LETTER

REPLY TO BADGER AND VOLKER:

Correctly estimating wind resources at large scales requires more than simple extrapolation

Lee M. Miller[a,1] and Axel Kleidon[b]

Badger and Volker (1) claim that our paper (2) incorrectly estimates the wind energy resource and underestimates it by more than 50%. However, a detailed reading of their work (3) reveals that their estimates are consistent with ours (and others; table 2 of ref. 2), yet their extrapolation to larger scales is flawed and so are their implications.

In contrast to ref. 1, we used an atmospheric general circulation model (GCM) that explicitly simulates the dynamics of generating and dissipating kinetic energy associated with the large-scale atmospheric circulation to derive the wind resource. These dynamics are very well understood and documented, and our GCM reproduces these energetics (4–6). While some smaller-scale meteorological phenomena such as land–sea and mountain–valley breezes may be important for local wind resources and may not be represented in ref. 2, we are not aware of any studies that suggest these small-scale effects add substantial kinetic energy to the global atmosphere.

Furthermore, the estimates by Badger and Volker (1) are consistent with ours (2, 7). However, these estimates cannot be extrapolated to larger scales, as in ref. 1, because regional wind-speed reductions are not accounted for, thus resulting in overestimates. They cited a generation of 0.69 $MW_e\ km^{-2}$ for a wind farm in the US Midwest with an installed capacity of 2.8 $MW_i\ km^{-2}$ (1, 3). This is essentially the same as our estimate in Kansas of 0.68 $MW_e\ km^{-2}$ for 2.5 $MW_i\ km^{-2}$ (7), which is substantially influenced by reduced wind speeds within the wind-farm region (7). It is also below the 0.8–1.1 $MW_e\ km^{-2}$ generation limit for this region (2, 7). This is an unusually windy region within the United States, and such a large wind farm would leave a substantial wake in the downwind region (7). Such estimates can thus not simply be extrapolated as six isolated wind farms and compared with the US electricity demand as done by Badger and Volker (1) because regional wind speed reductions are not accounted for.

For the North Sea, we estimate a large-scale limit of 1.3–1.5 $MW_e\ km^{-2}$ (2), which is lower than the 2.5 $MW_e\ km^{-2}$ estimate for a 340-km^2 wind farm with 6.4 $MW_i\ km^{-2}$ that Badger and Volker quote (1). When wind farms over 103,000 km^2 (18% of the North Sea) are considered, this generation rate drops to 1.6 $MW_e\ km^{-2}$ (3), which is consistent with our limit for the North Sea. This reduction in generation at a larger scale can be understood by the proportionally reduced influence of the horizontal influx of kinetic energy (see discussion in ref. 7). Their results from a smaller wind farm can thus not simply be extrapolated to larger scales.

In summary, the claims by Badger and Volker (1) are unsubstantiated, as their estimates are entirely consistent with our approach. However, they err in the extrapolation to larger scales and overestimate the wind resource, which is exactly the point we emphasize (2, 6, 7). A transition to renewable energy needs physically sound estimates of the wind resource, and this resource becomes smaller as wind energy is expanded to larger scales.

1 Badger J, Volker PJH (2017) Efficient large-scale wind turbine deployment can meet global electricity generation needs. *Proc Natl Acad Sci USA* 114:E8945.

2 Miller LM, Kleidon A (2016) Wind speed reductions by large-scale wind turbine deployments lower turbine efficiencies and set low generation limits. *Proc Natl Acad Sci USA* 113:13570–13575.

3 Volker P, Hahmann A, Badger J, Jøgensen H (2017) Prospects for generating electricity by large onshore and offshore wind farms. *Environ Res Lett* 12:034022.

4 Lucarini V, Fraedrich K, Lunkeit F (2010) Thermodynamic analysis of snowball Earth hysteresis experiment: Efficiency, entropy production, and irreversibility. *Q J R Meteorol Soc* 136:2–11.

5 Lucarini V, Fraedrich K, Lunkeit F (2010) Thermodynamics of climate change: Generalized sensitivities. *Atmos Chem Phys* 10:9729–9737.

6 Miller LM, Gans F, Kleidon A (2011) Estimating maximum global land surface wind power extractability and associated climatic consequences. *Earth Syst Dynam* 2:1–12.

7 Miller LM, et al. (2015) Two methods for estimating limits to large-scale wind power generation. *Proc Natl Acad Sci USA* 112:11169–11174.

[a]John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138; and [b]Biospheric Theory and Modelling Group, Max Planck Institute for Biogeochemistry, D-07701 Jena, Germany

Author contributions: L.M.M. analyzed data; and L.M.M. and A.K. wrote the paper.

The authors declare no conflict of interest.

[1]To whom correspondence should be addressed. Email: lmiller@seas.harvard.edu.

 www.pnas.org/cgi/doi/10.1073/pnas.1713240114