SUPERIOR COURT OF THE DISTRICT OF COLUMBIA
CIVIL DIVISION

Mark Z. Jacobson, Ph.D., Plaintiff,	)	
v.	)	2017 CA 006685 B
	)	Judge Elizabeth Wingo
Christopher T.M. Clack, Ph.D.,	)	Next Court Event:
	)	Initial Scheduling Conference:
and	)	12/29/2017
National Academy of Sciences, Defendants.	)	

MEMORANDUM OF POINTS AND AUTHORITIES IN SUPPORT OF DEFENDANT CHRISTOPHER CLACK'S SPECIAL MOTION TO DISMISS PURSUANT TO THE ANTI-SLAPP ACT OR IN THE ALTERNATIVE TO DISMISS FOR FAILURE TO STATE A CLAIM PURSUANT TO RULE 12(B)(6).

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PRELIMINARY STATEMENT

The District of Columbia Anti-SLAPP Act was enacted to prevent exactly the type of defamation claims presented by this lawsuit. In blatant violation of the protections afforded by the First Amendment, plaintiff is pursuing costly litigation to stifle debate on an important issue of public interest and to prevent his scientific theories from being fully scrutinized and evaluated. Plaintiff's theory of defamation, if accepted, would have a severe chilling effect on scientific debate in the United States and weaken the scientific method as a vehicle to advance the state of public knowledge. The statements at issue relate to published scientific work; they are not personal attacks and are not defamatory as a matter of law and, as such, plaintiff's claim should be dismissed by the Court.

Plaintiff, Dr. Mark Jacobson, a prominent energy and environmental scientist, published a paper promoting a shift in the United States' environmental priorities and policies toward almost exclusive reliance on wind, water and solar energy. In response, defendant Dr. Christopher Clack, along with 20 other prominent scientists and scholars, published a peer reviewed evaluation of that proposal pointing out what they regarded as flaws in its methodology, assumptions and conclusions. Their criticism challenged the substance of the paper but said nothing about the plaintiff personally. Notably, the Complaint contains no allegation that Dr. Clack questioned plaintiff's qualifications, honesty, integrity or good faith. Nevertheless, Dr. Jacobson took the extraordinary step of filing this lawsuit seeking to have the Court simply remove Dr. Clack and his co-authors' evaluation and views from the public debate. Courts have long recognized that litigation is not the appropriate vehicle to settle such scientific disagreements, and the Anti-SLAPP Act is intended to ensure that intimidation and threats of lawsuits do not stifle discussion, debate or criticism regarding issues important to the public interest.

Both Dr. Jacobson and Dr. Clack are prominent environmental scientists who have done influential work in the study of renewable energy. Both are supporters of transitioning the Unites States and the world to zero carbon emissions. The debate at issue in this case relates to *the demonstrated feasibility* of actually achieving 100% renewable energy use from only wind, water and solar power by the year 2050. Dr. Jacobson published a paper claiming such a 100% reliance target is achievable. Dr. Clack and his co-authors reviewed that paper and identified a number of issues that, in their collective scientific opinion, called into question Dr. Jacobson's conclusion. Dr. Jacobson took umbrage with this criticism and outside the public forum (through private emails and letters), he provided explanations for and arguments against the points raised by Dr. Clack and his co-authors and demanded that their evaluation not be published in light of these private communications. Although Dr. Jacobson contends that Dr. Clack and his co-authors were required to simply accept his private arguments and explanations, in each instance, they either simply disagreed with the arguments, determined that the explanations did not adequately address the problems or were inconsistent with the actual text, tables and figures in the paper being evaluated.

Scientific debate does not require that one side simply accept explanations or arguments that it finds implausible or unsupportable (especially when those arguments are not contained in the published work). Indeed, the scientific method only works where independent scrutiny is applied to scientists' publications and their work is challenged through additional published peer-reviewed papers. Dr. Clack and his co-authors fully disclosed and explained the bases and reasoning for each of their critical statements, and their evaluation can be assessed, challenged or disagreed with on its merits.

Dr. Clack's paper did exactly what such evaluations are supposed to do. It raised questions about plaintiff's methodology and conclusions; some of which Dr. Jacobson subsequently acknowledged and corrected. Indeed, it is important to note that *after filing this lawsuit*, Dr. Jacobson, for the first time, published a "clarification" to his paper identifying omissions directly related to issues which are the subject of the litigation. Had Dr. Clack and his co-authors not published their work, it is unlikely that the public record would have been clarified regarding these issues and future policy and further study would have proceeded based on an incomplete and erroneous understanding of Dr. Jacobson's methodology, assumptions and conclusions. This is precisely how scientific debate is supposed to be conducted. Scientists present arguments through peer reviewed journals and subject themselves to comment and criticism. That criticism is then rebutted or the initial findings are corrected, adjusted or clarified to address the points raised. This process breaks down where, as here, scientists with sufficient resources seek to use the courts to intimidate other scientists into silence under the threat of having to defend costly, protracted litigation. Indeed, the contention that a scientist can be liable for defamation because he or she argued that a study contained "mistakes" or faulty assumptions would have a devastating impact on the future of scientific discourse in the United States. Plaintiff has not identified statements that were defamatory and his claims should be dismissed pursuant to the Anti-SLAPP Act or, alternatively, under Superior Court Rule 12(b)(6) for failure to state a claim upon which relief may be granted.

FACTUAL BACKGROUND

A. Jacobson And His Co-Authors Publish 100% Renewable Energy Paper.

Plaintiff, Dr. Mark Jacobson, is a "renowned research scientist on global warming and air pollution and the development of large-scale clean, renewable energy solutions."[1] On December 8, 2015, Dr. Jacobson and three co-authors, Dr. Mark Delucchi, Dr. Bethany Frew and Ms. Mary Cameron (the "Jacobson Authors") published an article in the Proceedings of the National Academy of Sciences ("PNAS"),[2] claiming that a large scale U.S. transition to wind, water and solar power among all energy sectors could be achieved by 2050 (the "Jacobson Paper"). They further claimed that the transition would eliminate the need for other energy sources, particularly coal, oil and natural gas, without the need for nuclear power, fossil fuels with carbon capture, or biofuels, while enabling supply to match demand on the energy grid.[3] According to the Complaint, the paper described "results of original research of exceptional importance."[4]

B. Dr. Clack And His Co-Authors Publish An Evaluation Of The Jacobson Paper.

Defendant, Dr. Christopher Clack is an expert in energy grid planning and renewable energy. He currently is the CEO of Vibrant Clean Energy and was formerly a research scientist for the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder and the National Oceanic and Atmospheric Administration.[5] After the publication of the Jacobson Paper, Dr. Clack and twenty other prominent energy and climate

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[1] Plaintiff's Complaint and Jury Demand (hereinafter "Compl.") at ¶ 1.

[2] PNAS is published by the National Academy of Sciences ("NAS").

[3] *Id.* at ¶ 9.

[4] *Id.*

[5] Biography of Christopher Clack can be found at www.vibrantcleanenergy.com/about-us.

scientists (the "Clack Authors"),[6] who disagreed with its methodology and its conclusions submitted a paper to PNAS evaluating what they perceived to be flaws in the Jacobson Paper's methodology and conclusions ("Clack Paper").[7] The Clack Paper underwent a rigorous peer review process by anonymous, independent experts and was accepted for publication by the National Academy of Sciences in February 2017.[8]

The Clack Paper focused on the methodology, assumptions and conclusions in the Jacobson Paper. It did not suggest that Dr. Jacobson or his co-authors had engaged in misconduct or falsified any information or that they possessed improper motives or knowingly sought to mislead anyone. The Clack Paper described the basis and rationale for its criticisms and identified the criteria it was using to evaluate the Jacobson Paper:

> 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 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 [the Jacobson paper does] not meet these criteria and, accordingly do not show the technical, practical or economic feasibility of a 100% wind, solar and hydroelectric energy vision.

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[6] The 20 co-authors of the Clack Paper are identified on the first page of the Clack Paper, *infra* n.6. The co-authors include scientists from prestigious academic institutions including four of plaintiff's colleagues at Stanford University (Dr. Adam Brandt, Dr. James Sweeney, Dr. John Weyant and Dr. Kenneth Caldeira), the Lead Energy Specialist from the World Bank (Dr. Morgan Bazilian) and a senior scientist contributor from the Environmental Defense Fund (Dr. Jane Long).

[7] *See* Clack Paper, attached hereto as Clack Exh. A.

[8] All research papers published in PNAS go through a rigorous review process. A paper must first be reviewed and approved by the NAS editorial board. It is then assigned to an NAS editor who is an active scientist and researcher and then it must undergo independent peer review by at least two separate subject matter experts. Finally, the paper must receive final approval from an NAS editorial board member. *See* PNAS.org/site/misc/reviewprocess.pdf., attached hereto as Clack Exh. B.

Based on the evaluation of the information presented in the Jacobson Paper, the Clack Authors concluded that the feasibility of relying on a narrowed set of options (wind, water and solar) were not supported by the Jacobson Paper's analysis.[9]

C. Plaintiff Addresses Issues Raised By The Clack Authors.

After the publication of the Jacobson Paper but before the Clack Paper was published, Dr. Jacobson attempted to explain or clarify several of the issues identified by the authors of the Clack Paper.

1. February 2016 Email Communication Between Dr. Jacobson And Dr. Clack.

In February of 2016, Dr. Clack contacted Dr. Jacobson to discuss a substantial discrepancy he had identified in the Jacobson Paper relating to the paper's hydropower output model. Specifically, Dr. Clack noted that the total output of hydropower from the figures presented was far greater than what was shown in the tables and text and, therefore, was not supported by the model's assumptions. In response, Dr. Jacobson sent an email to Dr. Clack admitting that the Jacobson Paper failed to disclose a critical assumption contained in the model - *i.e.,* the model assumed a massive increase in the availability of hydropower by 2050 as compared to currently available levels.[10] Dr. Jacobson also admitted in his email that his model failed to factor in any cost associated with this increase, but claimed that he had subsequently determined that the costs would not be significant.[11] Dr. Clack still believed the model contained errors, however, not only because the assumption identified by Dr. Jacobson was not disclosed in

[9] Clack Paper, Clack Exh. A at 6723.

[10] Compl. at ¶ 51

[11] *Id.*

the paper itself, but also because he regarded the alleged assumption to be wholly unrealistic and he did not believe the costs associated with the assumption would be insignificant.[12]

Despite having privately admitted this omission in February 2016, for over a year, Dr. Jacobson did not amend his paper to fully disclose the hydropower assumption nor did he publicly clarify, correct or explain the alleged omission in PNAS or any other publication. Indeed, as of the publication of the Clack Paper, 16 months after Dr. Jacobson's private email exchange with Dr. Clack, a reader of Dr. Jacobson's paper would have had no way of knowing of this alleged assumption nor of assessing the implications of that assumption on the Jacobson Paper's conclusions and the alleged substantiation for those conclusions.

2. Dr. Jacobson Complains To NAS About The Clack Paper Criticism.

In February of 2017, after NAS had peer reviewed and accepted the Clack Paper for publication, it provided a courtesy copy to Dr. Jacobson and offered him the opportunity to write a letter responding to the points raised in the Clack Paper.[13] Upon receipt of the draft, Dr. Jacobson sent NAS a list of reasons why he contended the Clack Paper's criticisms were wrong, false or misleading.[14] NAS reviewed Dr. Jacobson's comments but determined that no substantive changes to the Clack Paper were warranted.[15] NAS sent a finalized version of the Clack Paper to Dr. Jacobson in May 2017.[16] Dr. Jacobson again complained to NAS about the substantive content of the Clack Paper and NAS agreed to send his list of issues to all of the Clack Authors. The 21 Clack Authors thereafter reviewed Dr. Jacobson's list of issues but none

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[12] *See* February 29 Email exchange, Compl., Exh. 4; *see also* Clack Authors' Response to Jacobson et. al. (June 2017), attached hereto as Clack Exh. C.

[13] Compl. at ¶12.

[14] *Id.* at ¶¶13-15.

[15] *Id.* at ¶¶16-17.

[16] *Id.* at ¶16.

of them felt that Dr. Jacobson's arguments warranted any change to the paper's findings or conclusions.[17] In some instances, the Clack Authors simply disagreed with Dr. Jacobson's points and in other instances they did not believe his *post hoc* explanations made sense given the actual content of the Jacobson Paper itself and the science at issue.[18]

In light of Dr. Jacobson's repeated complaints and threats of litigation, the NAS editorial board conducted an additional editorial board review of the Clack Paper and again determined there were no substantive issues.[19] NAS sent Dr. Jacobson a final version of the Clack Paper on May 9, 2017.[20] Dr. Jacobson again demanded that NAS not publish the paper. However, prior to NAS or anyone else publishing or publicizing the Clack Paper, on May 31, 2017, Dr. Jacobson, himself, published a version of it including his annotated comments.[21]

On June 19, 2017, NAS published the Clack Paper in PNAS and in the same online edition also published a Letter Response from the Jacobson Authors addressing the Clack Paper. In that letter response, the Jacobson Authors were given the opportunity to address the Clack Paper and to defend their modeling and conclusions.[22] On July 3, 2017, in response, Dr. Jacobson's demand that NAS retract the Clack Paper, NAS wrote to both Dr. Jacobson and Dr. Clack stating:

> Both the original Jacobson *et. al.* article from 2015 and the recent Clack *et al.* article passed muster through peer review. There is clearly a scientific disagreement about how to address these issues, and the scientific community will have to make their own assessment of these articles.

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[17] *Id*. at ¶18.

[18] *See* Clack Authors' Response, Clack Exh. C.

[19] *See* Compl., Exh. 17.

[20] Compl. at ¶ 18.

[21] *See* Compl., Exh. 26.

[22] Jacobson Letter Response, The United States Can Keep the Grid Stable at Low Cost with 100% Clean, Renewable Energy in All Sectors Despite Inaccurate Claims, attached hereto as Clack Exh. D.

…( )

We urge you to continue to work to resolve the matter through additional research.[23]

The Clack authors posted their substantive Response to the Jacobson Letter Response online.[24] However, rather than allow the scientific community "to make their own assessment" or seek "to resolve the matter through additional research," Dr. Jacobson filed this lawsuit on September 29, 2017 demanding that the Clack Paper and the points raised therein be removed entirely from the public debate. Dr. Jacobson also demanded that Dr. Clack and NAS each pay him $10 million as damages.

D. After The Filing Of This Suit The Jacobson Authors Publicly Clarify Issues In The Jacobson Paper.

After filing his lawsuit on November 7, 2017, Dr. Jacobson posted a "clarification" to the Jacobson Paper on his Stanford University website.[25] The Clarification addressed omissions related to issues publicly identified for the first time in the Clack Paper and for which Dr. Jacobson has sued Dr. Clack. Specifically, the Clarification disclosed that Table S2 includes "Canadian installations providing pre-existing imported hydropower." The Clarification also disclosed that the hydropower included in Table S2 "is not only the contemporary installed hydropower capacity, it is also the maximum *potential* annually average discharge rate of hydropower both today and in 2050," – *i.e.*, the model assumes the availability of significant additional hydroelectric power.

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[23] July 3, 2017 Letter from NAS to Clack and Jacobson, attached hereto as Clack Exh. E.

[24] Clack Author's Response, Clack Exh. C, published at www.vibrantenergy.com/wp-content/uploads/2017/06/ReplyResponse.pdf.

[25] *See* November 7 Errata Clarification (the "Clarification"), http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/Clarification-PNAS15.pdf, attached hereto as Clack Exh. F. To defendant's knowledge, Dr. Jacobson has not submitted this Clarification to PNAS for the purpose of correcting the published version of the Jacobson Paper.

ARGUMENT

I. Plaintiff's Claim Should Be Dismissed Under The D.C. Anti-SLAPP Act.

The D.C. Anti-SLAPP Act[26] was designed to allow defendants to counter lawsuits based on statements involving matters of public concern by filing a special motion to dismiss. D.C. Code 16-5502.[27] To challenge a lawsuit under the D.C. Anti-SLAPP Act, a defendant must show that the action is based on defendant's acts "in furtherance of the right of advocacy on issues of public interest."[28] The Act defines an "issue of public interest" as "an issue related to health or safety; environmental, economic, or community well-being….." D.C. Code § 16–5501 (3)

Under the Anti-SLAPP Act, once a defendant makes a prima facie showing that the claims at issue arise from an act in furtherance of the right of advocacy on issues of public interest, the burden shifts to the plaintiff, who must "demonstrate [] that the claim is likely to succeed on the merits." D.C. Code 16-5502(b). To meet this burden, a plaintiff must present evidence that would allow a jury to find in their favor under the applicable legal standard. *Competitive Enter. Inst. v. Mann*, 150 A.3d 1213, 1236 (D.C. 2016). If the plaintiff cannot produce such evidence, the plaintiff's claim must be dismissed with prejudice, and the litigation is brought to an end. *Id.*

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[26] SLAPP stands for a "strategic lawsuit against public participation."

[27] Under the Anti-SLAPP statute, a defendant is not limited to matters alleged in plaintiff's complaint. *See,Center for Advanced Defense Studies v. Kaalbye Shipping Intl. at al.,* No. 2014 CA 002273, 2015 WL 4477660 (D.C. Super April 7, 2015) at *4, n.9 (stating that SLAPP Act reflects a legislative judgment by the D.C. Council to ensure that those engaged in public policy debates are not intimidated or prevented from doing so and noting statute allows defendant to rely on matters outside the pleadings).

[28] D.C. Code § 16–5501 (1) An act in furtherance of the right of advocacy on issues of public interest" as:

(A) Any written or oral statement made:

(ii) In a place open to the public or a public forum in connection with an issue of public interest;

A. The Anti-SLAPP Act Applies To Plaintiff's Claim.

There can be no dispute that the Anti-SLAPP Act applies to plaintiff's defamation claim against Dr. Clack. The alleged defamatory statements were made in a peer reviewed academic journal as part of a public debate between acknowledged experts in the field of energy and climate science and concerns the feasibility of shifting public policy toward a 100% reliance on wind, water and solar renewable energy by the year 2050.[29] The D.C. Court of Appeals has ruled that the Anti-SLAPP statute specifically applies to statements relating to public debates about the environment and climate. *See Competitive Enter.*, 150 A.3d 1213 (D.C. 2016) (holding that case arising out of statements related to environmental issues subject to the Anti-SLAPP Act).

Further, Dr. Jacobson has put himself at the forefront of the debate on transitioning to wind, water and solar renewable energy. He has submitted written testimony to the United States Congress relating to the renewable energy position advocated in the Jacobson Paper and other similar studies.[30] In addition, Dr. Jacobson has publicly backed the bill to enact the 100 by '50 Act, which calls on the United States to be completely free of fossil fuels by 2050 and was introduced by U.S. Senators Jeff Merkley, Bernie Sanders, Edward J. Markey, and Cory Booker.[31] Dr. Jacobson is also a founder of the Solution Project which actively advocates that local and state governments move toward 100% wind, water and solar renewable energy models

[29] *See e.g.*, Jacobson Paper, Compl. Exh. 3.

[30] *See* Written Testimony to the United States House of Representatives Committee on Energy and Commerce Democratic Forum on Climate Change November 19, 2015, attached hereto as Clack Exh. G.

[31] 100 by '50 Act, S. 987, 115th Cong. (2017); *see* https://www.merkley.senate.gov/news/in-the-news/merkley-plans-100-renewable-power-push.

by 2050.[32] As such, the subject matter of this litigation clearly relates to important issues of public interest, and the claims against Dr. Clack are subject to the Anti-SLAPP Act.

B. Plaintiff Cannot Produce Evidence Sufficient To Show He Would Succeed On The Merits Of His Defamation Claim.

Plaintiff's claims must be dismissed with prejudice unless he can meet the burden imposed on him by the statute to produce sufficient evidence showing that his claims are likely to succeed on the merits. *See Farah v. Esquire Magazine Inc.,* 863 F. Supp. 2d 29, 38 (D.D.C. 2012) (dismissing claims under Anti-SLAPP); *Lehan v. Fox Television Stations, Inc.*, No. 2011 CA 004592 B, 2011 WL 11535276 (D.C. Sup. Ct. Dec. 2, 2011) (dismissing claims under Anti-SLAPP).

To succeed on a claim for defamation of a public figure such as Dr. Jacobson, a plaintiff must prove that the statements at issue are: i) defamatory; ii) capable of being proven true or false; iii) "of and concerning" the plaintiff; iv) false and v) made with actual malice, *i.e.,* with knowledge of falsity or with reckless disregard for whether or not they are true or false. *Coles v. Walsh Free Weekly, Inc.,* 881 F. Supp. 26, 30 (D.D.C. 1995), *aff'd*, 319 U.S. App. D.C. 215, 88 F.3d 1278 (1996). Moreover, the actual malice standard requires clear and convincing proof that the defendant published with actual subjective awareness of probable falsity. *Jankovic v. Int'l Crisis Group,* 822 F.3d 576, 590 (D.C. Cir. 2016).

"A statement is 'defamatory' if it tends to injure the plaintiff in his trade, profession or community standing, or lower him in the estimation of the community." *Moss v. Stockard*, 580 A.2d 1011, 1023 (D.C. 1990) (citations omitted). However, "an allegedly defamatory remark must be more than unpleasant or offensive; the language must make the plaintiff appear 'odious, infamous, or ridiculous." *Howard Univ. v. Best*, 484 A.2d 958, 989 (D.C. 1984) (citation

[32] Solution Project website at http://www.thesolutionsproject.org/.

omitted). "The plaintiff has the burden of proving the defamatory nature of the publication, and the publication must be considered as a whole, in the sense in which it would be understood by the readers to whom it is addressed." *Best, supra*, 484 A.2d at 989 (citations omitted). "[A]ny single statement or statements must be examined within the context of the entire [article]." *Heard v. Johnson*, 810 A.2d 871, 886 (D.C. 2002). In assessing allegedly defamatory statements, the D.C. Court of Appeals has admonished that "[a]ny risk that full and vigorous exposition and expression of opinion on matters of public interest may be stifled must be given great weight. In areas of doubt and conflicting considerations, it is thought better to err on the side of free speech." *Myers v. Plan Takoma, Inc.*, 472 A.2d 44, 48-49 (D.C. 1983).

Dr. Jacobson has identified three specific statements that he alleges are defamatory: 1) the statement that there is a modeling error reflected in Table 1 of the Jacobson Paper[33]; 2) the statement that a hydropower output discrepancy is so substantial that the authors "hope there is another explanation for the large amounts of hydropower depicted in these figures"[34]; and 3) a chart in the Clack paper that depicts historical hydroelectric power in the United States from 1990-2015.[35]

None of those statements can be considered defamatory. The first two statements relate to the Clack Authors' interpretation and evaluation of the methodologies or assumptions in the Jacobson Paper and the basis for each statement is clearly explained in the Clack Paper itself. The third statement does nothing more than relate historical data (which is not alleged to be false in and of itself). None of the statements are about the plaintiff. That Dr. Jacobson disagrees with the Clack Paper's points and criticisms (even vehemently) does not make the statements

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[33] Compl. at ¶ 42.

[34] *Id*. at ¶ 50.

[35] *Id*. at ¶ 62.

defamatory. Indeed, Dr. Jacobson's contention that scientists cannot call something an error or argue that it is a mistake for a model to incorporate unrealistic or inappropriate assumptions without fear of being sued for defamation would effectively shut down necessary scientific debate. Further, nor reasonable person could conclude that such statements in the context of a scientific debate cast plaintiff in an "odious, infamous or ridiculous light."

1. Plaintiff Cannot Establish That The Statements Made In Defendant's Scientific Evaluation Are False or Defamatory.

a. Statements Made In The Course Of Scientific Debate Are Not Defamatory.

The alleged defamatory statements cited by Dr. Jacobson were made in the context of evaluating the validity of what plaintiff, himself, has described as "original research of exceptional importance." Courts have regularly held that scientific debate is a matter of great public concern and, as such, "occupies the highest rung of the hierarchy of First Amendment values." *Dun & Bradstreet, Inc. v. Greenmoss Builders, Inc.*, 472 U.S. 749, 759 (1985) (plurality). "[I]n the area of freedom of speech… courts must always remain sensitive to any infringement on genuinely serious… scientific expression." *Miller v. California*, 413 U. S. 15, 23 (1973); *see also Bd. of Trs. of Leland Stanford Junior Univ. v. Sullivan*, 773 F. Supp. 472, 474 (D.D.C. 1991) ("[T]he First Amendment protects scientific expression and debate just as it protects political and artistic expression").

As recently as last year, the D.C. Court of Appeals reiterated the principal that statements that "take issue with the soundness of [plaintiff's] methodology and conclusions - *i.e.,* with ideas in a scientific or political debate - [] are protected by the First Amendment."[36] Other courts similarly hold that statements made regarding substantive scientific issues cannot form the basis

[36] *Competitive Enter.,* 150 A.3d at 1242.

for a defamation claim. The United States Court of Appeals for the Second Circuit has held that "as a matter of law, statements of scientific conclusions about unsettled matters of scientific debate cannot give rise to liability for damages sounding in defamation." *ONY v. Cornerstone Therapeutics, Inc.*, 720 F.3d 490, 492, 496-498 (2d Cir. 2013). The court went on to explain:

> Importantly, [scientific] conclusions are presented in publications directed to the relevant scientific community, ideally in peer-reviewed academic journals that warrant that research approved for publication demonstrates at least some degree of basic scientific competence. These conclusions are then available to other scientists who may respond by attempting to replicate the described experiments, conducting their own experiments, or analyzing or refuting the soundness of the experimental design or the validity of the inferences drawn from the results. In a sufficiently novel area of research, propositions of empirical "fact" addressed in the literature may be highly controversial and subject to rigorous debate by qualified experts. Needless to say, courts are ill-equipped to undertake to referee such controversies. Instead, the trial of ideas plays out in the pages of peer-reviewed journals, and the scientific public sits as the jury.

Id.

Similarly, in *Underwager v. Salter*, 22 F.3d 730, 736 (7th Cir. 1994), Judge Easterbrook admonished that "scientific controversies must be settled by the methods of science rather than by the methods of litigation. More papers, more discussion, better data, and more satisfactory models--not larger awards of damages--mark the path toward superior understanding of the world around us.") *See also Saad v. American Diabetes Assoc*, 123 F. Supp. 3d 175, 179 (D. Mass. 2015) (dispute over the reliability of the data in articles is not fit for resolution in the form of a defamation lawsuit); *Arthur v. Offit,* No. 01:09-cv-1398, 2010 WL 883745, at *6 (E.D. Va. Mar. 10, 2010) (plaintiff's defamation claim threatens to improperly ensnare the court in thorny and contentious scientific debate); *McMillan v. Togus Reg'l Office, Dept. of Veterans Affairs,* 294 F. Supp. 2d 305, 317 (E.D.N.Y. 2003) ("Scientists should not have to conduct their studies defensively, looking over their shoulders at unnecessary litigations."). Good faith scientific dispute and debate is simply not actionable as defamation. *Containment Techs. Grp., Inc. v. Am. Soc'y of Health Sys. Pharmacists,* 2009 WL 838549 at *16 (S.D. Ind. Mar. 26, 2009) (the only way plaintiff could show actual malice would be if clear and convincing evidence showed the entire study were rigged with the intent of publishing an article the authors knew would be false). The statements at issue here clearly constitute scientific debate and should be evaluated by the scientific community not by the courts. Differences between scientists on whether something should properly be characterized as an omission or an error is obviously not defamatory.

b. The Alleged Defamatory Statements Are Interpretations, Assessments and Opinions.

It is well settled that statements expressing interpretation, conjecture or surmise are not actionable as defamation. *Guilford Tranp. Indus., Inc. v. Wilner,* 760 A.2d 580, 596 (D.C. 2000). Whether a statement is one of fact or law is a question of law for the court, and in assessing whether a statement can fairly be characterized as an opinion, courts look to the context in which it appears. *See Dowd v. Calabrese,* 589 F. Supp. 1206, 1221 (D.D.C. 1984). Here, consideration of the challenged statements within the context of the Clack Paper as a whole conclusively demonstrate that the statements are the scientific interpretations and opinions of the Clack Authors.

The very title of the Clack Paper indicates that it is an *evaluation* and expressly sets forth the criteria being used to evaluate the Jacobson paper. The Clack Authors fully explain the basis and reasoning for their criticisms of the Jacobson Paper, including their assumptions in making such criticisms (*i.e.* that numbers are being treated as maximums or that a particular figure represents hydro output in the United States). As a threshold matter, courts have been clear that when a writer discloses the facts upon which a statement is based, the reader will understand that the statement reflects the writer's view based on an interpretation of the facts disclosed, such that the reader remains "free to draw his or her own conclusions based upon those facts." *Moldea v. N.Y. Times, Co.* 15 F.3d 1137, 1145 (D.C. Cir. 1994). Here, the Clack Authors explained in detail the basis for their criticisms. Moreover, disagreements on the proper way to model future energy usage or interpretation of how such models have been presented are not matters that can be fairly characterized as "false." Dr. Jacobson appears to believe that since he explained to the Clack Paper Authors why he believed their criticism was incorrect, they were required to accept that explanation, scrap their paper and refrain from further critique. That of course is not the law.

1) The Clack Paper's Criticism of Table 1 In The Jacobson Paper Is Not "False."

Dr. Jacobson contends that the Clack Authors' criticism of his modeling in Table 1 is "false" because the Clack authors assumed the values in that Table were maximums, but Dr. Jacobson claims they clearly represent averages.[37] First, contrary to Dr. Jacobson's contentions, nothing in Table 1 is "clearly labeled" as an annual average load. The language Dr. Jacobson points to in the Complaint does not in any way indicate that Table 1 includes average annual loads. Not one of the 21 authors of the Clack Paper read Table 1 to reasonably represent annual average loads, even in light of Dr. Jacobson's "explanation" provided after the Clack Paper was submitted for publication. The Clack Authors' rationale for interpreting the values in Table 1 as "total loads" used to calculate a maximum value is set forth in detail in the Supportive Information published with the Clack Paper.[38] Dr. Clack and his co-authors, were under no obligation to simply accept Dr. Jacobson's explanation or arguments regarding those values where, in the view of 21 highly respected experts in the field, the explanation was not consistent

[37] Compl. at ¶¶ 44-46.

[38] See Clack Paper (Supportive Information, Clack Exh. A at § 1.2, p. 3.

with their understanding of the text or data presented in the Jacobson Paper itself. The Clack Paper goes into detail regarding how it treats the values in Table 1 and explains how it calculates "a maximum value" assigned to the flexible load.[39] Dr. Jacobson was free to disagree with the Clack Author's interpretation and, in fact, he published an explanation of his position in a Letter Response to PNAS in the same online publication in which the Clack Paper appeared.

2) The Clack Paper's Statement About A Discrepancy In The Jacobson Paper's Hydro-Electric Power Output Model Is Not "False."

Dr. Jacobson states that the Clack Paper's discussion of the discrepancies in the Jacobson Paper's hydro-electric output numbers is defamatory. Notably, Dr. Jacobson admits that a key alleged assumption regarding those numbers (the availability of a massive amount of additional hydropower at no cost) "was not clear from the Jacobson Paper."[40] Nevertheless, Dr. Jacobson has sued Dr. Clack because the Clack Authors stated that they "hope there is another explanation for the discrepancy," than what is actually set forth in the paper itself. First, such a statement is not an assertion of fact that can give rise to a claim for defamation. *See e.g. Abbas v. Foreign Policy Group, LLC,* 783 F.3d 1328, 1338-39 (D.C. Cir. 2015) (raising a question no matter how embarrassing is not defamatory). Moreover, Dr. Clack did not accept the undisclosed assumption as a valid explanation when it was provided in February of 2016 and neither he nor his 21 co-authors accepted it as a valid explanation when plaintiff again raised it in May of 2017.[41] Dr. Clack and his authors were certainly not required to suggest arguments that the Jacobson Paper, itself, omits. Further, in the year following the February 2016 email exchange, Dr. Jacobson took no steps to clarify the public record, amend his paper to identify the alleged

[39] *Id.*

[40] Complaint ¶¶ 51-53.

[41] *See* Compl. at ¶57; Compl. Exh. 4; Clack Author's Response, Clack Exh. C.

assumption he made, provide support for the use of such an assumption or acknowledge the costs associated with the assumption. The public remained in the dark about this alleged assumption until the Clack Paper was published and Dr. Jacobson decided to publicly respond.

In any event, - each assuming the hydro-electric assumption were disclosed - the Clack authors *did* specifically address the possibility that the Jacobson Paper's modeling included undisclosed, additional hydro-electric power and concluded that such an assumption (even if it were included in the paper) would be inappropriate because it would be technically and economically impossible.[42] Thus, there is nothing even arguably "false" or misleading in the Clack paper.

3) The Clack Paper's Depiction Of Historic U.S. Hydro-Electric Power Output Is Not "False."

Dr. Jacobson suggests that a figure in Dr. Clack's article showing hydroelectric output from the United States is "false" because it does not include output imported from Canada. First, the Clack paper clearly identifies what is reflected in the chart *i.e.* the hydro-electric output for the United States,[43] so it is in no sense of the word false. To the extent that Dr. Jacobson's complaint is that Dr. Clack does not state that the Jacobson Paper allegedly adds imported power from Canada, that information is not contained anywhere in the Jacobson Paper. Dr. Jacobson never even raised this issue until after the Clack Paper had been published. Further, the relevant

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[42] The Clack Paper stated:

> One possible explanation for the errors in the hydroelectric modeling is that the authors assumed they could build capacity in hydroelectric plants for free within [the model]...The hydroelectric power plants that exist today do not have the space required to expand their capacity by 10-15 times. Indeed, the extra piping needed to supply water to these turbines would cause considerable engineering issues due to the age of the plants and the river flows. A report from IRENA shows that around the world the average cost of hydroelectric is $3500/kw...[factoring in only increased power the additional cost of the hydroelectric power would be] $3.1 Trillion.

Clack Paper, Supporting Information, Clack Exh. A at S.1.1 at p. 2.

[43] *See* Clack Paper, Clack Exh A at 6725 ("we plot in Fig. 3 the last 25 y of generation from the United States")

table in the Jacobson Paper's Supportive Information is labeled hydropower "in the CONUS" (meaning continental United States).[44] Notably, Dr. Jacobson has not identified anything in the Jacobson Paper that even suggests that its model establishing the United States has sufficient resources of wind, water and solar power for all purposes adds in hydroelectric power from Canada.

4) The Statements Incorporated By Reference In The Complaint Are Not Defamatory.

Dr. Jacobson purports to incorporate by reference every critique set forth in his line by line rebuttal to the Clack Paper, as a separate defamation claim.[45] As a threshold matter, there are no specific allegations in the Complaint that any of these additional statements are false, are defamatory, were made about Dr. Jacobson or were made with actual malice. Indeed, virtually all of the statements identified in the rebuttal relate to Dr. Jacobson's disagreements with interpretations, conclusions, opinion or citations made by the Clack Authors.

The additional statements set forth in the rebuttal are nothing more than standard academic disagreements. None of them can fairly be said to relate to Dr. Jacobson in any way. For example, statements 1, 2, 3, 4, 7, 8, 11 and 33 in Exhibit 12 simply state Dr. Jacobson's disagreement with the Clack Authors' characterization and interpretation of third party studies.[46] The claims are in no way defamatory. Similarly, statements 6, 12, 13, 17, 20, 24, 27, 29, 32, 36 and 37 relate to Dr. Jacobson's disagreements with the Clack Authors assessments of the feasibility or appropriateness of certain assumptions made by the Jacobson Paper or the appropriation of certain comparisons.[47] Again, this is pure scientific opinion and nothing set

[44] *See* Jacobson Paper Supportive Information, Compl. Exh. 3, Table S2 at 14.

[45] Comp. at ¶ 75; *see, e. g.* Jacobson Rebuttal, Compl., Exh. 12.

[46] Compl., Exh. 12.

[47] *Id.*

forth in the rebuttal is outside the normal parameters of scientific debates. For other statements, Dr. Jacobson simply contends that they are irrelevant to his main point in the paper - *i.e.*, 38 and 39.[48] The parties may debate the relevance of the statements, but that obviously does not make them defamatory. The remainder of the rebuttal simply rehashes the points Dr. Jacobson raised about the three specific issues which are actually included in the Complaint and are discussed above. Simply pointing to a series of letters containing vague assertions does not meet the pleading standards under the District of Columbia Rule of Civil Procedure and these allegations should be disregarded by the Court.

2. The Statements Do Not Cast Plaintiff In An Odious, Ridiculous Or Infamous Light

Defamatory statements must cast the subject in an "odious, ridiculous or infamous light." *Howard Univ. v. Best*, 484 A.2d 958, 989 (D.C. 1984). Courts have held that where a plaintiff is complaining about an attack on his ideas instead of his character, he has no claim for defamation. *Lott v. Levitt*, 556 F.3d 564, 570 (7th Cir. 2009). Dr. Jacobson's complaints all relate to substantive criticism of his methodology and conclusions as presented in the Jacobson Paper. There is no allegation that Dr. Clack ever criticized Dr. Jacobson personally or accused him of any type of misconduct. The Clack Authors simply identified areas in the Jacobson Paper where, in their assessment, the claims of the authors did not appear to be supported by the science and models as presented in the paper itself. Suggesting a study has errors or invalid assumptions does not cast the authors of such a study in an odious, ridiculous or infamous light and no reasonable person would conclude otherwise.

As noted above, the D.C. Court of Appeals recently addressed allegedly defamatory statements made in the context of a scientific dispute in *Competitive Enterprise Inst. v. Mann*,

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[48] *Id.*

150 A.3d 1213 (D.C. 2016). In that case, the Court of Appeals expressly stated that "[t]o the extent statements in [defendant's] articles take issue with the soundness of [plaintiff's] methodology and conclusions - *i.e.,* with ideas in a scientific or political debate - they are protected by the First Amendment." *Id.* at 1242. Those are precisely the type of statements at issue here and, as such, they are protected by the First Amendment. The Court of Appeals contrasted such protected substantive scientific statements with "personal attacks on an individual's honesty and integrity" including allegations that plaintiff "engaged in professional misconduct and deceit to manufacture the results he desired" *Id.*[49] No similar statements are at issue here.

3. Plaintiff Cannot Prove By Clear And Convincing Evidence That Dr. Clack Acted With Actual Malice.

Plaintiff cannot prove "actual malice." Under D.C. law, where a plaintiff is a public figure or a public figure for the limited purpose of the statements at issue, he or she must prove by clear and convincing evidence that defendant's statements were made with knowledge that they were false or with reckless disregard of whether they were false or not. *Beeton v District of Columbia*, 779 A.2d 918, 923-924 (D.C. 2001). To show reckless disregard, there must be sufficient evidence that indicates that the defendant had serious doubts regarding the truth of the published statements. *Id.* Courts may not infer "actual malice" from mere reason that the defamatory publication was made. *Nader v de Toledano*, 408 A.2d 31, 41 (D.C. 1979). The courts must look to the character and content of the publication, and the inherent seriousness of the defamation accusation. *Id.* Moreover, to prevail, the plaintiff bears a higher burden of proof

[49] The types of statements the Court of Appeals found were potentially actionable in *Mann* included statements that the plaintiff was the "poster boy of the corrupt and disgraced climate science echo chamber" and that he personally engaged in "wrongdoing," "deceptions," "data manipulation" and "academic and scientific misconduct." The article at issue also called the plaintiff "the Jerry Sandusky of climate science," comparing plaintiff's "'molest[ing] and tortur[ing] data in the service of politicized science' to Sandusky's 'molesting of children.'" *Competitive Enter.,* 150 A.3d at 1243.

than the preponderance of the evidence standard usually applicable in civil cases; the plaintiff must persuade the fact-finder that the defendant acted with actual malice in publishing the defamatory statements by clear and convincing evidence. *See N.Y. Times, Co. v. Sullivan*, 376 U.S. 254, 285-286 (1964) (referring to the "convincing clarity which the constitutional standard demands").

a. Plaintiff Is A Public Figure

Dr. Jacobson is undoubtedly a public figure with respect to the renewable energy debate and the policies advocated in the Jacobson Paper. In addition to writing and speaking regularly on this issue, Dr. Jacobson provided testimony before the United States Congress on the feasibility of 100% wind, water and solar reliance by the year 2050.[50] He also co-authored an article with a United States Senator advocating his 2050 proposal for the United States and is a public sponsor of the Senate 100 by '50 bill.[51] Indeed, Dr. Jacobson has placed himself at the forefront of this particular public policy issue in order to influence the resolution in favor of 100% wind water and solar including by affirmatively publishing the paper at issue in this litigation. *See e.g. Competitive Enter.*, 150 A.3d at 1251 n.51 (holding that climate scientist was limited public figure in area of study for purposes of defamation claim).

b. The Paper Reflects The Views Of Twenty-One Prominent Energy and Climate Researchers And Was Independently Peer Reviewed.

Far from being a personal attack on Dr. Jacobson, the Clack Paper reflects the views of a diverse and prestigious group of energy and climate scientists. There is no allegation that any of the 21 co-authors has any personal animosity toward Dr. Jacobson. In addition to representing

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[50] Clack Exh. H.

[51] https://www.theguardian.com/commentisfree/2017/apr/29/bernie-sanders-climate-change-big-oil. Article by Senator Bernie Sanders and Mark Jacobson; *see* footnote 33 *supra*.

the combined view of 21 separate authors, the Clack Paper also went through careful independent peer review and editorial board review at NAS.[52] The Clack Paper explains in detail the basis for its criticisms and conclusions. That the Clack Authors were unwilling to change their paper after reviewing Dr. Jacobson's criticisms of it in no way suggests they acted with malice. To the contrary, in conjunction with the NAS editorial board, the Clack Authors carefully considered the points raised and concluded that their criticisms were on sound scientific and academic ground.[53]

II. Plaintiff's Claim Should Be Dismissed For Failure To State A Claim Upon Which Relief May Be Granted.

District of Columbia Superior Court Rule 12(b)(6) vests the Court with the authority to dismiss an action when it "fail[s] to state a claim upon which relief can be granted." Super. Ct. R. 12(b)(6). Pursuant to this Rule, dismissal is warranted if the plaintiff cannot prove facts which would support his claim. Here, the statements alleged by plaintiff are not defamatory as a matter of law. Importantly, the D.C. Court of Appeals has advised that Rule 12(b)(6) motions are particularly appropriate with respect to defamation claims involving public debate:

> [P]erhaps more than any other [area], the early sifting of groundless allegations from meritorious claims made possible by a Rule 12(b)(6) motion is an altogether appropriate and necessary judicial function. At the threshold, it is the court, not the jury that must vigilantly stand guard against even slight encroachments on the fundamental constitutional right of all citizens to speak out on public issues without fear of reprisal."

Myers v. Plan Takoma, Inc., 472 A.2d at 50.

Defendant's motion to dismiss under D.C. Super. Ct R. 12(b)(6) rests on the same grounds as his Special Motion to Dismiss. The Supreme Court has clearly stated that defamation laws cannot be used to stifle free speech and that there exists a "profound national commitment

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[52] NAS peer review guidelines, Clack Exh. B.

[53] *See e.g.,* Clack Authors' Response, Clack Exh. C.

to the principle that debate on public issues should be uninhibited, robust, and wide-open." *New York Times*, 376 U.S. at 270. Whether a statement is capable of defamatory meaning is a question of law and if the alleged statement is not reasonably capable of defamatory meaning the claim must be dismissed. *Klayman v. Segal,* 782 A.2d 607, 612-13 (D.C. 2001).

Even if the Court were to assume plaintiff's allegations are true, and taking into account all of the documents incorporated by reference in the Complaint and its exhibits, the First Amendment forecloses plaintiff's recovery for the protected speech targeted by the Complaint. Here, the statements that plaintiff made an error, that the Clack Authors "hoped there was another explanation" for a discrepancy in the Jacobson Paper and the inclusion in their paper of a figure that accurately portrayed historic U.S. hydro-electric power cannot, as a matter of law, be construed as defamatory. As such, for all the reasons stated above, plaintiff's claim must be dismissed for failure to state a claim upon which relief may be granted under Rule 12(b)(6).

CONCLUSION

For the reasons set forth above, the defamation claim against Dr. Clack should be dismissed under the District of Columbia Anti-SLAPP Act or, in the alternative, under Rule 12(b)(6) for failure to state a claim upon which relief can be granted.

Dated: November 27, 2017

Respectfully submitted,

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CERTIFICATE OF SERVICE

I hereby certify that on this 27th day of November, 2017, I caused the foregoing Memorandum of Points and Authorities in Support of Defendant Christopher Clack's Special Motion to Dismiss Under the District of Columbia Anti-Slapp Act to be served via CaseFileXpress on the following:

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CLACK EXHIBIT A

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

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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

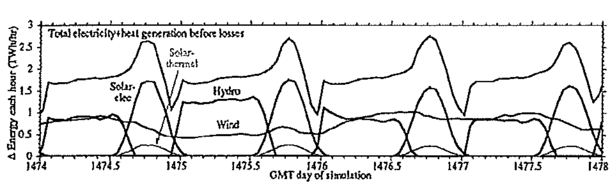

Fig. 1. This figure (figure 4B from ref. 11) shows hydropower supply rates peaking at nearly 1,300 GW, despite the fact that the proposal calls for less than 150 GW hydropower capacity. This discrepancy indicates a major error in their analysis. Modified from ref. 11.

[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."

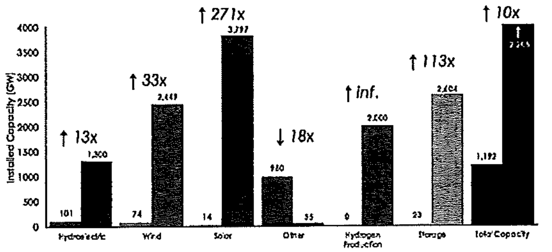

Fig. 2. Installed capacity values for 2015 (left column in each pair) and those used in the studies in refs. 11 and 12 (right column in each pair). These 100% wind, solar, and hydroelectric studies propose installing technologies at a scale equivalent to (or substantially greater than) the entire capacity 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%

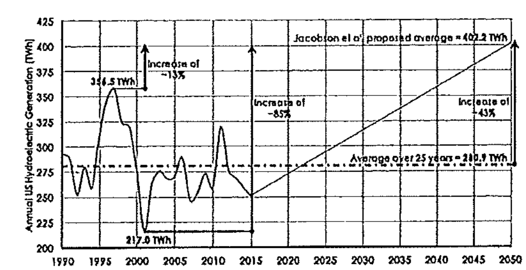

Fig. 3. Historical and proposed hydroelectric generation per year. The historical data (www.eia.gov/todayinenergy/detail.php?id=2650) show generation averaging 280.9 TWh/yr; generation proposed in ref. 11 is 402.2 TWh, 13% higher than the 25-y historical maximum of 356.5 TWh (1997) and 85% higher than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

[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.

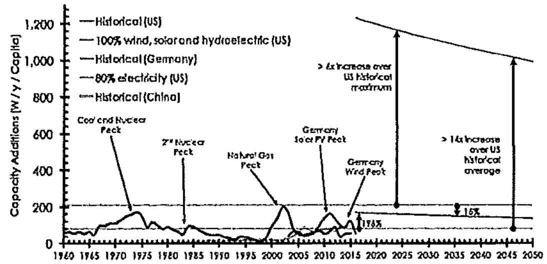

Fig. 4. The historical rates of installed electric-generating capacity per capita (watts per year per capita) for China (blue), Germany (gray), and the United States (black) are shown with the estimated values for the US proposals from the works by Jacobson et al. (11, 12) (red) and MacDonald et al. (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.

[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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Supporting Information for the paper "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar"

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The following document contains the supporting information for the paper "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar". In section S1, we examine important modeling errors that call into question the results in the studies. In section S2, we examine poorly documented and unsupported assumptions, including the cost and scalability of storage technologies and the use of hydrogen fuels, which underpin the energy system reliant on 100% wind, solar and hydroelectric power. In section S3, we focus on the studies' claims about the operational reliability of an electric power system, which are based on a model of load matching that does not fully capture the realistic operations of power systems. In section S4, we argue that the climate/weather model used for estimates of wind and solar energy production has not been sufficiently vetted and has not demonstrated the ability to accurately simulate wind speeds or solar insolation at the scales needed to assure the reliability of an energy system heavily reliant on variable energy sources.

S1: Modeling Errors

A primary concern with the analysis of ref. [11] is the presence of errors in the modeling of the proposed energy system. Errors arise with the treatment of hydroelectric output and also concern assumptions about the flexibility of major electricity loads. These errors are important because the flexibility of supply (notably hydropower) and demand are essential for understanding the reliability of electricity supply in an almost 100% wind, solar and hydroelectric power system (as with the main manuscript we shorten to 100% wind, solar and hydroelectric for simplicity).

S1.1: Hydroelectric Capacity. The analysis in ref. [11] relies on much more hydroelectric capacity than can reasonably be expected to be available. In ref. [11], the total installed hydroelectric power capacity in the U.S. system, as defined in Table S2 of its supporting information (SI), is 87.48 GW. In addition to this, Table S1 of its SI defines the maximum discharge rate for new pumped hydroelectric capacity (assuming that all of this is completely new capacity and not existing capacity with added pumping) to be 57.68 GW[1]. Thus, assuming that conventional hydroelectric generation and "pumped" hydroelectric power production capacity is separate, the total maximum theoretical output of all hydroelectric capacity postulated in ref. [11] is 145.16 GW.

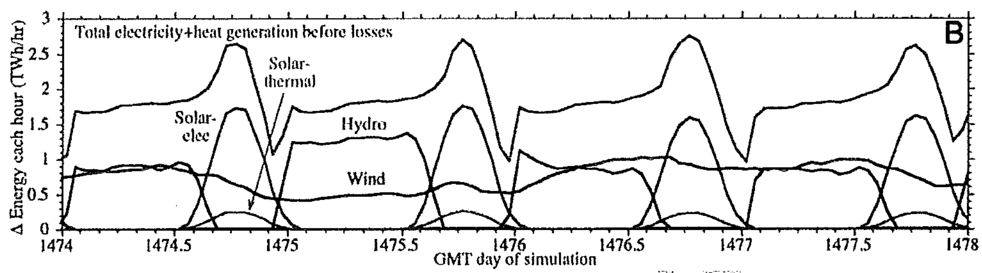

Fig. S1. Panel B of Figure 4 of ref. [11]

Figure S1 (which corresponds to Panel B of Figure 4 in ref. [11]), shows the power supplied by different sources in TWh/hr, which is effectively the average power for each hour in the unit of TW, for a period of four days in January of 2055. Readers of ref. [11] are given only a few snapshots of the modeling results, but as an example, for half of the simulated day of 15th of January 2055, hydropower is depicted as supplying ~84% of total system load, averaging 1.3 TW (1,300 GW) over a period of 13 hours, or approximately 9 times the theoretical maximum instantaneous output of all installed conventional hydropower and pumped storage combined. It is not feasible for an installed hydropower capacity of 87.48 to 145.16 GW (depending on whether pumped hydro is included in these figures in the hydro output or in non-underground thermal energy storage output) to produce 1,300 GW for hours at a time. It is worth noting that 1,300 GW is more than the current combined generating capacity of all the U.S. power plants. Furthermore, this error is not limited to a single figure in ref. [11]. The hydroelectric production profiles depicted throughout the dispatch figures reported in both the paper and its supplemental information routinely show hydroelectric output far exceeding the maximum installed capacity as well. Both Figures S4 and S5 of its SI, for example, depict hydroelectric generation rates exceeding 700 GW. This error is so substantial that we hope there is another explanation for the large amounts of hydropower output depicted in these figures. In [12] the authors state that "We constrain hydropower to existing capacity in each state except in the case of Alaska." Then in [11] the authors state values from [12] are used.

One possible explanation for the errors in the hydroelectric modeling is that the authors assumed they could build capacity in hydroelectric plants for free within the LOADMATCH model. If this were the case then, using their values from Table S2 [11] ($2,820 / kW), we estimate that the cost for 1,200 GW extra capacity would be $3.38 trillion. Table 2 from [11] states total cost for new generators would be $13.9 trillion. Therefore, the additional cost of the hydroelectric power plants would be an additional 24% of the cost of the entire 100% wind, solar and hydroelectric power system. Furthermore, in ref. [12] the authors state that "we do however assume that nationally most good hydropower sites already have been developed." So presumably new sites are necessary. The hydroelectric power plants that exist today do not have the space required to expand their capacity by 10-15 times. Indeed, the extra piping needed to supply water to these turbines would cause considerable engineering issues due to the age of the plants and the river flows. A report from IRENA[2] shows that around the world the average cost of hydroelectric is $3,500 / kW (see Fig 4.5 the IRENA report); of that cost, $911 / kW is for the reservoir. If the

[1] It is stated in ref. [11] that "PHS is limited to its present penetration plus preliminary and pending permits as of 2015". According to current Federal Energy Regulatory Commission (FERC) data [27], the total sum of pending and preliminary permits for PHS in the U.S. is 26.99 GW, and the existing capacity in PHS is 21.6 GW [28], which gives the actual total potential PHS according to the definition of ref. [11] as 48.59 GW, or 9.1 GW less than what is assumed in ref. [11]. FERC data for ref. [11] was accessed in December 2014, while FERC data from October 2016 was accessed for this evaluation, which means a change in the FERC data may be a source for this discrepancy.

[2] IRENA report found here: http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf

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hydroelectric capacity for the 100% wind, solar and hydroelectric power system was built in situ for current locations, the other costs would still apply (you need pipes, penstocks, power houses, etc.). If that is the case the cost of the new hydroelectric capacity would be \$2,589 / kW, reducing the additional cost to \$3.1 trillion instead of the \$3.38 trillion we estimated above.

Achievable peak hydropower output is likely to be significantly smaller than the theoretical maximum assumed by the authors in ref. [11] (145.16 GW), and certainly less than shown in its figures (i.e. 700 or 1,300 GW). This is because the total output of hydroelectric facilities is limited by overall river flows and further constrained by environmental considerations and other priorities for water use (e.g., navigation, irrigation, protection of endangered species and recreation). These constraints currently prevent all hydroelectric capacity from running at peak capacity simultaneously (see, e.g., Figure S5 from ref. [1]). In addition, a portion of U.S. hydropower facilities are "run-of-river" facilities without the ability to store water for on-demand power production behind the dams, and still more facilities have minimum and maximum flow rates imposed for environmental reasons that restrict their operating flexibility. Recent years have seen major environmental initiatives to restrict hydropower output and even remove dams; the courts and political processes have been receptive to these efforts and all indications point to even more restrictions in future.

To demonstrate the point regarding maximal output from U.S. hydroelectric power, we plot the average power from the entire U.S. hydroelectric fleet[3] for each month for the years 2006–2016 (up to September 2016) in Fig. S2. Figure S2 shows an annual cycle (which is driven by the hydrological cycle). The maximum monthly power output from the combined U.S. hydroelectric fleet (~101.6 GW) is shown to be ~44.8 GW. Thus, the peak month in the last decade had a monthly capacity factor of 44.1%. In contrast, Fig. 2 in ref. [11] shows that hydroelectricity provided in month 12 of the simulation totaled ~150-175 TWh of electricity. Assuming the mean value of this range (162.5 TWh), such generation would represent an average hourly power output for the month of 218.4 GW. That is over twice the installed capacity of hydroelectricity in 2015 generating electricity constantly for an entire month. Moreover, 162.5 TWh is ~40% of the allocated hydroelectric energy allowed by [11][4]. Therefore, the water would need to have been stored from earlier in the year. Indeed, Fig. 2 in ref. [11] shows precisely that; no hydroelectricity production from months 2 to 6 for the first year of the simulation (a common pattern followed for the other years). However, these early months of the year have substantial production in the current electric grid because of the hydrological cycle, irrigation needs, and reservoir restrictions. This is illustrated by Fig. S2 and Fig. S5 from ref. [1].

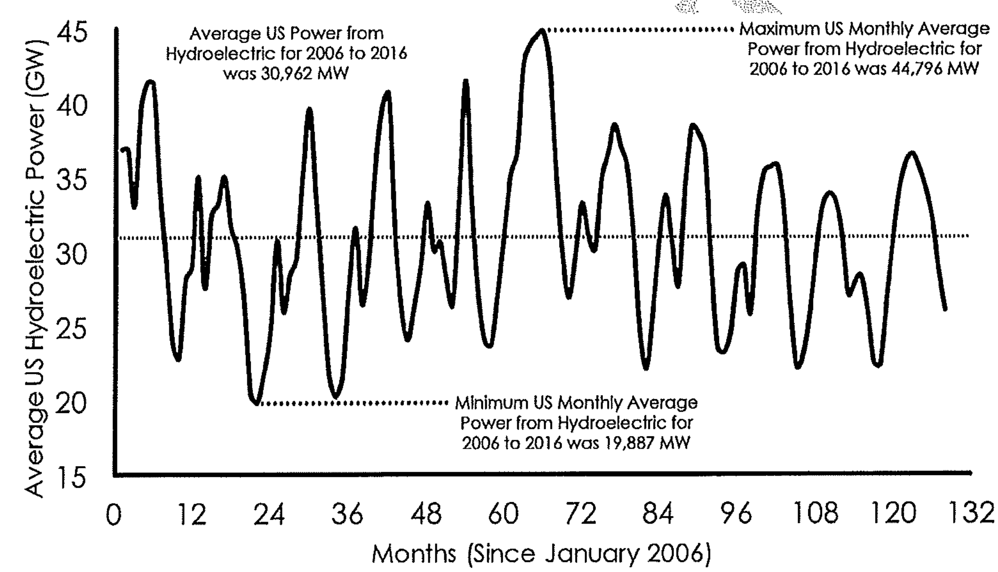

Fig. S2. The average power output from all the U.S. hydroelectric plants for 2006 through August 2016. The annual cycle from hydrology can be seen throughout the plot. The last five years are water constrained and the power output suffers as a result. The peak average monthly power is 44,796 MW for Spring 2011 (months 62-66). The minimum was 19,887 MW for late fall 2007. The average monthly value for the decade was 30,962 MW, or 30.5% of installed capacity.

S1.2: Flexible Demand. The analysis of a 100% wind, solar and hydroelectric power system [11] contains errors in the handling of flexible demand. The total amount of load that is labeled as flexible in the dispatch figures is inconsistent with the flexible load that is reported in the paper.

First, if one takes the total percentage of load that is flexible or coupled with TES or used for hydrogen production from Table 1 column (4) bottom row from [11] there would be 67.66% of the total load being flexible. That means there can only be a maximum of 1064.16 GW that can somehow be manipulated for load reshaping.

Deeper inspection of Table 1 column (4) in ref. [11] shows that the categories of transportation, on-site transportation in industry and high-temperature chemical or electrical processes within industry (Hi-T/chem/elec) have some fraction of

[3] data obtained from EIA: https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_01

[4] see its Table 2 and divide hydropower electricity by six for yearly values (2413/6 = 402.2 TWh).

load categorized as "flexible". For transportation it is labeled as 85% flexible (F), coupled to TES (S) or used for hydrogen production (H) [F, S, H]; while on-site transportation is labeled as 85% (F); and Hi-T/chem/elec is labeled as 70% (F, H). All other categories are only flexible with TES or hydrogen production (S, H). Using these values, and assuming all these loads can be exclusively flexible (F) then there would be 683.8 GW that is assigned to this category of flexible load. That is a value of 43.5% of the total load.

If instead one was to read Table 1 column (5) in ref. [11], which further decomposes the flexible loads with TES (F, S) [separated from (H)], it can be seen that 108.9 GW is available for (F, S) from transport, 4.31 GW is available for (F) from on-site transportation and 390.44 GW is available for (F) from Hi-T/chem/elec. This results in a maximum available flexible (F) loads of 503.65 GW or 32.0% of the total load.

Thus we have three values possible for "flexible" loads: an absolute maximum of 1064.16 GW (67.7% of total load) assuming that some things were mislabeled and the LOADMATCH model could make everything flexible rather than going to TES or hydrogen production; a maximum of 683.8 GW (43.5% of total load) if the labeling is correct in Table 1 in ref. [11] and we assume all flexible load, TES, and hydrogen production are interchangeable; or a maximum of 503.65 GW (32.0% of total load) if column (5) values are taken as correct.

Looking at Fig. 3 from [11] at the point representing day 912.6 there is a flexible load (green) value of 1,900 GW of a possible 2,400 TW of total load. This represents a flexible load of 79% a value that is far higher than any of the possible values from Table 1 in ref. [11] and is double the value of total flexible load allowed according to that table. In fact, each day in Fig. 3 of ref. [11] appears to break the 67.7% value for flexible load. This is further confirmed by Fig. 4 of ref. [11], where each day flexible load gets as high as 77% of the total load. In fact every single figure that shows the "flexible" load appears to break either the 67.7% value or the maximum capacity of flexible load of 1064.16 GW.

The only way this scale of flexible load would be feasible is if the fraction of demand from transport and industrial loads during these days is at least twice as large as the average shares reported in Table 1 of ref. [11], and if all of these loads are considered flexible (as opposed to being part of the separately labeled UTES output). The authors of ref. [11] do not provide evidence to justify this implausible scale of load flexibility. The idling capital-intensive industrial facilities when intermittent energy sources are unable to meet demand represents a large cost that is not included in ref. [11].

It should be noted that LOADMATCH models generation from wind and solar *a priori* and then aggregates them together. It does not determine the capacity of generation endogenously. The model is essentially one-dimensional; all loads, generation and storage are considered in a single place though time. Thus, the sensitivity analysis performed in ref. [11] ultimately relies only on changes in storage and demand response (and erroneous hydropower capacity) on a trial and error basis. The authors of ref. [11] assert in Table S3 and Fig. S14 that having zero demand response (DR) does not change the cost of energy and energy is supplied reliably. If this were to be true, what is the purpose of the flexible load in the model? The flexible load appears to shift demand to the end of the eight-hour blocks and is used substantially more in winter than summer. How can a considerably shifted demand profile (and associated economy) cost practically the same as an inelastic one? If ref. [11] included a transmission and capacity expansion model, it would become apparent that supplying these huge fluctuations in demand would create congestion and other issues within the grid. The lack of sensitivity to DR is particularly worrisome because it is the highest priority item in the LOADMATCH model after inflexible load and it is utilized so ubiquitously in the base case scenario.

S2: Implausible Assumptions

The 100% wind, solar and hydroelectric power system in ref. [11] includes only 18 GW of PCM-ice storage; just 30% of the total flexible cooling and refrigeration demand. Therefore, the vast majority of storage underlying the extremely high flexibility of air conditioning and refrigeration needs in the study must consist of UTES. It should be noted that the cost of retrofitting all heating, cooling, and refrigeration to be compatible with UTES or ice-PCM is not included in the analysis in ref. [11].

S2.1: Underground Thermal Energy Storage (UTES). Underground thermal energy storage systems using geothermal boreholes to store heat in the soil, as used in ref. [11], have to date been employed at a relatively small scale in only a handful of projects [29]. The largest UTES borehole storage system in the world appears to be a project in Crailsheim, Germany, which supplies seasonal thermal storage for 260 homes and two community buildings, and has a total storage capacity of 0.0041 TWh [30]. The UTES used in ref. [11] is specifically "patterned by" an even smaller borehole ground heating system which supplies Drake Landing, a master planned community of 52 custom-designed solar homes in Alberta, Canada. Both the Crailsheim and Drake Landing projects are supplemented by heating from conventional fossil-fueled heating systems.

The plan of the 100% wind, solar and hydroelectric power system [11] extrapolates from these small-scale demonstration projects to propose the ubiquitous deployment of UTES at every home, business, office building, hospital, school, and factory in the United States. The performance (and cost) of UTES systems is highly dependent on the underlying geology of the site, such as the thermal properties of the soil and the absence of any groundwater flow (which if present, will remove stored heat over time). In addition, the projects cited as the basis for the UTES systems appearing in ref. [11] supply only heating, yet the the study envisions 85% of residential air conditioning, 95% of commercial and industrial air conditioning, and 50% of commercial and industrial refrigeration being coupled with UTES and/or ice-based PCM storage systems.

UTES systems depend on heat pumps and/or liquid circulating pumps to deposit into and extract heat from the ground. The most efficient geothermal heat pumps available consume about one unit of electricity for every four to five units of heating or cooling they supply. So while much more efficient than electrical heating or cooling, UTES systems still consume electricity on demand whenever they supply heating or cooling needs (this is in addition to the energy needed to charge the system in the first place). It does not appear that this on-demand electricity consumption is modeled in ref. [11].

The supplemental material for ref. [11] reports a wide span of costs for underground thermal energy storage ranging from \$0.071 to \$1.71 / kWh_{th}, (with the higher estimate 24-times the lower) but does not adequately justify these numbers. One of the provided references consists of presentation slides by the company Rehau [30] in which no directly applicable cost data are provided. The other reference is a conference contribution [31] on simulating heat transfer rates from a CHP-coupled UTES system. Reliable cost figures cannot be obtained from the analysis in ref. [31]. With 515 TWh of UTES underlying the proposed balancing of U.S. thermal energy needs, the cost estimates reported for the 100% wind, solar and hydroelectrcic power system [11] imply a total cost ranging from a low of \$37 billion to a high of \$900 billion. However, the known capital costs for the Drake Landing system suggest a UTES installation cost of at least \$1.8 trillion for the 100% wind, solar and hydroelectric power system[5], double the high-end estimate reported in ref. [11]. In addition, this estimated cost excludes the cost of the requisite heating and cooling systems inside homes, businesses, and industrial facilities capable of making use of stored energy in UTES systems. Moreover, the handful of existing UTES systems that form the basis for extensive use in ref. [11] are all installed during the new construction of specifically-designed communities or feed into established district heating systems, and none of them appear to feature the capability of providing cooling or refrigeration. Costs to retrofit existing homes and buildings with heat pumps capable of interfacing with UTES systems and install UTES boreholes and insulating layers beneath existing structures are unlikely to be as affordable as new construction. Thus, the actual costs of deploying UTES ubiquitously at virtually all buildings in the United States, as the 100% wind, solar and hydroelectric power system requires [11], are likely to be much larger.

S2.2: Energy Storage in Phase-Change Materials (PCM). The use of phase change materials in high temperature storage applications is entirely unproven at scale and is still effectively in the research and demonstration stage [33]. To date, only a handful of concentrating solar power projects have been built worldwide with any thermal storage, and these systems exclusively employ more mature (and costly) molten salt storage systems [34]. Phase-change materials, so called due to their ability to store heat by transitioning from a solid to liquid state, include paraffin wax and certain salts. Employing these materials for high-temperature thermal energy storage could yield much higher energy densities and potentially lower costs than molten salt storage. But doing so requires solving a number of practical challenges before the technologies will be ready for commercial adoption, including designing methods to overcome the poor thermal conductivity of phase change materials; solving corrosion, material degradation and thermal stress-related durability problems; and developing cost-effective mass production methods [33–36]. In the 100% wind, solar and hydroelectric power system study [11], the PCM-CSP systems are cited as having a 99% round-trip energy efficiency (Table S1 of ref. [11]) - with the implication that much of this is for electrical power. However, the study [37] cited in ref. [11] refers to the energetic efficiency, and assumes that all usable heat can be exploited. The assumption of a very high round trip efficiency greatly (favorably) impacts the levelized cost of stored electricity assessment.

Phase-Change Materials (PCM) storage coupled to CSP plants represent 88% of all proposed electricity storage capacity in ref. [11], at a reported cost of \$10 to \$20 / kWh_{th}. As high-temp PCM for CSP applications remains pre-commercial, there is no reliable data for the current cost of PCM storage. The reference cited by ref. [11] is not a current technology cost, but

[5] Future projected cost estimates (which are significantly lower than actual costs) for the Drake Landing type UTES are given in Table 3 of ref. [32]. Excluding costs for collectors and their installations, and noting that in 2007, \$1 CAD≈\$1 USD, implies a system cost of \$3.5 billion (2015) per TWh, or \$1.8 trillion for the scale of UTES systems proposed in ref. [11].

rather the \$15 / kWh_{th} cost target proposed by the US Department of Energy SunShot program, which states that achieving these goals will require a combination of evolutionary and revolutionary technological changes [38]. A technical report by the IEA and IRENA [33] reports a much wider range of €10-50 / kWh_{th} for PCM (about \$11-55 / kWh_{th}), and this range is inclusive of more affordable low-temperature applications; such as inclusion of PCM in building materials. Whether high-temp PCM for CSP plants is commercially successful, and at what cost, remains speculative, and if costs fall to the higher range reported by IEA/IRENA, PCM storage for CSP could cost upwards of \$729 billion to install, or more than 3.5-times as much as assumed in ref. [11].

S2.3: Ease of Transition to a Hydrogen Economy. The 100% wind, solar and hydroelectric power system proposed in ref. [11] relies upon unsupported assumptions about the very widespread adoption of hydrogen production and consumption, which supplies nearly half of all transportation energy needs and 11% of the energy-intensive industrial processes (i.e. aluminum and steel production, chemical manufacturing). Moreover, the authors of ref. [11] postulate the availability of hydrogen storage giving the proposed system the ability to store the equivalent of more than a month of current U.S. electricity consumption. The authors of ref. [11] provide no information in ref. [11] (or its supplemental material) on how air, shipping, rail or long-haul freight transportation sectors or various energy-intensive industrial processes would use hydrogen. There is a long history of imagining a transition to hydrogen fuels in transportation, notably aircrafts. So far, little progress has been made because existing infrastructures readily "lock out" radical new systems such as hydrogen [39]. While early demonstrations of some of these hydrogen fuel applications (for example, commuter rail in Germany and heavy trucks in California) exist and much work has been done suggesting that hydrogen aircraft might be technically feasible in the future, the technical challenges and economic costs of such widespread applications of hydrogen as a fuel are not addressed in ref. [11].

In addition, it appears from the modeling results shown in ref. [11] that no physical limitations have been placed on the rate of hydrogen production in the system. In Figure S6 of its SI, it is shown that a hydrogen charge rate (power going to hydrogen production) of almost 2 TW is achieved, nearly double the total current installed generating capacity of the United States. The actual capacity for hydrogen production is never explicitly presented in ref. [11] and is not appropriately accounted for in the cost estimates[6]. The authors of ref. [11] provide no information regarding the hydrogen production equipment (electrolysis, etc.) that would enable a hydrogen production rate of at least 2 TW, as shown in the dispatch figures (see the lowermost panel of their Figure S6; shown here below in Figure S3).

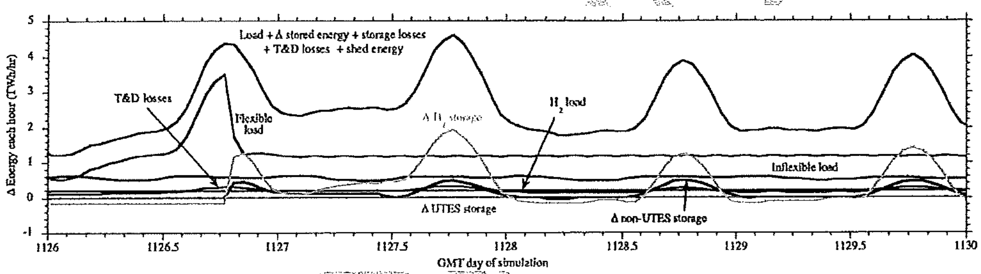

Fig. S3. Lowermost panel of Figure S6 of ref. [11]

For cost estimates of the hydrogen production system, the authors of ref. [11] cite their own previous work [41], which reports average costs of hydrogen production as 4 cents / kWh-to-H_2 for the electrolyzer, compressor, storage equipment, and water (with a range of 1.96-6.05 cent / kWh). Calculating costs in this way, as a simple levelized cost per kWh, is inappropriate for circumstances like those in ref. [11] where peak production is much higher than average production. The cost estimates presented in ref. [41] assume the electrolyzers operate with a 95% capacity factor (e.g. they produce at 95% of their maximum rated capacity on average throughout their economic life). But, according to the dispatch figures in ref. [11], the maximum production rate for hydrogen is about 2,000 GW; 11 times higher than the 180.2 GW average production given in Table 1 of the same paper. Thus, the capacity factor of electrolysis equipment in the 100% wind, solar and hydroelectric power system would be roughly 9%, or an order of magnitude less than the utilization rate assumed in ref. [41]. Consequently, the costs for electrolyzers necessary to produce hydrogen at a rate of 2,000 GW are at least 10-25 times[7] higher than those reported by ref. [11], with the capital cost for these components totaling approximately \$2 trillion. Additional variable costs associated with water consumption and other variable operations and maintenance should be explicitly reported as well. In short, the total costs of hydrogen production required by the 100% wind, solar and hydroelectric power system in ref. [11] do not represent the scale of hydrogen production and utilization implied by the dispatch of hydrogen represented in the LOADMATCH simulations.

The electrification of the entire economy in the manner proposed in ref. [11, 12] would also require significant capital beyond what is suggested. For example, it is proposed that air travel would be fueled by hydrogen, as would substantial portions of other modes of transport and industrial processes. However, the technologies required to use hydrogen fuels do not exist for a variety of the applications envisioned and are very expensive for those applications that have been demonstrated. While the

[6] The DOE cost reduction target for high volume production of electrolyzers is \$320 / kW, so 2 TW of hydrogen electrolyzer capacity would be in excess of \$600 billion, ignoring all of the costs of the infrastructure to store, distribute and dispense the fuel [40].

[7] The higher value refers to the high value for capital cost of electrolyzers from ref. [41]. Only the lower value was used in ref. [11].

costs of hydrogen storage are included in the study, the costs of retrofitting large swaths of the transportation and industrial sectors to run on hydrogen fuel - or even the costs to develop these technologies in the first place - are not accounted for in the analysis. These costs would be substantial and could potentially motivate a completely different approach to producing fuels for transportation, particularly aviation.

S2.4: Flexibility of Demand. In addition to the errors related to the flexible demand, there are problems with assumptions of that flexible demand. Indeed, 63% of all energy-intensive industrial demand is assumed to be flexible, able to freely reschedule all energy inputs within an eight-hour window (this is in addition to the use of hydrogen, discussed in the previous subsection). Some industrial producers do participate in demand response programs currently and temporarily reduce or interrupt demand during periods of supply shortages for short periods of time [42]. However, the authors of ref. [11] provide no explanation or justification as to how (and why) industrial producers would be able or willing to schedule their production around variable renewable energy output on a daily basis, nor do the authors quantify the resulting economic impacts of doing this.

In short, the reliability of the 100% wind, solar and hydroelectric power system postulated in ref. [11] relies on reshaping energy demand to become extremely flexible such that demand can be made to conform to the variable output of renewable energy; rather than energy supplies being shaped to match patterns of demand, as is the mandate of the current U.S. energy system. Although such a system is theoretically possible, the authors of ref. [11] provide no evidence that this system is practical or reliable and do not adequately account for its deployment or operational costs.

S2.5: Capacity Factors for Existing Generation Technologies. The economic analysis in ref. [11] depends on assumptions about the ability to increase the capacity factor of existing generation technologies. In Table 2, note f of ref. [11], the capacity factor of geothermal power plants is given as 92.1%. That is much greater than the capacity factor of existing U.S. geothermal power plants of 73.6% in 2013 or 74% in 2014 [43]. There is only a brief discussion in [12] with regards to why these capacity factors increase. Similarly, combined U.S. and Canadian hydropower is assumed to increase its capacity factor from ~39% to 52.5%, but the authors of ref. [11] do not present analysis justifying this assumption or explaining the cost associated with increasing this capacity factor [12] other than an erroneous connection to EIA data that states hydroelectric could increase to 42% capacity factor. Because running existing units at much higher capacity factors reduces the need for other generation and storage devices, these assumptions reduce the estimated costs reported in ref. [11].

Figure 3 of the present paper shows that the 100% wind, solar and hydroelectric power system in ref. [11] consumes 43% more annual hydroelectric energy than in recent history. This extra energy will be needed at different times, in addition to current activities at hydroelectric power plants. Presumably, the changes needed to be made would cause water levels to rise and fall quite dramatically throughout the year. The additional water needed for the increased energy is not accounted for in either [11] or [12]. The authors of ref. [11, 12] state that the reservoir sizes do not increase, but this cannot be the case because more power is being drawn and therefore the head level will decrease rapidly, lowing power output.

To demonstrate the difficulty of getting the energy needed, consider Hoover Dam. It has a capacity of 2.1 GW. If we assume there needs to be 10x capacity nationally, this would rise to 21 GW. Currently there are nineteen turbines in the power plant. The power produced by a hydroelectric plant is

$$P = E * D * F * g * h,$$

where P is the power (W), E is the efficiency (%), D is the density of water (kg/m^3), F is the flow rate (m^3/s), g is gravitational acceleration (m/s^2) and h is the head height (m). If we assume Hoover Dam has a head height of 180m and an efficiency of 80%. We can see the maximum flow rate today should be

$$F_{max} = \frac{2.08 * 10^9}{0.8 * 1000 * 9.81 * 180} = 1472.4 \text{ m}^3/\text{s}.$$

The average capacity factor (1947–2008) of Hoover Dam has been 23.05%[8]. Therefore, the total volume of water used on an average year is 10.7 km^3 (or 54.7% of Lake Mead's active capacity). In 2015, the capacity factor was 19.8%[9], illustrating the lower water availability for hydroelectric power in much of the U.S. in recent years. Since, the authors of ref. [11] assume an increase of 43% from historical average values (see our Fig. 3), then Hoover Dam must produce 43% more electricity for a total of 6.01 TWh[10]. Using the calculation above, the increase in electricity production would require an additional 4.6 km^3 of water. Thus, on average Hoover Dam would be required to use 78.2% of the active capacity of Lake Mead.

The calculation above is simply one of water use. It is clear that more water would need to be passed through the turbines at hydroelectric power plants, regardless of the capacity. The additional need for water is not explained in [11] or [12]. Further, to compound the issues, the higher capacity is used to generate more power when necessary. This extra power results in more water moving downstream. From the calculations above, for Hoover Dam to have 21 GW capacity the maximum flow rate would be 14,724 m^3/s, which is greater than the capacity of the spillways at Hoover Dam. The extra water will cause issues downstream for all the other uses of the water, particularly irrigation. At other times, the power plants will be shutdown to store the water, presumably leaving the river to dry up downstream.

[8] data from: http://www.usbr.gov/lc/hooverdam/faqs/powerfaq.html

[9] Data from: http://www.usbr.gov/lc/region/g4000/24mo/2015/DEC15.pdf

[10] Average electricity generation for 1947 to 2008 was 4.2 TWh; 2015 was 3.6 TWh.

S2.6: Electricity Transmission. The authors of ref. [12] state: "We assume that 30% to 45% of total WWS generation (all generators except offshore wind) is sent through the new onshore long-distance grid and that 15% to 25% of offshore wind generation is sent through the extended-transmission offshore grid". Presumably the same values are used in ref. [11], since no other information is given. Again, no modeling, motivation, or reference relating to any of these assumed values is given.

Building a power system dependent on renewable resources will require a substantial expansion of long-distance transmission capacity to access higher-quality resources and transmit power to load centers, particularly for the onshore wind resource that is relatively far away from major load centers. In addition, the U.S. power system today remains balkanized into three weakly coupled electricity grids (or interconnections). Freely assuming that power could move back and forth between these systems at the continental scale, as the authors of ref. [11] implicitly do, is not feasible today, and enabling such power exchanges would require a continent-spanning set of high-voltage power lines and associated AC-DC-AC interconnection points [1]. Furthermore, refs [1] and [44] showed that explicitly considering transmission expansion alters how the generating capacity is distributed across the United States, diversifying the resource and reducing the need for storage dramatically. A detailed study by the National Renewable Energy Laboratory [2] concluded that for renewable energy to supply 90% of U.S. electricity alone (not all energy needs, as in ref. [11]) would require doubling existing installed U.S. long-distance transmission capacity (an increase of 200 million MW-miles of high-voltage transmission lines[11]) as well as adding 80 GW of new AC-DC-AC intertie capacity between the U.S. grids. Informed people can disagree about whether the scenarios presented by refs [1] and [2] would be feasible given constraints on building electric transmission lines. However, long-distance transmission needed to accommodate the 100% wind, solar and hydroelectric power system set out in ref. [11, 12] would be even larger and costlier.

S2.7: Cost of Capital. The analysis of the 100% wind, solar and hydroelectric power system in ref. [11] relies on exceptionally low discount rates (ranging from 1.5% to 4.5% with a baseline value of 3%) to calculate the levelized cost of energy. Since the wind, solar and hydroelectric technologies are capital cost intensive (there are no fuel costs), the discount rate is decisive for the economic analysis. Reducing the discount rate by a factor of two reduces the projected cost of capital by an even greater amount. The IPCC baseline discount rate for calculating the cost from wind and solar investments is 8% [10]; the PRIMES model used by the European Union sets the discount rate at 9% for the power sector [46]; the National Renewable Energy Laboratory (NREL) estimates the after-tax inflation-adjusted U.S. discount rate at 6.5% for on-shore wind [47]; the NEWS model used a real discount rate of 6.6% [1]; while the International Renewable Energy Agency (IRENA) [48] estimates a span between 5.5% and 12.6%, with a baseline of 10%. Rates can be significantly higher for technology investments seen as riskier, which includes offshore wind, tidal and wave [49].

Assuming the investments needed to reach a 100% wind, solar and hydroelectric power system envisioned in ref. [11, 12] would be made by private firms, it is instructive to look at what firms pay for access to capital - a rate revealed in the corporate debt markets. Low-risk firms such as well-managed regulated electric utilities have debt costs similar to the numbers assumed in the energy studies described above and about double the rate assumed in ref. [11]. Higher risk firms, such as those that populate the residential solar market, have much higher rates. In other research, scholars have shown how more realistic assumptions about capital costs can have a radical impact on patterns of investment when cutting emissions of greenhouse gases - shifting investment away from higher risk speculative technologies and toward lower risk opportunities while raising the overall cost of mitigation substantially [50].

It is also worth noting that according to the cost assumptions in Table 5 of ref. [12], excluded options (such as nuclear power and fossil fueled sources with carbon capture and storage) are lower cost than the offshore wind, solar with CSP, CSP with storage, rooftop solar and wave / tidal power considered in ref. [11]. This means the costs associated with the 100% wind, solar and hydroelectric power system from ref. [11, 12] are greater than a more diversified low-carbon energy system.

S2.8: Scale of Buildout and Pace of Change. Increasing annual production of wind, solar and hydroelectric technologies in the U.S. will likely be possible at substantially higher GDP-normalized rates than in Germany, owing to the more advantageous conditions for both wind and solar power in many areas of the U.S. compared with Germany (which is reflected in the higher capacity factors achieved in existing wind and solar power in the United States). However, the rates at which ref. [11] plans to add wind, solar and hydroelectric production capability (measured in the amount of energy produced per year) are an order of magnitude greater than the rates achieved in the German Energiewende, as depicted in Figure S4 below.

The continuous rates of addition of wind, solar and hydroelectric energy production in ref. [11][12] are 13 times higher than the GDP-normalized average rate achieved in the last seven years of the Energiewende in Germany (2007-2014). In fact, the average GDP-normalized rates required by ref. [11] year after year are six times higher than that achieved in the single fastest year of wind, solar and hydroelectric installation achieved to date in the German Energiewende (see Fig. S4). We use this metric because it also accounts for the capacity factor differences between generator types. It demonstrates the amount of extra energy that is needed each year from these new technologies.

Another metric that is helpful in illustrating the scale that the authors of ref. [11] are proposing is the amount of capacity per capita that must be added each year until 2050. This metric can be compared to rates in other countries. We show historical data for China, Germany, and the U.S. in Fig. 4. In addition, we show the 100% wind, solar and hydroelectric power system proposed values [11] and the computed values for [1]. Figure 4 shows that the authors of ref. [11] are suggesting a pathway that involves installing capacity at a rate that is 14.5 times greater than the U.S. historical average and 6.2 times

[11] In ref. [45], Table ES-8, p. 26: "Existing total transmission capacity in the contiguous United States is estimated at 150-200 million MW-miles".

[12] The best estimate of the energy-production-averaged operational lifetime of the proposed system presented in ref. [11] is ~26.7 years (using EIA estimates for operational lifetime of each technology), which also defines the rate at which the entire system (on average) may need to be replaced (~3.7% of the total system each year).

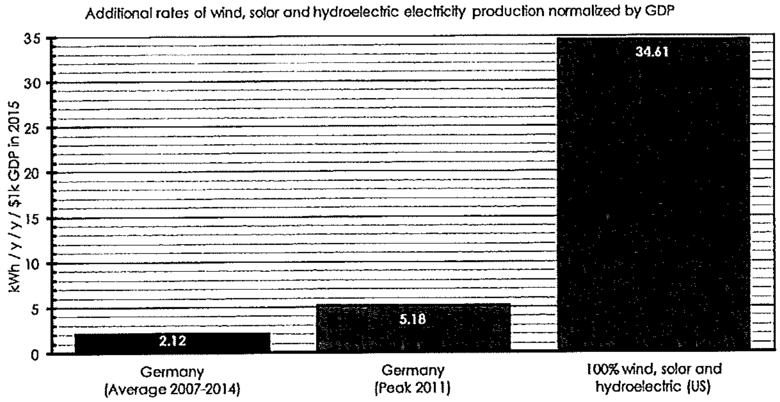

Fig. S4. GDP-normalized wind, solar and hydroelectric power addition rates of Germany (data from ref. [51]) and the rates implied for the 100% wind, solar and hydroelectric power system from ref. [11].

greater than the historical peak. The rate would have to be continued indefinitely because as 2050 is reached all units installed before 2020 would need to be replaced. From the "LRHG' scenario from ref. [1], it can be seen there is a requirement of increased capacity installations, but a rate lower than the historical peak within the United States.

A third metric of interest is the installation rate per year per $GDP. To do the analysis, estimations of GDP must be used. It is assumed that US GDP will grow at 2.08% per annum out to 2050[13]. In Fig. S5, we display historical rates for the United States, China, and Germany along with estimates for the 100% wind, solar and hydroelectric power system proposed in ref. [11] and the 80% carbon-free electricity system shown in ref. [1]. The 100% wind, solar and hydroelectric power system requires installation rates at twice the U.S. historical average (7.8 kW / y / $GDP). The rates would be on a level not seen since the 1970s in the U.S. and rival rates seen in China in the past few decades; where the economy was rapidly expanding. The average annual GDP growth rate of China for 1980 to 2015 was 9.77%[14], nearly five times the estimated GDP growth rate estimated for the US from 2016 to 2050. For comparison, the average installation rate (15.5 kW / y / $GDP) of the 100% wind, solar and hydroelectric power system is roughly seven times the average installation rate for the United States between 1980 and 2015 (2.3 kW / y / $GDP).

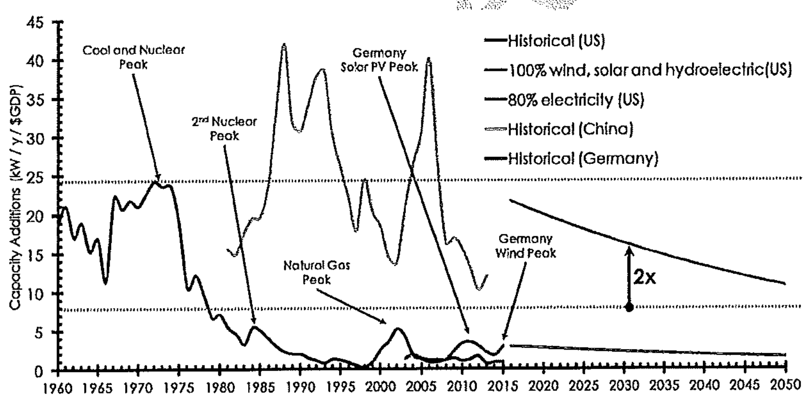

Fig. S5. Installed capacity per year per $ GDP. Historical data for the United States, China and Germany are shown along with the estimates for the 100% wind, solar and hydroelectric power system proposal [11] and the 80% carbon-free electricity system shown in ref. [1]. The 100% wind, solar and hydroelectric power system study requires installation rates at twice the historical average. China has a high rate due to the rapid expansion of their economy. The average annual GDP growth rate for 1980 to 2015 for China was 9.77%; nearly five times the estimate annual growth rate of the United States from 2016 to 2050. The average installation rate of the Jacobson et al. proposal is roughly seven times the average installation rate for the United States between 1980 and 2015.

It is clear that decarbonizing energy production using any combination of methods will be a huge challenge on many levels (economical, technological, societal). This is one of the most important reasons, as mentioned in the introduction of the present paper, why energy analysts and climate scientists across the globe propose to not exclude any potential technologies that could make the challenge more tractable. The implied premature decommissioning of existing (and under-construction) low emissions technology also add to the challenge in a very direct way. Over 60% of low-emission electricity production in the U.S. today is from nuclear power stations, many of which (including new plants nearing completion today) are to be prematurely

[13] US GDP growth rate of 2.08% is calculated from projections obtained from OECD: https://data.oecd.org/gdp/gdp-long-term-forecast.htm

[14] Data from: http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?end=2015&locations=CN&start=1980

decommissioned in the 100% wind, solar and hydroelectric power system plan. The costs of decommissioning these plants, including the opportunity cost, were not accounted for in ref. [11].

S2.9: Land-use Issues. Adding to the difficulty in the constrained 100% wind, solar and hydroelectric power system approach is the fact that the main energy sources (wind and solar) have a comparatively low areal energy density. According to NREL, the current best-estimate for land use of onshore wind farms is 0.33 km^2 / MW (= ~3 W / m^2, when including spacing) [52], which for the 100% wind, solar and hydroelectric power system proposal [11] translates to half a million square kilometers. To put this number in perspective, this is more than twice the total area of all urban areas in the U.S. combined[15] [53]. Added to this, an additional 100,000 square kilometers of land would be used for large-scale centralized solar PV and CSP plants [54], an area roughly the size of Kentucky. In the 100% wind, solar and hydroelectric power system plan [11], during a build-out period of 20-25 years (the assumed lifespan of wind turbines), over 65 km^2 of new U.S. land per day would have to be designated for energy production facilities. While this could theoretically be done, and indeed much of the land for wind turbines could remain dual-use (for instance for agriculture), the challenge of this undertaking should not be understated. In a system where a higher power density technologies are allowed to contribute, the land use requirements (and any associated scale-up challenges) for decarbonization of the energy system could be reduced dramatically.

[15] The Census Bureau method for estimating urban area includes urbanized areas with at least 50,000 people and urban clusters with 2,500-50,000 people but excludes portions of extended cities that are essentially rural in character and lands in rural residential uses.

S3: Insufficient Power System Modeling

The most fundamental elements missing from the LOADMATCH model used by authors of ref. [11] are: the ability to model frequency regulation and compute transmission power flows and associated reliability; the ability to show how much transmission would be needed, its costs, and where the transmission would need to be placed; the inclusion of operating reserves necessary to ensure reliability in the face of unexpected failures of generators or transmission lines, demand contingencies and renewable energy forecast errors.

The reliability and stability of power grids require frequency regulation resources, yet LOADMATCH does not have the capability to simulate these requirements. Instead, in ref. [12], the authors assert, "Frequency regulation of the grid can be provided by ramping up/down hydroelectric, stored CSP or pumped hydro; ramping down other WWS generators and storing the electricity in heat, cold, or hydrogen instead of curtailing; and using demand response". Ref. [12] does not cite analysis or demonstration of the viability of this approach. In addition, the authors present ref. [11] as a "grid integration" study, but do not mention frequency regulation in the main text. Inspection of the supplemental information of that paper reveals that frequency regulation was not modeled at all. While studies evaluating high penetration of renewables at a national level do not usually include frequency regulation, the authors of ref. [11] make the unique statement that frequency response can be provided, even though they did not analyze the viability of the statement.

While it is likely that future power systems could depend to a greater extent on synthetic inertia from asynchronous generators like wind and solar photovoltaic (PV) or management of loads or thermal storage, these techniques remain unproven at scale. Given current technologies, power system operators in isolated regions with high penetrations of wind and/or solar PV limit the instantaneous production of power from these asynchronous generation sources to 50-75% of total generation in order to preserve sufficient physical inertia to manage grid frequency [42, 55]. The issue of system inertia stability is an important and likely solvable challenge, but the models used in the 100% wind, solar and hydroelectric power system study [11] do not confront this challenge, which is critical to demonstrating the reliability of a system with high penetration of variable renewables. With 87.95% of annual energy supplied in 2050 by wind and solar PV on average in the 100% wind, solar and hydroelectric power system, these resources would, for much of the time, constitute 100% of instantaneous power generation; 100% power generation by variable generation for extended periods is beyond anything that has been proven technically feasible for the stability of an isolated grid. Only 7.4% of installed capacity (corresponding to a theoretical maximum of ~28% of estimated average load) in the proposed power system is capable of providing conventional inertia for frequency regulation, and of this capacity, 95% consists of hydroelectric and concentrating solar thermal power (CSP), the availability of which varies significantly on a seasonal basis.

An important gap in the analysis of ref. [11] is that it does not provide evidence that the proposed system can maintain sufficient frequency regulation to preserve power system stability. The designers of power markets have known for decades that there is a need for improved markets that reward ancillary services that contribute to grid reliability [56]. Yet, to date, these markets remain erratic; even the market that have made the greatest strides, the PJM ancillary services market, have a largely unfinished agenda.

In addition to not addressing the challenges associated with maintaining frequency regulation in a system with very high penetrations of variable and asynchronous generation, the LOADMATCH model does not provide the provision of operating reserves necessary to maintain reliability in the case of unplanned outages of transmission lines and generation or storage facilities and errors in forecasted wind and solar output and demand. Studies of existing wind and solar projects and experience in power systems with growing shares of variable renewable resources demonstrate that solar and wind energy forecast errors can be significant: for example, errors related to variable output caused by cloud cover and other meteorological conditions that have been documented at coastal and inland solar PV and CSP plants in California [57–59]. Again, this omission is substantial, given that the envisioned power system relies overwhelmingly on wind and solar energy generation with deterministic, but chaotic, output.

Further, the authors of ref. [11] state that the LOADMATCH model "assumes a fully interconnected grid" that does not include any transmission constraints. Those authors state that "the impact of transmission congestion on reliability is not modeled explicitly", and simply assume that there is unlimited transmission availability and that if "congestion is an issue at the baseline level of long-distance transmission, increasing the transmission capacity will relieve congestion with only a modest increase in cost". This is a striking set of assumptions given that it has proven extremely difficult to site vital transmission lines, notably near urban areas (where loads are concentrated).

We note that if hydroelectric power were expanded to the level implied by the numbers we find in [11], and there was an infinite super-grid that covered the whole of the contiguous U.S., then the frequency regulation problem would be substantially reduced. Hydroelectric turbines can do a large amount of fast ramping and contain significant inertia. If large amounts of hydroelectric power is coupled with advanced wind/solar frequency response systems and advanced demand response the most recent literature suggests that the frequency regulation issue is solvable.

S4: Inadequate Scrutiny of the Climate Model that is Employed

Instead of employing actual data from meteorological datasets, the authors of ref. [11] use time-dependent variable wind and solar resources (every 30 seconds for 6 years) predicted with a 3D global climate/weather model called GATOR-GCMOM. As the wind and solar resource values produced by GATOR-GCMOM are the core inputs to the energy production simulation employed by LOADMATCH, the performance, resolution, and accuracy of GATOR-GCMOM in predicting local wind speeds and solar resource levels are central to the conclusions reached in ref. [11, 12].

S4.1: Inadequate Evaluation of Climate Model Results. The authors of ref. [11] refer us to [60–62] for assessment of the appropriateness of the GATOR-GCMOM model for its present purpose. Referring to a model with a slightly different name (GATOR-GCMM), the authors of the ref. [60] report normalized gross wind-speed errors for their non-nested model of 46.1% with a bias of -35.7% for the domain surrounding San Francisco, California, which is the only domain evaluated. No broader evaluation of wind or solar intensity fields is provided in ref. [60]. In ref. [61], the only evaluation of modeled wind or solar fields is a single supplemental figure (Fig. S2 in that work) illustrating some first order correspondence between global wind fields over the ocean as projected by the model and as inferred from satellite imagery. No quantitative analysis is provided but visual inspection of the figure indicates factor of two errors in annual mean wind speeds in many locations. One can presume that errors are larger on shorter time scales. Further, no assessment is provided of reliability of the model to project winds speeds or solar intensity over land. In ref. [62], the only evaluation of the modeled wind or solar fields is the assessment of its ability to simulate peak winds in three hurricanes after the model has been run in assimilation mode. No evaluation of general wind or solar intensity fields is provided in ref. [62].

Unlike widely used major climate models, users of the GATOR-GCMOM model have never participated in any of the major international climate model inter-comparison projects (e.g., CMIP5 [63]) and thus, the validity of this model has not been assessed by the IPCC (e.g., [26, 64]). The authors of ref. [11] have not demonstrated that the weather data is suitable for estimating resource potential for either solar or wind power. There has been no peer reviewed evaluation of this model regarding its performance in predicting the statistics of wind speeds and associated temporal and spatial correlations. There has been no published evaluation of the model regarding its performance in predicting downward solar radiation near the Earth surface and its associated spatial and temporal correlations. Further, there has been no evaluation of model performance regarding correlation between wind speed and insolation. These quantities are central to the conclusions reached in ref. [11].

S4.2: Questions about Adequacy of Model Resolution. In contrast to the use of 30-second time steps in the matching of load and generation, the spatial resolution of the weather data is coarse. At the finest resolution (2° x 2.5°), the grid cells are ~220 km on a side. Thus, any wind turbines and solar panels within a single grid cell will be homogenous with respect to power output. It is well known that wind farms are not correlated with each other at a 30-second period over several hundreds of kilometers [65]. Further, the depiction of the terrain at those resolutions is not useful for monitoring wind speed acceleration over slopes. For example, the authors of ref. [1] utilized 13-km resolution data assimilation that blends actual observation data (about 25,000 per hour) and a background field to estimate the resource each hour [66–68].

Assumptions made by the authors of ref. [11] about wind turbine competition for kinetic energy are also problematic. Since many wind turbines are within the tens of thousands of square kilometer area represented by each model grid cell, the wakes of the turbines cannot be resolved and thus information about how they interact is lacking. Thus, estimates of power generated per wind turbine in ref. [11] is questionable.

S4.3: Representation of Correlations and Anti-correlations between Load and Weather. The load data used in the model by the authors of ref. [11] is not closely based on actual load data. Assumptions are made about the conversion of industries, heating, and transportation using yearly values. This is then temporally disaggregated into 30-second bins. Further, the load data are not related to the weather that is being supplied as the resource. Therefore, in the study [11], a main driver of electricity (and energy) use does not exhibit the observed correlations (and anti-correlations) with electricity (and energy) supply. In addition, it is assumed that all non-flexible loads behave exactly as the aggregated electricity demand did in 2006 and 2007, something there is insufficient evidence provided for.

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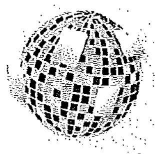
CLACK EXHIBIT B

PNAS Submission & Editorial Review

HOW IT WORKS . . .

1. OVERVIEW



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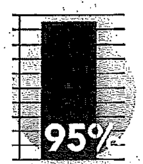

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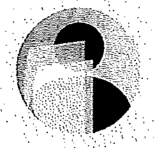

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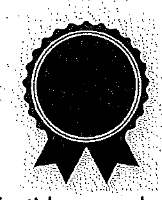

All articles are evaluated solely on their scientific merit by peers—not by staff editors. Accepted papers must be of exceptional scientific importance and intelligible to a broad scientific audience.

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CLACK EXHIBIT C

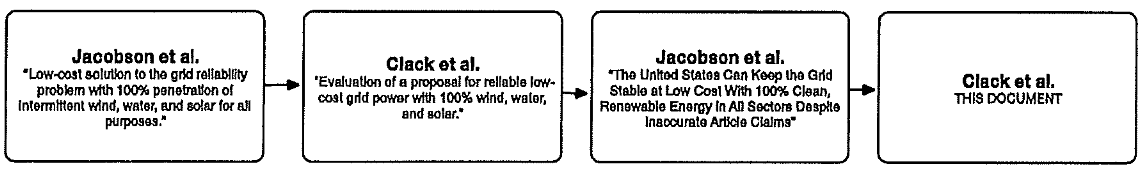
Response to Jacobson et al. (June 2017)

Introduction

This document contains point-by-point responses to the reply by Jacobson et al. to the article "*Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar*".

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. have suggested that future primary energy sources for the United States should be narrowed to almost exclusively wind, solar, and hydroelectric power and 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 have found and published that their analysis involves errors, inappropriate methods, and implausible assumptions. Jacobson et al. have, in their reply, tried to challenge some of the errors we have identified, and this is our response to that reply.

Publications timeline



Download links for reference:

1. Jacobson et al. original article
2. Clack et al. critique
3. Jacobson et al. reply
4. Clack et al response to reply (this document)

Contact information

For questions or comments about this document, please contact Dr Staffan Qvist at staffanq@gmail.com

Summary of Jacobson et al. reply critique

Answers to nearly all of the criticism by Jacobson et al. presented here can be found by reading the original Clack et al. paper and, crucially, its supporting information document. The Jacobson et al. critique to which we respond here comes in three general forms:

1. Attempted references (including several self-references) to studies that have made the same mistakes as Jacobson et al. and/or have used the same or similar assumptions or have reached similar conclusions. In some cases, this referencing effort includes misrepresenting statements from the IPCC and others.
2. Defense by critique of other studies, most notably one paper co-authored by Christopher Clack[1]. Again, this is irrelevant for the matter at hand here.
3. Purposefully refusing to acknowledge clear mistakes. This is most clearly seen in this exchange from the discussion of installed capacity of hydropower in the Jacobson et al. models.

Guide to this document

In this document, Jacobson reply-claims are stated in yellow boxes, our responses are in the attached grey boxes. In order to keep the claims in their exact original form, we refer the reader to the reference list of Jacobsons reply document for references written with square brackets: []. Most importantly, reference [1] refers to the Clack et al. critique of the Jacobson et al. paper, which is reference [2].

We have tried to keep answers here short, so for further information we refer the reader to the Supporting Information of the Clack et al. document, where most of these topics are expanded upon in greater detail.

[1] An interesting side-note is that Mark Jacobson, in stark contrast to these most recent comments, quite recently wrote favourably of this article "*the study pushes the envelope to show that intermittent renewables plus transmission can eliminate most fossil fuel electricity while matching power demand at lower cost than a fossil-fuel-based grid, even before storage is considered.*", until finding out that one of its co-authors was involved in pointing out the fundamental errors of his own studies (Jacobson 2016).

#1 Jacobson et. al claim
First, [1] implies [2] is an outlier for excluding nuclear and CCS. To the contrary, Jacobson et al. are in the mainstream, as grid stability studies finding low-cost up-to-100% clean, renewable solutions without nuclear or CCS are the majority [3-16].

#1 Response
The point made by Clack et. al is that the a priori exclusion of potentially major contributors to a low carbon energy system is likely to lead to a sub-optimal solution. For instance, nuclear power produces over 60% of total US low-carbon electricity today, but in Jacobson et al. they are omitted entirely from consideration (even the use of existing, profitable, operational plants).

Contrary to Jacobson et al's assertion that successful renewables-only pathways emerge from the "majority" of studies, in a large recent comprehensive review of decarbonization studies, the only studies that did not include a significant contribution from nuclear, biomass, hydropower, and/or carbon capture and storage are those that exclude these resources from consideration to begin with (Jenkins and Thernstrom 2017). The studies that Jacobson et. al. reference illustrates the point. Not one of the studies cited include nuclear or CCS as options for the electricity mix, making the statement that these studies "find" solutions without these components rather obvious (once they are excluded, nothing else is possible).

Reference [4] is a *self-reference* (co-authored by Jacobson), references [5-9] and [10-11] are all produced by the same authors. Excluding the self-reference, the cited studies are produced by a total of 5 different author groups, thus doing nothing to validate the scientifically irrelevant claim that the Jacobson et. al type of study design is "*mainstream*" or in the "*majority*". None of the studies referred to make the claims that Jacobson et al. have made, and are thus not applicable.[2]

For a more detailed discussion of the references, please download the following document: "RESPONSE TO JACOBSON ET AL. CLAIM THAT THERE ARE MANY 100% RE STUDIES THAT BACK UP THEIR CLAIM TO RELY ALMOST ENTIRELY ON WIND, SOLAR, AND HYDRO"

#2 Jacobson et. al claim
Second, IPCC [17] contradicts [1]'s claim that including nuclear or CCS reduces costs (7.6.1.1): "...high shares of variable RE power...may not be ideally complemented by nuclear, CCS,..." and

[2] For example, ref. [5] states more modestly: *"Although the results illustrate a potential 100% renewable energy-system for Ireland, they have been obtained based on numerous assumptions. Therefore, these will need to be improved in the future before a serious roadmap can be defined for Ireland's renewable energy transition."*

Ref. [12] states: *"The power capacities of the storage and balancing facilities are not determined; this would require a more complex modeling with explicit inclusion of power transmission. We focus on wind and solar power and assume no bottlenecks in the power grid, employ an optimal storage dispatch strategy* ***and ignore*** *storage charge and discharge capacities and* ***economic aspects."***

(7.8.2) "Without support from governments, investments in new nuclear power plants are currently generally not economically attractive within liberalized markets,..."

#2 Response
The above is a misrepresentation of the IPCC text, which clearly does not include any contradiction to anything stated in the Clack et al. analysis. IPCCs statement that "High shares of renewables ***may*** not be ***ideally complemented*** by nuclear and CCS" (emphasis added) is hardly motivation to not include either option in any analysis aimed at identifying optimal low-carbon energy systems.

#3 Jacobson et. al claim
Similarly, [18] state, *"...there is virtually no history of nuclear construction under the economic and institutional circumstances that prevail throughout much of Europe and the United States,"* and [19], who compared decarbonization scenarios, concluded, *"Neither fossil fuels with CCS or nuclear power enters the least-cost, low-carbon portfolio."*

Third, unlike Jacobson et al., IPCC, NOAA, NREL, or IEA has never performed or reviewed a cost analysis of grid stability under deep decarbonization. For example, [20]'s grid-stability analysis considered only electricity, which is only ~20% of total energy, thus far from deep decarbonization. Further, deep-decarbonization studies cited by [1] have never analyzed grid stability. [2] obtained grid stability for 100% WWS across all energy sectors, thus simulated complete energy decarbonization.

Fourth, [*1*]'s objectives, scope, and evaluation criteria are narrower than [*2*]'s, allowing [*1*] to include nuclear, CCS, and biofuels without accounting for their true costs or risks. [*2, 21*] sought to reduce health, climate, and energy reliability costs; catastrophic risk; and land requirements while increasing jobs. [*1*] focuses only on carbon. By ignoring air pollution, they ignored bioenergy, CCS, and even nuclear health costs [*22*]; by ignoring land use they ignored bioenergy feasibility; by ignoring risk and delays, they ignored nuclear feasibility, biasing their conclusions.

Fifth, [*1*] contends that [*2*] "places constraints" on technology options. To the contrary, Jacobson et al. include many technologies and processes not in Clack et al's models. For example, [*2*] includes but [*20*] excludes CSP, tidal, wave, geothermal, solar heat, any storage (CSP, pumped-hydro, hydropower, water, ice, rocks, hydrogen), demand-response, competition among wind turbines for kinetic energy, electrification of all energy sectors, calculations of load decrease upon electrification, etc. Model time steps in [*20*] are also 120- times longer than in [*2*],

#3 Response
While the co-authors of study [20] probably appreciate discussions on potential limitations of their model, all of the comparative statements above are entirely irrelevant to the matter at hand here.

#4 Jacobson et. al claim

[Clack] claims wrongly that [*MZJ*] assumes a maximum hydropower output of 145.26 GW even though [*2*] Table S.2 shows 87.48 GW. [*Clack*] then claims incorrectly that the 1,300 GW drawn in [*MZJ*] Fig. 4(b) is wrong because it exceeds 87.48 GW, not recognizing 1,300 GW is instantaneous and 87.48 GW, a maximum possible annual average (Table S.2, Footnote 4 and the available LOADMATCH code).

#4 Response

As is clearly stated in Clack et. al, 145.26 GW was the most generous interpretation that could be made (summing pumped hydro storage and hydropower outputs), somewhat reducing the massive hydropower modelling error in Jacobson et. al. This statement confirms that the error is actually more severe than this.

In addition, there is no basis or supporting analysis for the assumption that 87.48 GW could be an annual average hydropower output, since this would correspond to almost 3 times the average annual hydropower production in the US over the last three decades (US EIA 2017).

#5 Jacobson et. al claim

1,300 GW is correct, because turbines were assumed added to existing reservoirs to increase their peak instantaneous discharge rate without increasing their annual energy consumption, a solution not previously considered. Increasing peak instantaneous discharge rate was not a "modeling mistake" but an assumption consistent with [*2*]'s Table S.2, Footnote 4 and LOADMATCH, and written to Clack Feb. 29, 2016.

#5 Response

Nowhere in the 28 pages of main and supplemental material of the Jacobson et al. paper is there any mention or analysis of an expansion of hydropower. As confirmed above, the installed capacity of the hydroelectric system is stated as 87.48 GW.

Table S2. **CONUS installed WWS electric/thermal generator installed capacities in 2013 and proposed for 2050, along with capital costs of the generators and numbers of devices.**[1]

	CONUS installed 2013 (GW)	Proposed existing plus new CONUS 2050 installed (GW)
Hydropower[4]	87.42	87.48

Table S2, of the supporting information document of Jacobson et. al (2015)

The scale of this error is staggering. The maximum instantaneous electricity generation capacity of *all* electricity sources in the United States today is 1170 GW (U.S. Energy Information Administration 2017). ***Jacobson et al. neglects to mention an assumed 1500% expansion in generation capacity of hydropower, leading to this system being capable of producing more power than all sources combined in the US today.***

One should note that the 1300 GW number is only what we have been able to infer from Figure 4 in the Jacobson et. al paper – it does not appear that any upper limit has been imposed at all on this value in the model. The capacity factor of wind power during the night of simulation day 1475 (in which 1300+ GW of hydropower is shown to be used) is around 24%. Since this is far above the likely minimum combined capacity factor of wind power seen during a night in a 5-year period[3], the actual installed hydroelectric capacity used in the model is actually far higher than 1300 GW. Perhaps even more alarmingly, had Jacobson et al. selected a time period for Figure 4 that did not happen to include high hydropower output, this error may never have come to light.

For the benefit of the reader, the footnote on the fourteenth page of the supporting information of the Jacobson et al. paper (Table S.2. Footnote 4) does nothing to change this error. It states, in full: "*Hydropower use varies during the year but is limited by its annual power supply. When hydropower storage increases beyond a limit due to non-use, hydropower is then used for peaking before other storage is used.*"

#6 Jacobson et. al claim

[*2*] only neglects the cost of additional turbines, generators, and transformers needed to increase the maximum discharge rate. Such estimated cost for a 1000-MW plant [*23*] plus wider penstocks is ~$385 (325-450)/kW, or ~14% of hydropower capital cost. When multiplied by the additional turbines and hydropower's fraction of total energy, the additional infrastructure costs ~3% of the entire WWS system and thus doesn't impact [*2*]'s conclusions. Increasing CSP's, instead of hydropower's, peak discharge rate also works.

[1] (Fig. 3) then claims mistakenly that [2]'s annual hydropower energy output is 402 TWh/yr and too high, when it is 372 TWh/yr because they missed transmission and distribution losses. This is less than half the possible U.S. hydropower output today, well within reason.

[*1*] next claims wrongly that [*2*] Table 1 loads are "maximum possible" loads even though the text clearly indicates they are annual-average loads. The word "maximum" is never used. They compound this misrepresentation to claim flexible loads in [*2*]'s time figures are twice "maximum possible" loads even though [*2*] P.15,061 clearly states that the annual loads are distributed in time.

[3] For comparison, the minimum 1-hour combined capacity factor of all renewable energy sources in the EU (including wind power data from 12 countries and solar PV data from 5 countries) was 3.39%, 2.64% and 2.75% in 2012, 2013 and 2014 respectively.

#6 Response

In addition to not adding any costs at all to this, the Jacobson et al. study also neglects that additional turbines need extra water and therefore penstocks, tunnels, and space. Even disregarding all hydrological and legal constraints, one cannot simply assume that one can fit at least 15x more turbines in same space. A radically increased instantaneous flow rate would have a number of downstream impacts, such as: impact on other downstream (and upstream) hydro power plants, fisheries and ecosystem destruction, flooding of towns, illegal breach of water rights of downstream farmers and cities, loss of recreation and endangered species impacts.

For an output of 372 TWh/y, as stated above, the actual hydropower capacity factor of the WWS-system is at or below 3.26%. However, Jacobson et al. also states "*the annual average capacity factor of hydropower as used in LOADMATCH was given in Footnote d of Table 2 as 52.5% (before T&D losses)*". This is an assumed value based on a fictitious installed capacity of 87.48 GW and is therefore entirely nonsensical.

To illustrate one of the many problems that the omission of analysis regarding this capacity expansion entails, the Hoover Dam has been used as an example in Clack et. al supporting information section S.2.5.

Here are a couple more examples:

If the capacity at all major hydropower facilities are assumed to expand by the same relative amount, the Grand Coulee Dam would have a new peak power rating of 101 GW – more than all hydropower in the US combined today, and 4.5 times larger than the largest power plant of any kind ever constructed (the Three Gorges Dam). The required flow rate through the upgraded Grand Coulee Dam at full power would regularly need to be 5.5 times higher than the largest flow rate of its part of the river ever recorded in history, which occurred on June 12, 1948, during an historic Columbia River flood period (US Bureau of Reclamations 2017). This flow rate corresponds to 13 times the average discharge rate of the entire Columbia river system, 9 times higher than the peak discharge rate ever in January (when the Jacobson et. al. system assumes 1300 GW of total output), and 3.5 times the maximum spillway capacity of the Grand Coulee dam. One can only imagine the environmental impacts of the massive flooding of lands, towns and cities downstream of such reservoirs once water is released so rapidly.

The Robert Moses dam at the Niagara river (the 4th largest US hydro plant), once it is "upgraded", would then be relied upon to occasionally deliver up to 36.43 GW (by then also far larger than the world's largest-capacity power plant today). This would require a flow 6.3 times higher than the highest ever recorded flow rate of the entire Niagara river (recorded in May 1929), and about 18 times higher than its average total flow rate. To put it mildly, this project is hardly likely to be popular either with tourists, downstream and upstream residents or with the Canadians power plant operators drawing water from the same river.

The same type of examples as those above can be made for essentially all other major hydropower facilities in the US. As has been shown, the hydropower capacity error is one of many in the Jacobson et al. study, but it is so large (and so obvious) that it by itself invalidates the entire effort.

#7 Jacobson et. al claim

[*1*] asserts that UTES can't be expanded nationally, but we disagree. UTES is a form of district heating, which is already used worldwide (e.g., 60% of Denmark), UTES is technologically mature and inexpensive; moreover, hot water storage or heat pumps can substitute for UTES. Similarly, molten salt can substitute for PCM in CSP storage.

#7 Response

Clack et al. has not at all asserted that UTES (specifically BTES) *cannot* be expanded, but rather that the expansion suggested in Jacobson et al. is on an unrealistic scale and not appropriately costed. As stated, both UTES and PCM are promising resources, but 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 Jacobson et al. UTES analysis does not include an accounting of the costs of the physical infrastructure (pipes and distribution lines) to support these systems. The reference used by Jacobson et al. for costing of the UTES system is a 10-page conference publication, which includes a "financial model" spanning roughly half of one page, and a capital costs section of two paragraphs. The capital costs section actually ends midsentence (exact quote) (Gaine and Duffy 2010):

"The total of these add up to give the capital costs associated with the BTES system. Industry quotations, rates and estimates were obtained and were applied to each system analysed. Piping from the borehole headers to the energy centre have been accounted for based on an average pipe length of 75 meters. Labor rates used are based on industry quotations and"

It is not clear whether this information can or should be relied upon to accurately cost the main underpinning technology of the entire future US energy system.

Solar district heating (SDH) with UTES on large scales and at high rates of deployment is rare outside of Denmark. Countries that have seen significant usage of SDH, most notably Denmark, are outliers, and can do so specifically because of the high penetration of legacy district heating systems that pre-date the solar components of the system. Capital costs for SDH systems (including the majority, which do not have UTES) ranged from around 400-800 $\$/m^2$ of installed collector area in Europe, energy costs ranged from 5 cents / kWh in Denmark to 11 cents / kWh in Austria (Dalenbäck och Werner, Market for Solar District Heating (pg. 16) 2012) (Dalenbäck 2010). The cost of the Drake Landing system in Canada (the example UTES is modelled by in Jacobson et al.) is far higher. Capital costs for Drake Landing were over 1145 $\$/m^2$ of collector area (far higher than the most expensive SDH systems in Europe), due to the need to install brand new storage and distribution infrastructure (Sibbitt, The performance of a high solar fraction seasonal storage district heating system – five years of operation. 2012) (Sibbitt 2015). The capital costs for Drake Landing suggest a UTES installation cost of at least $1.8 trillion for the Jacobson et al. system, nearly four times the mean-estimate used by Jacobson et al.

The argument that hot water storage could substitute for UTES is nonsensical. Hot water storage is not a cost-effective seasonal energy storage strategy, as a hot water tank does not have the same heat flow properties as soil or concrete. In addition, moving heating sectors toward heat pumps will further increase electricity loads which would need to be included in the modelling.

#8 Jacobson et. al claim
[*1*] further criticizes [*2*]'s hydrogen scale-up, but this is easier than [*1*]'s proposed nuclear or CCS scale-up. [*1*] also questions whether aviation can adopt hydrogen, but a 1500-km- range, 4-seat hydrogen fuel cell plane already exists, several companies are now designing electric-only planes for up to 1500 km and [*21*] proposes aircraft conversion only by 2035- 2040.

#8 Response
This again is diversion from the matter at hand, which are the errors and implausible assumptions in the work of *Jacobson et. al.* The total worldwide production of hydrogen from electrolysis is approx. 2.6m tons/year, corresponding to an average electrolysis power consumption of ~16 MW (International Energy Agency 2012). The US electrolysis scale-up envisioned by Jacobson et al. is thus at least a factor *100,000x* increase over total world electrolysis capacity today.

In contrast, both Sweden and France decarbonized their electricity grids in less than two decades by expanding nuclear power. As has been shown (Qvist and Brook 2015), continued nuclear power plant construction at the relative (GDP-normalized) rates that France or Sweden have already achieved, could theoretically decarbonize global electricity production in three decades. While carbon capture and storage facilites of commercial scale have been in operation for nearly 50 years, CCS indeed remains to be implemented at commercial scale at power plants.

#9 Jacobson et. al claim
[*1*] questions whether industrial demand is flexible, yet the National Research Council review it cites ("Real Prospects for Energy Efficiency in The U.S". P. 251) states, "Demand response can be a lucrative enterprise for industrial customers."

#9 Response
It remains to be explained how it could be "lucrative" for an "industrial customer" to suffer frequent multi-hour blackouts at their production facilities without being paid any compensation. One of the many criticisms of the Jacobson et al. treatment of "flexible load" is that it has no associated costs. Indeed, the very statement by NRC that demand response can be lucrative suggests that grid operators need to offer substantial returns to industrial customers to induce them to shed load. That makes industrial load shedding less economically feasible, not more. Demand response in the sense that one can tailor electricity consumption to lower the average electricity costs, which indeed could be lucrative, is a voluntary exercise on the part of the "industrial customer" and an entirely different phenomena than what is imposed by the system in Jacobson et al.

#10 Jacobson et. al claim
[*1*] criticizes [*2*]'s use of a 1.5%-4.5% discount rate even though that figure is a well- referenced social discount rate for a social cost analysis of an intergenerational project [*21*, Supp. Info. P. 44].

#10 Response
Ref [21] is a self-reference to another Jacobson et al. publication, adding nothing to defend these numbers. An earlier version of the Jacobson et al. response included the statement "*The only relevant studies are those that are recent and among those, Lazard (10.0) is the most detailed and relied upon by the energy industry, and capital costs are consistent with that study and other contemporary studies*". The 3.0% (span of 1.5-4%) discount rate used by Jacobson et al. is less than half of the 8.0% used by the source that Jacobson et al. previously cited as support for their value (Lazard 2016), which may explain why it is no longer referred to and has been replaced by a self-reference.

Using realistic discount rates instead of those used by Jacobson et al. would alone *double* the estimated levelized cost of electricity.

#11 Jacobson et. al claim
[*1*] states misleadingly that [*2*]'s storage capacity is twice U.S. electricity capacity, failing to acknowledge [*2*] treats all energy, which is 5 times electricity, not just electricity, and [*2*] storage is only 2/5 all energy. Further, [*2*] storage is mostly heat.

#12 Response
The Clack et al. claim is correct: the total combined nameplate capacity (maximum theoretical output) of all electricity generators in the US today is estimated at 1.17 TW (U.S. Energy Information Administration, 2017), and is meant to give the reader a relatable sense of scale.

Furthermore, Jacobson et al. are wrong in their numbers even in this response. The fraction of electricity in US energy consumption is not 20% but rather 39% (US Energy Information Administration 2017), and this share is not likely to decrease with an electrification of additional sectors as proposed in the plans of Jacobson et al.

#13 Jacobson et. al claim
[*1*] claims the average installed wind density is 3 W/m^2, but fails to admit this includes land for future project expansion and double counts land where projects overlap. Also, real data from 12 European farms give 9.4 W/m^2 (P. Enevoldsen, pers. comm.)

#13 Response
Clack et al. accurately reports the value from the NREL study on the subject (Denholm 2009), as wrongly referenced by Jacobson et al. (2015). The NREL study conclusion is: "*Excluding the outliers, the reported data represents a capacity density range of 1.0 to 11.2 MW/km² and an overall average capacity density of 3.0 ± 1.7 MW/km².*"

A personal communciation reference added to a reply document 2 years after publication, the data and real source of which cannot be verified, does nothing to correct the erroneous reporting of data from the NREL report that was referenced in Jacobson et al. study. In addition, this new number is different from that used in the Jacobson et al. paper, so even if verified and shown to be applicable, this does not remove the error.

#14 Jacobson et. al claim
[1] claims [22] didn't rely on consensus data for CO2 lifecycle estimates although [22]'s nuclear estimate was 9-70 g-CO2/kWh, within IPCC's [17] range, 4-110 g-CO2/kWh. [1] claims falsely that [22] didn't include a planning-to-operation time for offshore wind, even though P. 156 states 2-5 yr.

#14 Response
As stated in the Clack et al. article: "*The life-cycle GHG emissions for nuclear power generation in [ref. 22] 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****. 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.***" (Emphasis added). 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 production from uranium.

Whether the values cited happen to fall within the range of IPCC or not is in this case irrelevant, since nuclear and other potentially contributing sources to the system were excluded from consideration, based on what can only be described as a highly "selective assessment" of its merits.

No opportunity costs related to planning and construction time of offshore wind farms were included in the [22] study. The only operational US offshore wind farm (the 30 MW Block Island Wind Farm) had a planning, permitting & construction period well above the upper limit of Jacobson et al. values (7+ years). The largest proposed off-shore wind farm (468 MW Cape Wind) is now in its 16th year of planning and permitting – it is not yet operational.

#15 Jacobson et. al claim
Clack et al. criticize [22] for considering weapons proliferation and other nuclear risks, although IPCC [17] agrees (Executive Summary): "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,...(robust evidence, high agreement)."

#15 Response
Jacobson's publication (ref. [22]) suggests that any use of civilian nuclear power will lead to nuclear wars to periodically reoccur on a 30-year cycle. This is quite far away from the IPCC statement, listing one of the barriers to the expanded use of nuclear energy as concerns regarding potential nuclear weapons proliferation.

#16 Jacobson et. al claim
Clack et al. claim falsely that GATOR-GCMOM "has never been adequately evaluated," despite it taking part in 11 published multi-model inter-comparisons and 20 published evaluations against wind, solar, and other data; [24]'s evaluation that GATOR-GCMOM is "the first fully-coupled online model in the history that accounts for all major feedbacks among major atmospheric processes based on first principles;" and hundreds of processes in it still not in any other model [25].

[*1*] contends LOADMATCH is not transparent even though LOADMATCH has been publicly available since [*2*]'s publication.

#16 Response
We refer the reader to Section S4.1: Inadequate Evaluation of Climate Model Results of Clack et al. for a detailed discussion on this.

We suggest that Jacobson et al. makes the full timeline of simulation output data available publicly, in addition to the four days of simulation that one can see in the paper itself.

#17 Jacobson et. al claim
[1] criticizes LOADMATCH for not treating power flows, and claims [2]'s transmission costs are "rough." Yet [1] doesn't show such costs are unreasonable or acknowledge [2]'s HVDC cost per km [21] are far more rigorous than [20]'s.

#17 Response
Remarkably, Jacobson et al. do not model the electricity grid at all in a paper claiming to solve the "grid reliability problem", making its title severely misleading. They neglect to show how much or where transmission would need to be built to get energy from sources to users. Comparisons to [21], which in stark constrast to Jacobson et al. does in fact model the electricity grid, are a diversion and not the subject of the Clack et al. critique or this response.

#18 Jacobson et. al claim
Finally, [1] falsely claims LOADMATCH has perfect foresight, thus is deterministic. However, LOADMATCH has zero foresight, knowing nothing about load or supply the next time step. It is prognostic, requiring trial and error, not an optimization model.

#18 Response
The actual claim by Clack et al. is; "It should be noted that LOADMATCH models generation from wind and solar a priori and then aggregates them together. It does not determine the capacity of generation endogenously. The model is essentially one-dimensional; all loads, generation and storage are considered in a single place though time. Thus, the sensitivity analysis performed ultimately relies only on changes in storage and demand response (and erroneous hydropower capacity) on a trial and error basis."

The LOADMATCH model also fails to account for a range of realistic power system operation constraints, including the need for various categories of operating reserves necessary to ensure demand and supply can remain balanced following errors in renewable energy forecasts, demand forecasts, or unanticipated failures of power plants or transmission lines. The model also does not account for typical constraints on thermal generators, including geothermal and concentrating solar thermal units (such as ramp rate constraints and minimum up and down times related to thermal stress on steam systems and minimum stable output levels for online units). Taking these factors into account is critical for appropriately evaluating the reliability of power systems with high shares of variable renewable resources (Palmintier och Webster 2016). As a deterministic model with perfect foresight, LOADMATCH does not perform a stochastic optimization that would endogenously account for uncertainty in renewable energy or load forecasts or power plant or transmission contingencies (Zheng, Wang och Liu 2015), nor does it deterministically model reserve requirements based on offline studies of forecast errors or plant/line failure probabilities as is best practice in modeling reliable power system operations (de Sisternes 2013). This can result in significant errors due to abstraction of relevant power system details and the failure to account for the full variability of renewable resources, demand, and contingencies. Claims that the model demonstrates the reliability of power systems with 100% WWS are therefore suspect.

#19 Jacobson et. al claim In sum, [1]'s analysis is riddled with errors and has no impact on [2]'s conclusions.
#19 Response The Jacobson et al. work has been show very clearly to contain a large number of fundamental errors, each on their own invalidating the results of the studies (many of which are not at all brought up by this response).

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CLACK EXHIBIT D

The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims

Mark Z. Jacobson[a,1], Mark A. Delucchi[b], Mary A. Cameron[a], and Bethany A. Frew[a]

The premise and all error claims by Clack et al. (1) in PNAS, about Jacobson et al.'s (2) report, are demonstrably false. We reaffirm Jacobson et al.'s conclusions.

False Premise

Clack et al.'s (1) premise that deep decarbonization studies conclude that using nuclear, carbon capture and storage (CCS), and bioenergy reduces costs relative to "other pathways," such as Jacobson et al.'s (2) 100% pathway, is false.

First Clack et al. (1) imply that Jacobson et al.'s (2) report is an outlier for excluding nuclear and CCS. To the contrary, Jacobson et al. are in the mainstream, as grid stability studies finding low-cost up-to-100% clean, renewable solutions without nuclear or CCS are the majority (3–16).

Second, the Intergovernmental Panel on Climate Change (IPCC) (17) contradicts Clack et al.'s (1) claim that including nuclear or CCS reduces costs (7.6.1.1): "...high shares of variable RE [renewable energy] power...may not be ideally complemented by nuclear, CCS,..." and (7.8.2) "Without support from governments, investments in new nuclear power plants are currently generally not economically attractive within liberalized markets,..." Similarly, Freed et al. (18) state, "...there is virtually no history of nuclear construction under the economic and institutional circumstances that prevail throughout much of Europe and the United States," and Cooper (19), who compared decarbonization scenarios, concluded, "Neither fossil fuels with CCS or nuclear power enters the least-cost, low-carbon portfolio."

Third, unlike Jacobson et al. (2), the IPCC, National Oceanic and Atmospheric Administration, National Renewable Energy Laboratory, and International Energy Agency have never performed or reviewed a cost analysis of grid stability under deep decarbonization. For example, MacDonald et al.'s (20) grid-stability analysis considered only electricity, which is only ~20% of total energy, thus far from deep decarbonization. Furthermore, deep-decarbonization studies cited by Clack et al. (1) have never analyzed grid stability. Jacobson et al. (2) obtained grid stability for 100% wind, water, and solar power across all energy sectors, and thus simulated complete energy decarbonization.

Fourth, Clack et al.'s (1) objectives, scope, and evaluation criteria are narrower than Jacobson et al.'s (2), allowing Clack et al. (1) to include nuclear, CCS, and biofuels without accounting for their true costs or risks. Jacobson et al. (2, 21) sought to reduce health, climate, and energy reliability costs, catastrophic risk, and land requirements while increasing jobs. Clack et al. (1) focus only on carbon. By ignoring air pollution, the authors ignore bioenergy, CCS, and even nuclear health costs (22); by ignoring land use they ignore bioenergy feasibility; by ignoring risk and delays, they ignore nuclear feasibility, biasing their conclusions.

Fifth, Clack et al. (1) contend that Jacobson et al. (2) place "constraints" on technology options. In contrast, Jacobson et al. include many technologies and processes not in Clack et al.'s (1) models. For example, Jacobson et al. (2) include, but MacDonald et al. (20) exclude, concentrated solar power (CSP), tidal, wave, geothermal, solar heat, any storage (CSP, pumped-hydro, hydropower, water, ice, rocks, hydrogen), demand-response, competition among wind turbines for kinetic energy, electrification of all energy sectors, calculations of load decrease upon electrification, and so forth. Model time steps in MacDonald et al. (20) are also 120-times longer than in Jacobson et al. (2).

False Error Claims

Clack et al. (1) claim wrongly that Jacobson et al. (2) assume a maximum hydropower output of 145.26 GW, even though table S2 in Jacobson et al. shows 87.48 GW. Clack et al. (1) then claim incorrectly that the 1,300 GW drawn in figure 4B of Jacobson et al. (2) is wrong because it exceeds 87.48 GW, not recognizing that 1,300 GW is instantaneous and 87.48 GW, a maximum possible annual average [table S2, footnote 4 in Jacobson et al. (2) and the available LOADMATCH code]. The value of 1,300 GW is correct, because turbines were

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Author contributions: M.Z.J. and M.A.D. designed research; M.Z.J., M.A.D., M.A.C., and B.A.F. performed research; M.Z.J. and M.A.D. contributed new reagents/analytic tools; M.Z.J. and M.A.D. analyzed data; and M.Z.J., M.A.D., M.A.C., and B.A.F. wrote the paper.

The authors declare no conflict of interest.

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assumed added to existing reservoirs to increase their peak instantaneous discharge rate without increasing their annual energy consumption, a solution not previously considered. Increasing peak instantaneous discharge rate was not a "modeling mistake" but an assumption consistent with Jacobson et al.'s (2) table S2, footnote 4, and LOADMATCH, and written to Clack on February 29, 2016.

Jacobson et al. (2) only neglect the cost of additional turbines, generators, and transformers needed to increase the maximum discharge rate. Such estimated cost for a 1000-MW plant (23) plus wider penstocks is ~\$385 (325–450)/kW, or ~14% of hydropower capital cost. When multiplied by the additional turbines and hydropower's fraction of total energy, the additional infrastructure costs ~3% of the entire wind, water, and solar power system and thus doesn't impact Jacobson et al.'s (2) conclusions. Increasing CSP's—instead of hydropower's—peak discharge rate also works.

In their figure 3, Clack et al. (1) then claim mistakenly that Jacobson et al.'s (2) annual hydropower energy output is 402 TWh/yr and too high, when it is actually 372 TWh/yr because they missed transmission and distribution losses. This is less than half the possible United States hydropower output today and well within reason.

Clack et al. (1) next claim wrongly that in Jacobson et al.'s (2) table 1, loads are "maximum possible" loads, even though the text clearly indicates they are annual-average loads. The word "maximum" is never used. Clack et al. (1) compound this misrepresentation by claiming flexible loads in Jacobson et al.'s (2) time figures are twice "maximum possible" loads, even though Jacobson et al. clearly state that the annual loads are distributed in time.

Unsubstantiated Claims About Assumptions. Clack et al. (1) assert that underground thermal energy storage (UTES) can't be expanded nationally, but we disagree. UTES is a form of district heating, which is already used worldwide (e.g., 60% of Denmark); UTES is technologically mature and inexpensive; moreover, hot-water storage or heat pumps can substitute for UTES. Similarly, molten salt can substitute for phase change materials in CSP storage.

Clack et al. (1) further criticize Jacobson et al.'s (2) hydrogen scale-up, but this is easier than Clack et al.'s (1) proposed nuclear or CCS scale-up. Clack et al. (1) also question whether aviation can adopt hydrogen, but a 1,500-km range, four-seat hydrogen fuel cell plane already exists, several companies are now designing electric-only planes for up to 1,500 km, and Jacobson et al. (21) propose aircraft conversion only by 2035–2040.

Clack et al. (1) question whether industrial demand is flexible, yet the National Academy of Sciences (24) review they cite states, "Demand response can be a lucrative enterprise for industrial customers."

Clack et al. (1) criticize Jacobson et al.'s (2) use of a 1.5–4.5% discount rate, even though that figure is a well-referenced social discount rate for a social cost analysis of an intergenerational project (21).

Clack et al. (1) state misleadingly that Jacobson et al.'s (2) storage capacity is twice United States electricity capacity, failing to acknowledge that Jacobson et al.'s (2) report treats all energy, which is five times electricity, not just electricity, and in Jacobson et al. (2), storage is only two-fifth of all energy. Furthermore, in Jacobson et al.'s (2) report, storage is mostly heat.

Clack et al. (1) claim the average installed wind density is 3 W/m^2, but fail to admit this includes land for future project expansion and double counts land where projects overlap. Furthermore, real data from 12 European and Australian farms give 9.4 W/m^2.

Clack et al. (1) claim that Jacobson (22) didn't rely on consensus data for CO_2 lifecycle estimates, although Jacobson's nuclear estimate was 9–70 g-CO_2/kWh, within the IPCC's (17) range, 4–110 g-CO_2/kWh.

Clack et al. (1) claim falsely that Jacobson (22) didn't include a planning-to-operation time for offshore wind, even though ref. 22 states 2–5 y.

Clack et al. (1) criticize Jacobson (22) for considering weapons proliferation and other nuclear risks, although the IPCC (17) agrees (Executive Summary): "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, . . .(robust evidence, high agreement)."

False Model Claims. Clack et al. (1) claim falsely that the gas, aerosol, transport, radiation-general circulation mesoscale, and ocean model (GATOR-GCMOM) "has never been adequately evaluated," despite it taking part in 11 published multimodel intercomparisons and 20 published evaluations against wind, solar, and other data; despite Zhang's (25) evaluation that GATOR-GCMOM is "the first fully-coupled online model in the history that accounts for all major feedbacks among major atmospheric processes based on first principles"; and despite hundreds of processes in it still not in any other model (26).

Clack et al. (1) contend that LOADMATCH is not transparent, even though LOADMATCH has been publicly available since Jacobson et al.'s (2) publication.

Clack et al. (1) criticize LOADMATCH for not treating power flows, and claim that Jacobson et al.'s (2) transmission costs are "rough." However Clack et al. (1) do not show such costs are unreasonable or acknowledge Jacobson et al.'s (2) high-voltage direct current cost per kilometer (21) are far more rigorous than MacDonald et al.'s (20).

Finally, Clack et al. (1) falsely claim that LOADMATCH has perfect foresight, thus is deterministic. However, LOADMATCH has zero foresight, knowing nothing about load or supply the next time step. It is prognostic, requiring trial and error, not an optimization model.

In sum, Clack et al.'s (1) analysis is riddled with errors and has no impact on Jacobson et al.'s (2) conclusions.

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CLACK EXHIBIT E

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Dear Drs. Clack and Jacobson,

We have now published both of your recent articles in PNAS and have considered the messages we subsequently received: 1) The request from Jacobson for a retraction and 2) the response from Clack et al. to this request (see enclosed).

Both the original Jacobson et al. article from 2015 and the recent Clack et al. article passed muster through peer review. There is clearly a scientific disagreement about how to address these issues, and the scientific community will have to make their own assessments of the articles.

PNAS will not continue to referee this situation and will not be taking further action. We urge you to continue to work to resolve the matter through additional research. If either party would like to clarify statements in their own papers, we would allow it. Otherwise, PNAS considers the matter closed.

Best wishes,

Inder M. Verma
Editor-in-Chief

CLACK EXHIBIT F

Errata

Clarification to "A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes, " by Mark Z. Jacobson, Mark A. Delucchi, Mary A. Cameron, and Bethany A. Frew, first published December 8, 2015; 10.1073/pnas.1510028112 (Proc Natl Acad Sci USA 112:15060-15065).

The authors clarify Footnote 4 of Table S2 (Supplementary Information) to state, "As stated in Section 5.4 of [1] but reiterated here, 9.036 GW of the 87.48 GW of previously-installed hydropower in this table are Canadian installations providing pre-existing imported hydropower. (The difference between the 87.48 GW here and the 87.86 GW in [1] is that the former is for the 48 contiguous United States and the latter is for all 50 states). The 87.48 GW in this table is not only the contemporary installed hydropower capacity, it is also the maximum *potential* annually averaged discharge rate of hydropower both today and in 2050 in this study. Thus, this maximum *potential* annually averaged rate is held constant over time here. The *actual* annually averaged discharge rate of hydropower in this study for 2050 is 45.92 GW (Table 2), which is much less than the 87.48 GW maximum *potential* annually averaged value. However, as indicated in Figures 2b, S4b, and S5b, it is assumed here that 1,282.5 GW of turbines are added to existing hydropower dams to increase the maximum *instantaneous* discharge rate of hydropower to a total 1,370 GW without changing the reservoir size or maximum *potential* annually averaged discharge rate of hydropower of 87.48 GW. Thus, while the peak discharge rate may increase significantly for some hours, it decreases significantly for others to ensure the *actual* annually averaged discharge rate of hydropower is not much different from today and much less than maximum annual value, 87.48 GW. This can be accomplished by modifying powerhouses to increase either the number or capacity of turbines and the instantaneous flow rate of water to them, by either adding pipes around or above dams or widening penstocks through dams. The cost of electrical equipment (turbines, generators, and transformers) in a hydropower plant ranges from ~\$560/kW for 500 MW plants to ~\$200-\$300/kW for 1000 MW plants (Figs. 4.5 and 4.7 of [2]). We start with the cost for a large 1000-MW plant and add costs for pipes or widening penstocks and for equipment housing and contingencies due to possible supply shortages to arrive at an estimated total cost of the additional hydropower turbines of roughly \$385 (325-450) per kW. This amounts to ~\$494 billion for all of the additional turbines proposed here, which would increase the total all-sector capital cost in Table 2 by a mean of just over 3%. We believe this cost increase has no impact on the main conclusions of this study. Even if costs were much higher, there are multiple other low-cost solutions with zero added hydropower turbines but more CSP and batteries instead, not only for North America, but also for 20 world regions, so the increase in hydropower peak instantaneous discharge is just one of several options."

1. M.Z. Jacobson, M.A. Delucchi, G. Bazouin, Z.A.F. Bauer, C.C. Heavey, E. Fisher, S.B. Morris, D.J.Y. Piekutowski, T.A. Vencill, T.W. Yeskoo, 100% clean and renewable wind, water, sunlight (WWS) all-sector energy roadmaps for the 50 United States, Energy and Environmental Sciences, 8 (2015) 2093-2117.
2. IRENA (International Renewable Energy Agency), Renewable Energy Technologies: Cost analysis series. Hydropower, Vol. 1(3), IRENA, Abu Dhabi, 2012.

CLACK EXHIBIT G

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Written Testimony to the United States House of Representatives Committee on Energy and Commerce Democratic Forum on Climate Change November 19, 2015 at 2 PM, Washington D.C.

By Mark Z. Jacobson, Stanford University (Witness)

Roadmaps for 139 Countries and the 50 United States to Transition to 100% Clean, Renewable Wind, Water, and Solar (WWS) Power for all Purposes by 2050 and 80% by 2030

Synopsis

- Researchers at Stanford University and the University of California have developed roadmaps to transition the energy infrastructures of 139 countries and the 50 United States to 100% clean, renewable infrastructures running on existing-technology wind, water, and solar (WWS) power for all purposes by 2050, with 80% conversion by 2030.

- All-purpose energy includes electricity, transportation, heating/cooling, industry, and agriculture/forestry/fishing.

- Converting the 50 states, 139 countries, and remaining countries of the world will have the following impacts: (1) eliminate 4-7 million annual worldwide premature air pollution mortalities and their costs, (2) eliminate global warming and its costs, (3) create over 20 million more 35-year global jobs than lost, (4) stabilize energy prices because fuel costs are near zero, (5) reduce international conflict by creating energy-independent regions, (6) reduce terrorism risk by decentralizing power, and (7) reduce the social cost (business + health + climate costs) of energy by 60%.

- The main barriers to a conversion are neither technical nor economic; rather, they are social and political.

- These roadmaps should give confidence to leaders at COP 21 in Paris that their countries can obtain 100% clean, renewable WWS energy by 2050 with substantial conversion by 2030, and that a commitment to a 100% by 2050 goal is scientifically based.

Methodology

- The idea is to electrify everything, thereby eliminating combustion (the burning of fuel) as a source of energy, pollution, and inefficiency. Electrifying everything reduces power demand relative to conventional fuels by ~32% averaged across all energy sectors due to the efficiency of electricity over combustion. Another ~7% reduction in demand can be obtained from end-use energy efficiency improvements beyond those that would occur by 2050 with conventional fuels.

- For electric power, the WWS technologies to be deployed include onshore and offshore wind turbines, rooftop and power-plant solar photovoltaics (PV), concentrated solar power (CSP) plants, solar heat collectors, geothermal power plants for electricity and heat, existing hydropower plants, and small numbers of tidal and wave devices.

- For ground transportation, the technologies to be used include battery electric vehicles (BEVs) and hydrogen fuel cell (HFC) vehicles, where the hydrogen is produced from electricity passing through water. BEVs with fast charging or battery swapping will dominate long-distance, light-duty ground transportation. Battery electric-HFC hybrids will dominate heavy-duty ground transportation and long-distance water-borne shipping. Batteries will power short-distance shipping. Electrolytic cryogenic hydrogen plus batteries will power aircraft.

- For air heating and cooling, the technologies to be used include electric heat pumps (ground-, air-, or water-source) and some electric-resistance heating. Heat pumps with electric resistance elements and/or solar hot water preheaters will be used to heat domestic water. Cook stoves will have either an electric induction or a resistance-heating element.

- Energy for high-temperature industrial processes will come from electric arc furnaces, induction furnaces, dielectric heaters, resistance heaters, and some combusted hydrogen.

- Storage for electricity includes hydroelectric plants, pumped-hydroelectric facilities, and CSP plants coupled with storage. Storage media for heat include water and rocks and soil under ground; for cold, they include water and ice. Excess electricity will also be used to produce hydrogen and to heat water and rocks.

Results

- Every country we looked at, including France, the Netherlands, Congo, South Africa, Bangladesh, Sri Lanka, Israel, Peru, Guatemala, and all major countries participating in the upcoming international climate negotiations, can ramp up to 100% clean, renewable energy by 2050. Across all continents, some combination of wind, water, and solar allows virtually every country to be energy independent and self sufficient in terms of annual-average power, although small countries and states will likely find advantage in exchanging electrical energy with neighbors.

- For example, a new study in the *Proceedings of the National Academy of Sciences* (embargoed until Monday, November 23) shows that a 100% conversion of the 48 contiguous United States to WWS will result in a 100% reliable grid 100% of the time even after accounting for the intermittency of wind, water, and solar resources and power demand, if the states are reasonable interconnected. Maintaining grid stability requires combining intermittent WWS generation with existing-technology low-cost electricity, heat, and cold storage and demand response.

- A 100% conversion to WWS worldwide will nearly eliminate 4-7 million premature air-pollution-caused mortalities per year worldwide and 60,000-65,000 premature mortalities per year in the United States. To put these findings in perspective, consider that the Centers for Disease Control and Prevention estimates that 6 million people die each year globally from tobacco-related diseases.

- In the United States, we calculate that 100% conversation to WWS will prevent 60,000-65,000 premature mortalities. Again, to put that in perspective, this is twice as many people as lost each year to motor vehicle accidents according to the National Highway Traffic and Safety Administration.

- Avoiding the mortalities, ten times more morbidities, and other environmental impacts of non-greenhouse-gas chemical air pollutants will save the United States and the world over 3% of their respective GDPs annually. Such savings accrue in the form of lower insurance rates, lower workman's compensation rates, lower taxes, higher worker productivity, fewer lost work days, fewer lost school days, fewer hospitalizations, fewer emergency room visits, less agricultural crop damage, less building, statuary, and tire erosion, and better quality of life.

- A 100% conversion worldwide will eliminate $16-20 trillion/year in global climate costs by 2050. 100% conversion in the U.S. alone will eliminated $3.3 trillion/year in global climate costs.

- A 100% conversion will stabilize energy prices because fuel costs of WWS electric power are zero, whereas fuel costs of fossil fuels are above zero and rise over time.

- A 100% conversion will save each U.S. consumer $260 (190-320)/year (in 2013 dollars) in energy costs in 2050 and will save the U.S. $1,500 (210-6,000)/year and $8,300 (4,700-17,600)/year per person in health and climate costs, respectively.

- A 100% conversion will create over 20 million more 35-year construction plus operation jobs worldwide than it costs. In the U.S., it will create over 2 million more jobs than it costs.

- A 100% conversion worldwide will require less than 0.4% of the world's land for the footprint of new devices and less than 1% of the land for spacing between onshore wind turbines. Spacing area can be used for multiple purposes.

- 100% conversions worldwide and in the U.S. will reduce terrorism risk by creating more distributed electric power sources, such as wind and rooftop solar, reducing the need for centralized power plants (such as coal, natural gas, and nuclear plants) and oil refineries that are subject to terrorist attack. As retired general and admirals at the Military Advisory Board recently concluded, a reliable grid is a safer grid (https://www.cna.org/CNA_files/PDF/National-Security-Assured-Electrical-Power.pdf).

- A 100% conversion worldwide and in the U.S. will reduce international conflict by reducing each country's dependence on energy from other countries.

- The 2050 business cost of a WWS energy, storage, plus long-distance transmission 100% reliable system is similar to the business cost of a 2050 business-as-usual system, but the 2050 social cost (business + health + climate costs) of a WWS system is ~40% that of a business-as-usual system.

- In sum, there is a significant benefit across the board and little downside to a 100% conversion to WWS for all purposes. The main barriers to a conversion are social and political, not technical or economic.

Resources

- Clickable maps summarizing each country and U.S. state roadmap are available at *The Solutions Project* website, http://thesolutionsproject.org and at the *National Geographic* website, http://www.nationalgeographic.com/climate-change/carbon-free-power-grid/#cover

- All papers and spreadsheets describing the roadmaps can be found at http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html.

- The specific published papers on the roadmaps to date include the following:

- **Roadmap to transition the world as a whole (but not individual countries):**

Jacobson, M.Z., and M.A. Delucchi, A path to sustainable energy by 2030, *Scientific American*, November 2009 (cover), www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.

- **Roadmap to transition the world as a whole in more detail and the U.S. as a whole (but not individual states or countries).**

Jacobson, M.Z., and M.A. Delucchi, Providing all Global Energy with Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials, *Energy Policy*, 39, 1154-1169, doi:10.1016/j.enpol.2010.11.040, 2011, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html

Delucchi, M.Z., and M.Z. Jacobson, Providing all global energy with wind, water, and solar power, Part II: Reliability, System and Transmission Costs, and Policies, *Energy Policy*, 39, 1170-1190, doi:10.1016/j.enpol.2010.11.045, 2011, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.

- **Roadmap to transition New York State:**

Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobies, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, and A.R. Ingraffea, Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, *Energy Policy*, 57, 585-601, 2013, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.

- **Roadmap to transition California:**

Jacobson, M.Z., M.A. Delucchi, A.R. Ingraffea, R.W. Howarth, G. Bazouin, B. Bridgeland, K. Burkhart, M. Chang, N. Chowdhury, R. Cook, G. Escher, M. Galka, L. Han, C. Heavey, A. Hernandez, D.F. Jacobson, D.S. Jacobson, B. Miranda, G. Novotny, M. Pellat, P. Quach, A. Romano, D. Stewart, L. Vogel, S. Wang, H. Wang, L. Willman, T. Yeskoo, A roadmap for repowering California for all purposes with wind, water, and sunlight, *Energy, 73,* 875-889, doi:10.1016/j.energy.2014.06.099, 2014, http://www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.

- **Roadmap to transition Washington State:**

Jacobson, M.Z., M.A. Delucchi, G. Bazouin, M.J. Dvorak, R. Arghandeh, Z. A.F. Bauer, A. Cotte, G.M.T.H. de Moor, E.G. Goldner, C. Heier, R.T. Holmes, S.A. Hughes, L. Jin, M. Kapadia, C. Menon, S.A. Mullendore, E.M. Paris, G.A. Provost, A.R. Romano, C. Srivastava, T.A. Vencill, N.S. Whitney, and T.W. Yeskoo, A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State, *Renewable Energy*, *86*, 75-88 2016, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html.

- **Roadmap to transition each of the 50 United States:**

Jacobson, M.Z., M.A. Delucchi, G. Bazouin, Z.A.F. Bauer, C.C. Heavey, E. Fisher, S. B. Morris, D.J.Y. Piekutowski, T.A. Vencill, T.W. Yeskoo, 100% clean and renewable wind, water, sunlight (WWS) all-sector energy roadmaps for the 50 United States, *Energy and Environmental Sciences*, *8*, 2093-2117, doi:10.1039/C5EE01283J, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html, http://pubs.rsc.org/en/content/articlelanding/2014/ee/c5ee01283j#!divAbstract

- **Grid reliability study of the 48 contiguous United States (Available Nov. 23)**

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes, *Proc. Nat. Acad. Sci.*, *112*, doi: 10.1073/pnas.1510028112, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html.

- **Roadmap to transition 139 countries of the world:**

Jacobson, M.Z., M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, Alphabetical: C. Bozonnat, L. Chobadi, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, S.H. Harrison, T.M. Kwasnik, J. Liu, J. Lo, C.J. Yi, S.B. Morris, K.R. Moy, P.L. O'Neill, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, and A.S. Yachanin, 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html.

Thank you for considering this testimony.

Sincerely,

Mark Z. Jacobson

Mark Z. Jacobson,

IN THE SUPERIOR COURT
FOR THE DISTRICT OF COLUMBIA
Civil Division

MARK Z. JACOBSON, Ph.D., **Plaintiff,** **v.** **CHRISTOPHER T. M. CLACK, Ph.D.** ***et al.*****,** **Defendants.**	**Civil Action No. 2017 CA 006685 B** **Hon. Elizabeth Carroll Wingo** **Next Court Date: December 29, 2017** **Event: Initial Conference**

[PROPOSED] ORDER

Upon consideration of Defendant Christopher Clack's' Special Motion to Dismiss Pursuant to the District of Columbia Anti-SLAPP Act or in the Alternative Pursuant to Rule 12(b)(6) and the opposition and reply brief thereto, it is this ___ day of ______________, 2018, hereby

ORDERED, that the Defendant Christopher Clack's Motion to Dismiss is GRANTED; and Count I of Plaintiff's Complaint is dismissed with prejudice; and it is further

ORDERED, that Defendant Christopher Clack may file a motion for his attorneys' fees and costs.

____
Judge Elizabeth Carroll Wingo
District of Columbia Superior Court

105782753\V-1

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