[3] Renewable Rap Battle: A scathing critique of Mark Jacobson's 100% renewable grid proposal

Some policy recommendations attain notoriety because they're simple, and because they appeal to the hopes of people who support them. The thankless work of a "critic", dating back to ancient Greece where the word was derived (κριτικός), is to judge if these policies make sense. Modern day energy critics separate innovations from illusions, and steer us towards actionable, achievable solutions.

In 2015, Stanford's Mark Jacobson and three other researchers published a paper on a low-cost solution to the US grid which would rely **100% on wind, hydro and solar power by 2050**. Their 2015 paper is an updated version of an article they first published in *Scientific American* in 2009[12]. You may have read about their all-renewable US grid idea, or their recent work applying the same concept to 139 countries. Many media outlets and energy blogs cite Jacobson's proposal as a vision of a possible renewable energy future, if only we just would reach for it.

In 2017, the battle began. A large team of scientists and researchers from US universities, think tanks and research labs published a paper in the *Proceedings of the National Academy of Sciences*[13] which (there is no other way to put this) **savaged** the Jacobson proposal. It's worth reviewing some of the arguments in their rebuttal, since they illustrate the challenges and complexity of designing real-world energy solutions. While 21 researchers participated in the PNAS paper, for simplicity, we refer to it here as the "Clack rebuttal". Here's their overarching **conclusion** on Jacobson's proposal:

> "The authors 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. However, the modeling errors described, 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."

Affiliations of the 21 authors participating in the Clack rebuttal

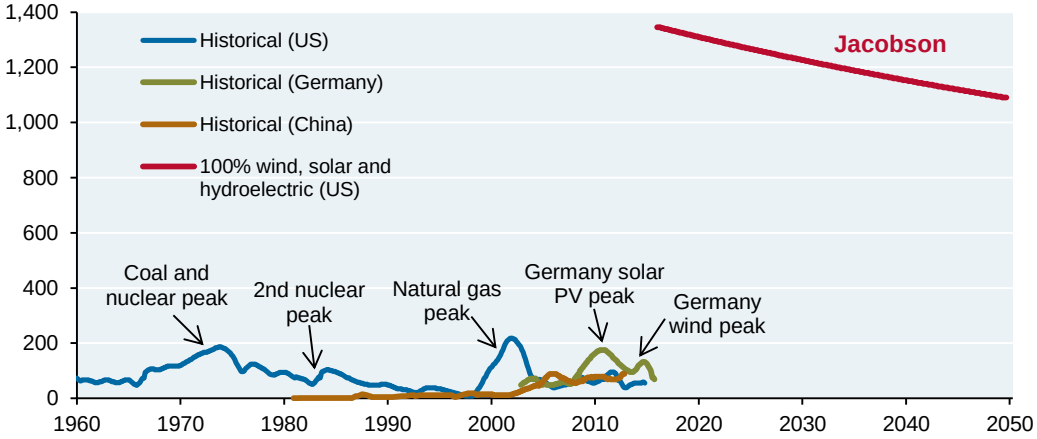
- Carnegie Institution for Science (Department of Global Ecology)
- Carnegie Mellon University (Department of Engineering and Public Policy; Tepper School of Business)
- Columbia University (Center for Global Energy Policy)
- Lawrence Livermore National Laboratory
- NOAA Earth System Research Laboratory
- Stanford University (Department of Energy Resources Engineering; Management Science and Engineering Department; Precourt Energy Efficiency Center)
- UC Berkeley (Energy and Resources Group; Goldman School of Public Policy; Renewable Energy Laboratory)
- UC Irvine (Department of Earth System Science)
- UC San Diego (Department of Mechanical and Aerospace Engineering; School of Global Policy and Strategy)
- Univ. of Colorado (Inst. for Research in Environmental Sciences; Renewable and Sustainable Energy Institute)
- University of Vermont (Electrical Engineering and Complex Systems Center)
- Uppsala University (Department of Physics and Astronomy)
- Brookings Institution and the Council on Foreign Relations

[12] **Even in 2009, Jacobson's thesis came under fire**. Physicist Michael Briggs at the University of New Hampshire wrote the following in response to Jacobson's article: "As a physicist focused on energy research, I find this paper so absurdly and poorly done that it is borderline irresponsible. There are so many mistakes, it would take hours of typing to point out all of the problems." [Source: M. Briggs, Letter to the editor, *Scientific American*, 2009].

[13] "*Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar*", Clack et al, *Proceedings of the National Academy of Sciences*, February 2017. Sources for Jacobson's original piece, the Clack rebuttal, the Jacobson response and another Clack rebuttal are found on p.33. In 2017, Jacobson sued Clack for intellectual defamation, but withdrew the lawsuit in 2018.

The simplest way to illustrate the scope of Jacobson's proposal is to compare it to the pace of prior capacity additions. The first chart shows annual electricity generation capacity additions from 1960 to 2015 for the US, Germany and China, measured per capita. Peak additions were associated with US nuclear and natural gas build-outs, Germany's solar and wind era and China's 21st century grid upgrade. Look at the red line: as per the Clack rebuttal, Jacobson proposed capacity additions are 14x larger than what took place over the prior 50 years, a staggering amount and pace of new generation.

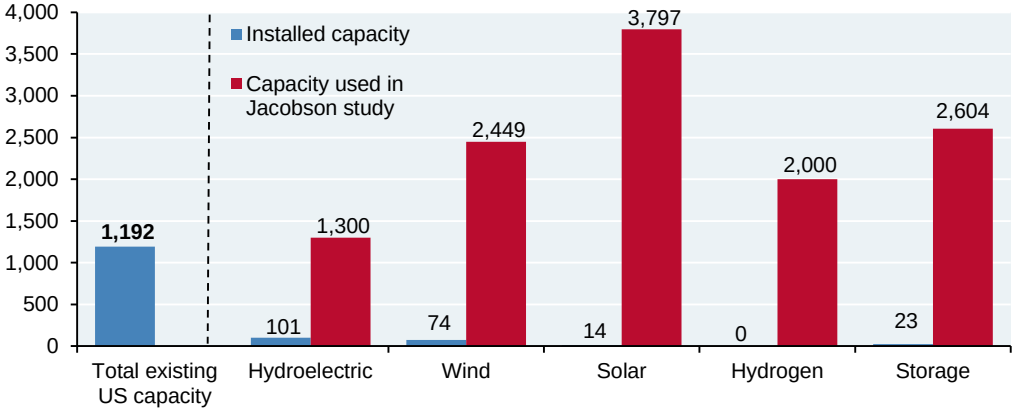
Historical rates of installed electric-generating capacity per capita
Capacity additions, watts per year per capita



Source: *"Evaluation of a proposal for reliable low-cost grid power with 100% wind, water and solar,"* Clack et al. 2017.

Another look: according to the Clack rebuttal, Jacobson assumes that new US solar, wind, hydro, hydrogen and storage capacity (red bars) will *each* be built out on a scale that **exceeds the *entire* US electricity generation system** as it exists today (blue bar).

Jacobson proposal: each of 5 renewable technologies are built-out to be larger than today's entire US electricity grid, GW



Source: *"Evaluation of a proposal for reliable low-cost grid power with 100% wind, water and solar"*, Clack et al. February 2017.

If the scope/cost of Jacobson's proposal were its only issues, I wouldn't write about it. The **implausible assumptions** cited in Clack's rebuttal are more concerning, and why such proposals should be evaluated based on substance rather than "vision". If you're interested, the next 2 pages get into the details.

On Jacobson's hydropower assumptions:

- The Clack rebuttal claims that Jacobson assumes a huge **13x hydropower capacity build-out.** However, this is not based on new projects: instead, Jacobson proposes that existing dams be retrofitted with additional turbines to increase potential instantaneous generation.
- According to the Clack rebuttal, this is highly implausible. US hydropower facilities are **generally already built over capacity**, and already have priority on the grid over thermal power as well as wind and solar: "the primary factor limiting hydroelectric capacity factor is water supply and environmental constraints" rather than under-optimized dams. Clack's rebuttal also states that Jacobson's paper is undermined by a hydro modeling error[14], and does not adequately incorporate the infrastructure cost of its assumed hydropower expansion.

Understanding the bizarre implications of Jacobson hydropower assumptions: The Grand Coulee Dam

If the Grand Coulee Dam in Washington state expanded by the same relative amount as Jacobson's overall hydro expansion, it would have a new peak power rating of 101 GW: more than all hydropower in the US combined today, and 4.5x larger than the largest power plant of any kind ever constructed (the Three Gorges Dam in Hubei Province, China). The required flow rate through this upgraded Grand Coulee Dam at full power would regularly need to be 5.5x 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. This flow rate corresponds to 13x the average discharge rate of the entire Columbia river system, and 3.5x the maximum spillway capacity of the Grand Coulee dam itself. [*Source: June 2017 Clack et al response to Jacobson*]

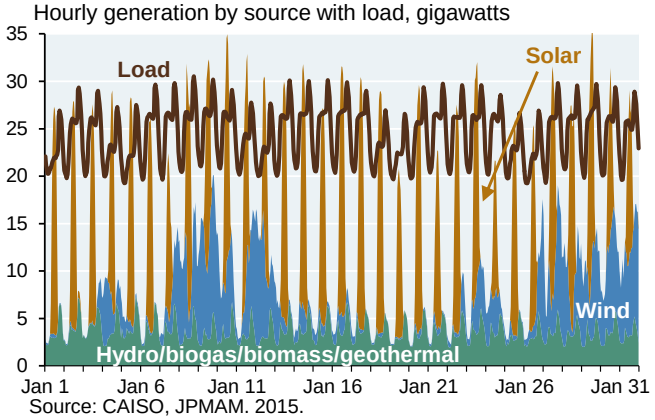
On Jacobson's assumed expansion of the hydrogen economy:

- As per the Clack rebuttal, in Jacobson's model, "hydrogen is produced at a peak rate consuming nearly 2,000 GW of electricity, nearly twice the current US electricity-generating capacity". To understand how large this is: "Total worldwide production of hydrogen from electrolysis is approx. 2.6m tons/year, corresponding to an average electrolysis power consumption of ~16 MW. The US electrolysis build-out envisioned by Jacobson is thus at least a **factor 100,000x increase** over total world electrolysis capacity today"
- And the price tag? "The costs for electrolyzers necessary to produce hydrogen at a rate of 2,000 GW are at least 10-25 times higher than those reported, with the capital cost for these components totaling approximately $2 trillion"; this is "not appropriately accounted for in the cost estimates".
- Jacobson's proposal "includes a wide range of currently un-costed 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**)".

[14] Clack's rebuttal cites a hydro **modeling error** in Jacobson's paper that is "so large (and so obvious) that it by itself invalidates the entire effort". In a rebuttal of his own, Jacobson refutes assertions of this error, and stands by the notion that hydroelectricity capacity that is larger than the current US electricity grid can be retrofitted on existing hydro plants. In our 2016 review of hydroelectric power, we cited research from Oak Ridge National Labs showing that US hydropower could increase from 6% to 9% of total electricity generation through development of existing non-powered dams and new stream development.

One challenge for a grid with a lot of renewable energy is the mismatch between renewable generation and electricity demand. In this chart from our 2015 energy paper, we plot load and renewable generation for California in January, broken down by hour. We assumed a large build-out of wind and solar, enough to provide 70%-80% of annual generation. As you can see, there would still be long periods in January during which there is insufficient renewable generation to meet demand. Jacobson proposes that gaps like these be addressed through both **energy storage and load-shifting** (requiring businesses to adjust to when electricity is available rather than when they need it). But….

California: January load vs. renewable generation
Hourly generation by source with load, gigawatts



Source: CAISO, JPMAM. 2015.

…On Jacobson's assumed massive increase in underground thermal energy storage:

- Current electricity storage systems store energy for a few hours at a time, and are not built to store excess wind or solar power for weeks or months. Jacobson assumes this problem is primarily solved through underground thermal energy storage (UTES), which utilizes geothermal boreholes to store heat in the ground. As per the Clack rebuttal, Jacobson assumes that UTES would be "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."
- And this: "Jacobson assumes a total of 2,604 GW of storage charging capacity, more than double the entire current generation capacity of all power plants in the United States. The energy storage capacity consists almost entirely of two technologies that remain unproven at any scale: 515 TWh of UTES (the largest UTES facility today is 0.004 TWh), and 13 TWh of phase-change materials. Although both UTES and phase-change materials are promising resources, **neither has reached the level of technological maturity to be confidently used as the main underpinning in a study aiming to show the technical reliability and feasibility of an energy system**. Solar district heating with UTES on large scales and at high rates of deployment is rare outside of Denmark".

…On Jacobson's assumption of flexible load-shifting:

Jacobson's models assume "free time-shifting of loads at large scale in response to variable energy provision", and assume that "**somewhere between 65% and 80% of Jacobson's daily loads are assumed to be flexible"**. This includes 60% of industrial demand, which is assumed to be able to freely reschedule all energy inputs within an 8-hour window. "The authors do not provide evidence to justify this **implausible scale of load flexibility**. The idling of capital-intensive industrial facilities when intermittent energy sources are unable to meet demand represents a large cost that is not included".

And finally, on the underestimation of transmission investment

According to the Clack rebuttal, Jacobson assumes that 45% of wind, hydro and solar generation will be sent through a new national long-distance grid. However, they found no explicit modeling, reference or cost information on transmission in Jacobson's proposal, and believe that "their analysis **ignores transmission capacity expansion**, power flow, and the logistics of transmission constraints". While there are estimates of transmission costs in Jacobson's proposal, Clack et al believe they are way too low.

The mic has been dropped.

IMPORTANT INFORMATION

Purpose of This Material: This material is for information purposes only. The views, opinions, estimates and strategies expressed herein constitutes Michael Cembalest's judgment based on current market conditions and are subject to change without notice, and may differ from those expressed by other areas of J.P. Morgan. **This information in no way constitutes J.P. Morgan Research and should not be treated as such.**

Non-Reliance: We believe the information contained in this material to be reliable and have sought to take reasonable care in its preparation; however, we do not represent or warrant its accuracy, reliability or completeness, or accept any liability for any loss or damage (whether direct or indirect) arising out of the use of all or any part of this material. We do not make any representation or warranty with regard to any computations, graphs, tables, diagrams or commentary in this material which are provided for illustration/reference purposes only. We assume no duty to update any information in this material in the event that such information changes. Any projected results and risks are based solely on hypothetical examples cited, and actual results and risks will vary depending on specific circumstances. Forward looking statements should not be considered as guarantees or predictions of future events. **Investors may get back less than they invested, and past performance is not a reliable indicator of future results.**

Risks, Considerations and Additional information: There may be different or additional factors which are not reflected in this material, but which may impact on a client's portfolio or investment decision. The information contained in this material is intended as general market commentary and should not be relied upon in isolation for the purpose of making an investment decision. Nothing in this document shall be construed as giving rise to any duty of care owed to, or advisory relationship with, you or any third party. Nothing in this document is intended to constitute a representation that any investment strategy or product is suitable for you. You should consider carefully whether any products and strategies discussed are suitable for your needs, and to obtain additional information prior to making an investment decision. Nothing in this document shall be regarded as an offer, solicitation, recommendation or advice (whether financial, accounting, legal, tax or other) given by J.P. Morgan and/or its officers or employees, irrespective of whether or not such communication was given at your request. J.P. Morgan and its affiliates and employees do not provide tax, legal or accounting advice. You should consult your own tax, legal and accounting advisors before engaging in any financial transactions.

Contact your J.P. Morgan representative for additional information concerning your personal investment goals. You should be aware of the general and specific risks relevant to the matters discussed in the material. You will independently, without any reliance on J.P. Morgan, make your own judgment and decision with respect to any investment referenced in this material.

J.P. Morgan may hold a position for itself or our other clients which may not be consistent with the information, opinions, estimates, investment strategies or views expressed in this document. JPMorgan Chase & Co. or its affiliates may hold a position or act as market maker in the financial instruments of any issuer discussed herein or act as an underwriter, placement agent, advisor or lender to such issuer.
References in this report to "J.P. Morgan" are to JPMorgan Chase & Co., its subsidiaries and affiliates worldwide.

Legal Entities and Regulatory Information: In the **United States**, Bank deposit accounts, such as checking, savings and bank lending, may be subject to approval. Deposit products and related services are offered by **JPMorgan Chase Bank, N.A.** Member FDIC.

JPMorgan Chase Bank, N.A. and its affiliates (collectively "**JPMCB**") offer investment products, which may include bank managed accounts and custody, as part of its trust and fiduciary services. Other investment products and services, such as brokerage and advisory accounts, are offered through **J.P. Morgan Securities LLC ("JPMS")**, a member of FINRA and SIPC**. JPMCB and JPMS** are affiliated companies under the common control of JPMorgan Chase & Co. Products not available in all states.

In the **United Kingdom**, this material is issued by J**.P. Morgan International Bank Limited (JPMIB)** with the registered office located at 25 Bank Street, Canary Wharf, London E14 5JP, registered in England No. 03838766. **JPMIB** is authorised by the Prudential Regulation Authority and regulated by the Financial Conduct Authority and the Prudential Regulation Authority. In addition, this material may be distributed by **JPMorgan Chase Bank, N.A. ("JPMCB")**, **Paris branch,** which is regulated by the French banking authorities Autorité de Contrôle Prudentiel et de Résolution and Autorité des Marchés Financiers or by **J.P. Morgan (Suisse) SA**, which is regulated in Switzerland by the Swiss Financial Market Supervisory Authority (FINMA).

In **Hong Kong**, this material is distributed by **JPMCB, Hong Kong branch**. JPMCB, Hong Kong branch is regulated by the Hong Kong Monetary Authority and the Securities and Futures Commission of Hong Kong. In Hong Kong, we will cease to use your personal data for our marketing purposes without charge if you so request. In **Singapore**, this material is distributed by **JPMCB, Singapore branch**. JPMCB, Singapore branch is regulated by the Monetary Authority of Singapore. Dealing and advisory services and discretionary investment management services are provided to you by JPMCB, Hong Kong/Singapore branch (as notified to you). Banking and custody services are provided to you by JPMIB and/or JPMCB Singapore Branch. The contents of this document have not been reviewed by any regulatory authority in Hong Kong, Singapore or any other jurisdictions. You are advised to exercise caution in relation to this document. If you are in any doubt about any of the contents of this document, you should obtain independent professional advice.

With respect to countries in **Latin America**, the distribution of this material may be restricted in certain jurisdictions. Receipt of this material does not constitute an offer or solicitation to any person in any jurisdiction in which such offer or solicitation is not authorized or to any person to whom it would be unlawful to make such offer or solicitation. To the extent this content makes reference to a fund, the Fund may not be publicly offered in any Latin American country, without previous registration of such fund's securities in compliance with the laws of the corresponding jurisdiction. Public Offering of any security, including the shares of the Fund, without previous registration at Brazilian Securities and Exchange Commission – CVM is completely prohibited. Some products or services contained in the materials might not be currently provided by the Brazilian and Mexican platforms.This material should not be duplicated or redistributed without our permission.