Applied Energy 279 (2020) 115789

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Would firm generators facilitate or deter variable renewable energy in a carbon-free electricity system?

Mengyao Yuan [a], Fan Tong [a,b], Lei Duan [a], Jacqueline A. Dowling [c], Steven J. Davis [d], Nathan S. Lewis [c], Ken Caldeira [a,e,*]

[a] *Department of Global Ecology, Carnegie Institution for Science, Stanford, CA, USA*
[b] *Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[c] *Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, CA, USA*
[d] *Department of Earth System Science, University of California, Irvine, Irvine, CA, USA*
[e] *Gates Ventures LLC, Kirkland, WA, USA*

HIGHLIGHTS

- A model tests whether low-cost firm energy would affect wind and solar deployment.
- Only technoeconomic factors in an idealized electricity system are considered.
- Expansion of firm generators such as nuclear tends to displace wind and solar.
- Expansion of wind and solar tends to displace firm generators such as nuclear.

ARTICLE INFO

Keywords:
Net-zero electricity systems
Firm carbon-free electricity generation
Variable renewable energy

ABSTRACT

To reduce atmospheric carbon dioxide emissions and mitigate impacts of climate change, countries across the world have mandated quotas for renewable electricity. But a question has remained largely unexplored: would low-cost, firm, zero-carbon electricity generation technologies enhance—or would they displace—deployment of variable renewable electricity generation technologies, i.e., wind and solar photovoltaics, in a least-cost, fully reliable, and deeply decarbonized electricity system? To address this question, we modeled idealized electricity systems based on historical weather data and considered only technoeconomic factors. We did not apply a predetermined use model. We found that cost reductions in firm generation technologies (starting at current costs, ramping down to nearly zero) uniformly resulted in increased penetration of the firm technologies and decreased penetration of variable renewable electricity generation, in electricity systems where technology deployment is primarily driven by relative costs, and across a wide array of future technology cost assumptions. Similarly, reduced costs of variable renewable electricity (starting at current costs, ramping down to nearly zero) drove out firm generation technologies. Yet relative to deployment of "must-run" firm generation technologies, and when the studied firm technologies have high fixed costs relative to variable costs, the addition of flexibility to firm generation technologies had only limited impacts on the system cost, less than a 9% system cost reduction in our idealized model. These results reveal that policies and funding that support particular technologies for low- or zero-carbon electricity generation can inhibit the development of other low- or zero-carbon alternatives.

1. Introduction

Variable renewable electricity (VRE) generation from wind and solar photovoltaics (PV) has exhibited rapid cost reductions and is projected to play a major role in future zero-emissions electricity systems in many places in the world [1–6]. The variability of wind and solar generation can be reduced by resource aggregation over large geographic areas and/or by energy storage. Nevertheless, substantial long-term mismatches between demand and supply can exist in a system solely utilizing VRE generation even when large geographic regions are spanned

* Corresponding author at: Department of Global Ecology, Carnegie Institution for Science, Stanford, CA, USA.
E-mail address: kcaldeira@carnegiescience.edu (K. Caldeira).

https://doi.org/10.1016/j.apenergy.2020.115789
Received 12 June 2020; Received in revised form 23 August 2020; Accepted 25 August 2020
Available online 14 September 2020

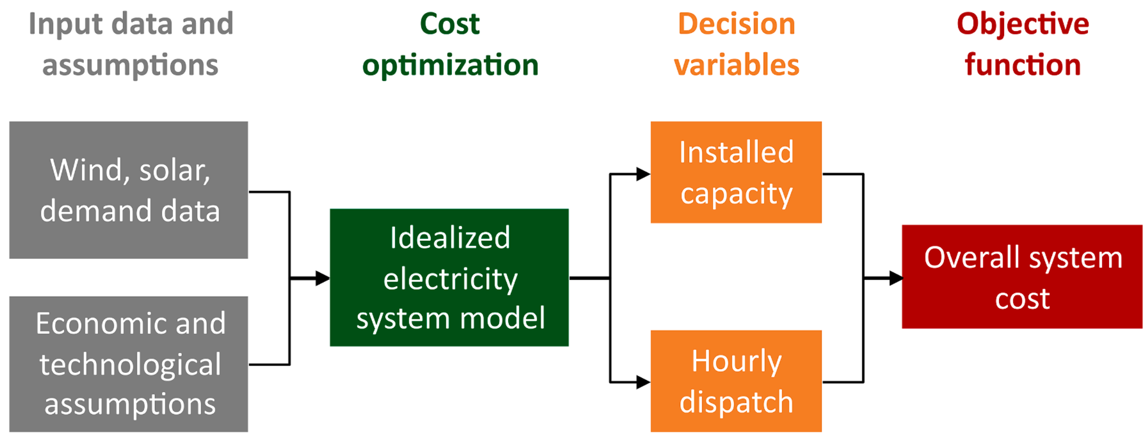

Fig. 1. An overview of the modeling framework used in this study.

with an ideal case of lossless transmission [3,6]. Various modeling studies have also shown that while a reliable, deeply decarbonized electricity system can be technically achieved by VRE deployment, deployed capacity and system costs would increase nonlinearly as VRE penetration approaches 100% [4]. The use of firm net-zero-carbon emissions technologies that can be dispatched on demand is among options that could avoid substantial VRE overcapacity and lower overall system cost, by providing capacity and generation needs during extended periods with low wind and solar resource availability [4,7].

There is an open debate as to whether the deployment of low-cost firm generation technologies would facilitate deeper penetration of variable renewable electricity, by providing a cost-effective mechanism to achieve high overall system reliability, or would instead displace VRE for electricity generation. Generation technologies with modest fixed costs and relatively low variable costs, such as natural gas power plants, provide such grid services at present, albeit with accompanying carbon emissions. In 100% renewable, or more broadly, zero-carbon electricity systems, technologies available to provide high reliability in conjunction with VRE generation are sometimes characterized by high fixed costs and low variable costs. The debate over whether the deployment of such generation technologies will increase the deployment of VRE or displace VRE in a least-cost zero-emissions electricity system is especially pronounced with respect to nuclear power, a scalable and zero-carbon technology that could provide firm power generation and capacity, especially when operated flexibly [8,9]. The objective of this study is to address this knowledge gap by assessing the dependence of electricity system costs as a function of the costs of firm zero-carbon technologies and the costs of VRE generation (herein exclusively wind and solar PV) in an idealized 100% reliable and zero-carbon electricity system constructed de novo.

The economics of any electricity generation technology that is only used intermittently depends critically on the value of reliable electricity generation, which in turn is sensitive to the timing, duration, and amount of electricity generated. A levelized cost of electricity (LCOE) analysis intrinsically assumes a specific use model to amortize the capital investment in the asset with respect to the total electricity generated over the asset's useful life. We have instead used a transparent idealized power system model to evaluate the extent to which firm generation technologies could compensate for the variability of VRE in a wide range of cost scenarios, in the presence and absence of energy storage (e.g., batteries). Electricity system costs can be dominated by costs to meet demand during infrequent but substantial decreases in VRE generation. Instead of assuming a use model, our analysis is driven by geophysical resource variability and is built fundamentally on hourly wind and solar energy data across the contiguous U.S. (CONUS), derived from a reanalysis dataset that captures the daily, seasonal, and interannual variability in VRE over a timescale commensurate with typical lifetimes of generation assets on an electricity grid [6].

In this study, we used nuclear fission power generation for our base case as an example of a firm zero-carbon technology, recognizing that challenges exist alongside promises for this technology. We considered a broad range of possible costs of firm generation technology relative to VRE generation costs. Hence low costs for firm or VRE generation should be interpreted in the context of a thought experiment, and we make no assertion per se regarding whether such costs are likely or even possible for a specific type of firm or VRE generation technology.

Other renewable and low- or zero-carbon technologies (such as hydropower and biomass) are expected to play substantial roles in achieving climate and sustainability goals, and various environmental, ecological, and socio-political considerations will influence the development of these technologies. We have focused exclusively on technoeconomic factors in our quantitative analysis, but these additional considerations are further discussed in Section 3.5.

2. Methods

The modeling framework used in this study is represented in the flowchart in Fig. 1, with details described in this section. Technology costs as of 2018 compiled by the U.S. Energy Information Administration (EIA) were used as the starting point of our analysis (see Appendix A1) [10,11]. Hourly wind and solar resource data for 2015 were derived from hourly weather data over the CONUS [6]. In an initial scoping analysis, we found that the qualitative results from our idealized model are robust to the choice of weather year. Hourly electricity demand for 2015 was sourced from the EIA [6,12]. In addition to using current technology costs, we considered scenarios in which the fixed and variable costs (simply referred to as "costs") were independently varied over a wide range relative to current technology costs. We made no assumptions about the likelihood of any specific future combination of absolute or relative technology costs, and instead described least-cost electricity systems that resulted from the cost assumptions and constraints of the model.

To better evaluate the relationships between the costs of firm zero-carbon and VRE generation technologies, our base case of a fully decarbonized and reliable electricity system consisted only of wind, solar PV, and firm generation, with nuclear power plants as the base case for firm generation providing constant generation at full capacity. The base case was then compared to systems with flexible firm power generation and/or energy storage. Additional cases were evaluated for systems having natural gas as a representative dispatchable resource. These results are not the focus of our comparative analysis of idealized carbon-free electricity systems and have therefore been included in the appendix (Appendix A3).

Our idealized modeling approach focuses on cost optimization based

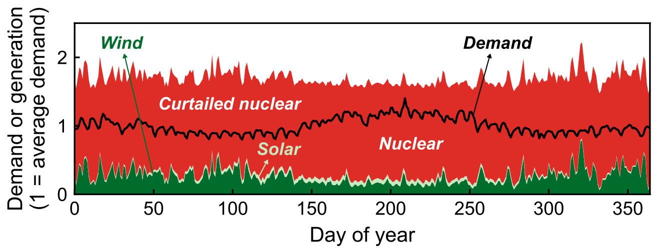

Fig. 2. The demand and least-cost generation profiles for the base case (wind, solar, constant nuclear generation) at 2018 technology costs per EIA estimates [10,11]. The black line shows demand. Dispatched and curtailed amounts of generation are shown below and above the demand curve, respectively. The system was energy-balanced and constrained to be 100% reliable at each hour. Results are reported as daily averages relative to average demand over the time period simulated (one year). At current technology costs, in a system constructed de novo, wind, solar, and nuclear power all appear as parts of a least-cost generation mix.

on geophysical and technoeconomic parameters in a system constructed de novo to assess the fundamental dynamical relationships between firm and VRE generation technologies. Market and policy mechanisms, existing assets, and various technological, economic, and socio-political factors not considered in our model could change the qualitative results from this study. These limitations and associated caveats are discussed in detail in Section 3.5.

2.1. Electricity demand and variable renewable generation data

Hourly wind and solar resource data were obtained from a reanalysis dataset, Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) [13], with a 0.5° by latitude and 0.625° by longitude spatial resolution over the CONUS for a continuous 36-year period [6]. The desired total wind and solar capacity was spatially averaged across the entire CONUS. The system minimized wind and solar variability by assuming lossless transmission from generation to load over all of the CONUS [6]. Electricity demand was based on hourly data for at least one continuous year taken from the EIA [6,12].

2.2. Economic and technological assumptions

Technologies modeled in our study included onshore wind, solar PV, nuclear power, natural gas (combined cycle), and energy storage (batteries). Fixed and variable costs for all technologies were calculated from a set of internally consistent cost and performance estimates from the EIA (see Appendix A1) [10,]. Fixed and variable costs were jointly scaled (i.e., fixed and variable costs scaled together) for nuclear power and variable renewable energy (wind and solar PV) with values ranging from 1×10^{-8} to 1 times current EIA cost estimates. The costs of wind and solar PV generators were varied by a common factor. Fixed and variable costs were varied relative to 2018 EIA estimates on a per kilowatt-hour (kWh; 1 kWh = 3.6×10^{6} J) basis (fixed costs were in \$/kW/h as associated with capacity, whereas variable costs were in \$/kWh as associated with dispatch; see Appendix A2). In the cases where nuclear generation was assumed to be flexible, nuclear power was modeled as having load-following capability at no additional cost (see Appendix A3). The least-cost system was obtained for each set of cost and technology assumptions. Factors not associated with direct costs (e.g., nuclear proliferation risk, public acceptance, and siting challenges) were not considered.

2.3. Idealized electricity system model

The idealized electricity system was represented as a linear optimization that minimizes total system cost (in the form of levelized cost of electricity, LCOE) by simultaneously varying installed capacity and time-varying dispatch of all technologies. A mathematical representation of the model formulation is provided in the appendix (Appendix A2). Least-cost solutions were found for systems with combinations of natural gas, firm zero-emissions generation (with nuclear power as the base case), wind, solar, and energy storage in the resource mix. The full set of results is provided in the appendix (Appendix A3).

A reliability constraint was imposed by stipulating that electricity supply must meet all demand for every hour over the simulation period (one year). In this study, the term "reliability" was used to reflect the North American Electric Reliability Corporation (NERC) resource adequacy planning criterion, which states that there shall be no more than one hour in a decade when hourly averaged demand is not met due to constraints associated with resource availability [14]. We did not consider reliability metrics that reflect planned and unplanned outages due to operational events and human error. Perfect foresight of demand and resource availability, perfect transmission (zero-loss and zero-cost transmission), and a perfectly efficient bulk energy market were assumed.

The time step in the model was one hour. Decision variables included generation capacity committed by each technology (assuming the same capacity is committed for the entire period modeled) and hourly dispatch from each generation technology (varied for every hour to meet demand). Hourly curtailed generation from wind, solar, and firm carbon-free generation (when assumed non-dispatchable) was calculated as installed capacity times hourly capacity factor minus dispatch of the respective technologies at each hour. When nuclear power generation as the base case for firm generation was assumed to be non-dispatchable, fuel cost and variable operating and maintenance (O&M) cost were modeled as components of the fixed cost to represent the scenario in which constant generation at full installed capacity is committed in advance. Quantitatively insignificant variable costs were assigned to wind, solar, and non-dispatchable nuclear power to assure a dispatch order and unique solutions (see Appendix A1). Cost optimization was solved by the Gurobi solver integrated with Python. All input

Table A1
Cost and performance assumptions used for generation technologies in this study.

	Natural gas (NGCC)	Nuclear	Wind	Solar PV
	Assumptions from references [1–3]			
Technology description	Conventional gas / oil combined cycle	Advanced nuclear	Wind, onshore	Solar PV, fixed tilt
Total overnight capital cost [\$/kW]	982	5946	1657	1851
Fuel cost [\$/MMBtu]	3	–	0	0
Fuel cost [\$/kWh]	–	0.00745	–	–
nth-of-a-kind heat rate [Btu/kWh]	6350	–	–	–
Fixed O&M cost [\$/kW/yr]	11.11	101.28	47.47	22.02
Variable O&M cost [\$/MWh]	3.54	2.32	0.00	0.00
Project life [yrs]	20	40	30	30
	Calculated levelized costs			
Fixed cost [\$/kW/h]	0.012	0.062	0.021	0.020
Variable cost [\$/kWh]	0.023	0.010	0	0

Conversions: 1 Btu = 1055 J. 1 MMBtu = 1.055 GJ.

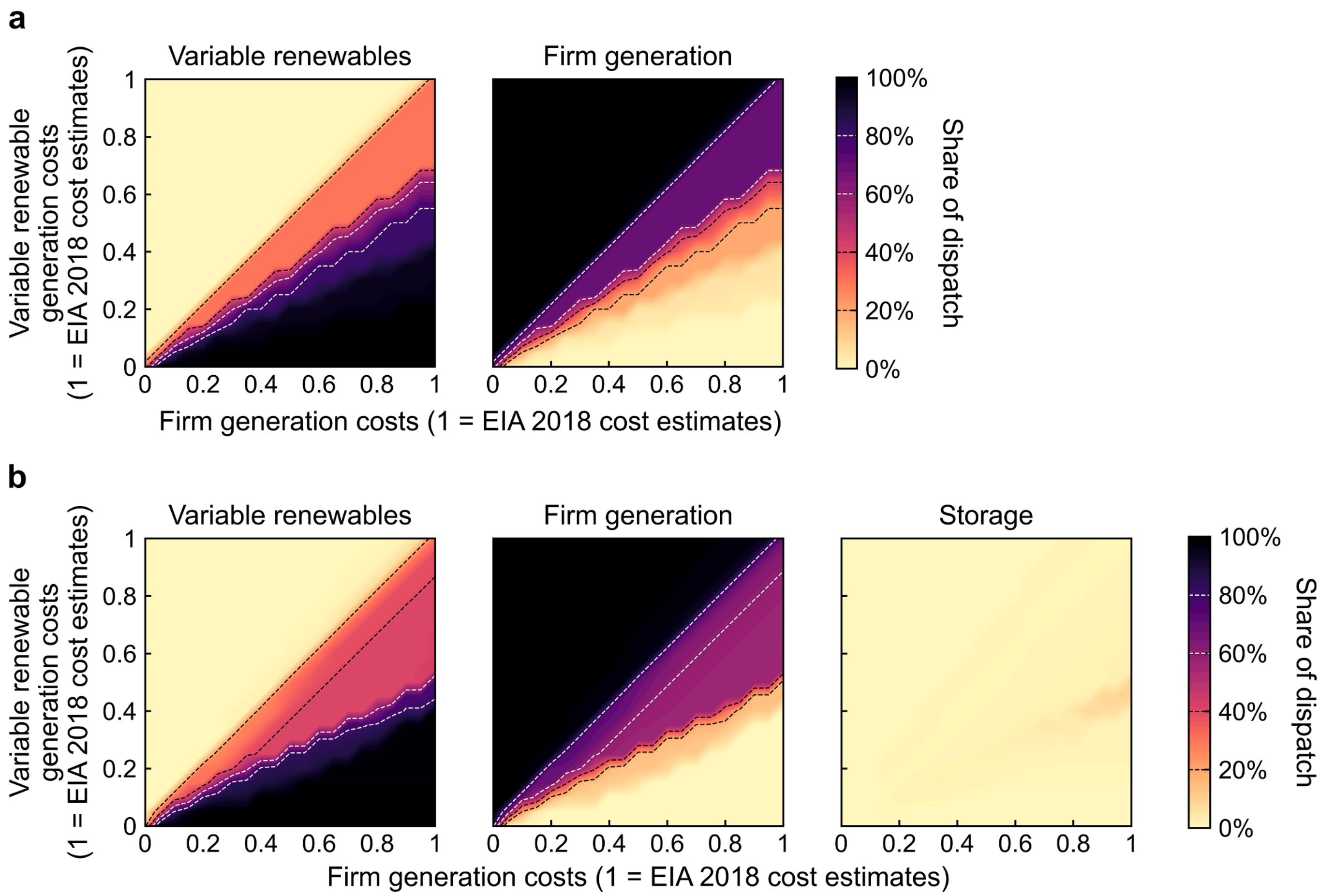

Fig. 3. The least-cost shares of dispatched generation for two cases: (a) base case (constant firm generation and variable renewable electricity, VRE); (b) system with constant firm generation, VRE, and energy storage. Results are shown as a function of the costs of firm generation technology (horizontal axis) and the costs of VRE (vertical axis). At any specific VRE cost, reduced costs of firm generation technology (i.e., moving horizontally from the right side to left side on these panels) result in decreased dispatch of VRE generation, and increased dispatch of firm generation. Similarly, reductions in VRE costs drive out firm generation from the least-cost electricity system.

data, model code, and outputs are available at: https://github.com/carnegie/SEM_public/tree/Yuan_et_al_2020.

3. Results and discussion

3.1. *Base case resource mix in an idealized zero-carbon electricity system at current technology costs*

Fig. 2 presents a least-cost, fully reliable, fully decarbonized idealized system consisting of variable renewable electricity (VRE; wind and solar PV) generation technologies and a firm generation technology represented by nuclear power. The technology costs reflect current costs of onshore wind, solar PV, and nuclear power per EIA estimates [10,11]. In such an idealized system, nuclear power, as well as VRE are deployed and dispatched (Fig. 2). This result highlights that changes in electricity system costs (driven by the technology mix in the system) in response to the deployment of marginal assets in an existing system (in which technologies such as natural gas could be used to compensate for variability in VRE generation) are very different from costs due to asset deployment in a system constructed de novo (with no existing assets) with high statutory reliability as a strict constraint.

Per EIA estimates [10,11], wind power has a slightly higher fixed cost than does solar PV, and both technologies have zero variable costs (Table A1). Based on historical data across the CONUS, wind generation had a higher average capacity factor than did solar PV (38% for wind and 20% for solar [6]; wind and solar generation modeled on an hourly basis). Thus, in our base case analysis, wind had a lower cost per kWh of electricity generated than did solar PV, and this lower cost resulted in the relatively high share of wind generation in Fig. 2. Solar PV appears in the generation mix in Fig. 2, primarily due to the positive correlation between solar resource availability and peak demand. Further results that considered natural gas in the electricity generation system show that, at current costs, wind, solar, and nuclear power were not dispatched relative to natural gas in idealized least-cost, fully reliable (albeit not emissions-free) electricity systems (Appendix Figs. A5 and A6).

3.2. *Competition on a cost basis between firm and variable renewable generation technologies*

Fig. 3a shows the dispatch mix for least-cost systems across a wide range of cost assumptions for firm (assumed to have constant full-capacity generation in Fig. 3) and VRE generation within our modeling framework of these idealized electricity systems. If the costs of the firm generation technology were to decrease substantially (starting at current costs and ranging down to nearly zero) relative to the base case costs of wind and solar generation, the firm technology would gradually substitute for wind and solar generation in the idealized least-cost system, and would eventually become the dominant generation technology in the idealized system exclusively on a cost basis (Fig. 3a). Conversely, if the costs of wind and solar technologies were to decrease substantially (starting at current costs and ranging down to nearly zero),

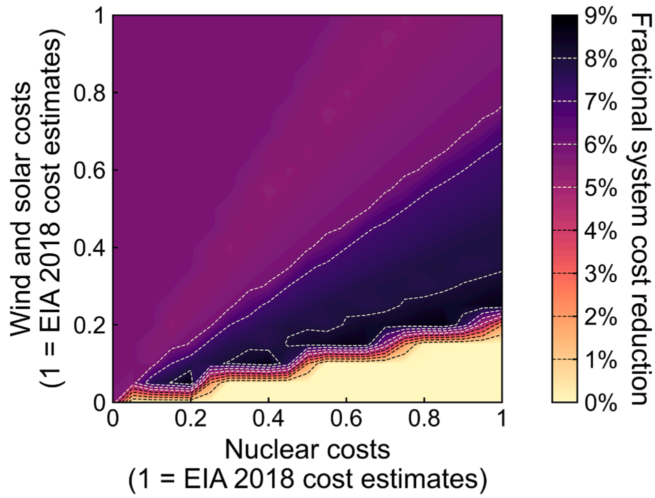

Fig. 4. The fractional difference in system cost as a function of the costs of nuclear power (horizontal axis) and costs of wind and solar electricity (vertical axis) for least-cost systems with wind, solar, and (constant or flexible) nuclear generation. The system cost difference was calculated as the cost of the case with constant nuclear generation minus the cost of the case with flexible nuclear generation. Relative to deployment of constant nuclear generation, deployment of flexible nuclear generation has a moderate impact on the system cost.

the overall penetration of wind and solar generation in the resulting idealized electricity system would increase. The same trends were observed when dispatch of the firm generation technology was assumed to be flexible (Appendix Fig. A2).

Our base case consisted only of wind, solar, and a firm generation technology, and least-cost solutions in this idealized electricity system deployed only the lowest-cost technologies to meet demand. The observed substitutional relationship between VRE and firm generation depicted in Fig. 3a was robust when other forms of firm and/or dispatchable technologies were assumed to be available in the system, such as energy storage (Fig. 3b and Appendix Fig. A4) or natural gas (Appendix Figs. A5 and A6). In all of these idealized, fully reliable, and least-cost electricity systems, introduction of low-cost firm technologies such as nuclear power reduced the deployment of VRE. The similarity of the cases with and without energy storage or natural gas also indicates that the qualitative results do not depend on the exact resource mix in the system. Fundamentally, both nuclear and VRE generation technologies are dominated by high fixed costs relative to variable costs, and as such are most cost-effective when used at high capacity factors.

The presence of energy storage did not change the fundamental dynamical relationship between firm and variable renewable generation observed in our work. Further, energy storage had a limited dispatch share in an idealized least-cost VRE/nuclear/storage electricity system (Fig. 3b and Appendix Fig. A4), even at a storage cost of $100/kWh, which is considered an aspirational target for grid-scale storage technologies [15]. This finding is consistent with previous conclusions obtained using more detailed electricity system models [5,7]. Hence, in all cases investigated in our analysis, cost reductions in firm generation technologies yielded increasing penetration of firm technologies and decreasing penetration of VRE technologies.

3.3. Impact of dispatchable firm technologies on system cost

The impact of a generator's dispatchability on system costs fundamentally depends on the variable costs of the technology relative to its fixed costs. In our analysis, we have used nuclear power as an example of a firm zero-carbon technology. Nuclear power plants are characterized by high fixed costs relative to variable costs [16,17]. High fixed costs favor the use of technologies at high capacity factors. Low variable costs result in small cost savings during flexible operation, and further incentivize the use of nuclear power as baseload generation.

As a result, compared to dispatching nuclear power as "must-run" generation, flexible dispatch of nuclear generation had a moderate impact on idealized VRE/nuclear system costs (Fig. 4). The largest impacts of flexibility in nuclear generation on system cost occurred when the costs of VRE generation were assumed to be about 20–60% of the costs of nuclear power (with base case costs per 2018 EIA cost estimates), in which case flexible nuclear generation reduced the system cost by about 9% relative to the idealized least-cost system deployed based on the same technology costs but instead constrained to have constant nuclear generation.

The value of dispatchability of a firm generator to lowering system costs would become smaller as the resource mix becomes more diversified. In the cases investigated in this study, reductions in system cost due to flexible nuclear generation were smaller when energy storage (Appendix Fig. A13) or natural gas (Appendix Fig. A14) were deployed. When natural gas power generation was present, the relative reductions in system cost produced by the deployment of flexible nuclear generation relative to constant nuclear generation remained small regardless of wind and solar costs (e.g., below 1% in most cases), unless the cost of firm generation decreased substantially from current costs. Specifically, the costs of nuclear power would need to decline to below ~40% of current costs (Appendix Fig. A14) before flexible nuclear power as firm generation would substantially reduce the cost of the idealized least-cost VRE/nuclear/gas system. In this case, the largest relative reduction in system cost produced by flexible nuclear generation relative to constant nuclear generation was 8%, which occurred when costs of nuclear power and VRE were reduced by very large factors, to 15% and 5%, respectively, of current costs (Appendix Fig. A14). Note that these findings flow directly from the intrinsic geophysical characteristics of the wind and solar resources and do not depend on any assumptions regarding the use model of specific grid assets.

3.4. Discussion

Results of this study were obtained by assuming only technology costs and constructing the system de novo. The resulting cost-optimized system in Fig. 2 serves as a base case for exploring the central question that motivated this study. Various factors could result in the actual costs of these generation technologies deviating from their EIA-estimated current technology costs. In the case of nuclear power, the investment costs of recent nuclear reactors have been estimated to be almost $12,000/kW in the UK [18]. After the Three Mile Island accident, distinctive cost escalation has been observed for nuclear reactors constructed in the U.S., with overnight construction costs as high as $11,000/kW [19]. Wind and solar generation costs are subject to resource availability in individual regional markets, as well as additional costs for building high-voltage direct-current (HVDC) transmission lines. Current technology costs were thus used only as a reference starting point, and we subsequently parameterized costs over a wide range of values to address the fundamental question that framed our study, as discussed in Sections 3.2 and 3.3. We consequently advance no favored scenario or opinion as to what these future costs would be.

Substantial cost reductions, such as those modeled in Fig. 3, would require rapid technology innovation and learning. For example, a learning rate of 20% per doubling of cumulative installed capacity, which is consistent with historical learning rates for solar PV [11,20], would lead to a 50% reduction in cost in three doublings of cumulative installed capacity. This level of learning, however, has not been observed for wind generation or nuclear power [6,11,19]. Large reductions in nuclear power costs have been proposed to be associated with the mass manufacture of standardized designs to reduce delays and permitting costs, and to maximize learning [21,22]. Other potential ways to reduce nuclear power costs include improved safety features, improved fuel efficiency, reduced waste production, improved project management, adoption of modular construction, and advanced concrete solutions and structural designs [21,22]. Some of these developments have been proposed to be realizable within a few decades [21].

The fully constant or fully flexible power generation assumed in our analysis represents two extremes of the spectrum of dispatchability. The resulting differences in system cost and resource mix thus represent an upper bound on the impact of flexibility of the firm generation technology modeled within the framework of this simple model and idealized system. In practice, the technical flexibility of power plant operation often lies between the two extremes of the spectrum. In the case of nuclear power plants, the ability to follow load is constrained by technical limits, e.g., ramping at 2–5% per minute and daily cycling at 50–100% of rated power [17,23]. These technical constraints could further limit the impact of flexible nuclear power on system cost. Nevertheless, compared to constant nuclear generation at the same costs, flexible nuclear generation could potentially facilitate the penetration of wind and solar generation, as can be seen by comparing Fig. 3a with Appendix Fig. A2.

The results shown in Fig. 4 suggest that due to economics, technically flexible nuclear power plants may not necessarily be operated flexibly in practice. That is, even though nuclear power plants could be operated flexibly in practice, their economic structure (relatively high fixed costs and limited savings associated with reduced generation) makes dispatchable nuclear generation only marginally more advantageous from the perspective of system cost reduction, than would generation with nearly 100% capacity factors. In contrast, technologies that have low fixed costs relative to variable costs, such as natural gas power plants (with or without the capability of carbon capture and storage, CCS), would be more economically suited for flexible operation. The magnitude of difference in system cost that would result from constant or flexible operation of firm generation technologies also depends on the seasonal and interannual variability of VRE generation, as well as infrequent weather-related events. The impact of such events was minimized in our idealized least-cost electricity systems by assuming that the CONUS was the load balancing region, in conjunction with lossless transmission between all generation and load.

Overall, our findings can be compared to other studies that have examined the role of dispatchable firm technologies in deeply decarbonized electricity systems. Jenkins and coworkers considered additional operational constraints on nuclear flexibility, and more complex energy market mechanisms with VRE and nuclear generation assets already in place, based on one year of hourly VRE generation and demand data [23]. Assuming operating and maintenance costs as the only variable costs for nuclear power plants, Jenkins et al. found that flexible nuclear operation resulted in less than 2% of reductions in total system cost. In addition, Jenkins et al. discussed other benefits of flexible nuclear operation, which included reducing the curtailment of VRE, reducing the frequency of negative energy prices, and increasing nuclear power plant revenues. Another study analyzed nearly 1000 cases in two regional electricity systems, covering varying CO_2 limits at a variety of future projected resource costs [7]. The study concluded that, within the constraints of the assumed use model, the availability of firm low-carbon technologies consistently lowered electricity costs relative to cases that contained solely VRE-based generation [7].

3.5. Caveats

The analyses performed herein represent “snapshots” of idealized least-cost electricity systems that would be obtained if the system were constructed de novo, with technology costs fixed throughout the construction period, and without constraints on potential capacity. In practice, construction of a full electricity system would take decades, during which technology costs would almost certainly evolve, and evolve at different rates for different technologies. Hence lock-in and switching costs would likely produce a different system mix than would the idealized least-cost solutions identified from the simple but illustrative representation of an electricity system, constrained by an idealized set of assumptions, to elicit the fundamental dynamical relationships between firm zero-carbon and VRE technologies evaluated herein.

In our analysis, technologies compete in a perfectly efficient energy market based purely on their fixed and variable costs. Features in real energy markets that were not considered in our idealized representation will influence actual electricity costs and result in different system dynamics. The costs of nuclear waste disposal, and other externalities for both nuclear power and VRE, were assumed to be incorporated into the parameterized future costs for each technology. The analysis does not consider transmission and distribution costs, such as costs for HVDC transmission. The costs of wind and solar integration would likely increase if HVDC were modeled in full detail. Transmission losses and localization of generation and demand would further result in increased gaps between VRE supply and demand.

While the time step in this model (i.e., one hour) represents a reasonably high temporal resolution, load in real energy markets needs to be balanced on the timescale of seconds-to-minutes. Mechanisms to ensure grid stability on these timescales were implicitly assumed in our analysis, and the use of hourly resolution ought to be adequate to evaluate weather-related daily and seasonal variability in generation, in accord with the statutory constraints associated with meeting hourly averaged demand through resource adequacy standards. We recognize that an hourly time step may give an advantage to wind and solar generation due to relaxed balancing requirements compared to actual energy market operations.

We also note that least-cost solutions do not reflect many practical considerations faced by electricity system planning and operations. Market and policy mechanisms not stipulated in this study, including actual energy or capacity market payment structures, may alter the qualitative system behavior relative to that produced by our idealized representation. Our idealized system did not include flexibility mechanisms such as demand response, or the conversion of electricity into fuel or heat. Differences in local and regional energy markets, such as the availability of wind and solar resources, could change the results presented here. Tax and carbon credits, dispatch order mandates, and resource adequacy requirements may cause changes in behavior relative to the idealized systems considered in this study.

Various economic, environmental, and social considerations could influence the technology choices and pathways to achieve a deeply decarbonized electricity system. Concerns over energy security, air pollution, and public acceptance could lead to preference for one resource over another. Impacts on natural and working lands (agricultural and rangelands) would likely affect the siting of wind, solar, and geothermal projects, and the long-term planning of renewable energy infrastructure in general [24]. The competition for land use between food and environmental conservation would likely impact the large-scale deployment of bioenergy [7]. Freshwater consumption, water allocation among energy production and competing uses, and other environmental and ecological impacts need to be actively assessed for the planning and operation of hydropower plants [25–27].

In certain parts of the world, deployment of nuclear power is confronted by economic and social barriers. Increased competition from low-cost natural gas as well as renewable electricity generation has led to the early retirement of nuclear power plants in the U.S. and Germany [18,28–30]. High capital costs, long construction times, and unfavorable public perception [21,29,31,32] have also negatively impacted investment in nuclear power plants, and remain as barriers to deeper penetration of nuclear power. At the same time, ideological trends in many regions favor VRE and other low- or zero-carbon technologies over nuclear power, and policy changes such as mandates and incentives have spurred the growth of the former.

Nevertheless, nuclear power is a scalable, firm zero-carbon technology that could complement VRE generation in a fully reliable and decarbonized electricity system. The potential role of nuclear power in low-carbon, low-cost electricity systems, as baseload or load-following generation, has been discussed extensively [7,23,30]. Real-world examples such as the French electricity system provide proof of the viability of a low-carbon electricity system based primarily on nuclear power [16]. These technological characteristics and the use case support nuclear power as a candidate for a firm zero-carbon technology for the purpose of this study.

In addition to nuclear power, firm low- or zero-carbon technologies such as fossil fuels with CCS, hydropower, geothermal, biomass, hydrogen, and long-duration storage technologies are all of great interest both in the academic literature and in industry. The roles of these technologies in a cost-competitive and deeply decarbonized electricity grid, as well as the challenges they face, have been discussed extensively [4,7,33,34].

Coal is not considered in the context of a zero-emissions electricity system in this study. We recognize that as of today, coal still plays a major role in the world's electricity mix, albeit accompanied by substantial greenhouse gas emissions and air pollution, despite continuing efficiency improvements of coal-fired power plants [35–38].

In this study, we modeled firm zero-carbon technologies primarily based on technoeconomic characteristics of nuclear power for our base case, and parameterized costs to encompass a wide range of possibilities that could in principle be met by other firm carbon-free generation technologies. The wide range of costs explored could also effectively capture potential uncertainties that could impact future technology costs, such as project financing and fuel prices. The role of any firm generation technology, including biomass, hydropower, or coal, can be readily assessed from the results in our work by simply considering the costs of the firm generation technology relative to the costs of VRE generation, without regard to resultant emissions. As a result, our qualitative findings would be robust to the choices of technology and cost assumptions, in the context of our idealized electricity system constructed de novo. Modeling of an abstract, idealized electricity system in which technology costs were explored in wide ranges allows high-level implications to be applicable to systems and technologies with comparable characteristics and constraints.

Due to the abstraction of real-world complexities however, this study does not attempt to draw conclusions about any individual energy system or technology. Although we have explored a wide range of absolute and relative costs for both firm zero-carbon and VRE technologies relative to current costs, we did not formulate estimates of the likelihood of any specific combination of absolute or relative future technology costs relative to present costs. We assumed independent changes in the cost of each technology and have no bias as to how the future costs could change. Instead of a transition path to certain scenarios, we evaluated the endpoint that these changes in costs could produce, with all endpoints being fully reliable, carbon-free electricity systems. Various technological, economic, political, and social elements could shape the transition path to a fully decarbonized energy system. Rather than make predictions or policy recommendations about the composition of future electricity systems, the results from our idealized representation illustrate fundamental cost-driven system dynamics.

4. Conclusions

Our analysis shows that, across a wide range of cost assumptions (parameterized from current costs to close to zero for both firm and variable renewable generation technologies), deployment of firm generation technologies would deter, as opposed to facilitate, deployment of variable renewable electricity generation in an idealized, fully reliable, and zero-carbon electricity system on only a cost basis. Specifically, substantial reductions in the costs of firm zero-carbon generation technologies resulted in increased deployment of these firm technologies and decreased deployment of variable renewable generation technologies. Similarly, substantial reductions in the costs of variable renewable generation technologies such as wind and solar resulted in increased deployment of these technologies and deterred, on a cost basis, deployment of firm zero-carbon generation technologies. These qualitative findings are robust to the inclusion of various technologies, such as nuclear power, battery storage, and natural gas, in idealized least-cost and deeply decarbonized electricity systems. Further studies should validate the idealized model by comparing it to real-world examples of the dynamical relationship between firm and variable renewable generation technologies.

The deployment of firm zero-carbon generation technologies could potentially avoid infrastructure overbuild and reduce the cost of a system that would otherwise consist solely of variable renewable energy. Nevertheless, the magnitude of system cost reduction that results from the flexible operation of a firm generation technology would vary depending on the ratio of the variable costs relative to the fixed costs of the technology, as well as the presence of other technologies (firm and variable) in the system. In our idealized electricity system, the maximum system cost reduction that resulted from dispatching firm generation flexibly, relative to a "must-run" case, was about 9% when the firm generation technology was dominated by high fixed costs, such as in the case of nuclear power.

It has been suggested that increased deployment of flexible firm generation technologies might facilitate the penetration of variable renewable electricity generation, because cost reductions in firm, dispatchable technologies could enable their use as backup generation. But in a least-cost system with given electricity demand, technologies will invariably compete on a cost basis. If a firm generator can supply low-cost electricity when the wind is not blowing and the sun is not shining, it can also provide low-cost electricity when the wind is blowing and the sun is shining. It is, however, unlikely that firm generators that are characterized by high fixed costs relative to variable costs would cost-effectively play a primary gap-filling role between variable renewable electricity generation and variable demand. These results reveal previously unrecognized future trade-offs that may emerge from current choices to support firm zero-carbon generation, variable renewable generation, and energy storage technologies, alone or in various combinations. Decision makers for low- or zero-carbon electricity systems may now consider policy and financial investments in light of the future consequences they portend. Fundamentally, our study indicates that electricity generation technologies that are dominated by fixed costs tend to directly compete with each other, because positive economic return on these technologies often depends on achieving high capacity factors.

CRediT authorship contribution statement

Mengyao Yuan: Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **Fan Tong:** Methodology, Writing - review & editing. **Lei Duan:** Methodology, Writing - review & editing. **Jacqueline A. Dowling:** Writing - review & editing. **Steven J. Davis:** Writing - review & editing. **Nathan S. Lewis:** Conceptualization, Writing - review & editing. **Ken Caldeira:** Conceptualization, Methodology, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank Mehdi Shahriari for early contributions to the model code, David J. Farnham for providing helpful insights, and Leslie Willoughby for editing the manuscript. We acknowledge support from a gift from Gates Ventures LLC, United States to the Carnegie Institution for Science.

Appendix A1. Economic and technological assumptions

All baseline cost assumptions for generation technologies were based on cost estimates by the U.S. Energy Information Administration (EIA) [10],[11],[39] and are summarized in Table A1. To be internally consistent with EIA assumptions, a discount rate of 7% was used for all technologies and cases. We recognize that this discount rate may be high, given present market conditions. Nevertheless, as discussed in the main text, the effects of varying discount rates were effectively captured in the wide range of absolute and relative costs. Wind and solar variable costs were effectively zero but were set to 1.05×10^{-8} \$/kWh and 1×10^{-8} \$/kWh, for wind and solar respectively, to set a dispatch order, obtain unique solutions, and minimize price arbitrage of energy storage. For the same reasons, when nuclear power was modeled as non-dispatchable, nuclear fixed cost was set equal to the sum of fixed and variable costs, and nuclear variable cost was set to 1.1×10^{-8} \$/kWh. These variable costs were so low that they had no discernible effect on the costs reported in our figures or tables.

The capital cost of energy storage was assumed to be \$100/kWh, which represents an aspirational goal for the development of grid-scale battery storage [15]. Using a lifetime of 10 years [40], and a 7% discount rate, the levelized cost of storage was calculated to be \$0.00162/kWh/h. The operating costs of energy storage facilities were assumed to be zero. A decay rate of 1%/month and a charging efficiency of 90% were assumed.

Appendix A2. Model formulation

Nomenclature

Symbol	Unit	Description
g (superscript)	–	Generation technology
s (superscript)	–	Energy storage
from s (superscript)	–	Discharge from energy storage
to s (superscript)	–	Charge to energy storage
t (subscript)	–	Time step, starting from 1 and ending at T
c_{capital}	\$/kW for generation \$/kWh for storage	(Overnight) capital cost
c_{fixed}	\$/kW/h for generation \$/kWh/h for storage	Fixed cost
$c_{\text{fixed O\&M}}$	\$/kW/yr	Fixed operating and maintenance (O&M) cost
c_{fuel}	\$/kWh	Fuel cost
c_{var}	\$/kWh	Variable cost
$c_{\text{var O\&M}}$	\$/kWh	Variable O&M cost
f	–	Capacity factor
h	h/yr	Average number of hours per year
i	–	Discount rate
n	yrs	Project life
Δt	h	Time step size, i.e., 1 h in the model
C	kW for generation kWh for storage	Capacity
D_t	kW	Dispatch at time step t
M_t	kWh	Demand at time step t
S_t	kWh	Energy remaining in storage at time step t
γ	1/yr	Capital recovery factor
δ	1/h	Storage decay rate, or energy loss per hour expressed as fraction of energy in storage
η^g	–	Generation efficiency, calculated from heat rate
η^s	–	Storage charging efficiency
τ	h	Storage charging duration

Fixed and variable costs

Fixed cost of generation technologies:

$$c^g_{\text{fixed}} = \frac{\gamma c^g_{\text{capital}} + c^g_{\text{fixed O\&M}}}{h}$$

Fixed cost of energy storage:

$$c^s_{\text{fixed}} = \frac{\gamma c^s_{\text{capital}}}{h}$$

Capital recovery factor:

$$\gamma = \frac{i(1+i)^n}{(1+i)^n - 1}$$

Variable cost of generation technologies:

$$c^g_{\text{var}} = \frac{c^g_{\text{fuel}}}{\eta^g} + c^g_{\text{var O\&M}}$$

Constraints

Capacity:

$$C^{g,s} \geq 0 \quad \forall g, s$$

Table A2
Summary of cases simulated.

Case number	Description	Technology mix	Assumption for dispatchability of nuclear power
#1	Wind + solar + constant nuclear generation	Wind, solar PV, nuclear	Constant output (non-dispatchable)
#2	Wind + solar + flexible nuclear generation	Wind, solar PV, nuclear	Fully dispatchable
#3	Wind + solar + constant nuclear generation + energy storage	Wind, solar PV, nuclear, battery storage	Constant output (non-dispatchable)
#4	Wind + solar + flexible nuclear generation + energy storage	Wind, solar PV, nuclear, battery storage	Fully dispatchable
#5	Wind + solar + constant nuclear generation + natural gas	Wind, solar PV, nuclear, NGCC	Constant output (non-dispatchable)
#6	Wind + solar + flexible nuclear generation + natural gas	Wind, solar PV, nuclear, NGCC	Fully dispatchable

Dispatch:

$$0 \le D_t^g \le C^g f_t^g \quad \forall g, t$$

$$0 \le D_t^{\text{to } s} \le \frac{C^s}{\tau^s} \quad \forall s, t$$

$$0 \le D_t^{\text{from } s} \le \frac{C^s}{\tau^s} \quad \forall s, t$$

$$0 \le S_t^s \le C^s \quad \forall s, t$$

$$0 \le D_t^{\text{from } s} \le S_t^s(1-\delta) \quad \forall s, t$$

Storage energy balance:

$$S_1 = (1-\delta)S_T\Delta t + \eta^s D_T^{\text{to } s}\Delta t - D_T^{\text{from } s}\Delta t \quad \forall s$$

$$S_{t+1} = (1-\delta)S_t\Delta t + \eta^s D_t^{\text{to } s}\Delta t - D_t^{\text{from } s}\Delta t \quad \forall s, t \in 1, \cdots, (T-1)$$

System energy balance:

$$\sum_g D_t^g \Delta t + D_t^{\text{from } s}\Delta t = M_t + D_t^{\text{to } s}\Delta t \quad \forall g, t$$

Objective function

minimize(system cost)

$$\text{system cost} = \sum_g c_{\text{fixed}}^g C^g + \sum_g \left(\frac{\sum_t c_{\text{var}}^g D_t^g}{T} \right) + c_{\text{fixed}}^s C^s + \frac{\sum_t c_{\text{var}}^{\text{to } s} D_t^s}{T} + \frac{\sum_t c_{\text{var}}^{\text{from } s} D_t^s}{T}$$

Appendix A3. Dispatch share and system cost results

Overview of simulations and results

Analyses were performed for six cases assuming two limiting cases for the dispatchability of nuclear power (Table A2). The base case discussed in the main text is Case #1 in Table A2. The baseline (1×) costs in all cases were levelized costs calculated from EIA estimates (Table A1).

Nuclear power plants were assumed either to produce electricity at full capacity 100% of the time ("constant nuclear generation") or to have load-following capability, with no additional costs, to accommodate flexibility ("flexible nuclear generation"). Studies based on nuclear power plant operation data suggest that while flexible operations could potentially incur additional costs (due to reasons such as increased outage rates, higher maintenance requirements, and unplanned load-following operations), these costs are likely small and need further assessment [41,42].

In the case of flexible nuclear generation, nuclear power plants were assumed to be as technically dispatchable as natural gas combined cycle (NGCC) systems. Given that the time step in the model was one hour, which is large compared to typical ramp rates of NGCCs (on the order of minutes [1]), no constraints were imposed on the ramp rates of either NGCC or flexible nuclear generation.

The dispatch and system cost results for all six cases are shown from Figs. A1 to A12. In Fig. A3 (same results as in Fig. 3b) and Fig. A4, contributions from generation technologies (wind, solar, nuclear power) to energy storage were calculated proportionally to the dispatch of the respective generation technology.

In all of the cases simulated, at every set of wind and solar costs, reduced nuclear costs (i.e., moving from the right side to left side on the panels in the dispatch contour plots) resulted in decreased dispatch of wind and solar electricity and increased dispatch of nuclear power. Similarly, reduced costs of variable renewable electricity drove out nuclear power generation.

Figs. A5 and A6 show that when natural gas generation was allowed in the initial generation mix, the resulting least-cost system (albeit with substantial accompanying CO_2 emissions) was dominated by natural gas generation at current costs. Under the current cost environment, wind and solar generation assets were not cost-competitive with natural gas power plants in a least-cost system. This observation is consistent with other modeling results using current technology costs [5]. In the systems in Figs. A5 and A6, wind, solar, nuclear power, and natural gas were allowed in the initial technology mix. In these systems, wind and solar started to appear in the least-cost generation mix when their costs have decreased to less than ~70% of current costs, and nuclear power started to appear in the least-cost generation mix when its costs have decreased to less than ~50% of current costs.

Least-cost dispatch shares

See Figs. A1–A6.

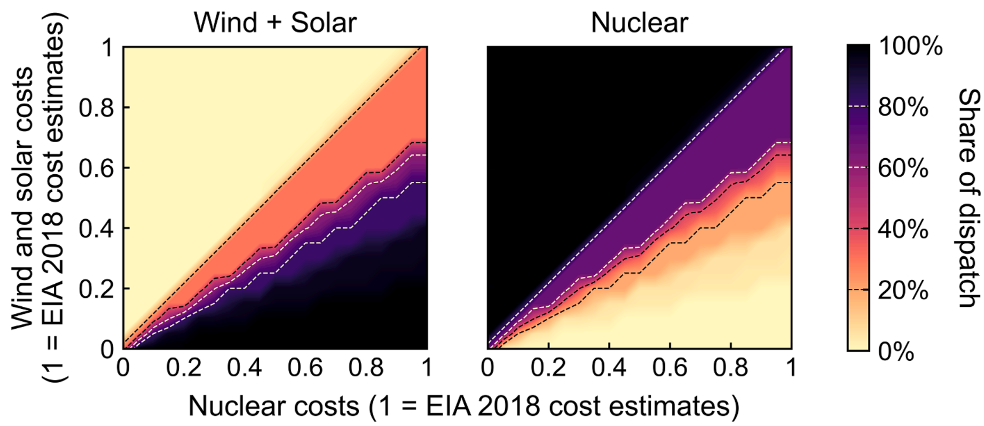

Fig. A1. Least-cost shares of dispatched generation for Case #1 (wind + solar + constant nuclear generation) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis). This figure shows the same results as Fig. 3a in the main text and is included here for completeness.

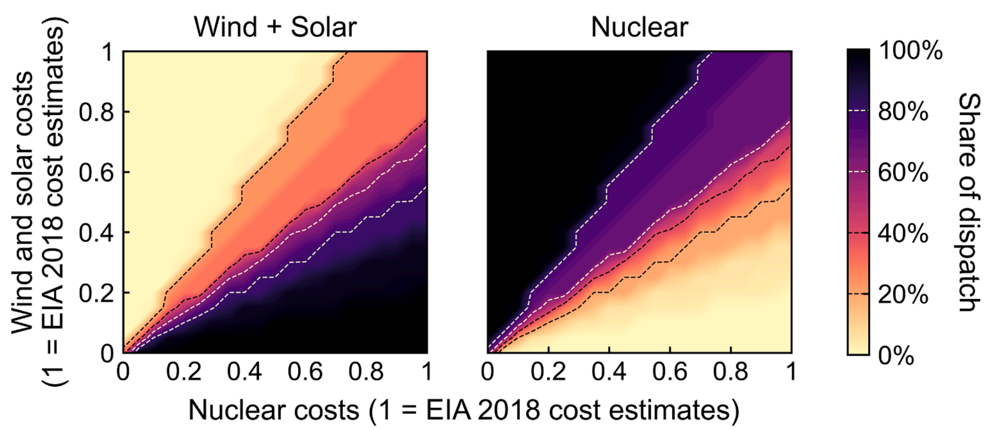

Fig. A2. Least-cost shares of dispatched generation for Case #2 (wind + solar + flexible nuclear generation) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

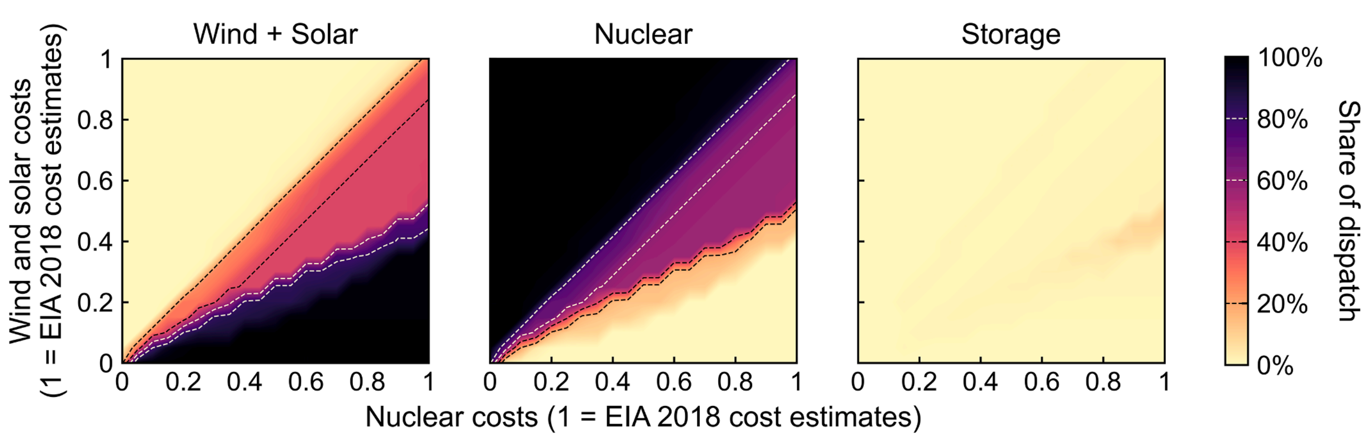

Fig. A3. Least-cost shares of dispatched generation for Case #3 (wind + solar + constant nuclear generation + energy storage) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis). This figure shows the same results as Fig. 3b in the main text and is included here for completeness.

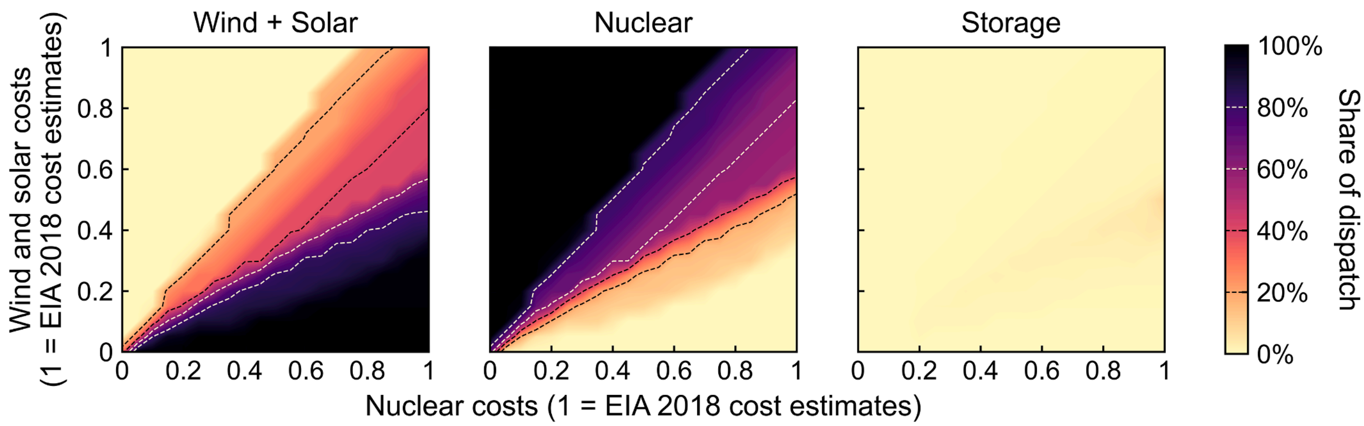

Fig. A4. Least-cost shares of dispatched generation for Case #4 (wind + solar + flexible nuclear generation + energy storage) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

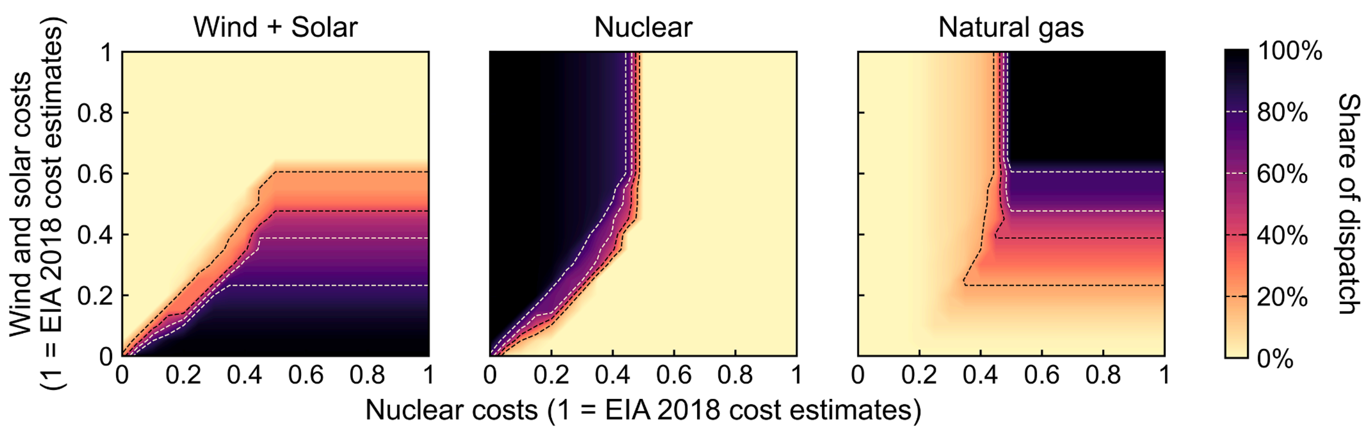

Fig. A5. Least-cost shares of dispatched generation for Case #5 (wind + solar + constant nuclear generation + natural gas) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

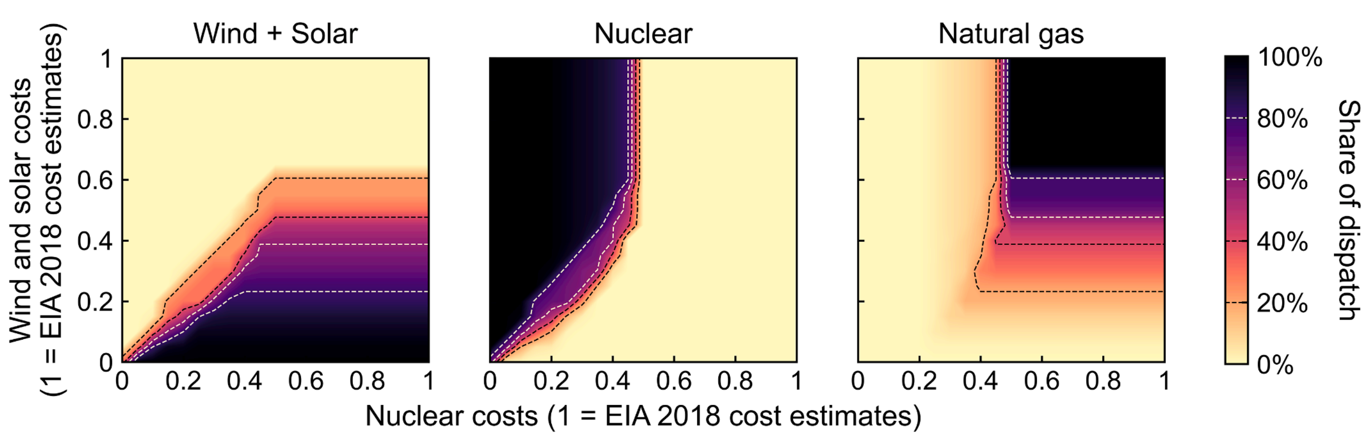

Fig. A6. Least-cost shares of dispatched generation for Case #6 (wind + solar + flexible nuclear generation + natural gas) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

System costs

See Figs. A7–A12.

Value of flexible nuclear generation

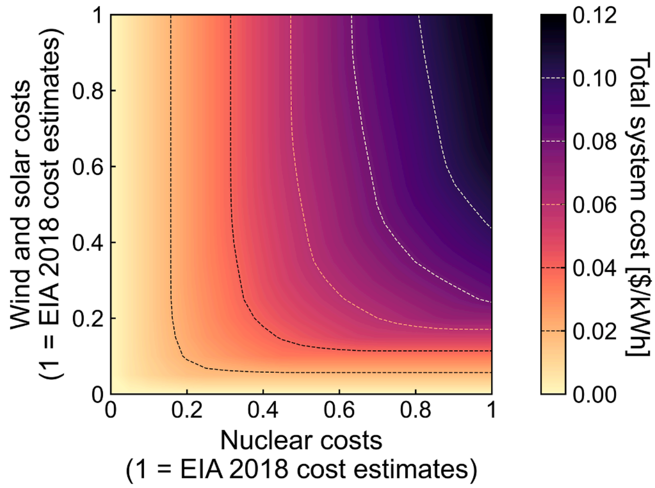

Fig. A7. Least-cost system costs for Case #1 (wind + solar + constant nuclear generation) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

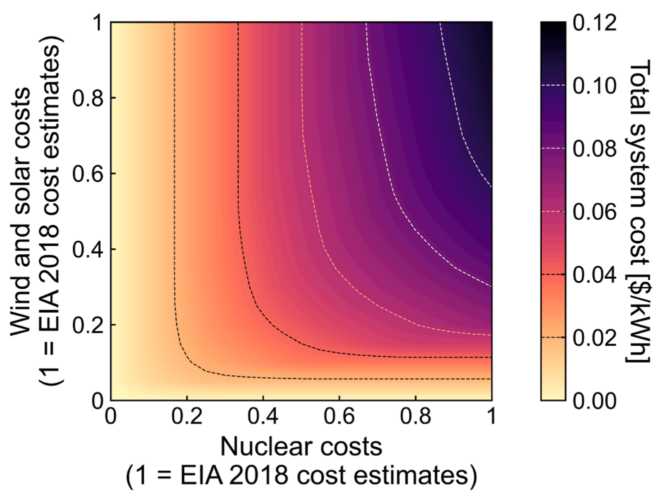

Fig. A8. Least-cost system costs for Case #2 (wind + solar + flexible nuclear generation) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

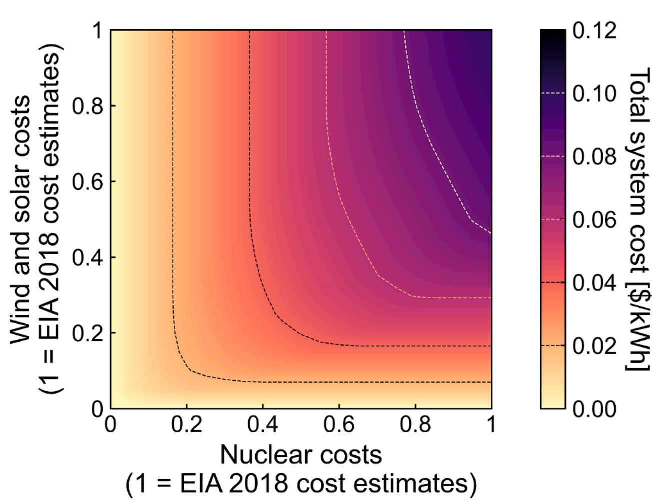

Fig. A9. Least-cost system costs for Case #3 (wind + solar + constant nuclear generation + energy storage) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

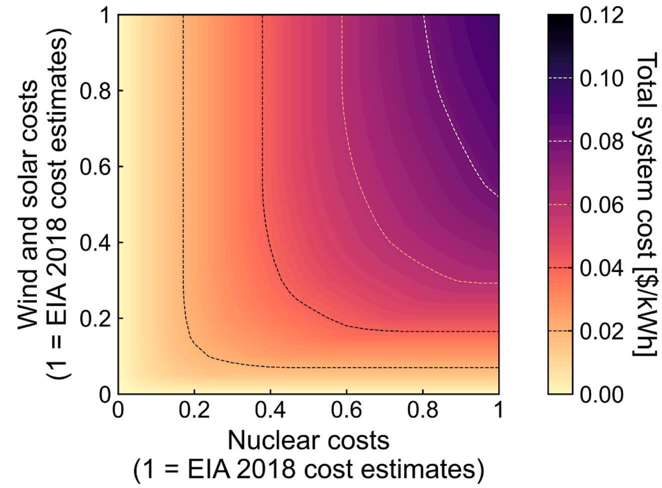

Fig. A10. Least-cost system costs for Case #4 (wind + solar + flexible nuclear generation + energy storage) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

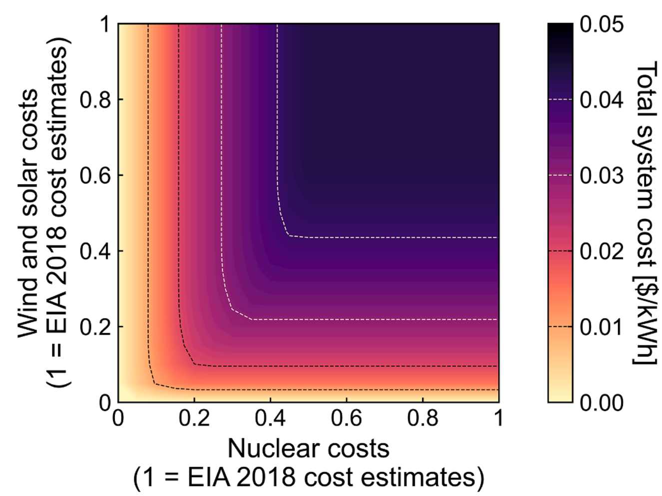

Fig. A11. Least-cost system costs for Case #5 (wind + solar + constant nuclear generation + natural gas) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

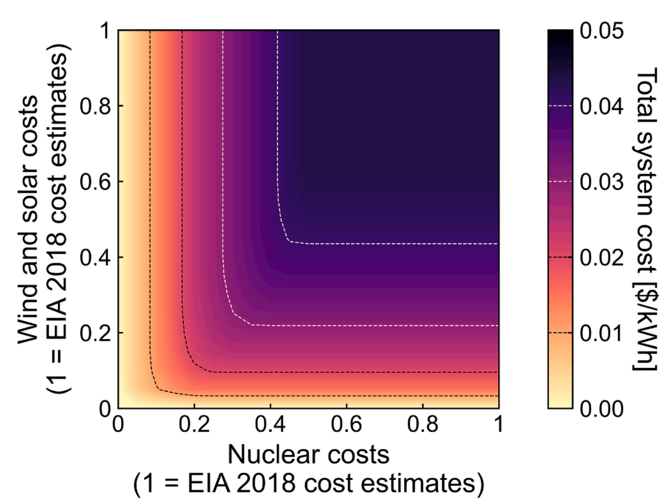

Fig. A12. Least-cost system costs for Case #6 (wind + solar + flexible nuclear generation + natural gas) as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis).

See Figs. A13 and A14.

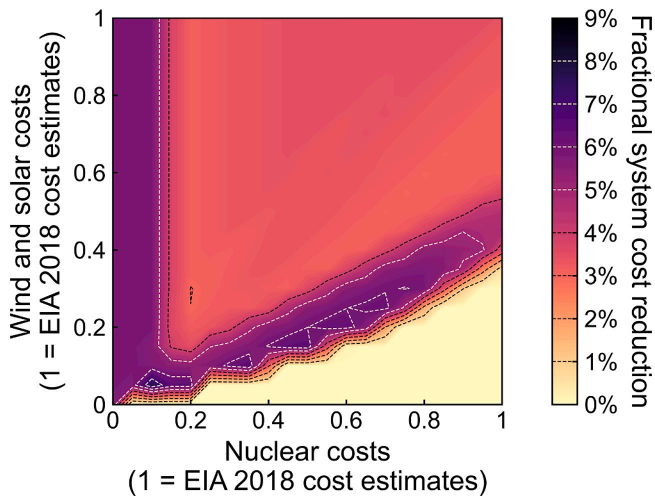

Fig. A13. Fractional difference in system cost as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis) for least-cost systems with wind, solar, constant or flexible nuclear generation, and energy storage (Case #3 and Case #4).

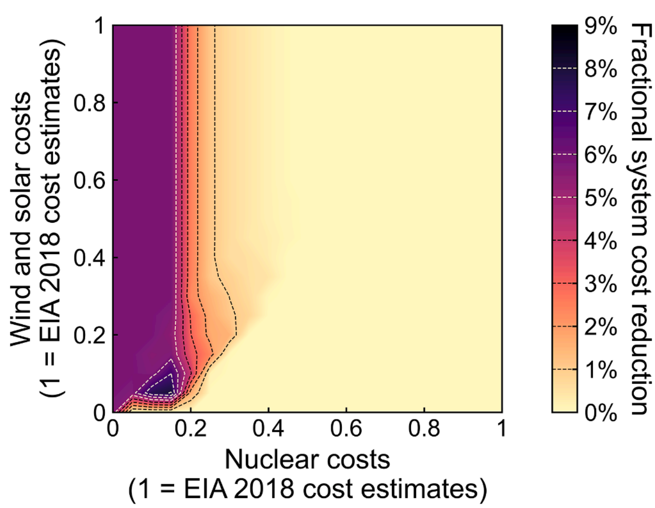

Fig. A14. Fractional difference in system cost as a function of costs of nuclear power (horizontal axis) and wind and solar electricity (vertical axis) for least-cost systems with wind, solar, constant or flexible nuclear generation, and natural gas (Case #5 and Case #6).

References

[1] Chu S, Majumdar A. Opportunities and challenges for a sustainable energy future. Nature 2012;488:294–303. https://doi.org/10.1038/nature11475.

[2] Collins S, Deane P, Gallachóir BÓ, Pfenninger S, Staffell I. Impacts of inter-annual wind and solar variations on the European power system. Joule. 2018;2:2076–90. https://doi.org/10.1016/j.joule.2018.06.020.

[3] Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, Azevedo IL, et al. Net-zero emissions energy systems. Science 2018;360:eaas9793.. https://doi.org/10.1126/science.aas9793.

[4] Jenkins JD, Luke M, Thernstrom S. Getting to zero carbon emissions in the electric power sector. Joule. 2018;2:2498–510. https://doi.org/10.1016/j.joule.2018.11.013.

[5] MacDonald AE, Clack CTM, Alexander A, Dunbar A, Wilczak J, Xie Y. Future cost-competitive electricity systems and their impact on US CO_2 emissions. Nat Clim Change. 2016;6:526–31. https://doi.org/10.1038/nclimate2921.

[6] Shaner MR, Davis SJ, Lewis NS, Caldeira K. Geophysical constraints on the reliability of solar and wind power in the United States. Energy & Environ Sci. 2018;11:914–25. https://doi.org/10.1039/C7EE03029K.

[7] Sepulveda NA, Jenkins JD, de Sisternes FJ, Lester RK. The role of firm low-carbon electricity resources in deep decarbonization of power generation. Joule. 2018;2: 2403–20. https://doi.org/10.1016/j.joule.2018.08.006.

[8] Deign J. Renewables or nuclear? A new front in the academic war over decarbonization, https://www.greentechmedia.com/articles/read/the-war-over-renewables-versus-nuclear; 2018 [accessed 8 August 2020].

[9] Jenkins JD. Can nuclear power and renewable energy learn to get along?, https://www.energycentral.com/c/ec/can-nuclear-power-and-renewable-energy-learn-get-along; 2014 [accessed 8 August 2020].

[10] U.S. Energy Information Administration. Electric Power Annual 2017. Washington, DC: U.S. Department of Energy; 2018. https://www.eia.gov/electricity/annual/archive/pdf/03482017.pdf.

[11] U.S. Energy Information Administration. Annual Energy Outlook 2018. Washington, DC: U.S. Department of Energy; 2018. https://www.eia.gov/outlooks/archive/aeo18/.

[12] U.S. Energy Information Administration. U.S. Electric System Operating Data, https://www.eia.gov/realtime_grid/; [accessed 8 August 2020].

[13] Gelaro R, McCarty W, Suárez MJ, Todling R, Molod A, Takacs L, et al. The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). J Clim 2017;30:5419–54. https://doi.org/10.1175/JCLI-D-16-0758.1.

[14] North American Electric Reliability Corporation (NERC). Planning Resource Adequacy Analysis, Assessment and Documentation. Standard BAL-502-RF-03. 2017. https://www.nerc.com/pa/Stand/Reliability%20Standards/BAL-502-RF-03.pdf.

[15] U.S. Department of Energy. Grid Energy Storage. U.S. Department of Energy; 2013. https://www.energy.gov/sites/prod/files/2014/09/f18/Grid%20Energy%20Storage%20December%202013.pdf.

[16] Brook BW, Alonso A, Meneley DA, Misak J, Blees T, van Erp JB. Why nuclear energy is sustainable and has to be part of the energy mix. Sustainable Mater Technol. 2014;1:8–16. https://doi.org/10.1016/j.susmat.2014.11.001.

[17] Lokhov A. Technical and economic aspects of load following with nuclear power plants. Paris, France: Nuclear Energy Agency, OECD; 2011.

[18] Froggatt A, Schneider M. Nuclear power versus renewable energy—A trend analysis. Proc IEEE. 2015;103:487–90. https://doi.org/10.1109/JPROC.2015.2414485.

[19] Lovering JR, Yip A, Nordhaus T. Historical construction costs of global nuclear power reactors. Energy Policy. 2016;91:371–82. https://doi.org/10.1016/j.enpol.2016.01.011.

[20] Rubin ES, Azevedo IML, Jaramillo P, Yeh S. A review of learning rates for electricity supply technologies. Energy Policy. 2015;86:198–218. https://doi.org/10.1016/j.enpol.2015.06.011.

[21] Cao J, Cohen A, Hansen J, Lester R, Peterson P, Xu H. China-U.S. cooperation to advance nuclear power. Science 2016;353:547–8. https://doi.org/10.1126/science.aaf7131.

[22] Parsons J, Buongiorno J, Corradini M, Petti D. A fresh look at nuclear energy. Science 2019;363:105. https://doi.org/10.1126/science.aaw5304.

[23] Jenkins JD, Zhou Z, Ponciroli R, Vilim R, Ganda F, de Sisternes F, et al. The benefits of nuclear flexibility in power system operations with renewable energy. Appl Energy. 2018;222:872–84. https://doi.org/10.1016/j.apenergy.2018.03.002.

[24] Wu GC, Leslie E, Allen D, Sawyerr O, Cameron D, Brand E, et al. Power of Place. Land Conservation and Clean Energy Pathways for California. 2019.

[25] Grubert EA. Water consumption from hydroelectricity in the United States. Adv Water Resour 2016;96:88–94. https://doi.org/10.1016/j.advwatres.2016.07.004.

[26] Kuriqi A, Pinheiro AN, Sordo-Ward A, Garrote L. Influence of hydrologically based environmental flow methods on flow alteration and energy production in a run-of-river hydropower plant. J Cleaner Prod 2019;232:1028–42. https://doi.org/10.1016/j.jclepro.2019.05.358.

[27] Kuriqi A, Pinheiro AN, Sordo-Ward A, Garrote L. Flow regime aspects in determining environmental flows and maximising energy production at run-of-river hydropower plants. Appl Energy 2019;256:113980. https://doi.org/10.1016/j.apenergy.2019.113980.

[28] Haratyk G. Early nuclear retirements in deregulated U.S. markets: Causes, implications and policy options. Energy Policy. 2017;110:150–66. https://doi.org/10.1016/j.enpol.2017.08.023.

[29] Morgan MG, Abdulla A, Ford MJ, Rath M. US nuclear power: The vanishing low-carbon wedge. Proc Natl Acad Sci U S A. 2018;115:7184–9. https://doi.org/10.1073/pnas.1804655115.

[30] Roth MB, Jaramillo P. Going nuclear for climate mitigation: An analysis of the cost effectiveness of preserving existing U.S. nuclear power plants as a carbon avoidance strategy. Energy. 2017;131:67–77. https://doi.org/10.1016/j.energy.2017.05.011.

[31] Poumadère M, Bertoldo R, Samadi J. Public perceptions and governance of controversial technologies to tackle climate change: nuclear power, carbon capture and storage, wind, and geoengineering. Wiley Interdiscip Rev Clim Change 2011;2: 712–27. https://doi.org/10.1002/wcc.134.

[32] Rogner H-H. World outlook for nuclear power. Energy Strategy Reviews. 2013;1: 291–5. https://doi.org/10.1016/j.esr.2012.12.001.

[33] Dowling JA, Rinaldi KZ, Ruggles TH, Davis SJ, Yuan M, Tong F, et al. Role of long-duration energy storage in variable renewable electricity systems. Joule. https://doi.org/10.1016/j.joule.2020.07.007.

[34] Tong F, Yuan M, Lewis NS, Davis SJ, Caldeira K. Effects of deep reductions in energy storage costs on highly reliable wind and solar electricity systems. iScience 2020:101484. https://doi.org/10.1016/j.isci.2020.101484.
[35] Burnard K, Jiang J, Li B, Brunet G, Bauer F. Emissions reduction through upgrade of coal-fired power plants. France: International Energy Agency; 2014.
[36] Campbell RJ. Increasing the efficiency of existing coal-fired power plants. Congressional Research Service 2013.
[37] Tollefson J. Can the world kick its fossil-fuel addiction fast enough. Nature 2018; 556:422–5. https://doi.org/10.1038/d41586-018-04931-6.
[38] Wu X, Chen G. Coal use embodied in globalized world economy: from source to sink through supply chain. Renew Sustain Energy Rev 2018;81:978–93. https://doi.org/10.1016/j.rser.2017.08.018.
[39] U.S. Energy Information Administration. Almost all U.S. nuclear plants require life extension past 60 years to operate beyond 2050, https://www.eia.gov/todayinenergy/detail.php?id=19091; 2014 [accessed 8 August 2020].
[40] Lazard. Levelized Cost of Storage Analysis Version 3.0. 2017. https://www.lazard.com/media/450338/lazard-levelized-cost-of-storage-version-30.pdf.
[41] Cany C, Mansilla C, Mathonnière G, Da Costa P. Nuclear power supply: Going against the misconceptions. Evidence of nuclear flexibility from the French experience. Energy. 2018;151:289–96. https://doi.org/10.1016/j.energy.2018.03.064.
[42] International Atomic Energy Agency (IAEA). Non-baseload operation in nuclear power plants: Load following and frequency control modes of flexible operation. Vienna: International Atomic Energy Agency; 2018.