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100% clean, renewable energy studies provide scientific solution that policymakers can rely on

Robert Procter writes in *The Electricity Journal* that our recent 100% clean, renewable energy roadmaps for the 50 United States (Jacobson et al., 2015a) and 139 countries (Jacobson et al., 2017a) are useful for high-level analysis but "have limited relevance for carbon policy." Much of his criticism centers on his claims that these studies are not near-term utility planning documents and don't evaluate costs associated with sub-hourly fluctuations between load and generation, variations in capacity factor, curtailment, and storage. As explained next, we believe both of these criticisms are misplaced and that our analyses are indeed relevant to energy and climate-change policymaking.

First, we suggest that Procter has the relationship between energy/climate policymaking and utility planning backwards: the former guide the latter, not the other way around. Thus, while it is certainly useful to expand upon our work with more detailed technical and economic studies of power-system planning and operation, such more detailed studies will be done in the context of energy and climate policies that are informed by work such as ours.

Second, and more important, Procter apparently is not aware of related work that we have done that directly addresses his claims that we have not adequately accounted for variation between load and generation, capacity factors, and so on. Whereas, the two papers Procter evaluated provide information about supplying 100% wind, water, and solar power for all purposes primarily to meet annual average load, we have two separate studies (Jacobson et al., 2015b, 2017b), which Procter doesn't mention, that simulate matching demand with supply and storage down to 30 s resolution for multiple years. Although the second of these two papers (Jacobson et al., 2017b) was not available when Proctor wrote his article, he still should have read the first paper, from 2015. If he had, he would have discovered that we *do* treat sub-hourly fluctuations, curtailment, and extreme variations in intermittent renewable supply, and find low-cost, stable grid solutions that include thermal, electricity, and hydrogen storage.

Moreover, at least 28 other peer-reviewed papers have found, as we did, that demand can match supply with 100% or near-100% renewable energy systems of different sizes (Lund and Mathiesen, 2009; Mason et al., 2010; Hart and Jacobson, 2011, 2012; Connolly et al., 2011, 2014, 2016; Mathiesen et al., 2011, 2012, 2015; Elliston et al., 2012, 2013, 2014; Rasmussen et al., 2012; Budischak et al., 2013; Steinke et al., 2013; Connolly and Mathiesen, 2014; Becker et al., 2014; Bogdanov and Breyer, 2016; Child and Breyer, 2016; Lund et al., 2016; Aghahosseini et al., 2016; Blakers et al., 2017; Barbosa et al., 2017; Lu et al., 2017; Gulagi et al., 2017a, 2017b, 2017c). Yet another paper, Brown et al. (Brown et al., 2017), provides a comprehensive review and analysis of the feasibility of 100% renewable electricity systems and decisively rebuts the claims of Heard et al., whom Procter cites several times in an effort to criticize our work.

In sum, Procter's main criticism – that our work fails to address costs associated with matching supply and demand at short time scales, curtailment, etc. – is invalid because it ignores relevant work by us and dozens of other experts. Along these lines, we note that while Procter cites other critiques of our studies, he fails to cite our extensive responses to several of these critiques (Delucchi and Jacobson, 2012; Jacobson and Delucchi, 2013; Jacobson et al., 2016) and thus misrepresents the state of the discussion in the scientific community and forces us to re-iterate arguments and corrections that we already have published.

Below are responses to some of Procter's more specific criticisms.

1. Procter claims we do not discuss externalities associated with wind, water, and solar (WWS) resource extraction, fabrication, shipping, construction, operation, and decommissioning. This statement is not true. Section S10.1 of Ref. (Jacobson et al., 2017a) states,

> During the transition, conventional fuels and existing WWS technologies are needed to produce the remaining WWS infrastructure. However, much of the conventional energy would be used in any case to produce conventional power plants and automobiles if the plans proposed here were not implemented. Further, as the fraction of WWS energy increases, conventional energy generation will decrease, ultimately to zero, at which point all new WWS devices will be produced with existing WWS. In sum, the creation of WWS infrastructure may result in a temporary increase in emissions before they are ultimately reduced to zero.

The foregoing applies to the main external costs of energy use – costs of air, soil and water pollution and climate change. Although it is true that minor external costs result from the use of some WWS technologies – for example, mining for raw materials can cause water pollution – these costs are one-time and very small compared with the costs of air, soil and water pollution and climate change, that are continuous forever with a fossil fuel system.

We are therefore confident in our assessment that the lifecycle external costs of WWS technology are *vastly* smaller than those of a conventional energy system.

2. Procter questions whether hydrogen is technically and economically feasible. In Ref. (Jacobson et al., 2017a), we propose hydrogen fuel cells (HFCs) for transportation only, and HFC road vehicles already are commercially available. Long-distance aircraft will ultimately need to be HFC-electric hybrids, yet short-distance, small HFC aircraft and pure electric aircraft already exist. We propose long-distance HFC aircraft to be available in the 2035–2040 timeframe, which is not implausible. Although the long-term cost of fully commercialized hydrogen transport systems is not perfectly known, there is little doubt that in the applications we propose the social cost of hydrogen transport

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will be less than the social cost of conventional (petroleum-based) transport.

3. Procter questions why our residential load in Ref. (Jacobson et al., 2017a) decreases by 26% with 100% WWS. The reduction is due to (a) eliminating energy to mine, transport, and refine fossil fuels used in residences, (b) the higher work out to energy in ratio of electricity over combustion, and (c) end-use energy efficiency improvements and reduction of energy use beyond the business-as-usual (BAU) case.

4. Procter claims Ref. (Jacobson et al., 2017a) assumes annual reductions in energy intensity much greater than the historic average. This is because he is confusing efficiency improvements alone in the historic data with (a) electrification in the WWS case, which itself reduces demand 23% worldwide due to the higher work out to energy in ratio of electricity over combustion, and (b) reducing demand another 12.6% in the WWS case by eliminating energy needed to mine, transport, and refine fossil fuels.

5. Procter claims there will be a stranded assets problem under our roadmaps. We addressed this issue in Section S10.1 of Ref. (Jacobson et al., 2017a) stating,

> Whereas, much new WWS infrastructure can be installed upon natural retirement of BAU infrastructure, new policies (e.g., Section S11) are needed to force remaining existing infrastructure to retire early to allow the complete conversion to WWS. Because the fuel, operating, and external costs of continuing to use existing BAU fossil-fuel capacity are in total much greater than the full annualized capital- plus-operating costs of building new WWS plants (indeed, the climate and air-pollution costs alone – 28.5 (11.2-72) ¢/kWh-BAU-all-energy – exceed the full cost of new WWS), and because substitution of WWS for BAU energy systems increase total jobs, it is beneficial to society to immediately stop operating existing BAU fossil-fuel plants and replace them with new WWS plants

6. Procter claims there is a cost associated with having to “learn how to operate a power system in the throes of being transformed.” He further lists other costs that he claims we are missing, and implies –without any evidence or analysis – that these costs are large enough to change the results of our analysis and render our conclusions suspect.

Not only are Proctor’s assertions unsubstantiated, they are in fact contradicted by available evidence and analysis. For example, Iowa’s share of electricity from wind increased from 17% in 2010 to 37% in 2017, yet the cost of electricity in Iowa declined from 9.2 cents/kWh during January-July 2010 to 8.9 cents/kWh during January-July 2017 while U.S.-averaged electricity stayed constant at 10.5 cents/kWh between the same periods (US Energy Information Administration, 2017). Further, a recent comprehensive analysis and review of the literature confirms that there are no technical barriers or large costs associated with adapting the power grid to accommodate extremely high levels of variable generation (Brown et al., 2017).

In general, 100% WWS can result in not only a low-cost system, but also one in which there is zero fuel cost so more stable electricity prices.

In sum, Procter ignores much of the pertinent published literature and fails to focus on the 100% WWS papers of relevance. He also compares apples with oranges by comparing a future system where all energy sectors have been electrified with the current system, where they are not. He further opines about costs while neither consulting the relevant literature nor analyzing costs on the ground for clean, renewable energy systems. His paper thus has no impact on our conclusions and no impact on the policy relevance of our conclusions.

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