A Critique of Jacobson and Delucchi's Proposals for a World Renewable Energy Supply

by Ted Trainer

Mark Jacobson and Mark Delucchi published a claim that all the world's energy needs in 2030, allowing for projected economic growth, can be met with wind, water and solar power. They assume that energy efficiency can reduce demand for energy by 5–15% by 2030. —Editors

Advocates of renewable energy technologies frequently refer to the many available and potential ways of reducing the effect of variability of renew able energy. However they usually do not show that these could be combined to enable constant energy delivery to the grid despite the magnitude of the shortfalls that typically occur in supply from renewable sources. Jacobson and Delucchi (2011a, 2011b) list possible strategies but do not show that these can provide the necessary quantities of energy to plug gaps in supply.

The magnitude of the variability problem

There are periods when there is close to no wind blowing anywhere in a large region, and these times can last for many days. Weather tends to comes from the west in large "synoptic patterns" and these can leave the entire continent of Europe under conditions of intense calm, cloud and cold for a week at a time.

Lenzen's graphs from Oswald et al, (2008) make the magnitude of the problem clear. They show wind energy availability over the whole of Ireland, UK and Germany for the first 300 hours of 2006, in midwinter, the best time of the year for wind energy. For half this time there was almost no wind input in any of these countries, with capacity factors averaging around 6%. For about 120 continuous hours UK capacity averaged about 3%. During this period UK electricity demand reached its peak high for the year, at a point in time when wind input was zero.

Clearly these periods of calm are not rare or minor. For several days in a winter month in good wind regions there would have to be almost total reliance on some other source. The capital cost of having a backup system capable of substituting for just about all wind capacity is rarely focused on.

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Davey and Coppin (2003) make the point for Australia, for instance indicating that for 20% of the time a wind system integrated across 1500 km from Adelaide to Brisbane would be operating at under 8% of peak capacity. Mackay (2008, p. 189) reports data from Ireland between Oct. 2006 and Feb. 2007, showing a 15-day lull over the whole country. For five days output from wind turbines was 5% of capacity and fell to 2% on one day. At times the Danish wind system contributes almost no electricity.

A similar problem associated with higher penetrations of wind and solar is to do with periods of over-supply and dumping. Lenzen (2009, p, 94) reports Hoogwijck et ,al. 2007 as finding that "...the amount of electricity that has to be discarded grows strongly for penetrations in excess of 25–30%." If wind and PV were to contribute 25% and 30% of electricity, then on sunny and windy days they would be generating more than twice average demand. Some degree of system "over-sizing" will probably make sense but the capital cost implications are easily overlooked. System capital costs should be divided by electricity delivered, not generated, to arrive at a realistic system capital cost per kilowatt [kW].

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Solar energy availability exhibits similar variability. Most obviously, even on a sunny day PV panels can provide no energy for about 16 hours of that day. Renewable energy enthusiasts tend to discuss in terms of average supply and demand, whereas it is the times of unusually high or low supply and demand which set the limits

Maxima or peaks in demand are also crucial. Energy supply infrastructures typically have to contain 30–50% more generating plant than would meet average demand, in order to cope with peak demand. In addition, the two events can coincide. That is demand can peak in periods of low renewable energy source availability. Such events are not unusual in winter. For instance Victoria, Australia winter energy demand peaks during periods of calm accompanied by low temperatures. When demand peaks the generating capacity required can be c. 1.5 times that which could meet annual average demand, and again it might not be possible to meet more than a negligible fraction of that demand from wind or solar. These are periods when almost all demand would have to be met by other than solar and wind sources, setting significant implications for the amounts of redundant plant required and total system capital costs, unless this can be done via very large scale energy storage.

Jacobson and Delucchi's solutions

Jacobson and Delucchi recognize the general variability problem but state that it can be overcome by the technologies they list. Their discussion of these options is superficial and far from convincing, and these technologies are not capable of solving the general variability problem. The crucial issue here is quantitative; i.e., the extent to which particular technologies can deal with variability and whether or not all combined can add to a sufficient capacity to get around the difficulties set by variability.

First it is important to again make the general point that Jacobson and Delucchi assume 50% of energy needed will come from wind. However Lenzen's review (2000) concludes that only 20+% of electricity, as distinct from total energy, can be supplied by wind due to integration difficulties created by its variability. Jacobson and Delucchi do not deal with this contradiction.

1. "Interconnect dispersed generators."

The half-page explanation of this strategy begins by stating that connecting renewable energy sources "smooths out electricity supply—and demand—significantly." A paragraph then refers to a study in which variation in modelled wind output from 16 turbines over a month was found to be even less than that for hydroelectricity output. The final paragraph explains that connecting PV sites also reduces variability.

These brief statements make the well-known observation that interconnections do reduce variability in supply from individual solar and wind devices, but they fall far short of a satisfactory case for the claim that connecting sources can make a *sufficient* contribution to overcoming the variability of renewable sources. When most of Europe is experiencing calm and cloudy conditions over large regions for days at a time the crucial question is not whether input from wind and sun has been "smoothed out;" it is whether there is any significant input at all from these combined sources.

2. "Use complementary and non-variable sources to help supply match demand."

The point made in this section is that "when the wind is not blowing, the sun is often shining, and vice versa." Again this is true but is of little consolation when neither source is available for days at a time. In addition the implications for plant redundancy and capital costs are overlooked.

To be able to always meet the wind quota would require several times the amount of plant needed to make wind's average annual contribution.

It is often said that "the wind is always blowing somewhere" without recognition of the implications. If the wind is blowing strongly today in region A and the total wind sector contribution is to be supplied by that region today, then it will have to contain enough wind generating plant to meet that contribution. If tomorrow the wind is only blowing well in region B, then that region will also have to contain enough generating capacity to meet the whole wind contribution.

Thus in every region which might be the only one where the wind is strong on a particular day we would need sufficient capacity to meet the whole wind quota. In other words, to be able to always meet the wind quota would require several times the amount of plant needed to make wind's *average* annual contribution, and most of it would be idle much of the time. Also, for much of the time the whole system would be producing far more than could be used.

The main "non-variable" alternative energy source referred to is geothermal. Even the renewables-optimistic *WWF Energy Report* (2010), and Jacobson and Delucchi themselves, only assume geothermal can contribute about 4% of world energy. Australia has much better hot dry rock heat resources than the rest of the world but it is not yet clear how effectively they can be tapped or at what energy-return value. It will require considerable amounts of energy to bore holes 5 km deep through rock, fracture rock at depth, pump water down and force it 500 metres across to the nearest rising hole. It is not known what will be the temperature and rate of flow of the water that comes up, and what generation efficiency these will enable. In addition in Australia there will be the dollar and energy costs of constructing very long transmission lines from the deserts where the hot rock is located. The only operating plant in Australia (not at the most promising location) can transform into electricity only 6% of the heat energy in the water, one-sixth the efficiency value for a coal-fired power station.

It is not likely that "smart, demand-response management" could make much difference.

3. "Use smart demand-response management to shift flexible loads to better match available ... generation."

The value of this strategy depends on the proportion of total load that is flexible, and this is likely to remain quite limited. Some heating and cooling functions can draw on heat energy stored for days, but all domestic and commercial energy use makes up only about 16% of total energy use, so their heating and cooling demand would probably be well under 10% of all energy. There would be virtually no scope for shifting the timing of electric vehicle battery recharge (see below), or of most energy-intensive industrial uses. Some industrial processes such as ammonia or cement manufacture do in principle allow postponement, e.g., until summer, but this means expensive plant sitting idle some/much of the time. Energy-intensive kilns and furnaces cannot be switched on and off to follow short solar and wind peaks. These functions do not add to a large fraction of energy demand.

Jacobson and Delucchi assume that the charging of electric vehicle batteries is "flexible:" "most electric vehicles would be charged at night." This is problematic as at night winds tend to be low and there is no input from PV systems.

Thus it is not likely that "smart, demand-response management" could make much difference to the general situation, let alone in those periods when there is negligible sun or wind in the region for days at a time.

4. Store electric power.

Jacobson and Delucchi list a number of ways in which electricity can in effect be stored, but these fall far short of being capable of storing the quantities required.

Pumped water storage. The gaps left by intermittent sources can be filled to some extent by electricity generated by water that has been pumped up into dams. However, the capacity compared with demand is very limited. World hydro-electric generation meets only about 15% of electricity demand, and the 10.7 EJ/y (exajoules per year) contribution is not likely to be doubled. Hydro electricity has been c. 9% of electricity supply in Australia but has fallen to 6% in recent dry years. It can provide only 18% of demand for a short period in Australia.

Reference to hydroelectric capacity is misleading because it refers to water released in a once-through flow from a high dam, whereas pumped up storage is not possible unless there is also a low dam close by to hold the large volume of water to be pumped. Thus the main limit is to do with how many dams have or could be given adequate low-dam capacity. The sea can be used as the low "dam" but this sets problems to do with seepage of salt into the ground at the high dam sites. This is why a proposal in South Australia was abandoned.

A major problem is in deciding at a point in time whether the need will be for empty high dams to store surplus energy from a coming surge in wind, for instance, or full high dams to enable generation through a coming lull in wind energy. There is also the need to keep dams somewhat empty to enable mitigation of floods, in an era in which the frequency of extreme weather events is likely to increase. The greenhouse problem is likely to reduce hydro capacity in future.

Smil (2010) points out that stop/start generation sets problems regarding high volume water flows over long distances through tunnels connecting low and high dams. Getting large volumes moving takes energy, lowering overall efficiency.

The cost of CAES would be prohibitively high for large scale use.

Lang (2010) explored the feasibility of tunnelling 50+ km between two dams in the Australian Snowy Mountains scheme and found that the venture would be too expensive. It would only generate 9 GW for 3 hours, but Australian average consumption is c. 30 GW. These considerations suggest that except in unusual regions pumped storage cannot make more than a quite small contribution to the storage task that would be involved in maintaining supply through periods of protracted cloudy and calm weather.

Compressed air energy storage (CAES) This seems to be the most promising option but its potential is not clear. Using electricity to compress air and then using the air to generate electricity later is claimed by some to be between 40% and 70% efficient. However Mackay (2008) states 18%, presumably referring to systems not using added heat at the expansion/regeneration stage.

Easily overlooked is the fact that we would have to pay the capital cost of at least two generating systems. The first would be the windmills creating the electrical energy, the second would be the equally large system of compressors converting the electrical energy into compressed air. (It is assumed that the compressing turbines can be reversed to do the subsequent regenerating.) To this generating capacity must be added the cost of the storage structures. Fthenakis (2009) says the cost of CAES is half that of lead-acid battery storage. If so it would be prohibitively high for very large scale use. Thus capital costs would probably be 2+ times that of the wind turbines, while energy delivered might be 40% less than they generate, meaning that the capital cost per kWh delivered would be around 3.5 times that for a windmill without storage.

It is difficult to see how an electric vehicle battery could be available for a useful length of time.

Very large storage volumes would be required to store significant quantities of energy. According to Fthenakis (2009) there is sufficient storage space in the US, especially in the form of old gas fields. Most other countries would have less of these.

The main storage task is coping with several calm and cloudy days in a row, as distinct from providing16 hours' night time supply from a PV system after a normally sunny day. Providing four days' capacity would set a storage task more than six times as large.

The biggest problem would seem to be the fact that high efficiency requires the burning of gas to provide heat to the air as it expands at the regeneration stage. In a wholly renewable energy world this will not be possible. Solar heat could be used, but this would mean solar plant would have to be added to collect energy in the form of heat equivalent to a large fraction of the energy collected by wind, and the plant to store it would also have to be built. Heat availability would be at its lowest in winter when wind energy for storage, and the need for stored energy, would both be at their highest. Heat released in the compression phase might be stored for this use, although this would also involve large scale capital costs.

New batteries and capacitors. New kinds of batteries are being developed for wind power, but the cost goal has been reported as $(US)500 per kWh. This would seem to be far too high for large scale use. To store the 16,000 MWh from a 1000 MW PV power station for night time supply would cost $8 billion, some four times the cost of a 1000 MW coal-fired plant.

Hydrogen. Jacobson and Delucchi include in their list of storage strategies using renewable sources to produce and store hydrogen. They do not explore the implications of the low energy efficiency of this path. The energy efficiencies of (a) producing hydrogen from electricity, (b) compressing, pumping and distributing it, and (c) re-generating electricity via (expensive) fuel cells are, optimistically, .7, .8 and .5, meaning that each kWh the wind turbines generated would deliver .28 kWh to use via this path. Again the implications for capital cost are significant, in effect multiplying the cost of generating plant per kWh delivered via hydrogen by 3.6.

To these costs those of the hydrogen-producing and storage plant would need to be added. If the strategy is to store hydrogen for the regeneration of electricity, almost as much generating capacity would be needed in the form of fuel cells as in the form of wind turbines, and their cost per kW of generating capacity is far higher than that of wind turbines.

Jacobson and Delucchi assume that liquid fuel for aircraft and other uses would be provided via liquid hydrogen. They do not discuss the implications for gaseous or liquid hydrogen use of quantities of plant, embodied energy costs or capital costs.

It is not clear whether thorough embodied energy accounting would show any net benefit in the hydrogen path, especially when liquid hydrogen or fuel cells are involved. If the energy needed to construct all equipment for dealing with the hydrogen was subtracted from the .28 kWh energy content of the hydrogen produced by 1 kWh of electricity, or from the .14 kWh of liquid hydrogen (requiring cooling plant), and if the embodied energy cost of renewable plant is around 10% (a probable figure for solar thermal, see Lenzen 1999), then it is possible that it would take about as much energy to provide the hydrogen as contained in it.

5. Store in electric vehicle batteries.

Jacobson and Delucchi regard this as an "especially promising" option. The main problem with this strategy is that vehicle batteries need to be fully charged when they are to be used, which is typically twice a day. It would take time to recharge the batteries from the drive to work; then there would be the storage time until the energy is needed, and the time that use takes; then it would take time to recharge the battery again to be ready for the drive home from work. At present it can take seven hours to recharge a battery. It is therefore difficult to see how an electric vehicle battery could be available for a useful length of time to perform a general electrical system storage contribution.

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Many car users could not predict confidently when they were likely to want to use the car, and would set safety margins reducing the available time. Vehicles would be most available for storage at night, but electricity demand falls markedly at night so there would not be that much need for storage then. Winds tend to be lower at night, and there would be no PV input.

The capital cost of a system would have to include the cost of two separate transformers (from 240 v to 12 v), battery chargers and inverters for supplying to the 240 v mains, for every vehicle. One set would need to be where the vehicle was parked overnight and the other where it was parked during the day.

A satisfactory analysis would show numerically how various plausible conservation and conversion steps might reduce the amounts of energy needed.

The limitation set by a seven-hour charging time could be eliminated by battery swap systems at "refuelling" stations. However, this would double the quantity of batteries required, with significant effects on system energy costs and the availability of materials.

Finally there are the economic implications for the car owner. If he pays 13¢/kWh for the electricity to charge his battery, loses some of this in charging and sells the remainder back to the grid at the c. 5 ¢/KWh which other electricity suppliers are paid he is not likely to want to be involved in the scheme This suggests that participants would have to be paid at least three times the wholesale price received by other generators, and probably significantly more, to compensate for the shortening of battery life due to the additional charging and discharging cycling.

6. "Forecast weather to plan energy supply needs better."

It is stated that this "gives operators more time to plan ahead for a backup energy supply when variable energy source might produce less than anticipated." (p. 1173)

Again the claim is true, but can make little difference. Even perfect forecasting capacity would bring virtually no greater ability to deal with those periods of several days at a time when solar and wind input is negligible.

The usually overlooked need for redundancy

Optimistic claims re the potential of renewable energy typically fail to recognise the need for large scale *redundancy* in generating capacity, caused by the fact that often one or more component systems will not be contributing much if anything.

This shows that the crucial question is the capital cost of the quantity of plant required to cope with (a) periods of minimal or zero energy availability, (b) periods of maximum demand, and (c) the required amount of plant redundancy to cope with variability which at times reduces or eliminates contributions from one or more components of the total system.

Investment costs

Jacobson and Delucchi estimate that their scheme would cost in the vicinity of $100 trillion over 20 years, meaning an annual investment cost of $5 trillion. It is not pointed out that an investment of $5 trillion per annum (p.a.) would be more than 11 times the early 2000s $450 billion p.a. total global energy investment sum. (Birol, 2003, Pfuger, 2004.) Nor is it made clear that this sum would have to be paid in perpetuity, as plant would need to be rebuilt after its lifetime had expired. (Jacobson and Delucchi refer to the IEA's assumption of 20-year lifetimes, but they assume 30 years. IEA, 2008)

The $100 trillion figure appears to be a correct derivation from Jacobson and Delucchi's assumptions regarding the number of wind turbines etc. required and the capital cost per kWh they assume. However some of their key assumptions are highly challengeable. They state that their cost figures are 30% lower than those of the IEA, without adequate explanation. More importantly, the 2050 supply target in their discussion, 11.7 TWh/y [terawatt (trillion-watt) hours per year], is 15% lower than *present* world consumption. Remarkably, this is not explained or justified and only three scattered sentences seem to be given to it throughout the two papers.

The 2050 supply target in their discussion is 15% lower than present world consumption.

The claim seems to be (e.g., p. 1159) that the innovations and savings involved in the proposed conversion of many functions to electricity would result in a reduction in final demand of this magnitude, but no attempt is made to show this numerically. It is an implausible claim as the target assumed is less than half the probable 2050 world energy demand that is indicated by IEA and other projections. Subtracting the embodied energy costs of all components would further reduce the efficiency gain, but Jacobson and Delucchi do not discuss the embodied energy costs of any renewable technology.

The appropriate beginning point for arriving at a target in exercises of this kind is the likely 2050 demand we are heading for under business as usual, which is in the region of twice present world energy consumption. A satisfactory analysis would show numerically how various plausible conservation and conversion steps might reduce the amounts of energy needed by the industrial, transport etc. sectors feeding into this total, and then consider how renewables might enable achievement of the resulting target. Had a more appropriate target been taken the amount of plant required and the associated capital costs would have been significantly higher than those Jacobson and Delucchi arrive at.

Trainer (2010a) derives a budget for renewable energy capable of meeting 2050 world demand in mid-winter, and estimates that annual investment would have to be much greater than $5 trillion p.a. The exercise did not take into account three factors that would markedly increase the required investment sum. First, no provision was attempted to deal with the variability of renewable energy sources, and had this been done the plant and capital conclusion arrived at would have been markedly higher. That is, the contributions from renewables were based on monthly *average* wind speeds and solar radiation levels, whereas a more realistic analysis would have focused on the plant needed to cope with *minimum* wind and radiation occurrences. Second, no provision was made for meeting peak demand; the supply target assumed was the annual average demand. As has been noted, the need to cope with peak demand can require building 1.5 or more times the amount of plant needed to meet average demand. Third the exercise did not take into account the cost of capital, which could double the investment figure arrived at when all other factors have been accounted.

Renewables can enable a satisfactory quality of life for all, but not in energy-intensive, consumer-capitalist societies.

It should also be noted that the supply target Jacobson and Delucchi take would provide the world's likely 2050 population with only around 45 gigajoules per person, which is only about 16% of the present Australian per capita energy consumption. If their claim for renewable energy is that it can provide present rich world energy consumption levels to all people then the figures for plant and capital costs would be some seven times the sum associated with their supply goal.

Unless the assumptions and derivations underlying the estimates above and in Trainer (2010a) are significantly mistaken, it would seem to be impossibly costly to provide all people with present or anticipated rich world energy-intensive "living standards" via renewable energy.

Policy implications

The foregoing analysis has not been an argument against attempting to transition to full reliance on renewable energy sources. Trainer (2010c, 2011) argues that such a transition should be undertaken as quickly as possible and that renewables can enable a satisfactory quality of life for all, but not in energy-intensive, consumer-capitalist societies.

The general "limits to growth" analysis of the global predicament identifies energy as only one of several accelerating problems that are insoluble unless the fundamental commitments of such societies to affluent "living standards" and economic growth are abandoned. A radically different "Simpler Way" could be viable and attractive. This vision embraces frugal lifestyles, small and highly self-sufficient local economies, and participatory and co-operative ways in an overall economy that is not driven by growth or market forces.

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