Energy Policy 57 (2013) 641–643

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Forum

Response to Trainer's second commentary on a plan to power the world with wind, water, and solar power

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ARTICLE INFO

Article history:
Received 5 November 2012
Accepted 6 November 2012
Available online 27 November 2012

1. Introduction

This is a response to Trainer's (this issue; T12b) new commentary on Jacobson and Delucchi (2011; JD11) and Delucchi and Jacobson (2011a, DJ11a). Previously, Trainer (2012) wrote a commentary and Delucchi and Jacobson (2011b, DJ11b) responded. We encourage a continued discussion and analysis of the potential to convert the world's all-purpose energy infrastructure to a clean and renewable one. However, we do not believe T12b's new commentary provides accurate information about our proposed plan or affects our original conclusions. First, T12b's literature discussion of the integration of variable energy generation sources misrepresents what was found in the most relevant paper and ignores many other papers. Second, the annualized social cost of a system that reliably delivers electricity is the relevant metric for comparing energy systems rather than the capital cost alone. Third, T12's analysis of vehicle-to-grid (V2G) goes further than we have envisioned and thus supports our study. Finally, T12's emphasis on embedded energy is misplaced. These points are discussed below.

2. Integration of variable sources of generation

In his first commentary, T12a missed the literature related to the integration of intermittent energy sources. T12b now critiques three studies pointed out to him in DJ11b. Yet, there are still many more papers on the subject that T12b has not addressed (e.g., Mason et al., 2010; Hart and Jacobson, 2011, 2012; Hart, 2012; Connolly et al., 2011; Elliston et al., 2012; NREL, 2012; Hart et al., 2012, Budischak et al., 2013). These papers support the contention that large penetrations of renewables can reliably meet large portions of system-wide electric power demand before additional measures are taken.

Nevertheless, most of T12b's criticisms of the three studies are not relevant to our work and other criticisms misrepresent the analyses in those studies. For example, T12b incorrectly claims that Figure 4 of Hart and Jacobson (2011; HJ11) show that natural gas contributed to 40–50% of electric power on those days. To the contrary, nearly all electric power on those days was supplied by wind, water, and solar (WWS). Nearly all natural gas was held in reserve and was not used for electricity. No gas was used for electricity on two of the days and little was used on the other two. Even though HJ11 assumed natural gas could be used for reserves, there are several ways to eliminate or reduce the need for such reserves, as discussed in DJ11a and HJ11. These include using demand response, oversizing wind, water, and solar (WWS) electric power generation to simplify meeting power demand with supply and using excess electricity to produce hydrogen instead of curtailing, using more CSP for storage, using vehicle-to-grid (VTG), using weather forecasting to reduce reserve requirements, and interconnecting geographically-dispersed wind and solar generators to reduce zero-power hours. In addition, excess wind and solar from an oversized electric grid can be used to provide opposite-season underground thermal storage, such as in the Drake Landing Solar Community (http://www.dlsc.ca/) and combined heat and power district heating (CHPDH), such as is done in Denmark (http://en.wikipedia.org/wiki/District_heating).

Second, T12b incorrectly implies that HJ11 did not account for days of virtually no wind or solar availability. This is not true. The study of HJ11 accounted for every hour of every day of the real electric power loads and spatially-distributed renewable resources in California for 2005 and 2006. The optimization constraint was the grid standard of a loss of load of no more than one day in 10 years. The study found that 99.8% of all electric power generated during those two years could be met by

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0301-4215/$ - see front matter
http://dx.doi.org/10.1016/j.enpol.2012.11.014

non-carbon emitting sources (Table 2 of HJ11). Thus, it accounted for nearly all combinations of weather events in California.

Third, T12b claims that the total generating capacity of the system in HJ11 is four times that needed for a coal, gas, or nuclear system. The generating capacity is an irrelevant metric for comparing energy technologies. What matters is the system direct plus externality cost. Further, as stated above and at the end of the abstract of HJ11, there are numerous ways to reduce the generation capacity in HJ11.

With regard to cost, T12b focused solely on capital cost. This is a mistake in cost-benefit analysis. What matters is the total annualized cost to society *of a system that reliably meets demand*. We explicitly estimated the costs of some of the components of such a system in JD11 and DJ11a. Next, we examine T12b's mistaken focus on capital costs more closely.

3. Capital cost

Much of T12b's concern relates to the capital cost of the systems in the three renewable integration studies he criticizes. He then hypothesizes his own costs. For example, he states, "110 GW of solar and 75 GW of wind capacity…indicate a capital cost of around $600 billion." However, the installed project cost of most U.S. wind in 2011 was ~$1.0–2.0 W^{-1} (Wiser and Bolinger, 2011, Fig. 20) and that of utility-scale solar was $2.24–2.90 W^{-1} (Hoium, 2012), suggesting an installed cost on the order of $350 billion for this system, almost half his estimate.

He then states that "100% renewable energy supply systems are likely to involve capital costs well in excess of 10 times the present capital costs of energy supply". However, notwithstanding his near factor-of-two error in the capital cost of wind and solar, he ignores the fuel, O&M, externality, and subsidy costs of the present energy system versus the renewable system and the fact that the fuel cost of wind and solar are zero forever. More significantly, he examines only the "business cost" rather that the more relevant "economic cost" of energy. The business cost is the direct cost that a consumer pays upon purchase of the fuel or use of electricity. The economic cost is the direct cost plus costs that the consumer pays through higher taxes, insurance rates, medical bills, workers compensation costs, and reduced property values, among other costs. Businesses make decisions based on business costs, whereas policies, such as decisions on whether to promote clean energies, are decided based on economic costs.

Moreover, capital cost on its own is not relevant for determining the economic or even just the business cost of a fuel. Table A.1a of DJ11a shows that the periodic costs (fuel+O&M) for natural gas are up to twice those of the amortized capital costs; thus, capital costs alone say little. Table 1 of the same paper indicates that the social (externality) cost of the conventional fuels is another 5–6 cents/kWh, nearly the same as their direct costs. Externality costs are absent from T12b's discussion. In addition, from 2002–2008, the tax code subsidies and payments by the US government to fossil fuel industries amounted to ~$72.5 billion, whereas those to wind and solar technologies were <$5 billion (http://www.elistore.org/Data/products/d19_07.pdf).

Even the business cost of wind power today is lower than that of average conventional fuels in the US. This can be demonstrated as follows. Statistics from the EIA (http://www.eia.gov/electricity/sales_revenue_price/) indicate that, in the US, the five states with the highest fraction of all their electric power from wind in 2011 (South Dakota, 22.3%; Iowa, 18.8%; North Dakota, 14.7%; Minnesota, 12.7%, and Wyoming, 10.1%) saw an increase in residential electric power direct costs from 2003 to 2011 of 2.0 cents/kWh. The remaining 45 US states, whose electric power was dominated by traditional fossil fuels and nuclear power, saw an average increase in direct costs of 3.6 cents/kWh. In other words, those states that converted the greatest fraction of their electric power generation to onshore wind saw the lowest increases in electricity prices. This suggests that the cost of integrating wind energy into a conventional system is not significant.

A reason for the low business cost of onshore wind is that it has zero fuel cost, so once it is installed, its costs are nearly fixed. Fossil fuels, on the other hand, are limited resources whose prices rise over time due to increasing exploration, mining, and transportation costs of the fuel. Hawaii is a case in point. Its energy is dominated by fossil fuels, which are not local to the islands. The high transportation costs plus the rising price of fossil fuels in general resulted in Hawaii's mean residential electricity prices more than doubling between 2003 and 2011, from 16.7 to 33.2 cents/kWh, the highest in the US

T12b goes on to say that levelized costs tell us "nothing about how many extra turbines, or solar, coal, gas, oil, or nuclear generating plants must also be built to provide a system with the back-up capacity that will enable the wind sector to meet its average contribution when there is little or no wind." This is inaccurate; in our context, the levelized cost is *the annualized social cost of a system that reliably meets demand*, accounting for all the generators needed (none of which are coal, gas, oil, or nuclear).

Further, the WWS world envisioned in JD11 and DJ11a does not require much "backup" for the reasons listed in DJ11a and HJ11. Namely, all sectors of the energy economy (electric power, transportation, heating/cooling, and industrial processes) will be powered by electricity *and* electricity-derived hydrogen. As a result, the installed power generation is larger than needed to supply end-use demand for on-demand electricity use, so it is easier to meet hourly on-demand electricity use. Capacity available in excess of that needed to supply on-demand electricity is used to produce hydrogen and heat that is stored in molten nitrate salt (for CSP), district heating, and underground seasonal storage, rather than curtailed. Demand response is also used to reduce demand at times of peak load. Transmission also brings in wind and solar from outside of an area. Existing hydroelectric is used to fill in gaps in supply when wind, solar, stored CSP energy, and battery energy are not available. Because backup beyond the methods listed above is not used (e.g., no natural gas) and all energy generated is used, our estimates of the total annualized social cost may approximate *the full cost to society of a complete WWS system that reliably meets demand.* Of course, the exact cost in each region of the world will vary depending on local resources available, and an optimization calculation is needed for each region to see exactly what mix of strategies delivers WWS power most reliably at the lowest total annualized system social cost.

4. V2G

T12b's criticism of our V2G analysis is unwarranted, since he proposes a greater V2G potential than we envision. T12b suggests that in Australia, for example, V2G could store about 25% of total electricity demand, much larger than we anticipated. In a system with many other methods of ensuring that supply reliably matches demand (DJ11a), V2G should not be needed at nearly this scale.

5. Embodied energy costs

T12b raises the issue of embodied energy costs of a new energy system. Embodied energy is analytically relevant, but not in the way T12b poses. First, we should dispense with the term "cost" and the notion of "Energy return on investment" (EROI).

In a cost analysis “embodied” energy has no special standing, and in an otherwise complete economic, social, and environmental analysis EROI has no special relevance. What *is* relevant but not important in a scoping analysis, which was what was done in JD11 and DJ11a, is figuring out energy supply and demand in a WWS world. To do this, one needs to take a systems (aka “lifecycle”) approach and estimate how all industries would change in a WWS world vs. the conventional baseline on which projections are based. In our energy projections in JD11 we made first-cut adjustments to account for this, based on extensive experience with lifecycle analysis. For the purposes of JD11 and JD11a, this level of simplicity is appropriate. Future analyses that attempt to optimize supply and demand systems will need to perform more detailed systems/lifecycle analyses of energy use in all sectors affected by the switch to WWS.

6. Conclusion

As the need to move to renewable energy becomes more pressing, the need for sophisticated analyses of renewable energy systems becomes more urgent. Such analyses should focus on system optimization and on technical and economic details. In this respect, most of the list in T12b’s conclusion should *not* serve as a guide: capital costs per se are *not* a relevant economic metric; the issue of system optimization is *not* usefully thought of in terms of “redundant” plants; embodied energy is *not* a useful concept in systematic energy-cost projections. We do not know exactly what an optimized global WWS system will look like, but we do believe that JD11 and DJ11a have set forth a plan that is both technically possible and necessary to prevent catastrophic climate, air pollution, and economic consequences to society.

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