online).

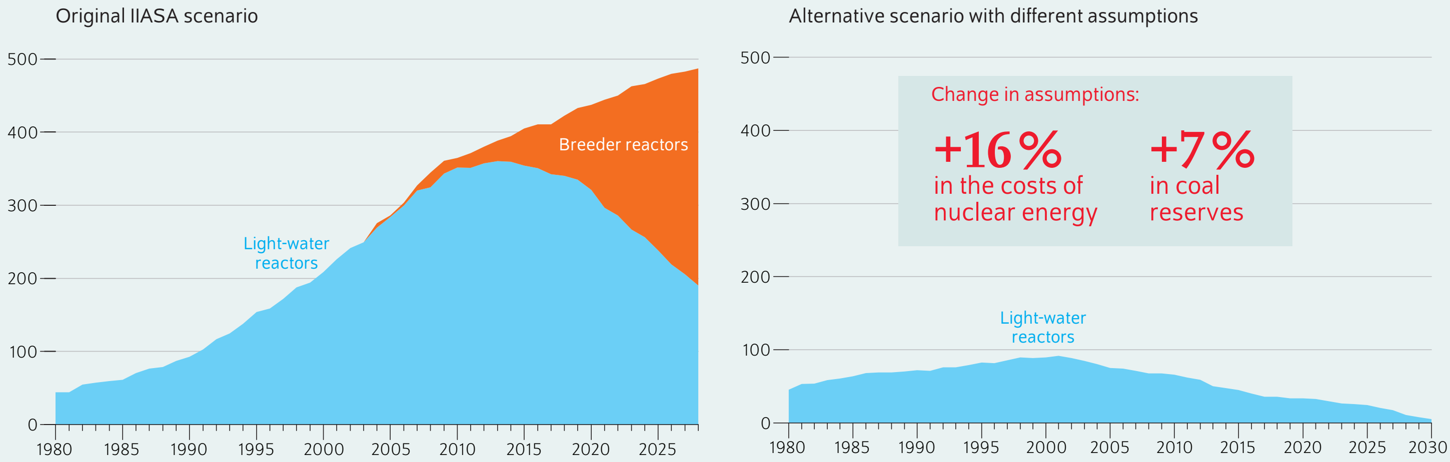
[15] Wolf Häfele et al., *Energy in a Finite World: A Global Systems Analysis (Volume 2)* (Cambridge, USA: 1981) (available online); Alte Midttun and Thomas Baumgartner, "Negotiating Energy Futures: The Politics of Energy Forecasting," *Energy Policy* 14, no. 3 (1986) (available online).

[16] Midttun and Baumgartner, "Negotiating Energy Futures."

[17] Alexander Wimmers et al., "Plans for Expanding Nuclear Power Plants Lack Technological and Economic Foundations," *DIW Weekly Report*, no. 10/11, 91–100 (available online).

Figure 3

Original 1981 IIASA scenario[1] on nuclear energy (left) and a scenario with different assumptions[2] (right)
Construction of nuclear power plants in gigawatts per year



1 Scenario from the International Institute for Applied Systems Analysis (IIASA) which assumes growth in electricity generated by light-water reactors or fast-breeder reactors.
2 In the alternative scenario, it is assumed that costs for nuclear energy increase by 16 percent and the coal reserves increase by seven percent.

Source: Midttun and Baumgartner, "Negotiating Energy Futures," 227.

The IIASA's scenario depended on sensitive assumptions, small changes to which led to substantially different results.

Current energy and climate scenarios include strongly increasing shares of nuclear energy generation

The euphoria surrounding energy, and later climate, scenarios with large shares of nuclear energy that has been observed since 1945 continued on into and even intensified at the beginning of the 21st century (Figure 1). It can be observed in studies by international organizations, including the IEA, the International Atomic Energy Agency (IAEA), and the World Energy Council (WEC), as well as in many scientific publications that are included in the reports of Working Group III (Mitigation of Climate Change) of the Intergovernmental Panel on Climate Change (IPCC) and also the Stanford Energy Modeling Forum.[18] In the IAEA scenario for example, electricity generated by nuclear energy increases from currently 2,700 terawatt hours to up to 5,700 terawatt hours in 2050. In the WEC scenario, it rises even higher to 6,800 terawatt hours. The IPCC Special Report on Global Warming of 1.5 °C assumes 7,344 terawatt-hours of nuclear energy in 2050.[19]

However, these assumed future developments are hardly compatible with reality. Over the coming decades, half of the nuclear energy plants currently running worldwide will be taken offline due to age. Even in the low IAEA scenario, which assumes constant electricity generation from nuclear energy plants; sustained market, technology, and resource trends; and few legal and political changes, would not function without the construction of several hundred new nuclear energy plants (Figure 1).

Thousands of climate scenarios, which IIASA has arranged systematically in a database and are considered below, confirm the observed trend of increasing shares of nuclear electricity generation (Figure 4). The share of nuclear energy of primary energy generation between 2020 and 2050 or 2100 increases considerably in the 409 scenarios (from 24 integrated evaluation models) in the IPCC Special Report on Global Warming of 1.5 °C as well as in the IPCC Sixth Assessment Report:[20] In the IPCC Special Report on Global Warming of 1.5 °C, the worldwide production of around 3,000 terawatt hours in 2020 will increase to around 14,000 terawatt hours by 2100. In the Sixth Assessment Report, a similar value of 13,440 terawatt hours will also be achieved by 2100.

The scenarios that include an increasing share of nuclear energy generation also show specific differences in the individual model assumptions that lead to different trajectories. This becomes obvious when comparing the integrated evaluation models AIM/CGE,[21] MESSAGEix,[22] and

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[18] Son H. Kim et al., *Nuclear power Response in the EMF27 Study. Climactic Change* (2014) (available online); Luis Sarmiento et al., "Comparing Net Zero Pathways across the Atlantic. A Model Inter-Comparison Exercise between the Energy Modeling Forum 37 and the European Climate and Energy Modeling Forum," *Energy and Climate Change* (in print).

[19] Short form: MESSAGE V.3 GEA_Eff_1p5C.

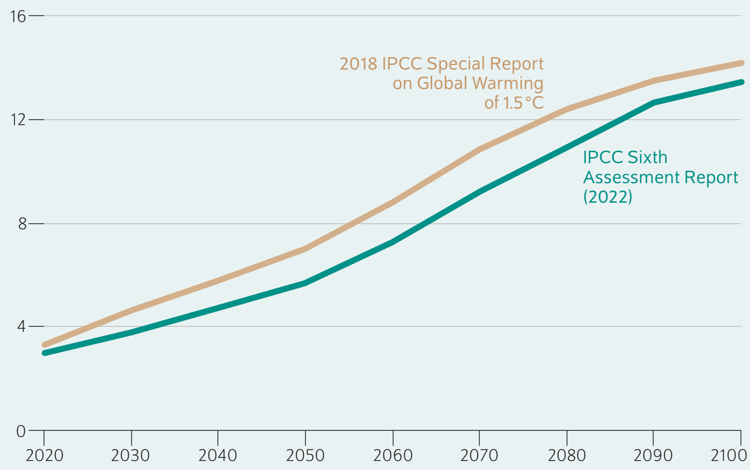
[20] Daniel Huppmann et al., *IAMC 1.5 °C Scenario Explorer and Data Hosted by IIASA* (2018) (available online); Edward Byers et al., *AR6 Scenarios Database* (2022) (available online).

[21] Asian-Pacific Integrated Model/Computable General.

[22] Model for Energy Supply Strategy Alternatives and their General Environmental Impact.

Figure 4

Development of nuclear energy in IPCC climate scenarios
Mean values of all scenarios in terawatt hours



Source: IIASA Scenario Explorer.

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On average, IPCC climate scenarios assume that electricity generated by nuclear energy will quadruple by 2100.

POLES[23] (Figure 5). The average of all model-related scenarios from the Intergovernmental Panel on Climate Change's Sixth Assessment Report is considered here, which assumes growth in electricity generated from nuclear energy between 2020 and 2100. Here, the share increases from around 11 percent (2020) to 18 percent (2100). In reality, however, the share of nuclear energy of global electricity generation has continually decreased since 1996 and was only nine percent in 2022.[24] This is a further example that shows that the scenarios' assumptions differ from reality.

Significant differences can be observed over time: MESSAGEix is a dynamic model that considers the evolution of energy systems and their interactions over time in addition to adaptations and investments in energy infrastructure over time. The POLES and the AIM/CGE models are generally considered static because they do not explicitly model temporal dynamics of energy systems. Thus, forecasts and scenarios for a specific point in time are considered without detailed modeling of changes over time. With these differences in the model design, the deviating development pathways and trends in the diverse scenarios in different models can be partially explained. In 2050, a new, non-specified nuclear technology will be introduced that will lead to a strong increase beginning in 2060. Moreover, the models also differ in terms of their energy, macroeconomic, and sociopolitical framework conditions.[25]

Lack of innovation and economic competitiveness

The very optimistic scenarios contradict the real economic developments in the nuclear industry. While a large number of nuclear energy plants were constructed in the 1960s and 70s and a good 400 remain in operation today, the hope of a global increase in electricity generated by nuclear energy has not come to fruition and there are no signs that, following three failed attempts to diffuse plutonium breeders, the current projects can change that. Currently, the share of electricity generated by nuclear energy is below ten percent and trending downward. Thus, the nuclear scenario paradox remains today: The aggregated amounts of nuclear electricity in the long-term scenarios are unplausible due to a permanent lack of competitiveness, a low number of newly constructed power plants (Figure 6), and an absence of technical innovations.

The competitiveness of nuclear electricity hoped for in the 1950s has not yet materialized.[26] Instead of fossil fuels, renewable energy sources (especially solar and wind), are now by far the most cost-effective competitors of nuclear energy. Current calculations of average electricity generation costs confirm the structural cost disadvantages of nuclear energy.[27] The investment bank Lazard taxes the electricity generation costs of nuclear energy at around 18 US cents per kilowatt hour (2023), much higher than solar and wind at six and five US cents per kilowatt hour (2023).[28]

The new construction boom that had been hoped for since 2000 also never occurred. Currently, only about 50 new construction projects are underway globally, which corresponds to a capacity of about 50 gigawatts, or 13 percent of the nuclear energy plants that would be operational in 2022 if they were connected to the grid.[29] However, 31 of the 50 projects are delayed, some of them significantly, and—based on previous trends—some of them will not even go online in the next few years.[30]

Conversely, due to the age structure, a large number of nuclear energy plants will go offline in the foreseeable future. With a planned runtime of 40 years, half (207) of the 415 reactors currently in operation (370 gigawatts) would be taken offline by 2030. If the optimistic scenario assumes a 59-percent increase in the construction rate, as in the IPCC Special

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[23] Prospective Outlook on Long-term Energy Systems.

[24] Energy Institute, *Statistical Review of World Energy 2023* (2023) (available online).

[25] Alexander Marx et al. "Nuclear Bias in Forecasting Energy Mix?" speech held at the AT-OM Research Workshop on the Economics and Technology of Nuclear Power on June 2, 2023, at the Technical University of Berlin (available online).

[26] Rothwell, "Projected Electricity Costs in International Nuclear Power Markets;" Wimmers et al., "Plans for Expanding Nuclear Power Plants Lack Technological and Economic Foundations;" the section of the DIW Berlin website on nuclear energy (in German; available online); John Bistline et al., "Modeling nuclear power's future role in decarbonized energy systems," *iScience* 26, no. 2 (2023): 105952 (available online) and Luke Haywood et al., "Why investing in new nuclear plants is bad for the climate," Joule 7, no. 1 (2023): 1675–1678 (available online).

[27] Fraunhofer ISE, Stromgestehungskosten *Erneuerbare Energien – Juli 2022* (2021) (in German; available online).

[28] See Lazard, *Lazard's Levelized Cost of Energy+ Analysis Version 16* (2023) (available online). Even if the costs of integrating fluctuating renewable energy generation are taken into account, the electricity generation cost only roughly doubles; in the case of nuclear energy, no system costs (such as reserve capacities, decommissioning, or disposal) are taken into account.

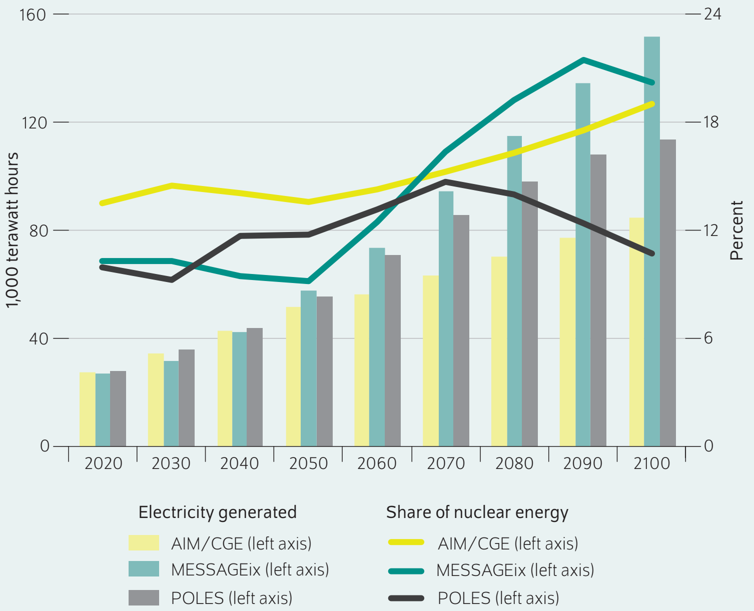
[29] This is a further example that shows that the scenarios' assumptions are not based in reality.

[30] Mycle Schneider et al., *World Nuclear Industry Status Report 2022* (Mycle Schneider Consulting: 2022) (available online).

Figure 5

Selected integrated evaluation models with increasing share of nuclear energy in the IPCC Sixth Assessment Report

Average electricity produced in 1,000 terawatt hours (left axis), average share of nuclear energy in percent (right axis)



Source: Marx et al. (2023).

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The average share of nuclear energy in electricity generation increases in the long term in all three models, but at different rates.

Report on Global Warming of 1.5 °C, more nuclear energy plants would have to be built in the next ten years than are currently connected to the grid. This is unrealistic.

Finally, from today's perspective, there are no foreseeable technological breakthroughs—which are the basis of the nuclear energy growth and the breakthrough of the plutonium economy. This hope of breakthroughs relates in particular to non-light-water reactor concepts that were developed in the 1940s but have not yet found their way into commercial applications, let alone been on their way to industry-wide diffusion.[31]

Approaches for explaining the nuclear energy scenario paradox

Politico-economic, institutional, and geopolitical factors can explain the nuclear energy scenario paradox.[32] A major driver of commercial nuclear energy development is its close connection to military use, which requires national innovation and production systems to further develop nuclear weapons and nuclear submarines.[33] Here, there is a misleading narrative that electricity generated by nuclear energy is clean, safe, reliable, and cost-effective, which is not true. Thus, the institutional framework of global governance structures in and around the United Nations is also closely linked to the development of the nuclear industry, especially the IAEA. A speech delivered by former US President Dwight D. Eisenhower was the inspiration for the creation of the IAEA, which is responsible for the management of fissile material and the dissemination of the technology. The IAEA has a strong self-interest in larger shares of nuclear energy in energy scenarios to justify the extensive activities of its several thousand employees.[34]

The omnipresence of nuclear energy in the international institutional system also influences science, which participates in the development of future scenarios along with politics and industry. As early as the 1980s, the approach to optimistically evaluating nuclear energy in energy system models—especially future plutonium breeders—could be observed, and it has persisted to this day, as shown above for the most recent IPCC reports. In contrast to techno-economic analyses of the transformation away from coal, natural gas, and oil, the nuclear industry occupies a niche position in international research on the energy transformation. This results in established organizations' scenarios being chosen as a point of reference for simplicity's sake and frequently remaining unscrutinized.

This contrasts with the economic failures of established industrial companies (Siemens, Westinghosue, General Electric) and their nationalization (Areva).[35] However, concentrated interest on the overly optimistic future scenarios for nuclear energy remains. In addition, during the fourth phase (since 2000), the start-up scene became interested in and began financing nuclear research and development using both private and public funds. The start-up scene still hopes that private companies would have the same market entry prospects in the nuclear industry as in the space industry, where they have been able to take large market shares from major state institutions, especially NASA.[36] An example of this is the industrial company TerraPower, co-financed by

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[31] Edwin Lyman, *Advanced isn't Always Better: Assessing the Safety, Security, and Environmental Impacts of Non-Light-Water Nuclear Reactors* (2021) (available online); Christoph Pistner et al., "Analyse und Bewertung des Entwicklungsstands, der Sicherheit und des regulatorischen Rahmens für sogenannte neuartige Reaktorkonzepte," Interim report to AP 1 and AP 1 of Vorhaben 4721F50501 (in German; available online).

[32] Christian von Hirschhausen, *Atomenergie – Geschichte und Zukunft einer riskanten Technologie* (C.H. Beck: 2023) (in German).

[33] Andy Stirling and Phil Johnstone, "A Global Picture of Industrial Interdependencies Between Civil and Military Nuclear Infrastructures," *SPRU Working Paper Series* (2018) (available online); Kacper Szulecki and Indra Overland, *Russian nuclear power diplomacy and its implications for energy security in the context of the war in Ukraine* (2023) (available online).

[34] Fanny Böse et al., *The Potential of Nuclear Power in the Context of Climate Change Mitigation—A Techno-Economic Reactor Technology Assessment* (2023) (available online).

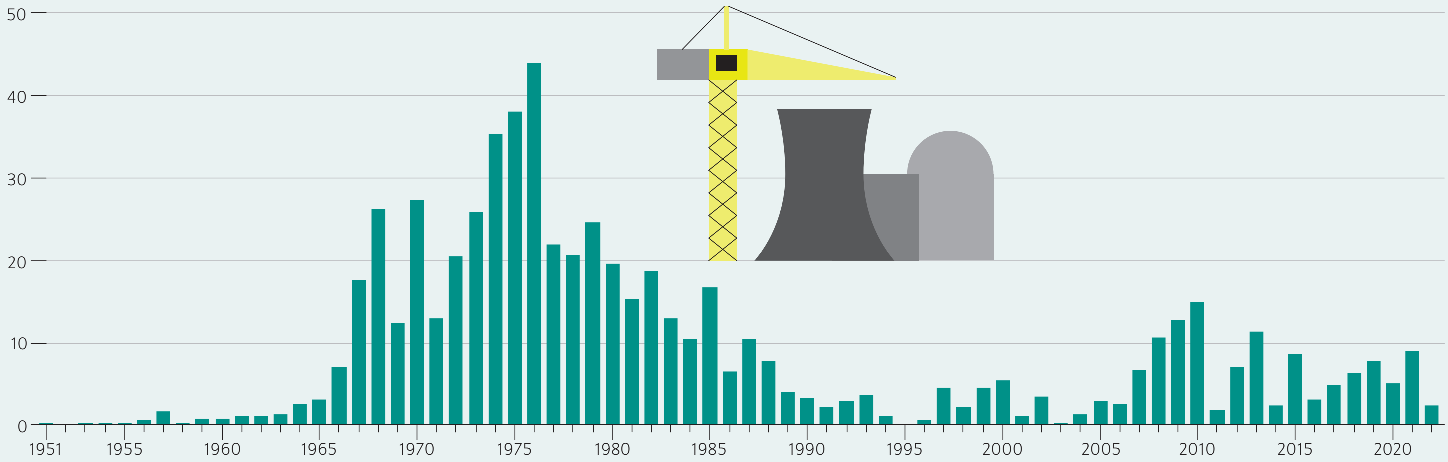
[35] For France, Julie Schweizer and Tamara L Mix, "It is a Tradition in the Nuclear Industry ... Secrecy: Political Opportunity Structures and Nuclear Knowledge Production in France," *Sociocogical Research Online* (2021) (available online); for the USA: Peter Stoett, "Toward Renewed Legitimacy? Nuclear Power, Global Warming, and Secruity," *Global Environmental Politics* (2003) (available online); and for Russia: Pami Aalto, "Russian nuclear power diplomacy in Finnland and Hungary," *Eurasian Geography and Ecoomics* (2017) (available online).

[36] Mariana Mazzucato and Douglas K.R. Robinson, "Co-Creating and Directing Innovation Ecosystems? NASA's Changing Approach to Public-Private Partnerships in Low-Earth Orbit," *Technological Forecasting and Social Change* 136 (2018): 166–177 (available online).

Figure 6

Started and completed reactor construction projects, 1951 to 2021

Constructed capacity in gigawatts per year



Source: Authors' depiction based on IAEA data.

Most nuclear reactor capacity was created in the 1970s.

Bill Gates. TerraPower is planning, among other things, to construct a plutonium reactor in the United States.[37]

Conclusion: Minimize the spread of the nuclear energy scenario paradox

All long-term energy and climate scenarios are subject to uncertainties regarding future socio-technological and climate policy developments. This is because it is impossible to predict societal developments and thus the future, which is why it has become necessary and established to use different scenarios. However, scenario-based, quantitative calculations of future developments can result in an illusion of definite knowledge for non-scientists and false conclusions for policymakers.[38] Therefore, scenario developers' assumptions and model logic should be made explicitly clear and reviewed by third parties before deriving any policy measures from the scenarios.

However, the climate scenarios examined assess the development of nuclear energy as systematically too optimistic, not so much because of uncertainties, but rather because of implausible assumptions about technology and cost development. The actual technical and economic developments from the nuclear industry looked different. This phenomenon is known as the nuclear energy scenario paradox, which plays a significant role in both science and politics.

Since the optimistic scenarios of the past never came to fruition, lessons should be learned and future scenarios critically scrutinized. In order to avoid false conclusions and policy measures, the systematically optimistic scenarios should be reviewed in terms of their feasibility. The scenarios include systematically implausible assumptions about technological developments. There are differences compared to reality, especially in terms of assumed costs.[39] Additionally, there is uncertainty surrounding the integration of system costs such as decommissioning, the disposal of radioactive waste, safeguarding against accidents, and considering proliferation risks.

A transparent disclosure of assumptions as well as model structure and code increase the possibility of a critical review. As information asymmetries between modelers and users of models cannot be fully reconciled, it is critical that researchers openly communicate the limitations of their scenarios and that users develop scenario literacy, i.e., an ability to critically question scenarios and their assumptions and interpret implications.

Portraying this optimistic image of nuclear energy's significance in climate change mitigation also poses the risk that public and private funds will be invested in this technology despite other technologies, especially renewable energy, having significantly better cost-performance ratios.

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[37] Cf. the website of the project (available online). However, the predecessor project, the Traveling Waver Reactor, which had been in the works for over a decade, does not appear to be being pursued at this time. Cf. Pistner et al., "Kernenergie: eine Technik für die Zukunft?"

[38] Robert Pindyck, "The Use and Misuse of Models for Climate Policy," *Review of Environmental Economics and Policy* 11, no. 1 (2017) (available online).

[39] Wimmers et al., "Plans for Expanding Nuclear Power Plants Lack Technological and Economic Foundations."

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