Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar

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A number of analyses, meta-analyses, and assessments, including those performed by the Intergovernmental Panel on Climate Change, the National Oceanic and Atmospheric Administration, the National Renewable Energy Laboratory, and the International Energy Agency, have concluded that deployment of a diverse portfolio of clean energy technologies makes a transition to a low-carbon-emission energy system both more feasible and less costly than other pathways. In contrast, Jacobson et al. [Jacobson MZ, Delucchi MA, Cameron MA, Frew BA (2015) Proc Natl Acad Sci USA 112(49):15060–15065] argue that it is feasible to provide "low-cost solutions to the grid reliability problem with 100% penetration of WWS [wind, water and solar power] across all energy sectors in the continental United States between 2050 and 2055", with only electricity and hydrogen as energy carriers. In this paper, we evaluate that study and find significant shortcomings in the analysis. In particular, we point out that this work used invalid modeling tools, contained modeling errors, and made implausible and inadequately supported assumptions. Policy makers should treat with caution any visions of a rapid, reliable, and low-cost transition to entire energy systems that relies almost exclusively on wind, solar, and hydroelectric power.

energy systems modeling | climate change | renewable energy | energy costs | grid stability

A number of studies, including a study by one of us, have concluded that an 80% decarbonization of the US electric grid could be achieved at reasonable cost (1, 2). The high level of decarbonization is facilitated by an optimally configured continental high-voltage transmission network. There seems to be some consensus that substantial amounts of greenhouse gas (GHG) emissions could be avoided with widespread deployment of solar and wind electric generation technologies along with supporting infrastructure.

Furthermore, it is not in question that it would be theoretically possible to build a reliable energy system excluding all bioenergy, nuclear energy, and fossil fuel sources. Given unlimited resources to build variable energy production facilities, while expanding the transmission grid and accompanying energy storage capacity enormously, one would eventually be able to meet any conceivable load. However, in developing a strategy to effectively mitigate global energy-related CO_2 emissions, it is critical that the scope of the challenge to achieve this in the real world is accurately defined and clearly communicated.

Wind and solar are variable energy sources, and some way must be found to address the issue of how to provide energy if their immediate output cannot continuously meet instantaneous demand. The main options are to (*i*) curtail load (i.e., modify or fail to satisfy demand) at times when energy is not available, (*ii*) deploy very large amounts of energy storage, or (*iii*) provide supplemental energy sources that can be dispatched when needed. It is not yet clear how much it is possible to curtail loads, especially over long durations, without incurring large economic costs. There are no electric storage systems available today that can

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Significance

Previous analyses have found that the most feasible route to a low-carbon energy future is one that adopts a diverse portfolio of technologies. In contrast, Jacobson et al. (2015) consider whether the future primary energy sources for the United States could be narrowed to almost exclusively wind, solar, and hydroelectric power and suggest that this can be done at "low-cost" in a way that supplies all power with a probability of loss of load "that exceeds electric-utility-industry standards for reliability". We find that their analysis involves errors, inappropriate methods, and implausible assumptions. Their study does not provide credible evidence for rejecting the conclusions of previous analyses that point to the benefits of considering a broad portfolio of energy system options. A policy prescription that overpromises on the benefits of relying on a narrower portfolio of technologies options could be counterproductive, seriously impeding the move to a cost effective decarbonized energy system.

affordably and dependably store the vast amounts of energy needed over weeks to reliably satisfy demand using expanded wind and solar power generation alone. These facts have led many US and global energy system analyses (1–10) to recognize the importance of a broad portfolio of electricity generation technologies, including sources that can be dispatched when needed.

Faults with the Jacobson et al. Analyses

Jacobson et al. (11) along with additional colleagues in a companion article (12) attempt to show the feasibility of supplying all energy end uses (in the continental United States) with almost exclusively wind, water, and solar (WWS) power (no coal, natural gas, bioenergy, or nuclear power), while meeting all loads, at reasonable cost. Ref. 11 does include 1.5% generation from geothermal, tidal, and wave energy. Throughout the remainder of the paper, we denote the scenarios in ref. 11 as 100% wind, solar, and hydroelectric power for simplicity. Such a scenario may be a useful way to explore the hypothesis that it is possible to meet the challenges associated with reliably supplying energy across all sectors almost exclusively with large quantities of a narrow range of variable energy resources. However, there is a difference between presenting such visions as thought experiments and asserting, as the authors do, that rapid and complete conversion to an almost 100% wind, solar, and hydroelectric power system is feasible with little downside (12). It is important to understand the distinction between physical possibility and feasibility in the real world. To be clear, the specific aim of the work by Jacobson et al. (11) is to provide "low-cost solutions to the grid reliability problem with 100% penetration of WWS [wind, water and solar power] across all energy sectors in the continental United States between 2050 and 2055."

Relying on 100% wind, solar, and hydroelectric power could make climate mitigation more difficult and more expensive than it needs to be. For example, the analyses by Jacobson et al. (11, 12) exclude from consideration several commercially available technologies, such as nuclear and bioenergy, that could potentially contribute to decarbonization of the global energy system, while also helping assure high levels of reliability in the power grid. Furthermore, Jacobson et al. (11, 12) exclude carbon capture and storage technologies for fossil fuel generation. An additional option not considered in the 100% wind, solar, and hydroelectric studies is bioenergy coupled with carbon capture and storage to create negative emissions within the system, which could help with emissions targets. With all available technologies at our disposal, achieving an 80% reduction in GHG emissions from the electricity sector at reasonable costs is extremely challenging, even using a new continental-scale high-voltage transmission grid. Decarbonizing the last 20% of the electricity sector as well as decarbonizing the rest of the economy that is difficult to electrify (e.g., cement manufacture and aviation) are even more challenging. These challenges are deepened by placing constraints on technological options.

In our view, to show that a proposed energy system is technically and economically feasible, a study must, at a minimum, show, through transparent inputs, outputs, analysis, and validated modeling (13), that the required technologies have been commercially proven at scale at a cost comparable with alternatives; that the technologies can, at scale, provide adequate and reliable energy; that the deployment rate required of such technologies and their associated infrastructure is plausible and commensurate with other historical examples in the energy sector; and that the deployment and operation of the technologies do not violate environmental regulations. We show that refs. 11 and 12 do not meet these criteria and, accordingly, do not show the technical, practical, or economic feasibility of a 100% wind, solar, and hydroelectric energy vision. As we detail below and in *SI Appendix*, ref. 11 contains modeling errors; incorrect, implausible, and/or inadequately supported assumptions; and the application of methods inappropriate to the task. In short, the analysis performed in ref. 11 does not support the claim that such a system would perform at reasonable cost and provide reliable power.

The vision proposed by the studies in refs. 11 and 12 narrows generation options but includes a wide range of currently uncosted innovations that would have to be deployed at large scale (e.g., replacement of our current aviation system with yet-to-be-developed hydrogen-powered planes). The system in ref. 11 assumes the availability of multiweek energy storage systems that are not yet proven at scale and deploys them at a capacity twice that of the entire United States' generating and storage capacity today. There would be underground thermal energy storage (UTES) systems deployed in nearly every community to provide services for every home, business, office building, hospital, school, and factory in the United States. However, the analysis does not include an accounting of the costs of the physical infrastructure (pipes and distribution lines) to support these systems. An analysis of district heating (14) showed that having existing infrastructure is key to effective deployment, because the high upfront costs of the infrastructure are prohibitive.

It is not difficult to match instantaneous energy demands for all purposes with variable electricity generation sources in real time as needed to assure reliable power supply if one assumes, as the authors of the ref. 11 do, that there exists a nationally integrated grid, that most loads can be flexibly shifted in time, that large amounts of multiweek and seasonal energy storage will be readily available at low cost, and that the entire economy can easily be electrified or made to use hydrogen. However, adequate support for the validity of these assumptions is lacking. Furthermore, the conclusions in ref. 11 rely heavily on free, nonmodeled hydroelectric capacity expansion (adding turbines that are unlikely to be feasible without major reconstruction of existing facilities) at current reservoirs without consideration of hydrological constraints or the need for additional supporting infrastructure (penstocks, tunnels, and space); massive scale-up of hydrogen production and use; unconstrained, nonmodeled transmission expansion with only rough cost estimates; and free time-shifting of loads at large scale in response to variable energy provision. None of these are going to be achieved without cost. Some assumed expansions, such as the hydroelectric power output, imply operating facilities way beyond existing constraints that have been established for important environmental reasons. Without these elements, the costs of the energy system in ref. 11 would be substantially higher than claimed.

In evaluating the 100% wind, solar, and hydroelectric power system (11), we focus on four major issues that are explored in more detail below and in *SI Appendix*. (*i*) We note several modeling errors presented in ref. 11 that invalidate the results in the studies, particularly with respect to the amount of hydropower available and the demand response of flexible loads (*SI Appendix*, section S1). (*ii*) We examine poorly documented and implausible assumptions, including the cost and scalability of storage technologies, the use of hydrogen fuels, lifecycle assessments of technologies, cost of capital and capacity factors of existing technologies, and land use (*SI Appendix*, section S2). (*iii*) We discuss the studies' lack of electric power system modeling of transmission, reserve margins, and frequency response, despite claims of system reliability (*SI Appendix*, section S3). (*iv*) Finally, we argue that the climate/weather model used for estimates of wind and solar energy production has not shown the ability to accurately simulate wind speeds or solar insolation at the scales needed to assure the technical reliability of an energy system relying so heavily on intermittent energy sources (*SI Appendix*, section S4).

Modeling Errors

As we detail in *SI Appendix*, section S1, ref. 11 includes several modeling mistakes that call into question the conclusions of the study. For example, the numbers given in the supporting information of ref. 11 imply that maximum output from hydroelectric facilities cannot exceed 145.26 GW (*SI Appendix*, section S1.1), about 50% more than exists in the United States today (15), but figure 4B of ref. 11 (Fig. 1) shows hydroelectric output exceeding 1,300 GW. Similarly, as detailed in *SI Appendix*, section S1.2, the total amount of load labeled as flexible in the figures of ref. 11 is much greater than the amount of flexible load represented in their supporting tabular data. In fact, the flexible load used by LOADMATCH is more than double the maximum possible value from table 1 of ref. 11. The maximum possible from table 1 of ref. 11 is given as 1,064.16 GW, whereas figure 3 of ref. 11 shows that flexible load (in green) used up to 1,944 GW (on day 912.6). Indeed, in all of the figures in ref. 11 that show flexible load, the restrictions enumerated in table 1 of ref. 11 are not satisfied.

In the analysis in ref. 11, the flexible loads can be accumulated in 8-h blocks, which raises a serious issue of extreme excess industrial/commercial/residential capacity to use the high power for short periods of time. Under these assumptions, there would need to be oversized facilities on both the demand and generation sides to compensate for their respective variabilities. These errors are critical, because the conclusions reached in ref. 11 depend on the availability of large amounts of dispatchable energy and a large degree of flexibility in demand. Ref. 11 also includes a scenario where zero demand response is allowed, and it shows that there is almost no cost changes and that the grid is still stable. Thus, there can be no cost associated with demand response (on either the supply or the consumption side); otherwise, there would be substantial changes in final costs caused by the complete reconfiguring of the US economy schedule.

Implausible Assumptions

The conclusions contained in ref. 11 rely on a number of unproven technologies and poorly substantiated assumptions as detailed in *SI Appendix*, section S2. In summary, the reliability of the proposed 100% wind, solar, and hydroelectric power system depends centrally on a large installed capacity of several different energy storage systems (11), collectively allowing their model to flexibly reshape energy demand to match the output of variable electricity generation technologies. The study (11) assumes a total of 2,604 GW[4] of storage charging capacity, more than double the entire current capacity of all power plants in the United States (16). The energy storage capacity consists almost entirely of two technologies that remain unproven at any scale: 514.6 TWh of UTES (the largest UTES facility today is 0.0041 TWh) (additional discussion is in *SI Appendix*, section S2.1) and 13.26 TWh of phase change materials (PCMs; effectively in research and demonstration phase) (additional discussion is in *SI Appendix*, section S2.2) coupled to concentrating solar thermal power (CSP). To give an idea of scale, the 100% wind, solar, and hydroelectric power system proposed in ref. 11 envisions UTES systems deployed in nearly every community for nearly every home, business, office building, hospital, school, and factory in the United States, although only a handful exist today.

Although both PCM and UTES are promising resources, neither technology has reached the level of technological maturity to be confidently used as the main underpinning technology in a study aiming to show the technical reliability and feasibility of an energy system. The relative immaturity of these technologies cannot be reconciled with the authors' assertion that the solutions proposed in ref. 11 and companion papers are ready to be implemented today at scale at low cost and that there are no technological or economical hurdles to the proposed system.[5]

The 100% wind, solar, and hydroelectric power system study (11) also makes unsupported assumptions about widespread adoption of hydrogen as an energy carrier, including the conversion of the aviation and steel industries to hydrogen and the ability to store in hydrogen an amount of energy equivalent to more than 1 month of current US electricity consumption. Furthermore, in figure S6 of ref. 11, hydrogen is being produced at a peak rate consuming nearly 2,000 GW of electricity, nearly twice the current US electricity-generating capacity. As detailed in *SI Appendix*, section S2.3, the costs and feasibility of this transition to a hydrogen economy are not appropriately accounted for by ref. 11. To show the scale of the additional capacities that are demanded in refs. 11 and 12, we plot them along with the electricity generation capacity in 2015 in Fig. 2. The data used for Fig. 2 can be found in Datasets S1 and S2.

Refs. 11 and 12 cite each other about the values of capacity. For example, ref. 12, which supposedly includes information for all 50 states, reports table S2 in ref. 11 as the source of the numbers. Then, ref. 11, which only includes information for the capacity in the 48 contiguous states, cites table 2 in ref. 12 as the source of the values. The values in the two papers do not agree, presumably because of the difference in the number of states included, and therefore, it is unclear how each reference can be the source of the values for the other one. Additionally, ref. 11 assumes that 63% of all energy-intensive industrial demand is

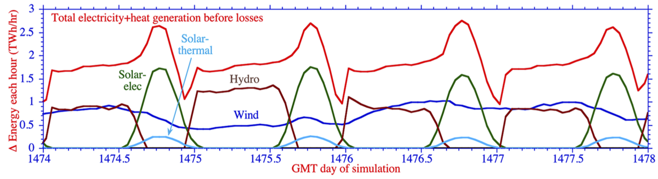

Fig. 1. This figure (figure 4B from ref. 11) shows hydropower supply rates peaking at nearly 1,300 GW, despite the fact that the proposal calls for less than 150 GW hydropower capacity. This discrepancy indicates a major error in their analysis. Modified from ref. 11.

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[4] Table S1 in ref. 11 shows non-UTES storage of 1,065 GW, UTES electric storage of 1,072 GW, and UTES thermal storage of 467 GW. In ref. 11, there is no description of how LOADMATCH differentiates energy types.

[5] In ref. 12, the authors state that "100% conversions [to WWS energy systems] are technically and economically feasible with little downside . . . Numerous low-cost solutions are found, suggesting that maintaining grid reliability upon 100% conversion to WWS is economically feasible and not a barrier to the conversion [to a 100% WWS system] . . . We do not believe a technical or economic barrier exists to ramping up production of WWS technologies. Based on the scientific results presented, current barriers to implementing the [100% WWS] roadmaps are neither technical nor economic." In January of 2016, Jacobson (16) said that "[o]ur goal is to get to 80% by 2030 and 100% by 2050. It is certainly technically and economically practical."

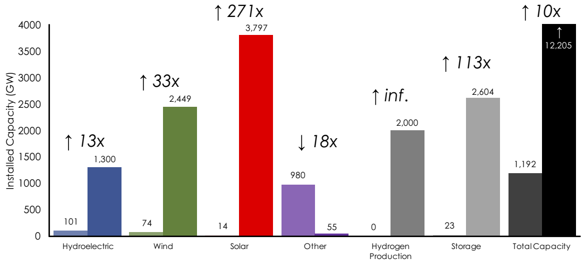

Fig. 2. Installed capacity values for 2015 (left column in each pair) and those used in the studies in refs. 11 and 12 (right column in each pair). These 100% wind, solar, and hydroelectric studies propose installing technologies at a scale equivalent to (or substantially greater than) the entire capacity of the existing electricity generation infrastructure. The other category includes coal, natural gas, and nuclear, all of which are removed by 2050.

flexible: able to reschedule all energy inputs within an 8-h window. As discussed in *SI Appendix*, section S2.4, and the National Research Council's "Real Prospects for Energy Efficiency in the United States," (17) it is infeasible for many industrial energy demands to be rapidly curtailed.

Similarly, ref. 11 assumes that the capacity factor (i.e., actual electricity generation divided by the theoretically maximum potential generation obtained by operating continuously at full nameplate capacity) for existing energy technologies will increase dramatically in the future. As described in *SI Appendix*, section S2.5, the authors of ref. 11 anticipate that individual hydropower facilities will increase generation by over 30%. They explain this by saying, "[i]ncreasing the capacity factor is feasible because existing dams currently provide much less than their maximum capacity, primarily due to an oversupply of energy available from fossil fuel sources, resulting in less demand for hydroelectricity" (12). From ref. 12, it is stated that hydroelectric and geothermal capacity factors increase, because "[f]or geothermal and hydropower, which are less variable on short time scales than wind and solar, the capacity-factor multipliers in our analysis are slightly greater than 100% on account of these being used more steadily in a 100% WWS system than in the base year." In addition to being inconsistent with their statement that hydropower is "used only as a last resort" (11), this explanation shows a fundamental misunderstanding of the operation of electricity markets and the factors determining hydroelectric supply. With near-zero marginal costs (free "fuel"), hydroelectric generators will essentially run whenever they are available; in those instances where they participate in merchant markets, they underbid fossil generators that must at least recover their coal or natural gas costs. The primary factor limiting hydroelectric capacity factor is water supply and environmental constraints, not lack of demand. Furthermore, there seems to be a mistake with the hydroelectric capacity factor adjustment: from EIA, it should only go up to 42%, not 52.5%.[6]

To illustrate the implausibility of the assumed increase in hydroelectric net generation (dispatched from the plants to the electricity grid) in the face of limited water supply, we plot in Fig. 3 the last 25 y of generation from hydropower in the United States along with the average for the studies in refs. 11 and 12. The data used for Fig. 3 can be found in Datasets S1 and S2. Average future generation assumed by refs. 11 and 12 is 13% higher than the highest peak year in the last 25 y and 85% higher than the minimum year in the last 25 y. Therefore, in addition to needing 1,300 GW of peak power from 150 GW of capacity, there also needs to be an extra 120 TWh of hydroelectric generation on top of the 280 TWh available. Additional difficulties in raising hydropower capacity factors are described in *SI Appendix*, section S2.5.

Most of the technologies considered in ref. 11 have high capital costs but relatively low operating costs. As a result, the cost of capital is a primary cost driver in the vision contained in ref. 11. As discussed in *SI Appendix*, section S2.7, the baseline value for cost of capital in ref. 11 is one-half to one-third of that used by most other studies. The 100% wind, solar, and hydroelectric energy system studies (11, 12) provide little evidence that the low cost of capital assumed in their study could be obtained by real investors in the capital markets. Using more realistic discount rates of 6–9% per year instead of the 3–4.5% used in ref. 11 could double the estimate of a cost of 11 cents/kWh of electricity to 22 cents/kWh, even before adding in the unaccounted for capital costs described above. One possible explanation of the lower discount rates used could be that they forecast lower (or negative) growth in domestic product. In the case of lower growth, there would likely be lower interest rates; however, that lower growth may also lead to lower energy demand and investment.

One of the global leaders of solar PV and wind energy installation in recent years is Germany, which through its "Energiewende," is attempting to shift toward an 80% renewables energy system. Germany, therefore, presents a suitable example against which to benchmark the feasibility of the plan set out in ref. 11 for the United States. In *SI Appendix*, section S2.8, we describe how ref. 11 assumes that the United States will build out new solar, wind, and hydroelectric facilities at a sustained rate that, on a per-unit gross domestic product basis, is 16 times greater than the average deployment rate in Germany's Energiewende initiative during the years 2007–2014 and over 6 times greater than Germany achieved in the peak year of 2011 (*SI Appendix*, Fig. S4).

In Fig. 4, we display another metric on the scale of expansion. It shows the rate of installation as watts per year per capita. Using this metric, we can compare the scale of capacity expansion in ref. 11 with historical data. Fig. 4 shows that the plans proposed in refs. 11 and 12 would require a sustained installation rate that is over 14 times the US average over the last 55 y and over 6 times the peak rate. For the sake of comparison, Fig. 4 includes the estimated rate for a solution that decarbonizes the US electric grid by 78% by 2030 (1), historical German data, and historical Chinese data. We note that ref. 1 considered large-scale storage but excluded it based on preliminary results showing that it was not cost-effective compared with a national transmission system. The data used for Fig. 4 can be found in Datasets S1 and S2. Sustaining public support for this scale of investment (and this scale of deployment of new wind turbines, power lines, etc.) could prove challenging. One of the reasons that this buildout may prove difficult is that the 100%

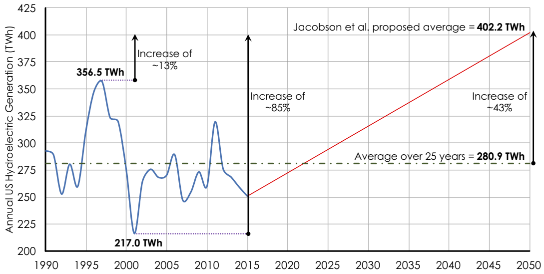

Fig. 3. Historical and proposed hydroelectric generation per year. The historical data (www.eia.gov/todayinenergy/detail.php?id=2650) show generation averaging 280.9 TWh/yr; generation proposed in ref. 11 is 402.2 TWh, 13% higher than the 25-y historical maximum of 356.5 TWh (1997) and 85% higher than the historical minimum of 217 TWh (2001).

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[6] Excel spreadsheets from refs. 11 and 12, Tab EIA capacity factors 2011–2075 are at web.stanford.edu/group/efmh/jacobson/Articles/I/USStates.xlsx.

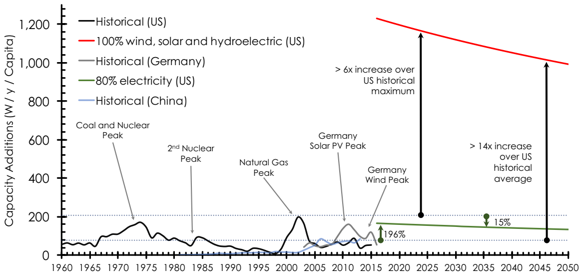

Fig. 4. The historical rates of installed electric-generating capacity per capita (watts per year per capita) for China (blue), Germany (gray), and the United States (black) are shown with the estimated values for the US proposals from the works by Jacobson et al. (11, 12) (red) and MacDonald et al. (1) (green). It shows that the 100% wind, solar, and hydropower power plan requires installation of new capacity at a rate more than an order of magnitude greater than that previously recorded in China, Germany, or the United States. The rate would have to be continued indefinitely because of replacing generation as it aged.

wind, solar, and hydroelectric system relies on energy sources with relatively low areal power density (additional details are in *SI Appendix*, section S2.9). According to NREL, average power density achieved in land-based wind farms is about 3 W/m^2, with a range of 1–11.2 W/m^2 (although at larger deployment scales, power densities would likely be lower) (18). At the average power densities, the scale of wind power envisioned in ref. 11 would require nearly 500,000 km^2 (134,000–1,500,000 km^2), which is roughly 6% of the continental United States and >1,500 m^2 of land for wind turbines for each American. Much of this land could be dual use, but the challenges associated with this level of scale-up should not be underestimated. The proposed transition in ref. 11 requires unprecedented rates of technology deployment. For example, increased pressure on materials, elevated commodity prices, and high demand for wind power installations produced elevated prices for wind power deployment between 2002 and 2008 (19, 20).

The rejection of many potential sources of low-carbon emission energy is based on an analysis presented by Jacobson in ref. 21. A full discussion of that paper is beyond the scope of our evaluation. However, one flaw is its failure to use other numbers already published in detailed studies on lifecycle GHG emissions, land use requirements, and human mortality of energy production technologies. Rather than using the results of the many detailed studies available from large international bodies, such as those surveyed by the Intergovernmental Panel on Climate Change, ref. 20 presents assessments that, in many cases, differ in method and granularity to produce results that differ markedly from those generally accepted in scientific and technical communities.

Selective assessments of lifecycle emissions can be used to favor or disfavor specific technologies. As an example, the lifecycle GHG emissions for nuclear power generation in ref. 21 include the emissions of the background fossil-based power system during an assumed planning and construction period for up to 19 y per nuclear plant.[7] Added to these emissions, the effects of a nuclear war, which is assumed to periodically reoccur on a 30-y cycle, are included in the analysis of emissions and mortality of civilian nuclear power.[8] In contrast, those same authors do not consider emissions for the fossil-based power system associated with construction and permitting delays for offshore wind farms (or the transmission infrastructure needed to connect these farms), which have already been a challenge in the development of US offshore wind resources. Although there is extensive experience outside of the United States with developing offshore wind resources, very few offshore wind facilities have been permitted in US territorial waters. The 100% wind, solar, and hydroelectric power system (11) envisions more than 150,000 5-MW turbines permitted and built offshore without delays.

Insufficient Power System Modeling

The study of a 100% wind, solar, and hydroelectric power system (11) purports to report the results of a "grid integration model." It is important to understand the limitations of the study with regard to what is usually meant by grid integration. Reliable operation of the grid involves myriad challenges beyond just matching total generation to total load. Its role in cascading failures and blackouts illustrates the important role of the transmission system (22). Reliable grid operation is further complicated by its ac nature, with real and reactive power flows and the need to closely maintain a constant frequency (23). Margins for generator failures must be provided through operational and planning reserves (24). The solution proposed by refs. 11 and 12 involves fundamental shifts in aspects of grid architecture that are critical to reliable operation. Wind generation, largely located far from load centers, will require new transmission. Solar generation and onsite storage connected to the distribution grid replace capability currently connected to the more centralized transmission grid. Rotating machines with substantial inertia that is critical for frequency stability are supplanted by asynchronous wind and solar generators.

Although a grid integration study is detailed and complex, the grid model of ref. 11 is spatially 0D; all loads, generation (sited before the LOADMATCH runs and placed precisely where existing generation resides), and storage are summed in a single place. Therefore, those authors do not perform any modeling or analysis of transmission. As a result, their analysis ignores transmission capacity expansion, power flow, and the logistics of transmission constraints (*SI Appendix*, section S2.6). Similarly, those authors do not account for operating reserves, a fundamental constraint necessary for the electric grid. Indeed, LOADMATCH used in ref. 11 is a simplified representation of electric power system operations that does not capture requirements for frequency regulation to ensure operating reliability (additional details are in *SI Appendix*, section S3).

Furthermore, the model is fully deterministic, implying perfect foresight about the electricity demand and the variability of wind and solar energy resources and neglecting the effect of forecast errors on reserve requirements (25). In a system where variable renewable resources make up over 95% of the US energy supply, renewable energy forecast errors would be a significant source of uncertainty in the daily operation of power systems. The LOADMATCH model does not show the technical ability of the proposed system from ref. 11 to operate reliably given the magnitude of the architectural changes to the grid and the degree of uncertainty imposed by renewable resources.

Inadequate Scrutiny of Input Climate Model

The climate model used to generate weather data in the work in ref. 11 has never been adequately evaluated. For example, results from this model have not been made available to the Climate Model Intercomparison Project (26) or opened to public inspection in ways similar to the results of major reanalysis projects (27). As detailed in *SI Appendix*, section S4, the fragmentary results that have been made available show poor correlation with reality in terms of resolution and accuracy. Because the conclusions from ref. 11 depend on the weather data used, their conclusions cannot be considered to be adequate without an appropriate evaluation of the weather data used.

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[7] The five sources cited in ref. 12 give construction time estimates of 5–8 y.

[8] In the almost 60 y of civilian nuclear power (two of the assumed war cycles), there have been no nuclear exchanges. The existence of nuclear weapons does not depend on civil power production from uranium.

Conclusions

Many previous studies of deep decarbonization of electric power illustrate that much can be done with wind and solar power but that it is extremely difficult to achieve complete decarbonization of the energy system, even when using every current technology and tool available, including energy efficiency and wind, hydroelectric, and solar energy as well as carbon capture and storage, bioenergy, and nuclear energy (1–6, 8–10). In contrast, ref. 11 asserts that it is cost-effective to fully decarbonize the US energy system primarily using just three inherently variable generating technologies: solar PV, solar CSP, and wind, to supply more than 95% of total energy in the proposal presented in ref. 11. Such an extraordinarily constrained conclusion demands a standard of proof that ref. 11 does not meet.

The scenarios of ref. 11 can, at best, be described as a poorly executed exploration of an interesting hypothesis. The study's numerous shortcomings and errors render it unreliable as a guide about the likely cost, technical reliability, or feasibility of a 100% wind, solar, and hydroelectric power system. It is one thing to explore the potential use of technologies in a clearly caveated hypothetical analysis; it is quite another to claim that a model using these technologies at an unprecedented scale conclusively shows the feasibility and reliability of the modeled energy system implemented by midcentury.

From the information given by ref. 11, it is clear that both hydroelectric power and flexible load have been modeled in erroneous ways and that these errors alone invalidate the study and its results. The study of 100% wind, solar, and hydroelectric power systems (11) extrapolates from a few small-scale installations of relatively immature energy storage technologies to assume ubiquitous adoption of high-temperature PCMs for storage at concentrating solar power plants; UTES for heating, cooling, and refrigeration for almost every building in the United States; and widespread use of hydrogen to fuel airplanes, rail, shipping, and most energy-intensive industrial processes. For the critical variable characteristics of wind and solar resources, the study in ref. 11 relies on a climate model that has not been independently scrutinized.

The authors of ref. 11 claim to have shown that their proposed system would be low cost and that there are no economic barriers to the implementation of their vision (12). However, the modeling errors described above, the speculative nature of the terawatt-scale storage technologies envisioned, the theoretical nature of the solutions proposed to handle critical stability aspects of the system, and a number of unsupported assumptions, including a cost of capital that is one-third to one-half lower than that used in practice in the real world, undermine that claim. Their LOADMATCH model does not consider aspects of transmission power flow, operating reserves, or frequency regulation that would typically be represented in a grid model aimed at assessing reliability. Furthermore, as detailed above and in *SI Appendix*, a large number of costs and barriers have not been considered in ref. 11.

Many researchers have been examining energy system transitions for a long time. Previous detailed studies have generally found that energy system transitions are extremely difficult and that a broad portfolio of technological options eases that transition. If one reaches a new conclusion by not addressing factors considered by others, making a large set of unsupported assumptions, using simpler models that do not consider important features, and then performing an analysis that contains critical mistakes, the anomalous conclusion cannot be heralded as a new discovery. The conclusions reached by the study contained in ref. 11 about the performance and cost of a system of "100% penetration of intermittent wind, water and solar for all purposes" are not supported by adequate and realistic analysis and do not provide a reliable guide to whether and at what cost such a transition might be achieved. In contrast, the weight of the evidence suggests that a broad portfolio of energy options will help facilitate an affordable transition to a near-zero emission energy system.

SI Appendix

SI Appendix contains the details of this evaluation. Datasets S1 and S2 contain data and calculations used to produce the figures. Within the spreadsheet are the data sources and collation of data.

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