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Forum

Response to "A critique of Jacobson and Delucchi's proposals for a world renewable energy supply" by Ted Trainer

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Ted Trainer's "A critique of Jacobson and Delucchi's proposals for a world renewable energy supply" (hereafter T11), directed at our two *Energy Policy* articles "Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials" (hereafter JD11) and "Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies" (hereafter DJ11), makes two main points:

(1) that JD11 and DJ11 do "not deal effectively with the problems set by the variability of renewable energy sources," and
(2) that the JD11/DJ11 "analysis of investment costs is inadequate."

Neither of these criticisms is valid. We show here that T11's first main point is based on a misrepresentation of what is stated and referenced in DJ11, and that his second main point is based on mistakes and unreasonable assumptions. As a result, T11's critique does not affect our original analyses or our conclusion that it is technically, economically, and environmentally feasible to provide all global energy with wind, water, and solar power.

We organize our response around T11's two main criticisms (variability and investment costs) and under each main criticism by T11's topic headings.

1. Variability

1.1. Magnitude of the variability problem

Most of this background information in T11 is well known and either is not specifically relevant to JD11/DJ11 or else is addressed in those papers. However, this section of T11 also contains an important error. T11 states:

> "Jacobson and Delucchi expect 50% of energy to come from wind. Again no attempt is made to explain where energy is supposed to come from during the kinds of weather events described above which can last for several consecutive days."

This statement is incorrect. Section 1.2 of DJ11 addresses the issue:

> "The figure (Figure 1) illustrates the potential for matching power demand hour by hour based on a Monte Carlo simulation that accounts for the stochastic nature of each resource (20 potential realizations each hour). Although results for only two days are shown, results for all hours of all days of both 2005 and 2006 (730 day total) suggest that 99.8% of delivered energy during these days could be produced from WWS technology. For these scenarios, natural gas was held as reserve backup and supplied energy for the few remaining hours. However, it is expected that natural gas reserves can be eliminated with the use of demand–response measures, storage beyond SP, electric vehicle charging and management, and increases in wind and solar capacities beyond the inflexible power demand, which would also allow the excess energy to produce hydrogen for commercial processes, thereby reducing emissions from another sector."

The reference for this result is provided as Hart and Jacobson (2011a), which was in review at the time, but a website was given for a copy of the paper. The paper has now been published. This analysis accounted for all anomalous weather conditions in California (e.g., consecutive days without wind or solar), which are similar to those anywhere in the world. It demonstrated that

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renewables can be combined optimally to match nearly all load with minimal storage under a constraint of a loss of load of one day in 10 years. The key is bundling renewables rather than treating them individually (such as wind alone or solar alone).

1.2. Jacobson and Delucchi's solutions

T11 states that we do not address the "contradiction" raised by a study (by Lenzen) that "concludes that only 20+% of electricity, as distinct from total energy, can be supplied by wind due to integration difficulties created by its variability." We do not know which work of Lenzen T11 is referring to because he does not include it in his references, but we expect that it refers to integrating wind power into a conventional electricity system, and almost certainly does not refer to limits determined in an optimization study of wind as part of a large-scale all-renewables system.

In subsection 1, "Interconnect dispersed generators," T11 wonders whether calm and cloudy conditions over most of Europe might result in insignificant (and presumably insufficient) energy supply, and implies that we have not adequately addressed this question, but his speculation and implication are off-base in several related ways. First, we have not claimed that WWS systems must be self-contained within Europe; rather, we have explicitly talked about much larger supergrids. Second (and closely related), we have cited studies of supergrids, including Czisch's optimization study including Europe, North Africa, and part of Asia (p. 1172 of DJ11). Third, we state in several places that the optimal configuration of a reliable WWS system is unknown, but will vary spatially and temporally (pp. 1173, 1175, 1176, 1178 of DJ11). Fourth, studies of Denmark alone at large penetrations of renewables (Lund and Mathiesen, 2009; Mathiesen and Lund, 2009), do not indicate the problems suggested by T11.

In conclusion, the primary errors in T11's commentary here (and in his subsection 2, on complementary sources) are that he ignored the analysis provided in JD11/DJ11 and references therein, ignored the concept of bundling WWS energy sources as one commodity, and ignored other published studies that have examined methods of facilitating the integration of renewable energy into the grid (e.g., Lund and Mathiesen, 2009; Mathiesen and Lund, 2009; Hart et al., 2011b). He selectively cites studies where one resource was examined in isolation, which is the most inefficient way of thinking about a solution to the problem. Integrating renewable energy into the grid is an optimization problem; yet T11 did not reference any studies on optimization.

As a result, T11's criticisms here are not valid and do not alter our conclusion that the variability of wind and solar can be addressed effectively by bundling these resources together with other wind, water, and solar (WWS) resources.

T11's criticisms, in subsection 3 (demand management), subsection 4 (storing electric power—here we exclude hydrogen storage, which we address separately), and subsection 6 (weather forecasting), are largely moot since such techniques might be needed to firm less than half of one percent of electric power demand due to the effectiveness of bundling resources, as demonstrated in Hart and Jacobson (2011a). Nevertheless, these criticisms are based on hand-waving, not on scientific research that considers how much they may or may not be needed. As such, T11 does not change our conclusions regarding their possible contribution to the optimized electric power grid.

However, hydrogen storage (part of TJ11's subsection 4) and storage in electric vehicle batteries (TJ11's subsection 5) do have significant potential, so here we explain how TJ11's criticism of these are mistaken.

TJ11 claims that we do not "explore the implications of the low energy efficiency" of the hydrogen path, and implies that we have overlooked some capital costs. This is incorrect. Table A1 of JD11 shows our assumptions regarding energy use and conversion efficiencies. The cost analyses in DJ11 fully account for all relevant factors, including unit capital costs, capacity factors, efficiency, operating costs, storage costs, transmission and distribution, etc. Finally, TJ11's discussion of embodied energy is irrelevant, because with an indefinitely renewable energy resource with no external costs, the full lifetime cost as we have estimated is the relevant factor—there is no additional pertinence to embodied energy per se.

TJ11 dismisses vehicle-to-grid (V2G) storage on the grounds that "vehicle batteries need to be fully charged when they are to be used, which is typically twice a day," and that this recharging will take 7 h, leaving no time for the batteries to be used for V2G during the day. This is incorrect. The Tesla Roadster, for example, requires 3.5 h for a full recharge of 240 miles with a 240-V, 70-A recharger. To replace the energy used for an average 24-mile round-trip commute (Santos et al., 2011) in the Tesla would require as little as 20 min every day or one hour every three days. Even a less efficient EV (e.g., 0.3 kWh/mi) traveling further (e.g., 30 miles) and using a lower-power recharging system (e.g., 240-V and 40-A—about 10 kW) can be recharged in less than one hour—an order of magnitude less than T11 assumes.

With respect to frequency of charging, studies of drivers of plug-in hybrid electric vehicles (Davies and Kurani, 2010) and battery-only EVs (Turrentine et al., 2011) confirm that there is no basis for T11's assumption that all drivers recharge their vehicles to 100% state of charge every opportunity they get.

T11 assumes that most or all vehicle trips are to and from work, and occur at roughly the same time every day. But this also is incorrect: according to the U.S. Nationwide Household Transportation Survey (Santos et al., 2011), only 22% of vehicle trips are for commuting to and from work, and all trips, work and non-work, are spread out over the day, with nearly 50% of all vehicle trips occurring between 9:00 am and 4:00 pm. Similarly, Pearre et al. (2011) instrumented 484 gasoline vehicles in the Atlanta metropolitan area for one year, with an eye towards determining when electric vehicles might recharge, and found that "less than 10% of fleet parks and plugs into recharge between 5 and 9 pm. In the worst evening peak hour, less than 4% of the vehicles park within that hour" (p. 1181).

Reasonable inferences based on available data and our general understanding of economics and consumer behavior suggest that V2G incentives, time-of-day pricing, the wide range of types of EVs and recharging opportunities available in a 100% WWS world, and consumer adaptation to new technologies will create opportunities for substantial amounts of potential V2G energy storage during the day. More research will help us better understand this potential for V2G. In any case, we believe that storage can be minimized when renewables are combined as a bundle to match load, as discussed earlier.

TJ11 also criticizes V2G as being too expensive, but we have accounted for all of the legitimate costs he raises, and our estimates are based on comprehensive, detailed, original, analyses calculated in a consistent manner, whereas TJ11's numbers are from inconsistent sets of secondary sources, some of which have not been reviewed.

1.3. Usually overlooked need for redundancy

Here T11 concludes that "the common practice of focusing on levelised costs in estimating total system capital costs leads to serious underestimation of system costs." This is incorrect. Levelised costs are based on the estimated capacity factor, where the capacity factor is what would be obtained in an optimized system (i.e., the least-cost system that reliably satisfies demand).

This is part of a correct and complete estimate of the average energy cost of the system; there is in principle no underestimation whatsoever.

As we mention above, nobody has modeled 100% WWS systems for large regions of the world in enough detail to know exactly what an optimized system looks, and hence nobody knows exactly what the average levelised energy costs in 100% WWS systems will be. In DJ11 and JD11 we make reasonable estimates based on plausible scenarios; one may disagree with our specific assumptions and scenarios, but our estimates are conceptually sound and in no sense can they be claimed to be "serious" underestimates. Optimization studies of WWS systems will help resolve the inevitable uncertainties surrounding our estimates.

2. Investment costs

The beginning of this section of T11 contains a long, but irrelevant discussion on capital cost, and the remainder contains several mistakes.

Estimates of the total capital cost are relevant only if one argues that there are some constraints on the availability of capital not adequately reflected in the opportunity cost of capital. T11 makes no such claim, so this discussion is irrelevant.

T11 claims that we do not justify our assumptions regarding capital costs or energy demand. His statement that we assume costs "30% lower than those IEA [sic—should be EIA], without adequate explanation," is incorrect. Our estimates are based on a detailed review and analysis of the literature (Table 1 of DJ11) along with our own detailed, fully documented original estimates (Tables A.1a-A.1d of DJ11). In one of the tables, A.1d, which we present as an "alternative" scenario, we use the Energy Information Administration's (EIA's) "falling costs" assumptions for WWS technologies; these EIA values are about 30% lower than the EIA's reference-case assumptions. Thus, our cost estimates are explained in considerable detail, and are not simply the result of assuming values 30% below EIA's.

Our estimates of energy demand are presented in Table 2 of JD11 and explained in detail in Appendix A.2 of JD11. Thus, T11's claim that our estimate "is not explained or justified" is untrue.

In sum, T11 provides no valid criticism of the detailed methods or assumptions of our analyses of energy cost and energy demand.

2.1. Policy implications

TJ11 concludes with a short section on "Policy implications," in which he argues that renewable energy can supply the world *only if* the world "embraces frugal lifestyles, small and highly self-sufficient local economies, and participatory and cooperative ways in an overall economy that is not driven by growth or market forces." This vision may or may not be desirable, but it was found in our study not to be *necessary* in order to power the world economically with wind, water, and solar energy.

3. Our conclusion here

T11's critiques do not affect our original analyses or our conclusion that it is technically, economically, and environmentally feasible to provide all global energy with wind, water, and solar power.

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