Nuclear power unnecessary for climate protection—there are more cost-efficient alternatives

By Claudia Kemfert, Thorsten Burandt, Karlo Hainsch, Konstantin Löffler, Pao-Yu Oei, and Christian von Hirschhausen

The world needs to continue working to protect the climate—this is generally undisputed. However, there is no agreement on which technologies should be used to decarbonize the energy sector. Many international scenarios still assume a relevant role for nuclear power in the future. However, a study by the German Institute for Economic Research shows that the Paris climate protection target—limiting global warming to below two degrees—can be achieved inexpensively without nuclear power. The results of a global energy system model indicate that no new nuclear power plants have to be built in order to meet the global climate target. It would be cheaper to use a combination of renewable energy and energy storage systems.

Upon signing the Treaty of Paris in 2015, virtually all nations worldwide committed to limiting global warming to below two degrees. In principle, each nation is free to choose specific technologies for achieving their national climate targets. For political reasons, some countries plan to keep using nuclear power because, among other reasons, it is closely connected to the development of nuclear weapons. For example, policy makers in the US are currently discussing a proposal to increase subsidies for nuclear power.[1] Existing direct and indirect support includes the costs for both the long-term storage of nuclear waste and possible accidents, such as the one in Fukushima in Japan.

Neither international organizations nor the scientific community can come to an agreement on nuclear power's role in climate protection. Some institutions, such as the International Atomic Energy Agency (IAEA) and EURATOM, the European Atomic Energy Community, have direct mandates to support nuclear power. The International Energy Agency (IEA) and the European Union typically see nuclear power as a relevant part of a future technology mix.[2] However, environmental and climate economists have strongly differing opinions on the future significance of nuclear power.[3]

On the other hand, the microeconomic perspective in the literature holds that nuclear power was not an economical form of electricity supply in the past. Analyses from

1 See US Department of Energy, "Grid Resilience Pricing Rule 18 CFR Part 35," (PDF, Department of Energy, Washington D.C., 2017) (available online, accessed November 3, 2017. This also applies to all other online references in this report as long as not stated otherwise).

2 See International Energy Agency, World Energy Outlook 2016, Paris: International Energy Agency, 2016; Pantelis Capros et al., "EU Reference Scenario 2016 —Energy, transport and GHG emissions trends to 2050," (Publications Office of the European Union, Luxembourg, 2016) (available online).

3 See the controversial discussion initiated by Mark Z. Jacobson et al., "The United States can keep the grid stable at low cost with 100 % clean, renewable energy in all sectors despite inaccurate claims," *Proceedings of the National Academy of Sciences* 114 (26) (2017); and Christopher T. M. Clack et al., "Evaluation of a proposal for reliable low-cost grid power with 100 % wind, water, and solar," *Proceedings of the National Academy of Sciences* 114 (26) (2017): 6722–6727.

a range of research institutes that examined the competitiveness of nuclear power in detail, including calculations made by DIW Berlin, underline this assertion.[4] Moreover, a comprehensive meta study determined that even more than 70 years after the first controlled nuclear chain reaction, the nuclear power industry has not been able to produce electricity under competitive conditions.[5] A historical reappraisal of the birth of all nuclear power plants since the 1950s provides empirical substantiation of the model calculations: Not one of the more than 500 nuclear power plants around the world was constructed under general circumstances of market-based competition. In fact, the costs were so high that they were always centrally planned investment projects and were heavily subsidized by the state or electricity consumers.[6]

This economic bulletin discusses the role of nuclear power in climate protection based on an energy system model. The simulation of the cost-optimized development of the global energy mix shows that nuclear power as a mitigation technology is not a cheaper option. Instead, renewable energy could supply the world with energy sustainably and cost-efficiently until 2050.

Energy system model: structure and assumptions

To examine the role of nuclear power in climate protection scenarios, this report used the Global Energy System Model (GENeSYS-MOD), derived from the established Open Source Energy Modelling System (OSeMOSYS), an open-source software for long-term energy system analyses (Box).[7] OSeMOSYS is further developed decentrally by many researchers worldwide and is used in numerous scientific publications and policy white papers.[8] For the analysis at hand, OSeMOSYS was used as the basis for the GENeSYS-MOD model.[9] The model's objective function encompasses the total cost of the global power supply to the electricity, transportation, and heat sectors. The model yields a cost-minimized combination of technologies designed to cover the energy demand at any time. Climate protection targets, such as carbon emission budgets, can be explicitly specified as general conditions for the model calculations.

Since the supply of the variable renewable energy sources wind and solar power fluctuates as weather conditions change, temporal and spatial balancing is essential in meeting energy demand at all times. To do so, several technologies for storing energy or sector coupling were implemented in the model. Lithium-ion batteries, in particular, compensate for the temporal fluctuations in energy supply and demand. Furthermore, coupling the electricity sector with the heat and transportation sectors facilitates their decarbonization.

Spatially, the model aggregates various countries into a total of ten larger regions. This allows to abstract from energy transport within these regions. Among regions, it is possible to exchange fuel but not electricity or heat. To maintain tractability and computability of the complex model, we also aggregated on the temporal level. To do this, the hourly resolution was reduced to six periods ("time slices") representing the seasonal and diurnal fluctuations in demand and the supply of renewable energy. In total, we considered the period from 2020 to 2050 in five-year increments, assuming perfect foresight with regard to future trends in demand, cost, and supply of renewable energy.

Falling costs are a reasonable assumption for renewable energy and storage

The assumptions about the future costs of technologies central to the model results are key input variables. GENeSYS-MOD contains default values for assumptions with regard to technology costs and energy consumption. We updated cost analyses performed at DIW Berlin for the present model calculations and refined them based on current trends and the international literature (Table).[10]

It is important to highlight the expected costs for photovoltaics, which are expected to fall significantly. This study is based on a number of established studies on

4 See Stephen Ansolabehere et al., "The Future of Nuclear Power," (Massachusetts Institute of Technology, Cambridge, 2003) (available online); Martin Castellano et al., "The Economic Future of Nuclear Power," (University of Chicago, Chicago, 2004) (available online); Paul L. Joskow and John E. Parsons, "The Future of Nuclear Power After Fukushima," *Economics of Energy & Environmental Policy* 1 (2) (2012): 99–113; and William D. D'haeseleer, "Final Report: Synthesis on the Economics of Nuclear Energy—Study for the European Commission," (European Commission, Leuven, 2013) (available online); and Claudia Kemfert et al., "European Climate Targets Achievable without Nuclear Power," *DIW Economic Bulletin* 47 (2015): 619–625 (available online).

5 See Lucas W. Davis, "Prospects for Nuclear Power," *Journal of Economic Perspectives* 26 (1) (2012): 49–66.

6 For an argument regarding the high historical construction costs of nuclear power plants, see Jonathan Koomey, Nathan E. Hultman, and Arnulf Grubler, "A reply to: Historical construction costs of global nuclear power reactors," *Energy Policy* 102 (2017): 640–643.

7 See the OSeMOSYS—Open Source Energy Modelling System project website (available online).

8 See for example Manuel Welsch et al., "Modelling elements of Smart Grids—Enhancing the OSeMOSYS (Open Source Energy Modelling System) code," *Energy* 46 (1) (2012): 337–350; Benjamin Lyseng et al., "Decarbonising the Alberta power system with carbon pricing," *Energy Strategy Reviews* 10 (2016): 40–52; and Constantinos Taliotis et al., "Natural gas in Cyprus: The need for consolidated planning," *Energy Policy* 107 (2017): 197–209.

9 This report is based on a technical article that contains a detailed model description. See Konstantin Löffler et al., "Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Modeling System (OSeMOSYS)," *Energies* 10 (10) (2017): 1468 (available online).

10 See Andreas Schröder et al., "Current and Prospective Costs of Electricity Generation until 2050," *DIW Data Documentation* 68 (2013) (available online).

Table

Cost assumptions for selected technologies for the period 2015–2050

Costs in euros per kilowatt

Technology	2015	2020	2025	2030	2035	2040	2045	2050	Source
Photovoltaics	1,000	800	650	550	490	440	400	370	Gulagi et al. (2017)
Wind onshore	1,250	1,150	1,060	1,000	965	940	915	900	Gulagi et al. (2017)
Wind offshore	3,470	2,880	2,730	2,580	2,480	2,380	2,330	2,280	JRC (2014)
Biomass power plant	2,890	2,620	2,495	2,370	2,260	2,150	2,050	1,950	JRC (2014)
Nuclear power plant	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	Schröder et al. (2013)
Coal power plant	1,400	1,400	1,400	1,400	1,400	1,400	1,400	1,400	Schröder et al. (2013)
Natural gas power plant	675	675	675	675	675	675	675	675	Schröder et al. (2013)
Lithium-ion-battery	1,500	1,300	1,300	1,000	1,000	800	800	700	Wietschel et al. (2015)
Heat pump	1,300	1,286	1,271	1,257	1,243	1,229	1,214	1,200	DAE and Energinet.dk (2012); Fraunhofer ISE (2012); UBA (2016)

Authors' own compilation, based on International Energy Agency, "Technology Roadmap Solar Thermal Electricity," (OECD/IEA, Paris, 2014) (available online); Danish Energy Agency (DEA) and Energinet.dk, "Technology Data for Energy Plants—Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion," (Copenhagen, 2012) (available online); Fraunhofer ISE, "100% Erneuerbare Energien für Strom und Wärme in Deutschland," (Freiburg, 2012) (available online); Schröder et al., "Current and prospective costs;" Joint Research Centre (JRC), "Energy Technology Reference Indicator (ETRI) projections for 2010–2050," (Luxembourg, 2014) (available online); Umweltbundesamt (UBA), "Klimaneutraler Gebäudebestand 2050," CLIMATE CHANGE 06/2016, (Dessau-Roßlau, 2016) (available online); Martin Wietschel et al., eds., Energietechnologien der Zukunft (Wiesbaden: Springer Fachmedien, 2015); and Ashish Gulagi et al., "Electricity system based on 100% renewable energy for India and SAARC," PLOS ONE 12 (7) (available online).

Especially for renewable energy technologies, a strong cost-decline can be assumed.

observed and forecast learning curves.[11] Due to ongoing improvements in technology and production processes, it is assumed that the costs of materials and installations will fall by one-third of their current values by 2050. Observations in the past showed that even optimistic forecasts of cost trends were typically topped in reality.[12] It is also assumed that the costs of wind power plants will fall in both the onshore and offshore areas. The costs of offshore wind parks, in particular, are expected to fall sharply in the near future. The expected learning curves and technological developments in the systems themselves and construction of offshore wind parks will both play a role.[13]

The decreasing costs of storage technologies, in particular lithium-ion batteries, are an additional assumption. Cheaper production in a growing market and falling material costs are ensuring lower battery storage costs.[14] In conjunction with more affordable photovoltaic systems, they represent an inexpensive form of electricity supply.

Cost of fossil and nuclear power plants will remain at current level

While the forecasts assume that the cost of renewable energy will decrease over the years, the cost of fossil-fueled power plants will remain at approximately the current level. This will make them increasingly less competitive. The cost estimates for nuclear power also remain at the level presumed at present of around 6,000 euros per kilowatt, a seemingly realistic estimate in light of recent experience constructing new nuclear power plants.[15] In the new calculations for the EU reference scenario, a long-term projection of the energy supply trend for Europe, the assumed costs of nuclear power are also of this magnitude.[16]

11 See Johannes N. Mayer et al., "Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems," (Fraunhofer Institute for Solar Energy Systems, Freiburg, 2015) (available online); World Energy Council, "World Energy Resources," (World Energy Council, London, 2016) (available online); and Harry Wirth, "Aktuelle Fakten zur Photovoltaik in Deutschland," (Fraunhofer Institute for Solar Energy Systems, Freiburg, 2017) (available online).

12 See Christian Breyer et al., "On the role of solar photovoltaics in global energy transition scenarios," *Progress in Photovoltaics Research and Applications* 25 (8) (2017): 727–745.

13 See David E. H. J. Gernaat et al., "Global long-term cost dynamics of offshore wind electricity generation," *Energy* 76 (2014): 663–672; and Bruce Valpy and Philip English, "Future renewable energy costs: offshore wind," (KIC InnoEnergy and BVG Associates, Eindhoven, 2014) (available online).

14 See Bloomberg New Energy Finance, "Lithium-ion Battery Costs and Market," (Bloomberg New Energy Finance, New York City, 2017) (available online); and Gert Berckmans et al., "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030," *Energies* 10 (10) (2017): 1314 (available onlnie).

15 For a detailed analysis of various cost data, see Schröder et al., "Current and Prospective Costs." The value for nuclear power at present equals the average expected value of the nuclear power plants under construction for which reproducible cost estimates are available—Olkiluoto (Finland), Flamanville (France), Hinkley Point C (UK), Vogtle and Virgil C. Summer (US)—offset by a 15 percent cost degression for economies of scale. The concrete amounts can be derived from the participating companies' annual reports. For the dismantling of decommissioned nuclear power plants and long-term storage of radioactive waste, 900 euros per kilowatt must be added. Also see the literature on systematic cost overruns in nuclear power plants, including Arnulf Grubler, "The cost of the French nuclear scale-up: A case of negative learning by doing," *Energy Policy* 38 (2010): 5174–5188; 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): 103–125; and the summary of the literature in Christian von Hirschhausen et al., "Europäische Stromerzeugung nach 2020: Beitrag erneuerbarer Energien nicht unterschätzen," *DIW Wochenbericht* 29 (2012): 3–13 (available online).

16 See Capros et al., "EU Reference Scenario 2016."

Energy demand and remaining carbon budget

For the electricity, heat, and transportation sectors in the ten regions of the world, we assumed different growth in demand to be met with technologies available now and in the future. The assumptions are based on established literature, including IEA scenarios. They involve several factors. For example, India was assumed to have a sharply rising population, while it was assumed to remain constant or fall in other regions. The further industrialization of developing countries would drive an increase in demand for both electricity and process heat for the industry in their regions. At the same time, the demand for residential space heating was assumed to be falling. This assumption is primarily based on increases in the efficiency of buildings. In heavily industrialized regions such as Europe and North America, the demand for electricity and heat was assumed to decrease in the long term due to continued improvements in energy efficiency, among other reasons.

The quantity of carbon that can still be emitted into the atmosphere is extremely limited if we want to achieve sane climate protection targets. According to different calculations, a carbon budget in the range of 550 to 1,000 billion tons of CO_2 equivalents remains to limit the rise in the average temperature of the Earth to below two degrees.[17] For example, extrapolating from the global carbon emissions of 36 billion tons in 2015, this budget would be used up within 16 to 27 years. In order to meet the targets of the Paris climate protection treaty, this study is based on a scenario in which the temperature rise remains below two degrees. As a result, the scenario assumes a remaining CO_2 budget of 650 billion tons—a figure that accommodates the emissions from agriculture and industrial processes that are not considered in the model.

Most international climate protection models make meeting a challenging target dependent on negative emissions. They assume it will be achieved using technologies that remove carbon from the atmosphere and store it permanently, such as bioenergy carbon capture and storage (BECCS) or climate engineering (for example, the distribution of particles in the atmosphere). However, these technologies are not tested on an industrial scale; nor is it possible to plausibly estimate their long-term cost development. For these reasons, they are not included in the following section.

17 CO_2 equivalents as a unit of measure makes the capacity of other greenhouse gases (such as methane or nitrous oxide) to damage the climate comparable to that of CO_2. As a result, the remaining emissions budget is listed in CO_2 equivalents in many analyses. See John Christensen et al., "The Emissions Gap Report 2015," (United Nations Environment Program, Nairobi, 2015) (available online). This report refers to carbon emissions only.

Results: Nuclear power not part of the cost-efficient energy mix

The model results showed that at a CO_2 budget of 650 billion tons, the cost-optimized, cross-sector energy mix shifts from fossil energy sources (coal, natural gas, and oil) to more affordable renewable energy sources (Figure 1). The results indicate that a "fuel switch" from coal to natural gas will not occur among fossil energy sources. Instead, coal will remain part of the energy mix longer than natural gas, which will lose its significance by the end of the time horizon. Of the renewable energy sources, photovoltaics, wind, and biomass are of approximately equally crucial importance. In order to realize a sustainable energy supply with optimal costs, the total capacity of renewable energy must be increased. For example, in 2030 photovoltaic systems with a capacity of just below 1,000 gigawatts will be installed throughout Europe, a figure projected to rise to 1,700 gigawatts by 2050.[18]

Starting in 2025, photovoltaics will play a dominant role in supplying electricity. Natural gas will continue to supply heat for industry over a longer period of time, but biomass will take on a greater role. When it comes to interior heating, heat pumps operated with (renewable) electricity will gain greatly in importance. In the transportation sector, oil will continue to play a starring role, but by 2050 it should be replaced by a mix of biofuel with hydrogen and electric drives.

In the case of nuclear power, the results show that electricity production will gradually decline over the coming decades from its 2015 level of 2,640 terawatt hours (Figure 2). Geographically, the distribution of nuclear power plants will mirror that of today's major nuclear electricity producers: China, the US, and France. Due to their high costs, new nuclear power plants will not be built, and production will fall as actively producing nuclear power plants are decommissioned.

Due to variations in climate conditions and potential for new construction, the proportions of photovoltaic, wind, and hydro power vary worldwide (Figure 3). For example, the model results indicate that the proportion of electricity production via photovoltaics in India will be over 50 percent in 2050. In Europe and North America, on the other hand, wind power will have a higher proportion. Even countries and regions for which particularly

18 These figures are essentially the same as those in similar studies that also examine the decarbonization of the global energy system. See Mark Z. Jacobson et al., "100 % Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World," *Joule* 1 (2017): 108–121 (available online); Breyer et al., "On the role of solar photovoltaics"; and Manish Ram et al., "Global Energy System based on 100 % Renewable Energy—Power Sector," (Lappeenranta University of Technology & Energy Watch Group, Lappeenranta, 2017) (available online).

Box

GENeSYS-MOD

The global energy system model GENeSYS-MOD[1] is based on the open-source model family OSeMOSYS (Open-Source Energy Modelling System).[2] The OSeMOSYS model family is characterized by a high level of transparency and low access barriers. All programming code and input data are made available under open license in order to facilitate reproducibility and critical discussion of the results.

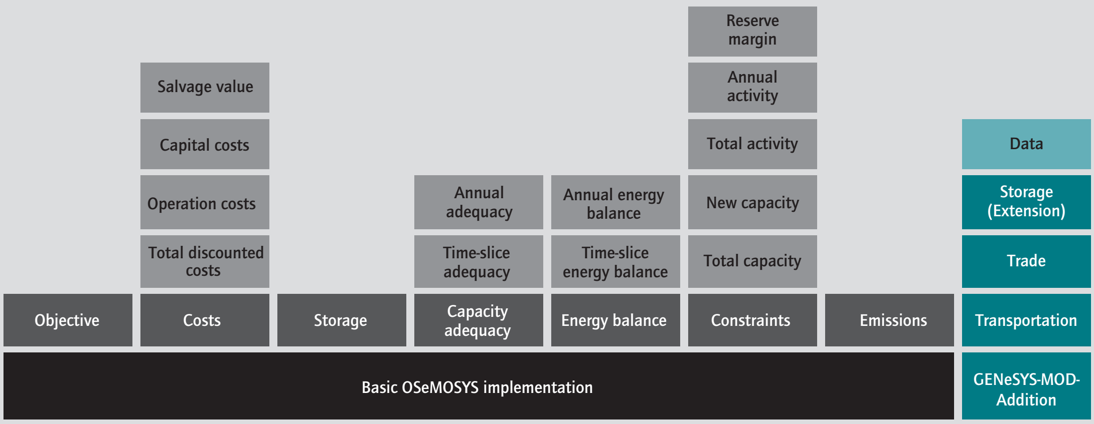
GENeSYS-MOD has a modular structure (Figure 1). Mathematically, the model is a linear optimization program that takes into account a number of technological and economic constraints and determines a cost-optimized technology mix for the energy system. The basic model consists of a target function that accounts for the various cost components. The discounted total costs for production plants, storage, and other flexibility options consist of capital and operating costs plus a residual book value at the end of the period of analysis. The model is divided into various time slices, and the energy demand from various sectors must be met constantly (capacity and energy balances). By defining additional requirements, such as on reserve capacities or emissions, regulatory or political conditions, such as climate policy targets, can be taken into consideration. GENeSYS-MOD expands upon the basic model with additional modules for international exchange and an improved representation of energy

1 For a detailed model description, see Konstantin Löffler et al., "Designing a Model for the Global Energy System – GENeSYS-MOD: An Application of the Open-Source Modeling System (OSeMOSYS)," *Energies* 10 (10) (2017): 1468 (available online).

2 See the OSeMOSYS project website (available online). For a basic introduction, see Mark Howells et al., "OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development," *Energy Policy* 39 (10) (2017): 5850–5870.

Figure 1

GENeSYS-MOD: The functional blocks of the energy system model



Source: Löffler et al., "GENeSYS-MOD," adapted from Howells et al., "OSeMOSYS."

GENeSYS-MOD adds new modules to the established energy modeling system OSeMOSYS.

storage capacity. Moreover, an up-to-date database accommodates assumptions on the costs and availability of various technologies.

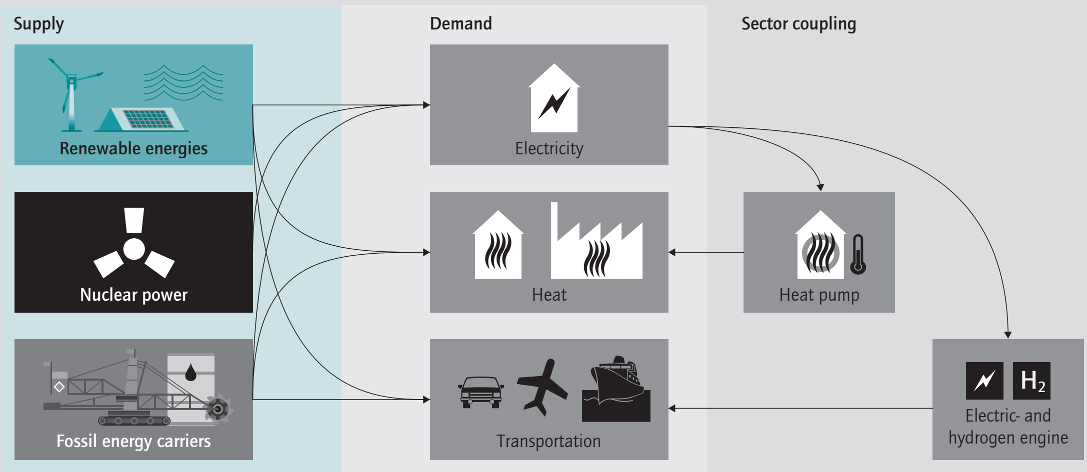
The model maps various conventional and renewable energy sources to be used in the electricity, transportation, and heat sectors (Figure 2). The respective energy demand is given exogenously. It is also possible to map the couplings of energy sectors by using electricity for heat and transportation, as well as the option of transforming electricity into other sources of energy, such as hydrogen.[3]

Depending on the subject of study, regions and time-slices are aggregated. In order to make the best of the limited computing capacity available, users must trade off detail and scope. For example, aggregation makes it possible to capture broad spatial and temporal relationships. On the other hand, some specific requirements for integrating renewable energy into the energy system can only be considered in stylized form.

3 In principle, the model can factor in interfaces to other models such as sector-specific bottom-up models or climate system models. And the degree of spatial detail is scalable. For example, the company, city, country, continent, or—as in the present study—the global level can be examined.

Figure 2

Technologies and sectors in the energy system model GENeSYS-MOD



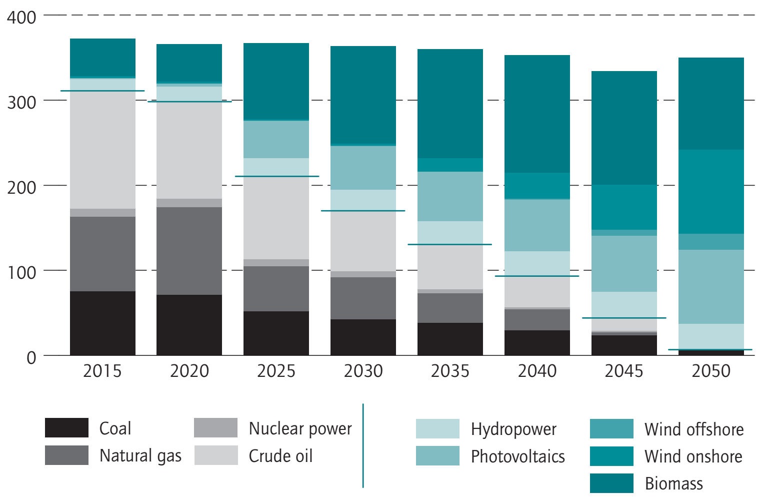
Source: Authors' own depiction, based on Löffler et al., "GENeSYS-MOD."

Various technologies generate energy to meet the demand in the sectors electricity, heat, and transportation.

Figure 1

Development of the global energy mix with a CO_2 budget of 650 billion tons

Energy supply in exajoule



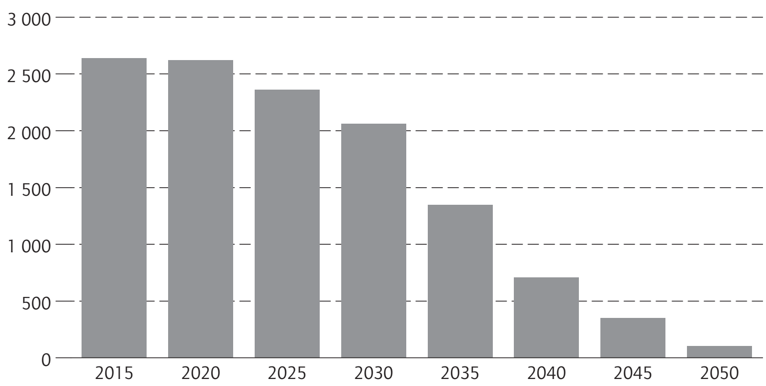
Sources: GENeSYS-MOD v1.0, see Löffler et al., "GENeSYS-MOD;" authors' own calculations.

In 2050, a decarbonized energy system will be achieved with renewable energies, not with nuclear power.

Figure 2

Global development of nuclear power until 2050

Electricity generation by nuclear power in terawatt hours



Sources: GENeSYS-MOD v1.0, see Löffler et al., "GENeSYS-MOD;" authors' own calculations.

When considering the cost-optimal energy supply, nuclear power is being phased out until 2050.

rapid growth of nuclear power has been forecast will be able to meet their electricity demand in a climate-friendly manner without nuclear power.

Nuclear power not a factor also when assuming other cost estimates

The cost estimates this report is based on are a key factor in interpreting the findings. In some studies, the IEA assumes lower investment costs than the most recent literature. They are around 3,000 U.S. dollars per kilowatt, for example, in China.[19] However, the empirical database these estimates are based on is unclear. In any case, nuclear power does not even play a role in the model results at these low costs.[20] For example, a global cost of 2,800 euros per kilowatt was assumed for nuclear power for a sensitivity calculation. The model results show that the lower assumed cost is not enough to make nuclear power competitive against renewable energy.[21] The findings remain quantitatively unchanged: no new nuclear power plants were required in the model calculation.

Further, the amount of the investment is less relevant from an economic perspective because it only represents a small portion of the total cost. Alongside investment costs, the following are all relevant: operating costs, the costs of decommissioning and long-term storage, system costs such as research and development, and the external costs of nuclear power in case of accidents, for example. From a welfare economics perspective, therefore, it is obvious that new nuclear power plants should not be built or used—not even as a technology that supposedly protects the climate.[22]

19 See International Energy Agency, "Power generation assumptions in the New Policies and 450 Scenarios in the World Energy Outlook 2016," (OECD/IEA, Paris, 2016) (available online).

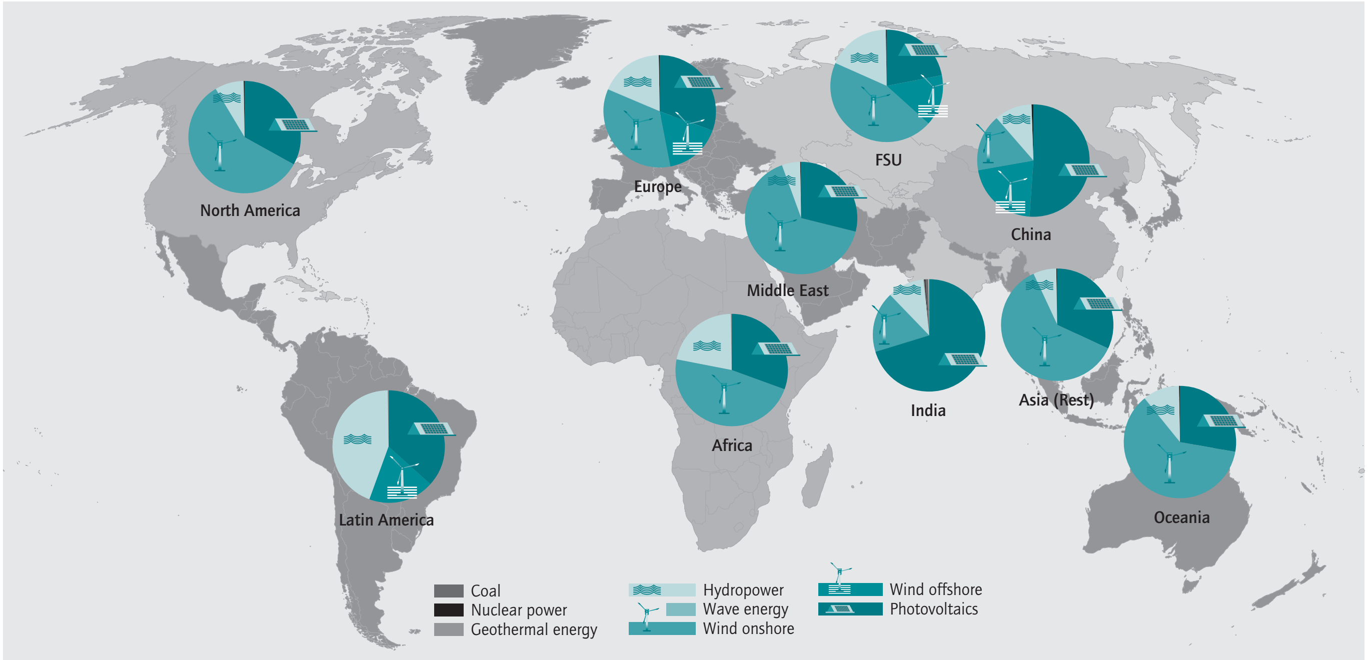
20 Actually, the high proportion of nuclear power in the IEA scenarios can be explained by a substantial exaggeration of the cost of renewable energy. This artifact has been criticized by the scientific community. See Mathieu Metayer, Christian Breyer, and Hans-Josef Fell, "The projections for the future and quality in the past of the world energy outlook for solar PV and other renewable energy technologies," *Proceedings of the 31st European Photovoltaic Solar Energy Conference* (2015): 3112–3238; and Felix Creutzig et al., "The underestimated potential of solar energy to mitigate climate change," *Nature Energy* 2 (9) (2017): 17140.

21 These model calculations do not imply that no countries will ever build new nuclear power plants. For example, India and China are currently planning to increase their capacity significantly in the near future. The results actually indicate that nuclear power is not an inexpensive option in these countries either and would not be considered if the decision were based on cost alone.

22 For a differentiated view of the cost concept and a review of the literature, see Christian von Hirschhausen, "Nuclear Power in the 21st Century–An Assessment (Part I)," *DIW Discussion Paper* 1700 (2017).

Figure 3

Regional electricity generation in the year 2050



Source: Authors' own depiction, based on Löffler et al., "GENeSYS-MOD."

The regional mix of renewable energy reflects the climatic and geographic potentials.

On temporal and spatial aggregation

When using a global model with a time horizon far in the future, as is the case in this study, it is necessary to make simplifying assumptions. Specifically, this report used a simplified representation of the temporal and spatial dimensions involved in integrating renewable energy into the electricity system.

For example, the model used six time-slices per year—for three seasons, one day and one night each—in order to approach the temporal variability of energy demand and the availability of renewable energy. A major portion of the variability is thus not explicitly considered, and it is possible that the model overestimated the contributions of wind power and photovoltaics. While in reality the fluctuation in supply could lead to longer phases with very low production, a reduction in the time slices implies an optimistic view of their availability. We assumed that within a time slice and a region, the production of renewable energy would equal a specific proportion of the installed capacity. This generally involves an underestimation of the demand for supplementary temporal flexibility for the system integration of renewable energy, such as using energy storage systems. According to the calculations at hand, there will be approximately 5,000 gigawatts of energy storage worldwide by 2050. Lithium-ion batteries could shift power from day to night, and pump storage and power-to-gas systems could compensate for seasonal variation. A detailed examination of temporal fluctuations in the supply of renewable energy would likely indicate higher demand—for renewable energy plants and storage capacity—and therefore higher costs as well. At present, it is not clear how this will explicitly affect the optimal technology mix.

The spatial aggregation of countries into regions also abstracts from possible regional bottlenecks. In reality, locations with a reliable supply of renewable energy must not necessarily coincide with the locations where demand is concentrated. We also assumed unlimited transmission capacity within the ten model regions. To the extent that the model abstracts from a concrete representation of spatial balancing, technological issues regarding optimal grid dimensioning and management were not explicitly considered either. A spatially differentiated representation could involve higher expansion rates for renewable energy or downstream infrastructure—and therefore higher costs. However, nuclear and fossil technologies would also require a certain level of infrastructure for the spatial distribution of the energy they produce. As a result of spatial aggregation, we used a simplified map of the quality of locations for wind power and photovoltaics.

Conclusions

International studies are not in agreement on their estimates of the importance of nuclear power as a technology for climate protection. There is still a discrepancy among the perspectives of a number of studies that examine the future development of the global energy system, including those of international organizations, and a microeconomic viewpoint that attributes virtually no importance to nuclear power in a competitive environment. In order to map climate protection scenarios in a global environment, this report further developed and applied an established open-source energy system model. The model optimizes the expansion pathways for different technologies by minimizing the global costs of supplying energy for electricity, heat, and transportation. In the process, it includes a remaining CO_2 budget of 650 billion tons in accordance with the target of limiting global warming to a maximum of two degrees. However, this broad spatial and temporal scope goes hand in hand with a simplified map of system integration for renewable energy.

The model results indicate that nuclear power is unnecessary for achieving future climate protection targets. In view of the high cost of nuclear power and the cost degression of renewable energy and energy storage, in purely economic terms nuclear power will be entirely phased out within the next two to three decades. It does not pay to build new nuclear power plants. Depending on the region, the cost-optimized energy mix consists of solar, wind, and hydro power, plus bioenergy supported by energy storage technologies and coupling the electricity, heat, and transportation sectors. Above and beyond the direct costs of investment and operation, the environmental costs and risks of nuclear power are highly relevant. The risks include accidents and proliferation, as well as the undetermined long-term strategy of storing nuclear waste. The present study does not address these aspects, but they must be kept in mind when abandoning an argument based exclusively on costs in favor of a comprehensive economic assessment.

Accordingly, promoting nuclear power can be viewed as counterproductive because it can hinder the development of other, less expensive sources of energy. Resources for research and development and international funding should be diverted to renewable energy, storage technologies, and the opportunities inherent in sector coupling.

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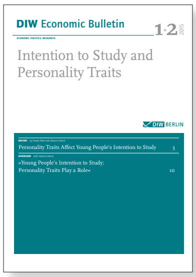

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