REPLY TO BISTLINE AND BLANFORD:

Letter reaffirms conclusions and highlights flaws in previous research

Mark Z. Jacobson[a,1], Mark A. Delucchi[b], Mary A. Cameron[a], and Bethany A. Frew[a]

Bistline and Blanford's (1) (hereinafter BB16) comments about Jacobson et al. (2) (hereinafter J15) are incorrect or unsubstantiated, and thus affect no conclusion in J15. However, their remarks highlight the failure of previous decarbonization studies to treat many existing storage options, load reduction upon electrification, accurate wind power, and true nuclear and carbon capture costs.

i) BB16 (1) provide no evidence that J15's (2) cost, demand flexibility, or electrification assumptions are aggressive. Further, J15's cost ranges are neither confidence intervals nor narrow (e.g., underground storage capital costs span over an order of magnitude), and, by far, most technologies proposed are commercial or extant for years.

ii) BB16 (1) provide no evidence that J15's (2) results are not applicable regionally. Instead, each state, let alone region, has a diverse mix of wind, water, and solar (WWS) and storage potential (3). Also, the United States is already interconnected, and J15 accounted for additional long-distance transmission costs to increase interconnection.

iii) BB16 (1) provide no evidence that J15's (2) time-dependent loads extrapolated to 2050–2055 were sufficiently inconsistent with modeled 2050–2055 wind/solar fields to affect conclusions. Instead, J15 find solutions for different load profiles, accounting for extreme variability. Moreover, ref. 4, cited by BB16 as treating synchronous loads, did not, because ref. 4's winds were erroneously high, thus inconsistent with loads, as they ignored turbine competition for kinetic energy, and their fields were from 2010, and thus inconsistent with the future scenarios simulated.

iv) The claim that ref. 4 or others have performed high-temporal resolution scenarios accounting for most economic drivers is false. Ref. 4 performed diagnostic, not prognostic, optimization calculations for only 86 staggered hourly time steps, thus only 10% of 1 y, because, as they state, their optimization technique is "intractable." Conversely, J15 (2) obtained >300 prognostic time-dependent solutions, each for 6.3 million consecutive 30-s steps over 6 y. Further, J15 accounted for generation, storage, transmission, distribution, health, and climate costs. Conversely, ref. 4 mention no health, climate, transmission, or distribution costs and use outdated solar/wind costs.

v) There is no inconsistency between J15 (2) and the decarbonization studies in ref. 5, because objectives differed: J15's goal is to demonstrate low-cost solutions, including storage, to the grid problem given a 100% WWS system; ref. 5's goal was to find low-cost technology mixes, ignoring most storage, that reduce emissions 50–80%. J15 started by assuming 100% WWS in 2050; ref. 5 started with current energy, and then examined pathways to 50–80% abatement. No model compared in ref. 5 performed high-temporal-resolution calculations as in J15, and none examined a 100% WWS system. No author in ref. 5 developed state plans to electrify all sectors; thus, they missed reducing load due to the higher energy-to-work ratio of WWS electricity over combustion and to reducing energy for mining, transporting, and refining fuels. Ref. 5 also largely neglected electricity storage and omitted heat, cold, and hydrogen storage and air pollution costs, treated in J15. Finally, ref. 5 included nuclear, carbon capture, and biofuels, which all entail greater catastrophic and/or health/water/land risks than 100% WWS, yet ref. 5 failed to quantify costs of such risks.

vi) Ref. 5 cannot show the "best" way because they neither provide time-dependent calculations, nor include all storage options, nor examine 100% WWS that J15 (2) and ref. 3 show provide maximum environmental benefits at reasonable cost.

[a]Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305; and [b]Institute of Transportation Studies, University of California, Berkeley, CA 94720

Author contributions: M.Z.J., M.A.D., M.A.C., and B.A.F. wrote the paper.

The authors declare no conflict of interest.

[1]To whom correspondence should be addressed. Email: jacobson@stanford.edu.

1 Bistline JE, Blanford GJ (2016) More than one arrow in the quiver: Why "100% renewables" misses the mark. *Proc Natl Acad Sci USA*, 10.1073/pnas.1603072113.
2 Jacobson MZ, Delucchi MA, Cameron MA, Frew BA (2015) Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proc Natl Acad Sci USA* 112(49):15060–15065.
3 Jacobson MZ, et al. (2015) 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy Environ Sci* 8(7): 2093–2117.
4 Blanford GJ, Merrick JH, Young D (2014) A clean energy standard analysis with the US-REGEN model. *Energy J* 35(SI1):137–164.
5 Clarke LE, et al. (2014) Technology and U.S. emissions reductions goals: Results of the EMF 24 modeling exercise. *Energy J* 35(SI1):9–31.