Energy & Environmental Science

COMMENT

View Article Online
View Journal

Cite this: DOI: 10.1039/d2ee03964h

Reply to the 'Comment on "Low-cost solutions to global warming, air pollution, and energy security for 145 countries"' by J. Goudriaan, *Energy & Environmental Science*, 2023, 16, DOI: 10.1039/D2EE03680K

Mark Z. Jacobson,* Anna-Katharina von Krauland, Stephen J. Coughlin, Emily Dukas, Alexander J.H. Nelson, Frances C. Palmer and Kylie R. Rasmussen

Received 8th December 2022,
Accepted 30th January 2023

DOI: 10.1039/d2ee03964h

rsc.li/ees

Broader context

J. Goudriaan has written a commentary on our paper, "Low-cost solutions to global warming, air pollution, and energy security for 145 countries." In our response, we show that his claims are either incorrect, unproven, or irrelevant. As such, the conclusions in our paper still stand: transitioning countries to 100% wind-water-solar and storage for all energy purposes reduces energy and social costs, saves lives, reduces climate damage, increases net employment, and uses only ~0.53% of the world's land for new energy. Investments in new nuclear power, fossil fuels with or without carbon capture, and bioenergy are not needed in a transition and, in fact, are opportunity costs that will damage our ability to transition at the pace needed.

The claims by Goudriaan[1] (hereinafter Goudriaan) about Jacobson *et al.*[2] (hereinafter Jacobson *et al.*) are either incorrect, unproven, or irrelevant thus have no effect on the conclusions of Jacobson *et al.*

First, Goudriaan criticizes Jacobson *et al.*'s "low" cost of additional HVDC lines proposed in Africa and Southeast Asia, but shows no flaw in the cost calculation, which was provided transparently. He also acknowledges that matching demand with supply in small regions is not so difficult. His main argument is that interconnecting all of Africa is difficult. This is admitted as a political uncertainty in Section 4.11 of Jacobson *et al.*, but as shown in ref. 3 even if a country cannot easily interconnect with multiple other countries, that country can either provide 100% of its own energy with wind-water-solar (WWS) or interconnect with fewer countries at only slightly higher cost than interconnecting with more countries. Given that a conversion of a well-interconnected Africa to 100% WWS for all energy reduces annual energy costs by 71% and annual social costs by 95% (Table S20 of Jacobson *et al.*) *versus* business-as-usual (BAU), even a larger annual energy cost due to breaking Africa up into several isolated regions, as done in ref. 3 for Europe, still results in much lower energy and social costs with WWS than with BAU, thus has no effect on the conclusions in Jacobson *et al.*

Goudriaan admits that Jacobson *et al.* proposes using hydrogen fuel cells for long-distance air and ship transport but then states that, based on ref. 4, battery energy density is too low for this task. This comment is moot, since Jacobson *et al.* excluded batteries for such long-distance transport for this reason. Goudriaan then says aircraft would need cryogenic hydrogen, and energy is needed for a fuel cell. Yet,[4] accounted for these factors. They found, for example, that, based on technologies in the published literature, a cryogenic hydrogen fuel cell 747-8 could travel the same distance and have the same thrust-to-weight ratio as a jet fuel 747-8, but at 22% lower mass and 21% larger volume. Goudriaan provides no evidence disputing this.

Goudriaan next correctly states that Jacobson *et al.*'s claim that the new land footprint plus spacing area (0.53% of 145-country land) is "small relative to the land covered by the fossil fuel industry" was unreferenced. This oversight is corrected here. Ref. 5–7 report that 1.3% of U.S. land is occupied by the fossil fuel industry. This occupation is increasing due to the addition of tens of thousands of new oil and gas wells drilled yearly. For direct comparison, Jacobson *et al.* reports (Table S23) that only 1.15% of U.S. land is needed for new WWS footprint and spacing in the U.S. Part of this reason is that rooftop solar takes up no new land, no new hydropower is

Department of Civil and Environmental Engineering, Stanford University, Stanford, California 94305-4020, USA. E-mail: jacobson@stanford.edu

added, and geothermal additions are small. The only new land for footprint is for utility PV and CSP. The only new land for spacing is onshore wind. As such, new land requirements with 100% WWS are expected to be lower than land required for the current energy infrastructure in many countries.

Goudriaan then claims that the energy densities of wind, water, and solar power are low *versus* fossil fuels. Although that fact is true, Goudriaan fails to account for the land required for active and abandoned oil and natural gas wells and coal mines; oil refineries; oil and gas pipelines; coal, oil, and natural gas power plants; gasoline and diesel fueling stations, and natural gas storage facilities[6] and the fact that fossil fuel drilling, extraction, and capping is continuous and, thus increasing over time. WWS requires no mining for continuous fuels.

Goudriaan then uses a method of calculating the installed and output power densities of a wind farm in the Netherlands to overestimate the spacing area required for wind. A recent study of installed and output power densities of multiple offshore and onshore wind farms in Europe[8] concluded, based on a consistent methodology, that the installed and output power densities of offshore wind farms in Europe are 7.2 (3.3–20.2) MW km^{-2} and 2.94 (1.15–6.32) W m^{-2}, respectively. Those for onshore wind farms are 19.8 (6.2–46.9) MW km^{-2} and 6.64 (2.3–8.2) W m^{-2}, respectively. The method used in ref. 8 corrects previous erroneous methods of calculating wind farm installed and output power densities, including the method used by Goudriaan: it eliminates the erroneous counting of space outside of wind farm boundaries, space between clusters of turbines, and overlapping space that results when assuming a large, fixed area around each turbine.

Goudriaan then incorrectly represents Jacobson *et al.*'s calculation of land area for onshore wind in the Netherlands, wrongly claiming that the nameplate capacity in Table S9 is all for new generators, when it is for new plus existing generators. Subtracting existing onshore wind (4.174 GW from Table S8) from 17.53 GW gives 13.36 GW of new generators in the Netherlands. At a data-based installed power density of 19.8 W m^{-2} from ref. 8, the land required is 675 km^2, the exact spacing area reported in Table S23. Goudriaan incorrectly claims the output power density is 1.5 W m^{-2}, when data for European wind farms indicates it is 6.64 (2.3–8.2) W m^{-2},[8] resulting in a capacity factor of 33.5%. Goudriaan continues his mistake with similar erroneous numbers for all of Europe.

Goudriaan's discussion of reliability contains a substantial misunderstanding. Goudriaan states, "Without resorting to a backup by fossil energy or by nuclear energy, there is no way to level out these peaks." However, nuclear doesn't provides peaking power anywhere in the world. In all but France and Germany, nuclear provides only baseload power. In France and Germany, it provides load-following, not peaking power. During load following, the maximum ramp rate of nuclear is 100% in 20 to 100 minutes, much slower than that of a natural gas open cycle gas turbine (100% in 5 minutes), hydropower (100% in 15 seconds), or a battery (100% in $\ll$ 1 second) [Table 2.1 of ref. 7]. Even solar and wind can load follow, since if a generator is projected, due to weather forecasting, to have electricity available over a coming period, it can compete in a real-time electricity market to sell the electricity for load following [Section 8.1.6.1 of ref. 7]. For peaking power, the ramp rate needs to be 5 to 10 times the minimum ramp rate required for load following [Section 8.1.6.2 of ref. 7]. Nuclear power's ramp rate is too slow for peaking. However, hydropower, batteries, pumped hydropower storage, flywheel storage, compressed air storage, and gravitational storage, all WWS technologies, have ramp rates fast enough to provide peaking power [Table 2.1 of ref. 7].

Goudriaan further claims without evidence that "no single country can obtain self-sufficiency of energy from WWS, unless it is blessed with sufficient hydropower potential." Whereas hydropower can provide baseload, load-following, and peaking power, so is very helpful with grid stability in a 100% WWS system, it is not required. Of the 31 countries whose electricity generation is with over 50% WWS, three (Uruguay – 41.5% wind, Denmark – 56.9% wind, and Lithuania – 28.1% wind) are dominated by wind and one (Kenya) is dominated by 45.5% geothermal.[9] In addition, Scotland produces the equivalent of 70.9% of its consumption from wind; South Dakota, 77%.[9] Over 700 scientific papers have shown that 100% renewable systems are possible throughout the world with no nuclear or fossil fuels.[10]

Goudriaan then states that, because the *R*-value in Figure 3B of Jacobson *et al.* is small, wind and solar are not complementary in nature. However, Table S26 shows the *R*-value for all regions, and the results indicate an anti-correlation between wind and solar in every region, albeit either weak or very weak. If no correlation existed, some locations would have a positive correlation. Wind and solar are anticorrelated for a meteorological reason.[11]

Goudriaan then incorrectly claims that the "longest duration of battery discharging required in their simulation is 61 h." No, 61 hours is the highest ratio of energy needed by batteries (GWh) to their peak discharge rate (GW). The lowest ratio was 4 hours. That just means that storage duration of longer than 61 hours at the peak discharge rate is not useful since it prohibits the ability of batteries to provide the full peaking power that is actually needed. It says nothing about how many hours of storage in a row concatenated batteries are providing energy or power for.

Goudriaan then mistakenly claims that "hydrogen is the only option for long-term storage," not recognizing that concatenated batteries accomplish the exact same goal, but with one-half to one-third the number of WWS electricity generators (thus less land), due to the higher efficiency of batteries than of a hydrogen fuel cell system, and at much lower cost. Although hydrogen storage is less expensive than batteries, 4 hour batteries provide both peak power and energy storage. For hydrogen to provide both equivalently, many fuel cells (and additional electricity generators) are needed in addition to storage, driving the cost of hydrogen beyond that of batteries for stationary grid storage.

Next, in evaluating Jacobson *et al.*'s cost analysis, Goudriaan compares apples (cost of hydrogen per unit of all electricity on the grid) with oranges (cost per unit of electricity produced by hydrogen). He also misses the fact that electricity produced by hydrogen is on the order of only one-half to one-third the electricity needed to produce the same hydrogen.

Finally, Goudriaan ignores the costs and problems with nuclear, claiming that it would be helpful in a transition. However, new nuclear electricity is unhelpful for the reasons discussed in Section 3.3 of ref. 7: cost, excessive delays between planning and operation, meltdown risk, weapons proliferation risk, radioactive waste risk, carbon-equivalent emissions, and underground uranium mining risk. In particular, new nuclear reactors take anywhere from 11–21 years between planning and operation *versus* 0.5–3 years for new wind and solar. The 2022 capital cost of the two Georgia Vogtle reactors is about \$15.2/watt *versus* about \$1/watt for new onshore wind and utility solar PV. The resulting cost per unit energy of new nuclear is $\sim$7.5 times that of new wind and solar. We need to solve 80% of the climate and pollution problems we face by 2030. New nuclear can play zero role in meeting this goal due to the long planning-to-operation time alone.

In sum, Goudriaan's comments, while welcome, are based on erroneous assumptions or claims and do not change the conclusions of Jacobson *et al.*

Conflicts of interest

There are no conflicts to declare.

References

1 J. Goudriaan, *Energy Environ. Sci.*, 2023, **16**, DOI: 10.1039/D2EE03680K.

2 M. Z. Jacobson, A.-K. 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, DOI: 10.1039/d2ee00722c.

3 M. Z. Jacobson, *Renewable Energy*, 2021, **179**, 1065–1075, DOI: 10.1016/j.renene.2021.07.115.

4 M. Katalenich and M. Z. Jacobson, *Energy*, 2022, **254**, 12435.

5 M. Z. Jacobson, A.-K. von Krauland, S. J. Coughlin, F. C. Palmer and M. M. Smith, *Renewable Energy*, 2022, **184**, 430–444.

6 M. Z. Jacobson, 2021, Land area occupied by the fossil fuel and nuclear industries in California and the U.S., https://web.stanford.edu/group/efmh/jacobson/Articles/I/LandFossil.pdf.

7 M. Z. Jacobson, *100% Clean, Renewable Energy and Storage for Everything*, Cambridge University Press, New York, 2020, p. 427.

8 P. Enevoldsen and M. Z. Jacobson, *Energy Sustainable Dev.*, 2021, **60**, 40–51.

9 M. Z. Jacobson, 31 countries whose electricity generation is with over 50% wind-water-solar, 2022, https://web.stanford.edu/group/efmh/jacobson/WWSBook/Countries100Pct.pdf.

10 C. Breyer, S. Khalili, D. Bogdanov, M. Ram, A. S. Oyewo, A. Aghahosseini, A. Gulagi, A. A. Solomon, D. Keiner, G. Lopez, P. A. Østergaard, H. Lund, B. V. Mathiesen, M. Z. Jacobson, M. Victoria, S. Teske, T. Pregger, V. Fthenakis, M. Raugei, H. Holttinen, U. Bardi, A. Hoekstra and B. K. Sovacool, *IEEE Access*, 2022, **10**, 78176–78218.

11 M. Z. Jacobson, *Smart Energy*, 2021, **1**, 100009.