BACKGROUNDER

Summary of flaws in the analysis of 100% renewable scenario by Jacobson et al. (Jacobson, 2015) **identified in Clack et al. "Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar"** (Clack, 2017)

In their new analysis, (Clack, 2017) note that the central challenge in establishing a zero-carbon electric grid is to exclusively use non-polluting resources but still supply electricity when and where needed. That is why comprehensive deep decarbonization studies see complementary roles for sources like wind and sun, which vary in their availability, alongside other technologies like nuclear energy, biomass energy, and even fossil energy with carbon capture, which can supply energy during multiple days, weeks and seasons when sun and wind energy are low. In a large recent 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 & Thernstrom, 2017).

In contrast, a few people have proposed that we don't need a diversity of zero-carbon energy options to reach our goal of zero emissions sometime after 2050. They argue that essentially wind and solar energy alone, with a small amount of hydro-electric power and tiny additions of geothermal and tidal and wave power, can meet all of our energy needs. The most prominent advocate of this view is Professor Mark Jacobson at Stanford University. In a series of papers, Jacobson and his colleagues argue that a "WWS" (Wind, Water, Solar)[1] system can provide reliable low-cost 24/7 power, in the US and all over the world.

The (Clack, 2017) paper shows that even the most comprehensive and detailed of Jacobson et al.'s studies [(Jacobson, 2015)] are severely compromised by modeling errors, unrealistic methods and incorrect, implausible, or inadequately supported assumptions:

- **Modeling errors.**
    - To compensate for periods of low wind and sun for the electric grid, Jacobson's model "solves" the problem in large part by dispatching more than nine times the amount of hydroelectric dam capacity than is stated to exist in his study, and roughly fifteen times the amount that exists in the United States today – the equivalent of 600 new Hoover Dams. The study does not acknowledge the existence of this suddenly appearing water power, much less explain where or

[1] In (Jacobson, 2015), 98% of installed capacity is wind or solar power in the proposed US electricity system.

how such a massive amount of hydro-electric capacity – equal to more than ***all*** US electric capacity today[2] – could be built, how they would be operated, or what it would cost to do so.[3]

- From the information provided in the paper, it is not clear what fractions of load can have the classification "flexible" (unfortunately for any consumers in this category, this means the (Jacobson, 2015) system can choose not to supply them with energy. From the data tables, an absolute maximum of 67.7% of total load (1064.66 GW) can potentially be labeled "flexible". In (Jacobson, 2015), every single figure that shows the "flexible" load appears to break either this 67.7% value or the maximum capacity of flexible load of 1064.16 GW, indicating another serious modeling error.

- **No modeling of the electricity grid.**
  - Remarkably, Jacobson and his colleagues do not model the electricity grid at all in their "grid reliability problem" study. They neglect to show how much or where transmission would need to be built to get from sources to users to keep the lights on.

- **Vast amounts of energy storage that do not exist at scale**
  - The Jacobson et al. paper assumes we can construct vast amounts of energy storage with an output capacity[4] that is two and a half times the entire current US electrical system, nearly all of which (99.7%) consists of two technologies that do not yet exist today at commercial scale, and for which there is no reliable cost information. These systems would have a collective capability to store more than seven weeks' worth of total U.S. electricity consumption. To put these figures in perspective, the ten largest pumped hydro storage facilities in the U.S. are collectively capable of storing a total of ~43 minutes' worth of U.S. electricity consumption.
  - The (Jacobson, 2015) study imagines that one of those technologies – underground thermal energy storage systems – would be deployed to provide services for nearly every home, business, office building, hospital, school, and factory in the United States. Yet the analysis

[2] 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). The current average electricity demand over the year is 0.465 TW (U.S. Energy Information Administration, 2017).

[3] Jacobson et al. has since stated "*Jacobson et al. (2015) assumed zero expansion of hydroelectric power reservoirs, only expansion of turbine capacity. The cost of turbine expansion was not included in the paper, but the cost has since been calculated for the U.S. and worldwide. The mean U.S. cost is 0.2 cents/kWh, which is roughly 2% of the cost of overall energy.*" Naturally, additional turbines need extra water and therefore penstocks, tunnels, and space. Even disregarding all hydrological and legal constraints, one cannot simply assume that you can fit up to 15x more turbines in same space. It is clear that this modelling mistake alone invalidates the entire (Jacobson, 2015) effort.

[4] The (Jacobson, 2015) storage system output values are for both electricity, heat and cold.

does not include an accounting of the costs of the physical infrastructure to support these systems.
  - Jacobson and colleagues also envision massive hydrogen production facilities to produce transportation fuels, capable of using twice as much electric generating capacity as exists in America today[5], and with the capacity to store enough hydrogen to meet another 5-6 weeks of current U.S. electricity demand. As has been shown in the Clack et al. analysis, the real costs of these systems have been underestimated by least 10-25 times in the Jacobson et al. studies.

- **Unrealistic generation system scale and build-out.**
  - As noted above, Jacobson and his colleagues implicitly assume a fifteen-fold expansion in US hydroelectric capacity, where even small dams have often been fiercely contested. They claim this expansion would occur "only at existing dams", without any analysis or support for how, or if, this would be possible, and at what cost.
  - They also assume that the US will continuously[6] build out new solar, wind, and hydroelectric facilities at a rate that is 6 times faster than the fastest single year rate Germany achieved in their energy transition (the "Energiewende", in 2011), adjusting for population size.
  - Relative to current installed capacity, the (Jacobson, 2015) plan calls for a simultaneous capacity expansion by 2050 of:
    - 27x for solar power,
    - 113x for storage (excluding hydrogen),
    - 33x for wind power,
    - 10x of total electricity system capacity
    - (*Unknown*) expansion of electricity transmission capacity

- **Unrealistic cost of capital numbers**
  - The cost of capital used in (Jacobson, 2015) is one-half to one-third of that used by most other studies. Most strikingly, the 3.0% (span of 1.5-4%) discount rate used by (Jacobson, 2015) is less than half of the 8.0% used by the very source that (Jacobson, 2015) cites as support

[5] 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, 2015) is thus approximately a factor *100000x* increase over total world electrolysis capacity today.

[6] The best-estimate for the operational life-span of the main components of the "WWS" plan (which is 98% solar PV and wind power) is less than 30 years. 2050 is 33 years away today – a significant proportion of the "WWS" system will be retired by then. An "energy transition" is not an isolated event but rather a continuous (never-ending) process. This is true for any energy source (all have limited operational time spans), but the numbers are dramatically different if one makes more use of longer-lifespan sources like nuclear (up to 80 years), CCS-plants (up to 50 years) or hydropower (up to 100+ years).

for their value (Lazard, 2016)[7]. All of the technologies considered in (Jacobson, 2015) have high capital costs and low operating costs – as a result, the cost of capital is the primary cost driver. This assumption leads to a very serious underestimation of likely costs.

- **Extreme land-use requirements**
  - In the (Jacobson, 2015) plan, 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. Once fully expanded, this system would cover an area larger the entire combined area of all human-made land coverage in the US to date[8]. 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.[9]

- **Industrial energy demand that is flexible and freely curtailed.**
  - Jacobson and his colleagues assume that more than 60% of all industrial energy demand could be rescheduled within an eight-hour window on a frequent and continuous year-round basis. They provide no explanation or justification as to how (and why) US industry would do this, and neglect to quantify the resulting economic impacts of starting and stopping industrial production to match the availability of wind and sun.[10]

The coauthors of the new (Clack, 2017) paper agree that wind, solar, and hydroelectric energy can play an important role in reducing carbon emissions from the US energy system. The (Clack, 2017) paper should not in any way be construed to support action against policies to encourage renewable energy

---

[7] "*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.*" - M.Z. Jacobson

[8] Based on the (Liu, He, Zhou, & Wu, 2014) review of North Americas 'impervious surface,'' which refers to human-made land covers through which water cannot penetrate, including rooftops, roads, driveways, sidewalks, and parking lots". The actual value for this for all of North America is 0.78% of land area (compared to >%5 of US covered by WWS-system wind farms).

[9] The main reference for this is (Denholm, 2009), which states: "Excluding the outliers, the reported data represents a capacity density range of 1.0 to 11.2 MW/km^2 and an overall average capacity density of 3.0 ± 1.7 MW/km^2."

[10] Remarkably, Figure S14 on page 23 of the supplemental information accompanying the (Jacobson, 2015) study, shows the economic impact of reducing flexible load down to 0 hours as non-existent. If the extreme flexibility of demand that is suggested in the main paper does not impact costs in the (Jacobson, 2015) model at all, there is obviously no reason to employ it. This suggest even more severe modelling errors exist than has been explained in (Clack, 2017).

development. Rather, (Clack, 2017) asserts that wind, solar and hydropower alone likely do not represent a complete, reliable or cost-effective pathway to decarbonization.

References

Clack, C. T. et al. (2017). Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proceedings of the National Academies of Science*.

Denholm, P. et al. (2009). *Land-use requirements of modern wind power plants in the United States.* National Renewable Energy Laboratory.

International Energy Agency. (2012). *Hydrogen Production & Distribution.*

Jacobson, M. Z. et al. (2015). Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proceedings of the National Academy of Sciences, 112*(49), 15060–15065.

Jenkins, J., & Thernstrom, S. (2017). *DEEP DECARBONIZATION OF THE ELECTRIC POWER SECTOR INSIGHTS FROM RECENT LITERATURE" (2017).* Energy Innovation Reform Project.

Lazard. (2016). *LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS — VERSION 10.0.*

Liu, Z., He, C., Zhou, Y., & Wu, J. (2014). How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. *Landscape Ecology, 29*(5), 763-771.

U.S. Energy Information Administration. (2017, 05 17). *SHORT-TERM ENERGY OUTLOOK.* Retrieved from https://www.eia.gov/outlooks/steo/report/electricity.cfm

U.S. Energy Information Administration. (2017, 05 17). *Table 4.3. Existing Capacity by Energy Source, 2015 (Megawatts).* Retrieved from https://www.eia.gov/electricity/annual/html/epa_04_03.html