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COMMENT

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Comment on "Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries" by M. Z. Jacobson, A. von Krauland, S. J. Coughlin, E. Dukas, A. J. H. Nelson, F. C. Palmer and K. R. Rasmussen, *Energy Environ. Sci.*, 2022, 15, 3343–3359

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According to Jacobson *et al.* the energy transition from fossil fuels (Business as Usual, BAU) to energy using wind, water and sun (WWS) can be completed by the year 2050 at minimal costs and with a land occupation of less than 1% of the total land area. This claim relies on unrealistic assumptions and is therefore misleading. In their ambition to show the road to a better world without pollution from energy production, the authors stretched some basic underlying parameter values beyond what is physically possible. The authors wrongly excluded nuclear energy as an option.

1. Introduction

Jacobson *et al.* depict a rosy future for energy transition from fossil fuels (Business as Usual, BAU) to energy using wind, water and sun (WWS). They say that this transition can be completed by the year 2050 at low costs and with a land occupation for WWS at less than 1% of the total land area. The mortality due to air pollution will be reduced by 90%. We will also have less financial costs and more new jobs. The stability of the electric grid will be maintained. Unfortunately, these claims are based on flawed assumptions and doubtful methodology. The authors wrongly excluded nuclear energy as an option, which makes the proposed transition practically impossible.

2. On methodology

Jacobson *et al.* distinguish 24 regions in the world that are extremely different in size. The smallest region is Mauritius (2000 km^2). By far the largest region is the whole continent of Africa (30 million km^2). Other large regions are South-America and South-East Asia. They used a computer model (LOADMATCH) to match variable energy demand with variable energy supply and storage. This sounds fine for a small region such as Mauritius where transport may be feasible, but how can one assume that reliable transport is possible from Algeria to South-Africa, and that at a cost of 0.142 c per kW h only (Table S19)? Or between Myanmar and Indonesia? It is methodologically doubtful to treat such a large diversity in size, geographic and social conditions, political, technological and economic development on an equal footing. The supporting tables are overwhelming but the displayed number grinding does not improve the quality of the output which depends first of all on the underlying assumptions.

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3. On transportation

For the year 2050 the paper assumes: "Hydrogen fuel-cell-electric vehicles power all long-distance transport by road, rail, water, and air. They also power long-distance air, water, and land military transport". They base this assertion on a paper by S. M. Katalenich and M. Z. Jacobson[1] Fig. 5 in this paper shows that the specific energy content in batteries is still one or two orders of magnitude too small for this task. What about hydrogen? Steel cylinders that store 5.6 kg of compressed hydrogen at 700 bars, have an empty weight of 100 kg, resulting in an energy/weight ratio of 1.75 kW h kg^{-1}.[2] Carbon fibre cylinders can reach 2.0 kW h kg^{-1} of hydrogen,[3] but this ratio is still way below the 21 kW h kg^{-1} needed.[1] It turns out that this high value can only be reached with cryogenic storage.[1] However, liquefaction of hydrogen consumes at least 30% of its own energy content.[4] The conversion loss in the fuel cell to electricity is another 30%. The liquid hydrogen must be kept below

−253 °C. To believe that this is possible in mass transport vehicles on a practical scale is pure phantasy.

4. On area requirement

4.1 WWS is area greedy

In the ''Broader context'' paragraph the authors write: ''The new land and footprint areas required for WWS systems are small relative to the land taken up by the fossil fuel industry''. This is a statement for which no evidence or reference is given. It cannot be correct. Up to now, the actual energy production by WWS is still much less than the energy produced by fossil fuel plants, yet the areas occupied by wind turbines and solar panels are already enormous compared to those of fossil fuel plants.[5] This difference in land requirement is due to the much smaller energy density of wind, water and solar radiation in comparison to that of fossil fuel. The industrial revolution would not have been possible if mankind had not replaced the medieval wind and water mills by fossil fuel plants.[6] Sure, there may still be some technical innovations to come in wind turbines and solar panels, but a jump in efficiency by one or two orders of magnitude is impossible, given the laws of nature. Yet, this is what Jacobson *et al.* assumed, as can be shown by the examples given below for The Netherlands and also for Europe. It makes one doubt about the realism for the other regions.

4.2 The Netherlands

The offshore Gemini wind park in The Netherlands has an average electricity production of 4.4 W m^{-2} of sea area.[7] It produces about 300 MW as an annual average. Onshore the production of wind energy per area is much smaller, at most about 1.5 W m^{-2}, because of the lower wind velocity on land.

As of 2021 the wind turbines onshore in The Netherlands cover about 900 km^2 and produce about 1.1 GW as an annual average, which is 8% of the annual electricity demand.[8]

These are the facts. What do Jacobson *et al.* foresee? In their Table S23 they mention that the required area for new onshore wind turbines in The Netherlands in 2050 will be 675 km^2, thus raising the total onshore area for wind turbines in The Netherlands to about 1575 km^2. At an efficiency of 1.5 W m^{-2} for onshore wind, this area can produce about 2 GW of power on average. However, according to Table S9, the onshore wind power in The Netherlands is supposed to have a nameplate capacity of 17.53 GW, which means a potential of 11 W m^{-2}. Such a high value for efficiency is impossible for onshore wind.

4.3 Europe

Is the example of disputable expectations for The Netherlands perhaps an exception? According to Table S8 in Jacobson *et al.* the nameplate power of onshore wind in Europe is currently 185 GW. At a capacity factor around 0.25 the actual average power produced will be about 46 GW, which leads to an estimate of 40 000 km^2 of area presently occupied. In Table S9 the expected nameplate capacity onshore in Europe in the year 2050 will be 1174 GW, which is about six times more than at present. According to their Table S23 the required area for new onshore wind turbines in Europe is supposed to be 0.88% or almost 50 000 km^2. This means that the foreseen total area is not six times larger, it is just barely doubled. It is impossible that the capacity factor can be raised by a factor three (six times more power divided by twice the area) from the present value of 0.25 to 0.75. So, for the whole of Europe it is by and large the same story as it is for The Netherlands: it is characterized by an irresponsible optimism about the potential of WWS.

5. On reliability

It is true that modern wind turbines and solar panels can produce a sizeable amount of electricity as long as weather is favourable, thus reducing fossil energy use at those periods of time. However, the modern industrialized society needs a guaranteed continuous supply of electric power at a constant voltage and frequency. There will always be periods of low wind or without sun. Such periods can be short (a night), or long (in winter). Solar energy has such a strong variation that its capacity factor is hardly better than 10 percent in Northern countries. This small value of capacity factor means that the diurnal peak of produced power must be ten times larger than the annual average energy production. Without resorting to a backup by fossil energy or by nuclear energy, there is no way to level out these peaks other than by storing them in batteries or in hydropower. No single country can obtain self-sufficiency of energy from WWS, unless it is blessed with sufficient hydropower potential.

Unlike Jacobson *et al.* contend in section 3.3 and again at the end of 3.5, sun and wind are not complementary in nature. Even their own graphs contradict their claim. The scatter in the bottom row graphs of their Fig. 3 is enormous. An R^2 as small as 0.03 shown in their Fig. 3B, is in fact proof of absence of correlation.

It is crucial that another energy source is available during such periods of low wind or no sun. The authors of Jacobson *et al.* are well aware of this. They say that batteries with a 4 h capacity can be concatenated in series. The longest duration of battery discharging required in their simulation is 61 h, less than three days. It is obvious that such a short duration is not sufficient to get us through long periods of still weather in winter. We will then have to rely on either hydrogen or hydropower. There is very little additional hydropower available, so that hydrogen is the only option for long term storage.

6. On costs

The cost of hydrogen is prohibitive. Jacobson *et al.* give a hydrogen cost of 0.31 c per kW h (Paragraph 3.3), levelized over all electricity consumed. In reality hydrogen costs at least 3.3 \$ kg^{-1}, or about 10 c per kW h.[9] The difference is a factor 30! Given the large role ascribed to hydrogen in this paper, it is unlikely that the price increment of LCOE due to hydrogen alone can be reduced that much. If such a large reduction is obtained by distributing this cost over the total electricity consumption (as they do), it means that electricity from hydrogen will constitute only 3% of the total electricity consumption.

Such a small percentage rules out hydrogen as a serious option for industry, certainly during the winter months in Northern countries.

7. On nuclear power

By excluding nuclear power, the authors have unnecessarily complicated their mission to figure out a feasible pathway to reduce global warming and to get rid of deadly air pollution. They argue that there are concerns with nuclear power without further underpinning their opinion. While such concerns might have been valid in the early days of nuclear power, they are outdated in view of mounting scientific evidence.[10–13] When comparing costs it should be remembered that a service with a guaranteed delivery may rightly cost a little more than a product that is only available at irregular and prolonged intervals.[14,15]

8. Conclusions

It is unlikely that the energy transition from BAU to WWS can be completed by the year 2050 at low costs and with a land occupation for WWS at less than 1% of the total land area. In their ambition to show the road to a better world without pollution from energy production, the authors stretched some basic underlying parameter values beyond what is physically possible. Unfortunately they ignored nuclear energy. There is growing evidence that their concerns about it are unfounded. Nuclear energy has the potential to solve the problem of intermittency, thus ensuring a reliable electric grid. A new study that does include nuclear energy as an option, is highly needed.

Conflicts of interest

There are no conflicts to declare.

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