

# Response to Miller and Keith “Observation-based solar and wind power capacity factors and power densities” (*Environmental Research Letters*, 2018)

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Miller and Keith (*Environmental Research Letters*, 2018, “Observation-based solar and wind power capacity factors and power densities”) conclude that solar and wind power output densities in the United States are  $\sim 5 \text{ We/m}^2$  and  $0.5 \text{ We/m}^2$ , respectively. These numbers are underestimated by factors of 3.5-8 and 8-17, respectively. Real output power densities are on the order of 30-40  $\text{We/m}^2$  for rooftop and canopy PV, 17.4-22  $\text{We/m}^2$  for utility PV, and 4-8.5  $\text{We/m}^2$  for onshore wind.

## 1) Solar PV

The solar output of  $5 \text{ We/m}^2$  from Miller and Keith is easily disproven.

A solar single 327 W Sunpower solar panel has an area of  $1.63 \text{ m}^2$

<https://us.sunpower.com/sites/sunpower/files/media-library/data-sheets/ds-e20-series-327-320-residential-ac-modules.pdf>

giving an installed power density of  $200.6 \text{ W/m}^2$ .

**Rooftop PV.** Assuming fixed tilt panels on a rooftop or parking lot or parking garage canopy or canopy over a school field, where the panels are adjacent to each other and the equipment is below the canopy or in the garage below the roof:

<https://news.energysage.com/solar-canopy-installations-bring-shade-clean-energy-parking-lot/>

and assuming conservatively a capacity factor of 15-20%, the AC output is 30.1-40.1  $\text{We/m}^2$  for rooftop PV, which is 6-8 times that proposed by Miller and Keith ( $5 \text{ We/m}^2$ ).

**Utility PV.** For utility PV, additional space is needed between rows of panels and for tilting/tracking. As discussed and referenced in

<http://web.stanford.edu/group/efmh/jacobson/Articles/I/CountriesWWS.pdf>

on Page 87 of the Supplemental Information, the spacing factor for road servicing is 1.45-2 and for single-axis tracking is 1.25-1.4 giving an overall spacing factor of 1.8-2.8, with a selected value of 2.3. Given the higher capacity factors of utility PV (assuming 20-25% here, close to Miller and Keith), that gives output power densities of 17.4-22 We/m<sup>2</sup> for utility PV, which is 3.5-4.4 times the output proposed in Miller and Keith.

## 2) Wind

With respect to wind, Miller and Keith's numbers are also wrong. Their error lies in their methodology, which is to estimate some polygon area representative of a wind turbine in a wind farm then to multiply the number of turbines by this area.

This is wrong because (1) it includes large amounts of space on the outside boundary of each wind farm (on the edge of outer-boundary turbines) that is not actually occupied by a turbine; (2) it arbitrarily designates each turbine with an unrealistically large area in all directions surrounding it that allows areas between some turbines to overlap; and (3) the scheme does not take into account at all the fact that wind farms have irregular shapes, so their outside boundaries, where no area should be counted, are much larger in reality than assumed by Miller and Keith, where each turbine is assumed to occupy a polygon area that never accounts for the fact that the turbine is on the outside edge of a wind farm.

Figure 1. Envelope around the Tule wind farm east of San Diego, California. The farm consists of 57 GE 2.3 MW turbines. The envelope gives an installed power density of 2.85 MW/km<sup>2</sup> (or, with a capacity factor of 30%, an output power density of 0.86 We/m<sup>2</sup>, even higher than 0.5 We/m<sup>2</sup> from Miller and Keith). An actual analysis of the area around turbines such as the type illustrated in Figure 2 gives an installed power density of 29.0 MW/km<sup>2</sup> (or an output power density of 8.7 We/m<sup>2</sup>).

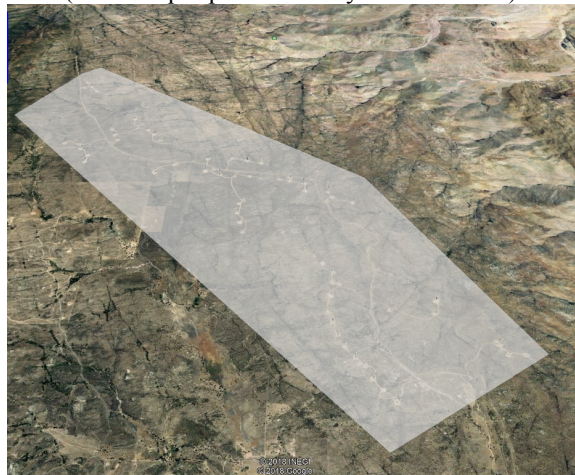
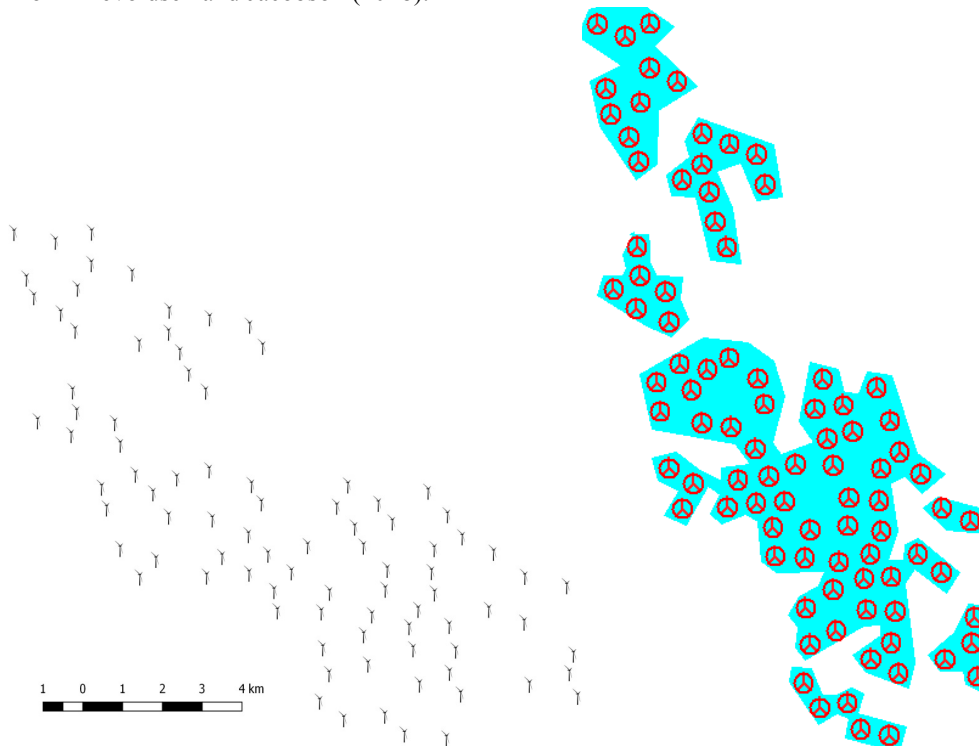


Figure 1 illustrates the great inaccuracy of the assumption made by Miller and Keith. It shows an envelope around the Tule wind farm east of San Diego, California. The envelope represents an installed power density of 2.85 MW/km<sup>2</sup>, even larger than that assumed by Miller and Keith. A 30% capacity factor, slightly less than the average determined in Miller and Keith, gives an output power density of 0.86 We/m<sup>2</sup>, even larger than the 0.5 We/m<sup>2</sup> average in Miller and Keith. Clearly, though, the envelope includes large swaths of land that have nothing to do with the wind farm, just as Miller

and Keith's paper assumes. Their calculation is based on land beyond the edges of the farm and between clusters of turbines that have nothing to do with the wind farm except that it might be property owned by the wind farm developer.

A proper analysis of spacing area of a wind farm requires tracing the boundary around a wind farm, accounting for its odd shape, not include spacing area outside of the wind farm's boundary, and not including spacing between clusters of turbines, as illustrated in Figure 2 (Enevoldsen and Jacobson, 2018).

Figure 2. Illustration of tracing boundaries around a wind farm to determine its installed power density. From Enevoldsen and Jacobson (2018).



For the Tule farm in Figure 1, such an analysis yields an installed power density of 29.0 MW/km<sup>2</sup> and, with a 30% capacity factor, an output density of 8.7 We/m<sup>2</sup>, 17 times higher than the 0.5 We/m<sup>2</sup> proposed by Miller and Keith.

Similarly an analysis of data from over 1,200 operating wind turbines in 16 onshore and 7 offshore wind farms in 12 countries across 5 continents during 2016 (Enevoldsen and Jacobson, 2018) gives the following mean (and range) of installed and output power densities

Onshore in Europe, 14.1 (6.2-28.9) MW/km<sup>2</sup> and 4.26 (2.3-8.2) We/m<sup>2</sup>

Onshore wind outside of Europe: 20.5 (16.5-48) MW/km<sup>2</sup> and 6.84 (4.81-11.2) We/m<sup>2</sup>

A subsequent analysis of over 100 additional farms yields similar results. These big differences compared with the output power density of 0.5 We/m<sup>2</sup> from Miller and Keith,

are simply due to Miller and Keith's incredible overestimate of the land areas required for wind farms.

**Reference:**

Enevoldsen, P., and M.Z. Jacobson, Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide, *in review*, 2018.