May 25, 2017

Line-by-Line Response by M.Z. Jacobson, M.A. Delucchi to

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.

(1) This statement by Clack et al. (hereinafter C17) falsely implies that certain studies have found that a "diverse" portfolio of energy technologies can achieve the same or better benefits as can an all-sector 100% WWS pathway, but at lower cost.

However, the statement a) misrepresents the conclusions of such studies; b) falsely implies those studies performed or reviewed an all-sector 100% clean (thus deep-decarbonization), national grid integration study as was done in Jacobson et al. (2015b, hereinafter J15); and c) falsely implies any of those studies has even a remotely similar *scope* or set of *evaluation criteria* as in the 100% WWS studies.

First, the IPCC report does not endorse any portfolio, let alone a "diverse portfolio" of energy options. In fact, the report makes clear that nuclear, for example, would not work well with renewables and is expensive thus has little chance of growth in liberalized markets:

IPCC Working Group III, Chapter 7
Section 7.6.1.1. P. 534. …*high shares of variable RE power, for example, may not be ideally complemented by nuclear, CCS, and CHP plants (without heat storage).*

"*Without support from governments investments in new nuclear power plants are currently generally not economically attractive within liberalized markets…*" (IPCC Working Group III, Chapter 7, Section 7.8.2. P. 542).

Similarly, statements by Freed et al. (2017) contradict the notion that including nuclear helps make for a "less costly" energy system:

"*Indeed, there is virtually no history of nuclear*

construction under the economic and institutional circumstances that prevail throughout much of Europe and the United States" **(Freed et al., 2017).**

Finally, Cooper (2016) who compared 100% WWS with decarbonization scenarios that included nuclear and CCS, concluded, "*Neither fossil fuels with CCS or nuclear power enters the least-cost, low-carbon portfolio*."

(2) Second, neither IPCC, NOAA, NREL, or IEA has ever reviewed or performed a 100% clean (zero-emission – thus deep decarbonization) grid integration study for all energy, which J15 did. For example, MacDonald et al. (2016) and NREL (2012), which were grid integration studies, considered only the electricity sector, which is only ~20% of current energy, and thus were not close to 100% zero-emission (or deep decarbonization) for all sectors. Several of the remaining studies considered more energy sectors, but did not attempt to perform a grid integration study, thus did not examine costs of keeping the grid stable. J15, on the other hand, performed a grid integration study after electrifying all energy sectors (electricity, transportation, heating/cooling, industry), thus performed a true "deep-decarbonization" all-sector grid integration study, unlike any study cited by Clack et al (2017, hereinafter C17)

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(3) No C17 study remotely compares with J15 in scope or evaluation criteria. J15 sought to reduce health, climate, and energy costs; catastrophic risk; and land requirements while creating jobs. C17 studies ignore pollution, land, risk, and jobs, opening the door to biofuels, CCS, and nuclear. Their failure to include pollution cost alone as a system cost renders these studies policy-irrelevant.

The studies cited by C17 explore some of the system costs of having the energy system, or often just the electricity sector alone, meet *one* limited environmental objective, such as 80% decarbonization. By contrast, J15 evaluate a wide range of metrics, including system-reliability costs, air quality costs, climate change costs, land use constraints and requirements, and jobs/job revenues, associated with transitioning the entire energy system to what arguably is the cleanest, most sustainable configuration – 100% WWS. In general terms, the results from a limited cost-effectiveness analysis of subsystem *X* (as in the studies cited by C17) have no relation to the results from a broader (albeit still partial) cost-benefit analysis of a much larger system *Y (*as in J15). Moreover, in this case, it is difficult even to properly compare intermediate estimates for nominally similar subsystems in both analyses, because of different methods and scope. For example, none of the C17 studies, including MacDonald et al. (2016), NREL (2012), UNDDP (2015), and EMF (2014), etc. account for (a) a reduction in power demand of around 13% due to eliminating energy from mining, refining, and transporting fossil fuels and uranium; (b) a reduction in power demand of around 23% due to the higher work to energy ratio of electricity over combustion resulting from electrification and providing electricity from clean, renewable energy.

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 reli- ability problem with 100% penetration of WWS [wind, water and solar power] across all energy sectors in the continental United States be- tween 2050 and 2055", with only electricity and hydrogen as energy carriers.

(4) This is misleading. C17 seem to focus on J15 as if it were the only study of 100% WWS, but in fact there are many other grid integration studies examining 100% or close to 100% clean, renewable energy in one or multiple sectors (Mason et al., 2010; Hart and Jacobson, 2011, 2012; Connolly et al., 2011; 2014; 2016 Mathiesen et al., 2011; 2015; Elliston et al., 2012, 2013, 2015; Rasmussen et al., 2012; Budischak et al., 2013; Steinke et al., 2013; Connolly and Mathiesen, 2014; Becker et al., 2014; Bogdanov and Breyer, 2016).

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.

(5) We will show here that C17 have not substantiated any error or implausible assumption in our analysis, and, conversely, their two claims of

"Modeling error" by Jacobson et al. (2015) are fictitious (in one case, they make up out of thin air that numbers in our Table 1 are maximum numbers when they are annual averages and in the other case, they falsely claim we made a modeling error by increasing the hydropower maximum discharge rate when they had full knowledge this was an intentional assumption). In the second case, they go so far as to pretend in their SI they are unaware of this assumption by claiming "We hope there is another explanation" despite having received and responded to two documents ahead of publication clearly providing our explanation. They further make a false comparison in their Figure 3 of U.S. hydropower versus U.S. plus imported Canadian hydropower, among numerous other errors throughout their document.

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.

(6) J15 do not rely "almost exclusively on wind, solar and hydroelectric power," because they also include geothermal, tidal, wave, water storage, ice storage, rock storage, pumped hydro storage, CSP storage, hydrogen storage, short-and-long-distance transmission, and demand response.

Energy Systems Modelling | 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 U.S. 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 appears to be some consensus that substantial amounts of greenhouse gas emissions could be avoided with widespread deployment of solar and wind electric generation technologies along with supporting infrastructure.

(7) 80% decarbonization of the electricity sector alone is not a "high level of decarbonization," since it ignores all other energy sectors, and electricity is only 20% of all energy. But regardless of the terminology, it is clear that a study about an 80% reduction in CO_2 emissions from a minority sector of the energy system is significantly different in aim and scope from a study that eliminates 100% of GHG emissions and air-pollutant emissions from all energy sectors.

Further, it is not in question that it would be theoretically possible to build a reliable energy system while 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. Yet 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: (1) curtail load (i.e., modify or fail to satisfy demand) at times when energy is not available, (2) deploy very large amounts of energy storage, or (3) 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 affordably

Significance Statement

Previous analyses have found that the most feasible route to a low-carbon energy future is one that adopts a diverse portfolio of technologies. **(8) False. See Response (1)..** 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 hydro- electric power **(9) False. See response (6)** 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 reliabil- ity". We find that their analysis involves errors **(10) False. See response (5)** inappropriate methods, and implausible assumptions. Their study does not provide credible evidence for rejecting the conclusions of previ- ous analyses that point to the benefits of considering a broad portfolio of energy system options. A policy prescription that over-promises 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.

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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 U.S. 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.

(11) Again, on the one hand, none of these references performs a "deep decarbonization" grid integration study as J15 did (see Response 1), and on the other hand, there are numerous studies that exclude such portfolios and obtain stable grids with 100% or near 100% clean, renewable energy, as listed under Response (4).

Faults with the Jacobson et al. analyses

Jacobson et al. [11], along with additional colleagues in a companion article [12], attempt to demonstrate 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. Reference [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 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 analysis 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. Further, 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 (CCS) 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 greenhouse gas 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, aviation), is even more challenging. These challenges are deepened by placing constraints on technological options.

(12) We exclude biofuels and CCS with fossil fuels because our overall objective is to estimate the costs and benefits of a reliable energy system that provides the maximum possible air quality, climate-change, water-quality, water-use, and biodiversity benefits, and biofuels and CCS are (far) worse than are wind and solar by all of these metrics. We exclude nuclear power because compared with wind and solar power it has a range of well-documented risks (See Response 41) without any environmental advantages.

C17 have a different and considerably more limited objective – making a modest improvement in one partial metric (CO2 emissions) for just one environmental impact (climate change). In itself, this difference in objectives is not an issue; rather, the problem is that C17 think, incorrectly, that they and we have the *same* overall analytical objective but that our general analytical approach to that same objective is faulty. This is not correct: we have framed our analysis differently because we have a markedly different objective.

It also is worth noting that even though our environmental and risk criteria eliminate biofuels, fossil-fuel CCS, and nuclear power, we allow for a number of other technologies that other studies often ignore. As a result, the energy and storage portfolio in J15 is broader than in any of the studies referenced by C17. For example, MacDonald et al. (2016) did not include CSP, tidal, wave, geothermal, any storage technology (water, ice, rocks, CSP-with-storage, pumped hydro storage, hydroelectric storage, hydrogen storage), or even demand response. (Moreover, MacDonald et al. (2016) also did not treat CCS or bioenergy.) Similarly, EMF (2014) excluded storage and demand response and did not estimate the costs of the risks associated with nuclear and CCS. In fact, no grid integration study prior to J15 has included the combination of UTES storage, hot/cold storage in water, cold storage in ice, electrical storage (CSP, pumped hydro, hydropower) and hydrogen storage.

In our view, to demonstrate that a proposed energy system is technically and economically feasible, a study must, at a minimum, demonstrate through transparent inputs, outputs, analysis,

(13) This statement baselessly implies that our analysis was not transparent. The entire LOADMATCH model (including inputs and outputs) has been available on request since J15 was published, and multiple people have requested and obtained the model. Further, the 50-state paper spreadsheet to this day is posted on the internet, available for anyone to see. Every number in both papers is transparent.

and validated modeling [13] that the required technologies have been commercially demonstrated at scale at a cost comparable to 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 historic examples in the energy sector; and the deployment and operation of the technologies do not violate environmental regulations. We demonstrate that ref. [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 the Supporting Information, 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.

(14) False. As we show here, C17 have not demonstrated any modeling errors.

The vision proposed by the studies in ref. [11, 12] narrows generation options, yet 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 multi-week energy storage systems that are not yet demonstrated at scale and deploys them at a capacity twice that of the entire U.S. generating and storage capacity today.

(15) See response (12)

(16) This is misleading. C17 fail to acknowledge that J15's 100% WWS plans require electrifying all energy sectors. C17 then misleadingly compare how much storage is needed with the capacity of the U.S. power sector today, not recognizing the U.S. power sector is only one-fifth of all U.S. energy. J15 propose a solution for 100% of all energy, not just electricity, so the storage capacity is 2/5 of the energy modeled, not 2 times.

There would be underground thermal energy storage systems deployed in nearly every community to provide services for every home, business, office building, hospital, school, and factory in the United States.

(17) C17 appear unaware that UTES is merely a form of district heating, which is already widespread worldwide. For example, right now, 60% of Denmark's heat comes from district heating, but with water instead of rocks, so the implication that this can't be done on a large scale is false. As referenced in J15, the cost of rock storage is on

the order of 1/300th that of battery storage and 1/30th that of water and ice storage per kWh stored.

Yet the analysis does not include an accounting of the costs of the physical infrastructure (pipes, distribution lines) to support these systems. An analysis of district heating [14] showed that having existing infrastructure is key to effective deployment because of the high upfront costs of with the infrastructure is 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 multi-week 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. But adequate support for the validity of these assumptions is lacking. Furthermore, the conclusions in ref. [11] rely heavily on free, non-modeled 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 to for additional supporting infrastructure (penstocks, tunnels, space);

(18) First, it is not clear what C17 mean when they claim that our results "rely heavily" on hydroelectric capacity expansion. Quantitatively, the addition of hydropower turbines accounts for only a small portion of grid balancing in J15, as seen in Figure 2b of Jacobson et al. (2015). More importantly, J15 assumed zero expansion of hydroelectric power reservoirs, only expansion of turbine capacity. The cost of turbine expansion was not included in the paper, but the cost has since been calculated for the U.S. and worldwide. The mean U.S. cost is ~3% of the cost of overall energy. This cost is derived from the fact that the cost of electrical equipment (turbines, generators, and transformers) in a 1000 MW hydropower plant is ~$200-$300/kW (Figs. 4.5 and 4.7 of IRENA, 2012). We assume costs of large 1000-MW plants since this proposal is for a large scale, but also account for costs to widen or increase the number of penstocks and housing, so we assume the additional cost per MW of hydropower turbines is $385 (325-450) / kW, or ~14% of the hydropower capital cost. When this cost is multiplied by the additional turbine capacity needed and the fraction of total end use energy from hydro, the additional hydropower turbine portion of total energy cost is ~3%. Finally, increasing turbine capacity results in one solution to 100% WWS, but there are many other solutions by using, for example, more CSP storage and less or zero hydro turbine expansion.

massive scale-up of hydrogen production and use;

(19) The scale-up of hydrogen proposed is much less than the scale-up of transmission required in MacDonald et al (2016) and less than the nuclear or coal-CCS scale-up required in the other papers cited by C17. Further, the cost of the hydrogen fueling infrastructure is accounted for.

unconstrained, non-modeled transmission expansion with only rough cost estimates;

(20) C17 make no effort to show that the cost estimates provided for transmission expansion are unreasonable or underestimated. And our cost estimates are not "rough" in the sense of being crudely simplistic; rather they are reasonably detailed (at least as detailed as most other estimates in the literature), but *uncertain*. We account for the uncertainty by presenting high and low results (spreadsheet published with Jacobson et al., 2015a).

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.

(21) False. See Responses (18), (19), and (20). The only relevant significant cost omitted was the hydropower turbine expansion, and that cost is ~3% of the overall energy cost. Demand response within reasonable bounds is very inexpensive. C17 provide no evidence that our cost estimates would or should be "substantially higher".

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 the Supporting Information. (i)

We note several modeling errors presented in ref. [11] that invalidate the results in the studies,

(22) False. C17 show no modeling errors.

particularly with respect to the amount of hydropower available and the demand response of flexible loads (SI Appendix section S1).

(23) As we show below, these claims are negligently false, because C17 were provided the correct numbers and meanings from J15 yet still chose to publish incorrect numbers and meanings.

(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) Lastly, we argue that the climate/weather model used for estimates of wind and solar energy production has has not demonstrated 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).

(24). Below we address and rebut the claims in (ii) and (iii); here, we show that the claim in (iv) is incorrect. GATOR-GCMOM has been taken part in 11 reviewed and published model intercomparions and validated against paired-in-time-and-space wind and solar data as well as against cloud, humidity, and stability fields at high and low resolution in multiple studies, not only by Jacobson et al. (1996, 2007, 2014) and Jacobson and Kaufman (2006), Jacobson and Archer (2012), and Jacobson (1997, 1998, 1999a,b, 2001a,b, 2002, 2004, 2010, 2012, 2014), but also others (e.g., Whitt et al., 2011; Ten Hoeve et al., 2012), and more.

Further, Zhang (2008), who reviewed coupled climate-air quality models, determined GATOR-GCMOM to be "the first fully-coupled online model in the history that accounts for all major feedbacks among major atmospheric processes based on first principles." As such, it is the most complete model worldwide thus the most appropriate for providing time-dependent wind and solar fields.

Further, GATOR-GCMOM accounts for the reduction in wind power available due to the competition among wind turbines for available kinetic energy. No other wind-power prediction model worldwide used for grid studies does this, yet C17 seem to believe that other models produce more realistic fields.

In addition, over 1000 researchers have used algorithms from GATOR-GCMOM and dozens have either used or seen the inner workings of the code. Further a textbook was written describing many algorithms and all other algorithms are described in over 50 peer-reviewed papers where the model has been developed, evaluated, and/or applied.

Finally, virtually every weather-climate model has copied or adopted some or many its techniques, including interactively coupling aerosols, clouds, radiation, and meteorology with feedback. In one example, the NCAR WRF-CHEM model started using the GATOR-GCMOM technique of online coupling between gases, aerosols, and meteorology only in 2005, 11 years after GATOR-GCMOM developed that technique, as described in Jacobson (2006, Comment on "fully coupled 'online' chemistry within the WRF model," by Grell et al. 2005. *Atmos. Environ*, *39*, 6957-6975, *Atmos. Environ. 40*, 4646-4648). GATOR-GCMOM also contains hundreds of processes still not treated in any other global model.

http://web.stanford.edu/group/efmh/jacobson/GATOR/GATOR-GCMOMHist.pdf

Modeling errors

As we detail in Supporting Information section S1 of this paper, 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 (see our Section S1.1), about 50% more than exists in the U.S. today [15], yet Figure 4(b) of ref. [11] (our Fig. 1) shows hydroelectric output exceeding 1,300 GW.

(25). This claim of "Modeling error" is an intentionally false claim. All authors were informed of the correct interpretation of our hydropower assumption prior to publication. Yet, the authors refused to print the correct interpretation in fact pretending that they were not aware of the correct interpretation in their Supplemental Information, stating "We hope there is another explanation for the large amount of hydropower output depicted in these figures," when they had been informed ahead of time the exact interpretation of our hydropower assumption.

Specifically, on February 29, 2016, Dr. Clack was provided with an email stating the following:

"This result is based on the assumption that we would increase the discharge rate of conventional hydro while holding the 2050 annual energy output constant (as stated in Footnote 4 of Table S.2 of the paper)."

Dr. Clack responded to this email so was aware. All authors, including Dr. Clack, were subsequently informed of the same information weeks prior to publication and were requested to correct their misstatements but they did not.

Further, Dr. Clack, on behalf of all coauthors, requested our model output only on 7/10/17, weeks after publication of their article, demonstrating the authors did not even check whether any "Model error" existed in our results prior to publication of their article.

In sum, increasing the maximum hydropower discharge rate was not a "modeling mistake" but an intentional model assumption, and Dr. Clack and co-workers were well aware that it was not a "modeling mistake."

To demonstrate further the assumption was not a "Modeling error," we posted the entire 30-second-resolution 6-year time series of hydropower output at

http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/HydroTimeSeriesPNAS2015.xlsx

which shows that our annual average hydropower is conserved as written in the paper, even with over 1300 GW of maximum instantaneous hydropower discharge.

Further, Figure 2(b) and Table 6 of Jacobson et al. (2015) provide the 6-year simulation total hydropower output (before T&D losses) of 2,413 TWh for U.S. + imported Canadian hydro, which averages to 402 TWh/year, or 45.9 GW of average output (before T&D losses). These numbers are entirely reasonable and consistent with the LOADMATCH model assumption of holding annual output constant, again demonstrating that C17's claim of model error was fallacious.

Further, Figure 4(b) of Reference 11 (Fig. 1 of C17) correctly shows an instantaneous hydropower output of 1300 GW because LOADMATCH assumed for the study that turbines could be added to existing reservoirs to increase the maximum hydropower output while without changing annual energy output from the reservoir. This was a new idea.

Despite being clear about keeping annual hydropower energy output constant and clear in Figure 4(b) that we increased the peak discharge rate of hydro and clear that we used hydropower only as a last resort in these simulations, we did not state clearly in the text that we increased the peak discharge rate of hydro while holding the annual energy output constant and we neglected the cost of the additional hydropower turbines. However, we informed Clack individually and all his coauthors a second time prior to publication of C17 of our exact assumption so as to be unambiguous, yet the authors pretended as if they were not aware of our assumption in C17. Further, there was no modeling error whatsoever with this intentional assumption.

The cost of the additional turbines, expanded penstocks, etc. needed to increase the discharge rate, and that are ~3% of the overall energy cost (see Response 18), thus had no impact on the conclusions of the study.

Finally, additional simulations with LOADMATCH have indicated that it is possible to keep a stable grid

for the U.S. either using more CSP and batteries and without increasing the hydropower discharge rate at all or with a hydropower discharge rate down to 700 GW (rather than 1300 GW), without changing total annual hydropower energy use. In sum, adding hydropower turbines without changing annual hydropower energy is only one way to balance load at low cost, not the only way.

Similarly, as detailed in our 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 over double the maximum possible value from their Table 1. The maximum possible from Table 1 from ref. [11] is given as 1,064.16 GW, while Fig. 3 of [11] shows flexible load (in green) used up to 1,944 GW (on day 912.6). Indeed, in all the figures in [11] that show flexible load, the restrictions enumerated in their Table 1 are not satisfied.

(26) This is the second intentionally false claim of model error by the C17 authors. It is intentional because the authors were informed of their error prior to publication of their article but refused to correct it. As clearly stated on the second page of J15 p. 15,061) the values in Table 1 are annual loads, not maximum loads. Further, as clearly stated on page 15,061, the annual heating and cooling loads are distributed every 30 seconds according to the number of heating and cooling degree days, respectively, each year. Flexible loads substantially include heating and cooling loads, as clearly shown in Table 1.

The specific quote is, "The 2050 annual cooling and heating loads (Table 1) are distributed in LOADMATCH each 30-s time step each month in proportion to the number of cooling-and heating-degree days, respectively, each month averaged over the United States from 1949 to 2011."

Thus, the flexible load at any moment may be higher or lower than the average load in Table 1. Figure 3 shows the instantaneous load, and the instantaneous load, averaged over a year, matches the annual average load given in Table 1. Thus, the figure is perfectly fine. The LOADMATCH code also contains this information, which the authors of the commentary could have requested but didn't.

The authors of C17 were informed of their error prior to publication of their article but refused to withdraw their claim.

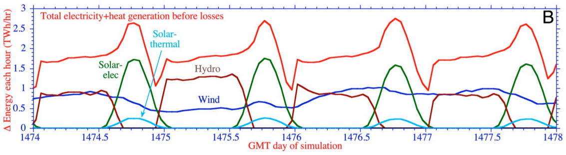

Fig. 1. This figure (Figure 4(b) from ref. [11]) shows hydropower supply rates peaking at nearly 1,300 GW despite the fact that their proposal calls for less than 150 GW of hydropower capacity. This indicates a major error in their analysis.

In the analysis in ref. [11], the flexible loads can be ac- cumulated in eight-hour blocks; which raises a serious issue of extreme excess industrial/commercial/residential capacity to utilize 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, as the conclusions reached by ref. [11] depend on the availability of large amounts of dispatchable energy and a large degree of flexibility in demand. Reference [11] also includes a scenario where zero demand response is allowed, and it shows that there is almost no cost changes and the grid is still stable.

(27) False. C17 have a fundamental misunderstanding of how load shifting works in J15. Flexible loads are not "accumulated" in eight-hour blocks, they are shifted by from 30 seconds to 8 hours. C17 falsely imply that a load from hour 0 can be added to a load from hour 1, etc., so that in hour 8, 8 hours worth of load must be satisfied. This is false. A load from hour 0 has 8 hours (hours 0-8) to be satisfied; a load from 30 seconds later has a different 8 hours to be satisfied (30 s to 8 hrs and 30 s), etc. All flexible loads for each time step are tracked and can be shifted by up to 8 hours. Further, the 8 hours itself is not the only possibility. It can be 0 hours, 4 hours, or anything else.

Load shifting in J15 does not affect demand-side or generation-side capacity. On the demand side, there is no-change in demand-side capacity, since the total energy required is the same. Only the time that the energy is used is shifted. On the generation side, the purpose of load shifting is to better align consumption with instantaneous generation, so there is no modification to generation capacity at all. To the contrary, load

shifting reduces the need for storage, thus decreases the burden on the system. C17's comments are misinformed.

Thus, there can be no cost associated with demand response (either in the supply nor consumption side) otherwise there would be substantial changes in final costs due to the complete reconfiguring of the U.S. economy schedule.

Implausible assumptions

The conclusions contained in ref. [11] rely on a number of unproven technologies and poorly substantiated assumptions, as detailed in section S2 of our SI Appendix. In summary, the reliability of the 100% wind, solar and hydroelectric power system proposed scheme depends centrally on a large installed capacity of several different energy storage systems [11], which collectively allow their model to flexibly reshape energy de- mand to match the output of variable electricity generation technologies. The study [11] assumes a total of 2,604 GW[1] of storage charging capacity, more than double the entire cur- rent capacity of all power plants in the United States [16].

(28) See response (16).

The energy storage capacity consists almost entirely of two technologies that remain unproven at any scale: 514.6 TWh of underground thermal energy storage (UTES; the largest UTES facility today is 0.0041 TWh; further discussed in Sec- tion S2.1 of our SI Appendix), and 13.26 terawatt-hours (TWh) of phase-change materials (PCM; effectively, in research and demonstration phase; further discussed in Section S2.2 of our SI Appendix) 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 un- derground thermal energy storage (UTES) systems deployed in nearly every community for nearly every home, business, office building, hospital, school and factory in the United States, while only a handful exist today.

(29) UTES has been demonstrated at the scale it needs to be deployed-neighborhood and complex scale, and it has been tested in more extreme conditions (Canada seasonally) than it would be needed for in the United States. Further, its cost is so low it has already far surpassed more "mature" technologies. It is also a form of district heating, which is used worldwide already. For example, Denmark supplies 60% of its building heat through district heating.

With regard to CSP, molten salt has been used commercially in a number of plants, and PCM is only marginally better than molten salt, so even if PCM didn't work well, the fallback works perfectly fine at only slightly higher cost.

Although both PCM and UTES are promising resources, neither technology has reached the level of technological ma- turity to be confidently employed as the main underpinning technology in a study aiming to demonstrate 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[2].

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 con- version of the aviation and steel industries to hydrogen, and the ability to store in hydrogen an amount of energy equivalent to more than a month of current U.S. electricity consumption. Further, in Figure S6 of ref. [11], hydrogen is being pro- duced at a peak rate consuming nearly 2,000 GW of electricity, nearly twice the current U.S. electricity generating capacity.

(30) Our assumptions about the adoption of hydrogen are aggressive but reasonable. As stated on Page 2112 of Jacobson et al. (2015a), we don't expect to convert fully short-haul aircraft until 2035 and long-haul aircraft until 2040. Given that a short-haul hydrogen fuel cell aircraft that seats four and has a range of 1500 km already existed in 2016, these goals seem attainable. With regard to using hydrogen in industry, our latest U.S. and world studies do not consider that option; opting instead to electrify all industry, so the issue is moot. The U.S. and world grid stays stable. The production rate of hydrogen relative to the current U.S. electrical demand is irrelevant given that we propose to electrify all energy sectors and electricity is currently only 20% of all energy.

As detailed in Section S2.3 of our SI Appendix, the costs and feasibility of this transition to a hydrogen economy are not

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

[2] "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" [12]. "Our goal is to get to 80 per cent by 2030 and 100 per cent by 2050. It is certainly technically and economically practical." Mark Jacobson, Jan 2016 [16]

appropriately accounted for by ref. [11]. To demonstrate the scale of the additional capacities that are demanded in ref. [11, 12] we plot them along with the electricity generation ca- pacity in 2015 in Fig. 2. The data used for Fig. 2 can be found in two spreadsheets (and references therein) accompanying the manuscript.

References [11] and [12] cite each other about the values of capacity. For example, ref [12], which supposedly includes information for all 50 states, reports ref. [11] [Tables S2] as the source of the numbers.

Then ref. [11], which only includes information for the capacity in the 48 contiguous states, cites ref. [12] [Table 2] as the source of the values. The values in the two papers do not agree, presumably because of the difference in number of states included, so it is unclear how each reference can be the source of the values for the other one.

(31) Jacobson et al. (2015a) (Ref 12 in C17) was published prior to Jacobson et al. (2015b) (Reference 11 in C17) and provided energy data for all 50 U.S. states. Jacobson et al. (2015b) did a grid study of the 48 contiguous states (CONUS), taking data for those states from Jacobson et al. (2015a), except that estimates of additional CSP turbines and CSP plus UTES storage from the grid integration study in J15 were available on time to be used for cost estimates of Jacobson et al. (2015a) (Ref 12 in C17).

Additionally, ref. [11] assumes that 63% of all energy-intensive industrial demand is flexible, able to reschedule all energy inputs within an 8-hour window. As discussed in Section S2.4 of our SI Appendix and in the National Research Council "Real Prospects for Energy Efficiency", it is infeasible for many industrial energy demands to be rapidly curtailed.

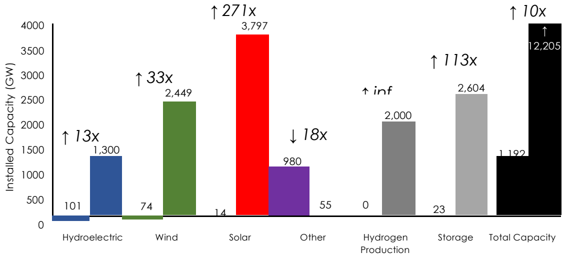

Fig. 2. Installed capacity values for 2015 (left column in each pair) and the ref. studies [11, 12]. These 100% wind, solar and hydroelectric studies propose installing technologies at a scale equivalent to (or substantially greater than) the entire capacity of the existing electricity generation infrastructure.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

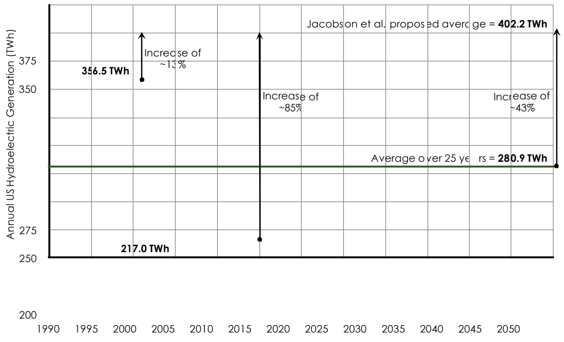

Fig. 3. Historical and proposed hydroelectric generation per year. The historical data (http://www.eia.gov/todayinenergy/detail.php?id=2650) show generation averaging 280.9 TWh per year; generation proposed in [11] is 402.2 TWh, 13% higher than the 25-year historical maximum of 356.5 TWh (1997) and 85%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

(32) The National Research Council (2010) states the exact opposite. Specifically, it states (P. 251): "*The ability of industry to cut peak electric loads is a motivator for utilities to incentivize demand response (shifting loads to off-peak periods) in industry…In combination with peak-load pricing for electricity, energy efficiency and demand response can be a lucrative enterprise for industrial customers.*" Further, as shown in Figure S14 of J15, a low-cost, zero-load-loss solution was obtained for 0 hours of demand response.

Similarly, ref. [11] assumes that the capacity factor (i.e., actual electricity generation divided by the theoretically maxi- mum potential generation obtained by operating continuously at full nameplate capacity) for existing energy technologies will increase dramatically in the future. As described in Section S2.5 of our SI Appendix, the authors of ref. [11] anticipate that individual hydropower facilities are assumed to increase generation by over 30%. They explain this by saying, “Increasing 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 [12] it is stated that hydroelectric and geothermal capacity factors increase because “For 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 demonstrates 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. Further, there appears to be a mistake with the hydroelectric capacity factor adjustment: from EIA it should only go up to 42% not 52.5%[3].

(34) Ref. (12) is not inconsistent with (11) because Reference (12) was published before (11) and the result in 11 regarding using hydropower as a last resort was a new finding

(34) False. J15’s hydropower CF increased to 0.925 x 52.5% = 48.6% relative to the current U.S. capacity factor of 38%, where the 0.925 accounts for transmission and distribution losses. This number is entirely reasonable.

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 years of generation from hydropower in the U.S. along with the average for the studies in ref. [11, 12]. The data used for Fig. 3 can be found in two spreadsheets (and references therein) accompanying the manuscript. Average future generation assumed by ref. [11, 12] is 13% higher than the highest peak year in the last 25 and 85% higher than the minimum year in the last 25. So 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. Further difficulties in raising hydropower capacity factors are described in our SI Appendix, Section 2.5.

(35) Figure 3 of C17 is a false comparison because it compares U.S. hydropower output from “data” provided by C17 with U.S. plus imported Canadian hydropower output from Jacobson et al. (2015). Thus, C17 show apples versus oranges, failing to point out clearly the difference in numbers in the figure itself or the figure caption. The comparison should never have been made. The Canadian portion of the 402.2 TWh from the Jacobson et al. studies (Refs 11 and 12 of C17) is 45 TWh, or 11.2% of the total. Subtracting 45 TWh from 402.2 TWh gives 357.2 TWh, which is only 0.2% different from the 356.5 TWh historic maximum listed in Figure 3 of C17, not 13% higher. And again, the 1,300 GW peak power for hydro with an annual average hydro power output of 87.5 GW (not 150 GW) of capacity is possible as explained clearly under Response (24).

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 Section S2.7 of our SI Appendix, the baseline value for cost of capital in ref. [11] is one-half to one-third of that used by most other studies.

(36) The nomenclature here is confusing: when C17 say “the cost of capital,” we take it that they mean the discount rate, not for example the $/kW capital cost of a technology. To that end, please see Response (37).

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% in ref. [11] could double the estimate of an 11 cents/kWh cost 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 growth (or negative) gross 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.

(37) This is wrong. J15 estimate costs in the context of a social cost analysis, and for this purpose the pertinent *social discount rate* is between 1.5% and 4.5%, as documented on Page 44 of the SI of Jacobson et al. (2015a), repeated below:

Annual discount rate

The U.S. Office of Management and Budget (OMB) (2003) recommends that cost-benefit analysis of public investments and regulatory impacts use two discount rates: one that reflects the opportunity cost of capital in the private sector, and one that reflects the time value of private consumption. In 2003, the OMB (2003) estimated that the former was 7% (based on the real before-tax rate of return on private investment) and that the latter was 3% (based on the real rate of return on long-term government debt, such as 10-year treasury notes). However, from 2003 to 2013 the real rate of return on 10-year treasury notes has averaged only 1.4% (http://www.federalreserve.gov/releases/h15/data.htm; "Market yield on U.S. Treasury securities at 10-year constant maturity, quoted on investment basis, inflation-indexed"). In line with this, the OMB (2013) now recommends using a real discount rate of 1.9% for cost-effectiveness analysis (which the OMB treats differently from cost-benefit and regulatory-impact analysis). Moreover, the OMB (2003) adds that "if your rule will have important intergenerational benefits or costs you might consider a further sensitivity analysis using a lower but positive discount rate," and suggests a range of 1-3%.

Other analyses, more comprehensive than the OMB's, indicate that for two reasons, the OMB's upper-range value of 7% is too high. First, the real pre-tax rate of return on private investment likely is less than 7% -- Moore et al. (2004) estimate that it is about 4.5%. Second, the pre-tax rate of return to private investment is the appropriate discount rate only for relatively short-term public projects that dollar-for-dollar crowd out private investment; for projects that have a longer time horizon or that affect consumption as well private investment, a lower discount rate is appropriate (Moore et al., 2004; National Center for Environmental Economics, 2014). Moore et al. (2004) review the accepted methods for estimating the social discount rate (SDR), and conclude that "no matter which method one chooses, the estimates for the SDR vary between 1.5 and 4.5 percent for intragenerational projects, and between 0 and 3.5 percent for projects with intergenerational impacts" (p. 809). The National Center for Environmental Economics (2014) has a similar discussion and indicates (without explicitly recommending) that a reasonable range is 2% to 5%.

With these considerations, we use a rate of 1.5% in our "low" cost (LCHB) scenarios and a rate of 4.5% in our "high" cost (HCLB) scenarios.

(We also note that the Federal Discount rate on May 5, 2017 was 1.50% and the WSJ Prime rate was 4.0%).

One of the global leaders of solar PV and wind energy installation in recent years is Germany, which through its "En- ergiewende" is attempting to shift toward an 80% renewables

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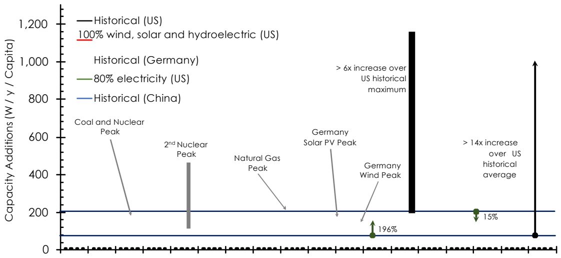
[3] See Excel spreadsheets from [11] and [12], Tab EIA capacity factors 2011-2075: http://web.stanford.edu/group/efmh/jacobson/Articles/I/USStates.xlsx

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 Section S2.8 of our SI Appendix, we describe how ref. [11] assumes that the U.S. will build out new solar, wind and hydro facilities at a sustained rate that, on a per unit GDP basis, is 16 times greater than the average deployment rate in Germany's Energiewende initiative during the years 2007 to 2014, and over 6 times greater than Germany achieved in the peak year of 2011 (see our Fig. S4).

(38) This claim says nothing about what is possible, and therefore is completely irrelevant.

In Fig. 4, we display another metric on the scale of ex- pansion. 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 historic data. Figure 4 shows that the plans proposed in references [11] and [12] would require a sustained installation rate that is over 14 times the U.S. average over the last 55 years; and over 6 times the peak rate. For the sake of comparison, Fig. 4 includes the estimated rate for a solution that decarbonizes the U.S. 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 upon preliminary results showing that it was not cost effective compared to a national transmission system. The data used for Fig. **??** can be found in two spread- sheets (and references therein) accompanying the manuscript. 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 this buildout may prove difficult, is that the 100% wind, solar and hydro- electric system relies on energy sources with relatively low areal power density (see Section S2.9 of our SI Appendix for further details). According to NREL, average power densities 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) [17].

(39) Again, this entire discussion says nothing about what is possible, and therefore is utterly irrelevant. As regards to the remark about land area, actual unpublished data from 1.3 GW of onshore wind turbines spread across 12 wind farms in 8 countries in Europe give a mean installed capacity of 9.4 W/m^2 (P. Enevoldsen, personal communication) over three times what C17 claim. The NREL study states specifically that the 3 W/m2 number is lower than other studies because of "the inclusion of land that was set aside for future project expansion and double counting of land where projects overlap." It also doesn't define wind farm boundaries. Further, it was from 2009 and does not represent most U.S. wind farms, which have subsequently been erected.



At the average power densities, the scale of wind power envisioned in ref. [would require nearly 500,000 km^2 (134,000–1,500,000 km^2), which is roughly of the continental U.S. and >1,500 m^2 of land for wind turbines for each America

(37) False. C17 used an erroneous installed power density and failed to consider the entire range, miscalculating areas by up to a factor of 3.5.

Much of this land could be dual use, but the challenges associated with this leve scale up should not be underestimated. The pro- pose transition in ref. [11] requ unprecedented rates of technology deployment. For example, increased pressure materials, elevated commodity prices and high demand for wind power installati produced elevated prices for wind power deployment between 2002 and 2008 [19].

The rejection of many potential sources of low-carbon- emission energy is ba on an analysis presented by Jacobson et al. in ref. [20]. A full discussion of t paper is beyond the scope of our current evaluation. However, one flaw is its fail to use other numbers already published detailed studies on life-cycle greenhouse (GHG) emissions, land-use require- ments and human mortality of ene production technologies. Rather than using the results of the many detailed stu available from large international bodies such as those surveyed by Intergovernmental Panel on Climate Change, ref. [20] presents assessments tha many cases differ in method and granularity to produce results that differ marke from those generally accepted in scientific and technical communities.

(40) False. Reference 20 is consistent with the literatu including IPCC, in terms of quantities that the literature h to provide. For example, IPCC estimates the range lifecycle costs of nuclear power as 4-110 g-CO2/kWh, whi compares well with 9-70 g-CO2/kWh from Jacobson et (2009):

IPCC Working Group III, Chapter 7
Section 7.8.1. P. 540. ***The ranges of harmonized lifecy greenhouse gas emissions reported in the literature are… 110 gCO2eq/kWh for nuclear power…***

Fig. 4. The historical rate of installed electric generating capacity per Capita (W/y/Capita) for China (blue), Germany (grey) and the U.S. (black) are shown with the estimated values for the Jacobson et al. [11, 12] (red) and MacDonald et al. [1] (green) U.S. proposals. 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 due to replacing generation as it aged.

Selective assessments of life-cycle emissions can be used to favor or disfavor specific technologies. As an example, the lifecycle GHG-emissions for nuclear power generation in ref. [20] include the emissions of the background fossil-based power system during an assumed planning and construction period for up to 19 years per nuclear plant[4].

(41) False. The full range for nuclear was 10-19 years. C17 pretend that nuclear does not have planning-to-operation delays, misleading the public into thinking nuclear does not have opportunity cost emissions or costs associated with nuclear weapons proliferation or meltdown risk although the international community knows otherwise:

IPCC Working Group III, Chapter 7
Executive Summary. P. 517. ***Barriers to and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapons proliferation concerns, and adverse public opinion (robust evidence, high agreement).***

Added to this, the effects of a nuclear war, which is assumed to periodically re-occur on a 30-year cycle, is included in the analysis of emissions and mortality of civilian nuclear power[5]. In contrast, those same authors do not consider emissions for the fossil-based power system associated with construction and permitting delays for off-shore wind farms (or the transmission infrastructure needed to connect these farms), which has already been a challenge in the development of U.S. offshore wind resources.

(42) False. Jacobson (2009) (Ref. 20) assumed 2-5 yea between planning and operation of onshore and offsho wind farms.

While there is extensive experience outside of the U.S. with developing offshore wind resources, very few offshore wind facilities have been permitted in the U.S. 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 integra- tion 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 a myriad of challenges beyond just matching total generation to total load. Its role in cascading failures and blackouts illustrates the important role of the transmission system [21]. 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 [22]. Margins for generator failures must be provided through operational and planning reserves [23]. The solution proposed by ref. [11, 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 on-site storage connected to the distribution grid replace capability currently connected to the more-centralized transmission grid. Rotating machines whose substantial inertia is critical for frequency stability are supplanted by asynchronous wind and solar generators.

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[4] The five sources cited in ref. [12] give construction time estimates of 5-8 years.

[5] In the almost 60 years 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 produc- tion from uranium.

While a grid integration study is detailed and complex, the grid model of ref. [11] is spatially zero-dimensional; 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 (see our 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 (see further details in Section S3 of our SI Appendix).

(43) This critique is wrong in critical respects and fails to demonstrate *any* important errors in our economic analysis. In the first place, we do not ignore transmission capacity expansion – we make an explicit estimate of the cost of additional HVDC transmission, documented in Jacobson et al. (2015a) and used in Jacobson et al. (2015b). Secondly, while it is true that we do not model frequency regulation, it will not be difficult to provide frequency regulation in a 100% WWS system -- as C17 acknowledge themselves, in their SI – at what we are confident will be relatively minor cost. C17 provide no reason to believe that our estimates of the T&D system cost are significantly low.

Furthermore, while all models have simplifications, LOADMATCH, despite having 0 spatial dimensions, includes more variables and takes shorter times steps (30 s) than any grid integration model used to study high penetrations of renewables. It wind field inputs with high penetrations of wind are also provably far more realistic than those of other models.

For example, MacDonald et al. (2016) took 1-hour times steps, with 120 times lower resolution that LOADMATCH. It also considered only 3 years rather than 6 years of data in Jacobson et al. (2015). Further, that study failed to include storage, allowing excess energy to be unnecessarily shed.

In addition, MacDonald et al. (2016) failed to account for competition among wind turbines f available kinetic energy, thus overestimated its wi output by 5-10%. By contrast, although LOADMATC is 0-D, it uses 3-D wind fields from GATOR-GCMO that account for extraction of kinetic energy by turbin something that no other wind prediction moc worldwide does. As such, results from studies such MacDonald et al. (2016) cannot be correct.

Further, MacDonald et al. did not electrify all ener sectors, and instead looked only at electric power. Th also did not have a realistic placement of wind turbin or solar, implausibly placing huge numbers of turbines Maine (Jacobson, 2016). In addition, they did n examine changes in demand due to electrification and d not consider 100% WWS systems. On the other han MacDonald et al. (2016) included nuclear, which enta greater catastrophic and/or health/ water/land risks th 100% WWS, but did not quantify costs of such risk Finally, they failed to consider the impossibility planning plus building nuclear plants in any reasonat time frame.

Further, the model is fully deterministic, implying perfect foresight about electricity demand and the variability of wind and solar energy resour neglecting the effect of forecast errors on reserve requirements [24]. In a syst where variable renewable resources make up over 95% of U.S. energy sup renewable energy forecast errors would be a significant source of uncertainty the daily operation of power systems. The LOADMATCH model does demonstrate the technical ability of the proposed system from ref. [11] to oper reliably given the magnitude of the architectural changes to the grid and degree of uncertainty imposed by renewable resources.

(44) LOADMATCH is neither deterministic nor an optimization model. It knows nothing about the future electricity demand or variability of the wind or solar resources each time step; it steps forward in time not knowing what either the load or the supply will be the next time step. If load is not met at any time, the simulation must be abandoned and restarted with another configuration of generation or storage or something else, until a stable solution is found. Thus, it is a trial and error model.. As clearly stated in Section S1.M of J15, “LOADMATCH simulations here are similar to those of a pure stochastic model…” Thus, it is not a deterministic model.

Inadequate scrutiny of input climate model

The climate model used to generate weather data used by ref. [11] has never been adequately evaluated. For example, results from this model have not been made available to the Climate Model Intercomparison Project [25] or been opened to public inspection in ways similar to the results for major reanalysis projects [26]. As detailed in section S4 of our SI Appendix, the fragmentary results that have been made available show poor correlation with reality in terms of resolution and accuracy. Since 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.

(45) False. See Response (24).

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 employing every current technology and tool available, including energy efficiency and wind, hydro, and solar energy, but also 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 U.S. 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 employing these technologies at an unprecedented scale conclusively demonstrates the feasibility and reliability of the modeled energy system implemented by mid-century.

From the information given by ref. [11], it is clear that both hydroelectric power and flexible load have been modeled in erroneous ways, and 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 instal- lations of relatively immature energy storage technologies to assume ubiquitous adoption of high-temperature phase-change materials for storage at concentrating solar power plants, un- derground thermal energy storage for heating, cooling, and refrigeration for almost every building in the United States, and widespread use of hydrogen to fuel airplanes, rail, ship- ping, and most energy-intensive industrial processes. For the critical variable characteristics of wind and solar resources, they rely on a climate model that has not been independently scrutinized.

The authors of ref. [11] claim to have demonstrated 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 TW-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 a third to a half lower than is used in practice in the real world, undermine that claim. Their LOADMATCH model does not consider aspects of transmission power flow, operating reserves or of frequency regulation that would typically be represented in a grid model aimed at assessing reliability. Further, as detailed above and in the 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, by making a large set of un- supported assumptions, by using simpler models that do not consider important features, and then performing an analysis that contains critical mistakes, the anomalous conclusion can- not be heralded as a new discovery. The conclusions reached by the study contained within 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.

(46) In summary, the premise and arguments of C17 are off-base and incorrect, and consequently their overall conclusion is without merit. Their premise – that our work is substantially similar in its objective to prior work, and that the prior work has come to a radically different conclusion –simply is untrue. As we state in response (3), the prior work they cite is a limited look at some of the costs of

meeting one modest environmental objective; our work examines a wide range of costs and benefits of a typically much larger system aimed at satisfying a much wider range of more stringent environmental objectives. Nothing about the results of the prior work bears on the results of our work.

Our work and that other prior work (with a different objective) do share some areas of method and data, but C17's criticisms of our methods and assumptions are, almost without exception, either incorrect or unreasonable. They have failed to show even one example of where we have clearly and unambiguously underestimated costs enough to undermine our conclusions. As a result, we can re-assert with some confidence that 100% (or near 100%) WWS systems can provide the widest possible range of environmental benefits reliably and at reasonable cost.

Supporting Information (SI) Appendix. The Supporting Informa- tion document contains the details of this evaluation.

SI Appendix Dataset. Two Excel files contain data and calcula- tions used to produce the figures in this article. Within the spreadsheet are the data sources and collation of data.

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