The Maximum Extractable Wind Power On Earth is 58 Times That Needed to Power 37.1 Percent of the World For All Purposes With Wind in 2050 After All Sectors Have Been Electrified

In

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Contact: Jacobson@stanford.edu; Twitter @mzjacobson

6.8.6. World Saturation Wind Power Potential

Wind turbines compete with each other for the same kinetic energy in the wind. When one wind turbine converts kinetic energy to mechanical energy to spin a turbine's blades, and its generator converts the mechanical energy to electricity, less kinetic energy is available for other wind turbines in the wind farm and in the world. As more turbines become operational, each turbine is able to extract less and less energy. At some point, the addition of one more turbine worldwide results in no additional power generation (kinetic energy extraction). At that point, the annual average power extracted by the existing turbines is called the **saturation wind power potential** (**SWPP**) (Jacobson and Archer, 2012). The SWPP is important because it gives the upper limit to how much power is available from wind worldwide (land plus ocean) or over land alone for turbines at a given hub height.

The reduction in wind speed due to wind turbines can be described mathematically as follows. The kinetic energy (J) in the wind at a given time t and location is

$$E(t) = \frac{1}{2} M_a v(t)^2 \tag{6.35}$$

where M_a is the mass of air (kg) and $v(t)$ is the instantaneous wind speed (m/s) at time t. Suppose, during a time increment Δt (s), a wind turbine extracts an amount of energy (J) from the wind equal to

$$\Delta E(t) = P_b\left[v(t)\right]\Delta t \tag{6.36}$$

where P_b is the instantaneous power (W) generated by the turbine's blades as a function of wind speed $v(t)$. P_b is determined from the turbine's power curve. The remaining kinetic energy in the wind at time $t+\Delta t$ is thus

$$E(t+\Delta t) = E(t) - P_b\left[v(t)\right]\Delta t = \frac{1}{2} M_a v(t+\Delta t)^2 \tag{6.37}$$

Solving for the resulting wind speed at the new time gives

$$v(t+\Delta t) = \sqrt{\frac{2\left[E(t) - P_b\left[v(t)\right]\Delta t\right]}{M_a}} \tag{6.38}$$

As such, the extraction of kinetic energy by a wind turbine reduces the wind speed seen by other turbines.

Depending on the purpose of the calculation, the air mass used in the above equations can be either the mass of the air flowing through the turbine during a specific time interval [e.g. $M_a = \rho_a A_t v(t)\Delta t$, where ρ_a is air density (kg/m^3) and A_t is turbine swept area (m^2)], or it can be the mass of all air in a large volume that has mean wind speed $v(t)$. The former would be used to estimate the wind speed immediately downstream of one turbine. The latter would be used to estimate the change in mean wind speed over a large volume of air encompassing one or more turbines. In the former case, Equation 6.38 is independent of the time increment Δt because that cancels out of all terms on the right side of the equation. In the latter case, final wind speed varies with the time increment. Example 6.14 illustrates the results in the two cases.

Example 6.14. Extracting kinetic energy from the wind.
Estimate the wind speed in two cases (a) downstream of a single turbine and (b) averaged over a large 5 km × 5 km horizontal area × 126 m vertical thickness region in which one turbine resides. In both cases, assume the upstream wind speed is 10 m/s, the turbine extracts 3,000 kW at that wind speed, the turbine blade diameter is 126 m, and the air density is 1.23 kg/m^3. For each case, find the downstream wind speed after 1 minute and 10 minutes.

Solution:
The wind turbine swept area is π × (126 m / 2)^2 = 12,469 m^2. In case (a), the mass of air passing through the turbine blades over 1 minute is M_a = 1.23 kg/m^3 × 12,469 m^2 × 10 m/s × 1 min. × 60 s/min = 9.20 × 10^6 kg. The initial kinetic energy in the wind, from Equation 6.35, is E = 0.5 × 9.20 × 10^6 kg × (10 m/s)^2 = 4.6 × 10^8 J. The energy extracted by the wind turbine is 3 × 10^6 J/s × 60 s = 1.8 × 10^8 J. From Equation 6.38, the downstream wind speed is 7.8 m/s, so the turbine reduces the wind speed by 22.2 percent. Over 10 minutes, the downstream wind speed is also 7.8 m/s because all terms in Equation 6.38 M_a, $E(t)$, and $P_b\Delta t$ all have a Δt term that cancels out, so the result is independent of time.

In case (b), the mass of air is the mass of all air in the region, not just the air that goes through the turbine blade. As such, M_a = 1.23 kg/m^3 × (5,000 m)^2 × 126 m = 3.97 × 10^9 kg. The initial kinetic energy in the wind, from Equation 6.35, is E = 0.5 × 3.97 × 10^9 kg × (10 m/s)^2 = 1.9 × 10^{11} J. From Equation 6.38, the volume averaged wind speed is 9.995 m/s, so the turbine reduced the volume averaged wind speed by 0.05 percent. Over 10 minutes, the volume averaged wind speed is 9.95 m/s, so the turbine reduced the overall wind speed by 0.47 percent.

In sum, whereas the wind speed downwind of an individual turbine stays constant with time if the upstream wind speed stays constant, the mean wind speed averaged over a volume of air decreases if the extraction of kinetic energy is allowed to affect the overall kinetic energy in the volume of air.

The extraction of kinetic energy and reduction in wind speed by wind turbines must reach a limit. Figure 6.25(a) provides an estimate of this limit worldwide and over all world land. The figure was obtained by running global, three-dimensional computer model simulations for several model years. Each simulation contained a different number of wind turbines with a hub height of 100 m over land or over land plus ocean.

In the model, wind turbines extracted kinetic energy to produce electric power, and wind speeds were adjusted accordingly each time increment in a manner similar to with Equations 6.34 to 6.37. Because the model was three dimensional, it accounted for the increased vertical transport, due to turbulence, of faster horizontal winds aloft down to the hub height, where winds were depleted behind the turbines. As shown in Figure 6.26, this resulted in wind speeds above hub height also decreasing due to energy extraction by wind turbines at hub height.

Figure 6.25. (a) Annual average electric power generation by wind turbines as a function of their installed (nameplate) capacity worldwide (Global SWPP curve) and over all land outside Antarctica (Land SWPP). Also shown is power output if no competition among turbines were allowed (Global-No extraction). (b) Annual average power generation at three installed power densities, each consisting of 4 million 5 MW wind turbines (20 TW total nameplate capacity). Also shown is a line indicating the power output needed to provide 5.75 TW of power from wind worldwide. From Jacobson and Archer (2012).

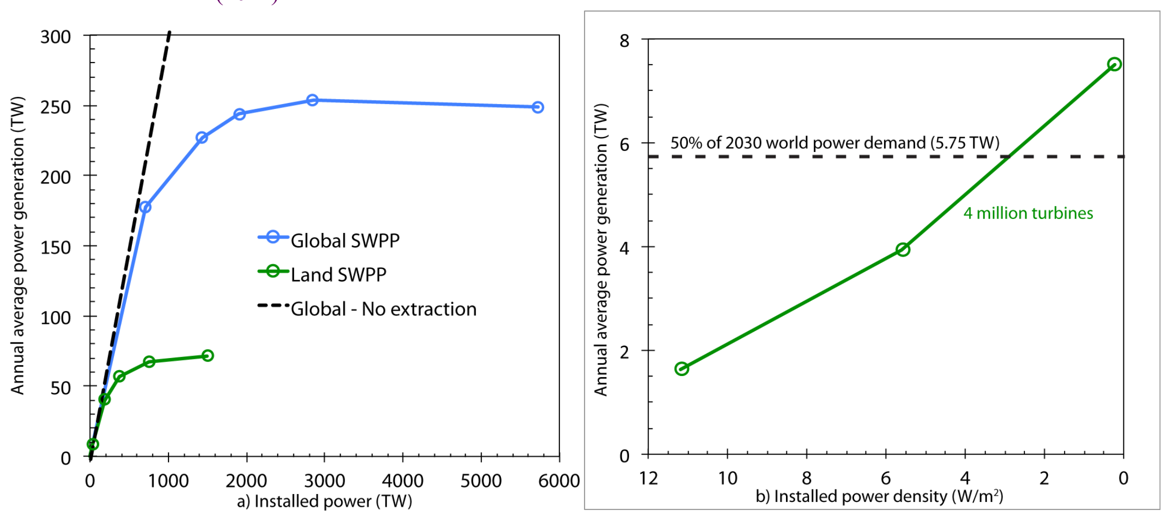


Figure 6.25(a) indicates that, as the installed (nameplate) capacity of wind turbines increases over land plus ocean worldwide, the extractable power among all wind turbines increases, but with diminishing returns. In fact, above 3,000 TW of nameplate capacity, no additional power from the wind at 100 m can be extracted. Table 6.8 indicates that the worldwide limit to extractable power is about 253 TW. Over land outside of Antarctica, the limit is about 72 TW.

For comparison, the world needs only about 3.9 TW of annual average power output from wind in 2050 for wind to provide 45.0 percent of the world's end-use power demand after all energy sectors have been electrified (Jacobson et al., 2019). As such, **18.5 times more extractable wind power over land is available than is needed, and 65 times more extractable power over land plus ocean worldwide is available than is needed** to power the world's all-purpose energy with 45.0 percent wind in 2050. Thus, there is no resource barrier to obtaining even 100 percent of the world's all-purpose electric power in 2050 from wind.

Table 6.8. Saturation wind power potential (SWPP) at 100 m above ground level (AGL) globally, 100 m AGL over land outside Antarctica, and at 10 km in the jet streams (from 10 °S to 70 °S and 10 °N to 70 °N). Also shown is the annual average power available worldwide at 100 m AGL if kinetic energy extraction by wind turbines were not accounted for. From Jacobson and Archer (2012). Also shown ("Wind needed in 2050") is the end use wind power supply needed over land plus ocean in 2050 for wind to provide 45.0 percent of the world's end-use power demand for all purposes after all energy has been electrified. That supply would be obtained with a projected nameplate capacity of 12.1 TW (Jacobson et al., 2019).

Region	Annual Power Output (TW)
Global (No extraction)	1,750
Global-SWPP	253
Land-SWPP	72.0
Jet streams	378
Wind needed in 2050	3.9

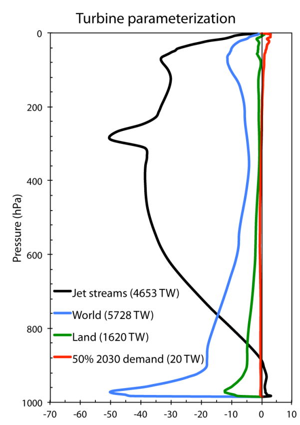
Figure 6.25(a) also shows the power output from a case (dashed line) where wind turbines covering the world extract kinetic energy to produce electricity at the modeled wind speeds, but the wind speeds are not reduced. In this case, wind turbines have no impact on the wind speeds and turbines extract 1,750 TW of power (Table 6.8). This compares with 253 TW when wind turbines do reduce wind speeds (Table 6.8). Thus, not accounting for wind turbine reduction in wind speed can result in a factor of 7 error in the overall wind power output in the limit of complete coverage of the world with wind turbines.

Finally, Table 6.8 indicates that, in the jet streams, about 378 TW of annual average power is available. However, as of 2019, it is not cost effective to extract wind power from the jet streams commercially although some companies have tried.

Figure 6.25(b) examines the impact on total power output with different installed wind power densities but with the same overall nameplate capacity. It examines a situation with 4 million 5-MW turbines (20 TW total nameplate capacity) in three configurations. In the first configuration, the 20 TW are compressed into three wind farms globally. In the second, they are expanded slightly to 8 wind farms globally. In the third, the 20 TW are spread out over land from 15 ^{o}S to 60 ^{o}S and from 15 ^{o}N to 60.56 ^{o}N (Arctic Circle). The figure indicates that, **when wind farms are separated from each other, their output power can increase by up to a factor of 4.6 for the same nameplate capacity.** This is due to the reduced competition for available kinetic energy among wind turbines when wind farm are separated.

Finally, Figure 6.26 shows the vertical profile of the percent change in world wind speed for each kinetic energy extraction case in Table 6.8. It shows that saturating the world with wind turbines at 100 m or at 10 km reduces the global average wind speeds at those altitudes by 50 percent. Saturating land reduces the global average 100-m wind speed by about 12.2 percent. Using 4 million 5-MW turbines reduces the global average 100-m wind speed by only about 0.36 percent.

Figure 6.26. Percent wind speed reduction averaged globally as a function of altitude (air pressure) due to using wind turbines to extract kinetic energy to produce electricity. The jet stream case is with 930.6 million 5-MW wind turbines at 10 km from 10 ^{o}S to 70 ^{o}S and 10 ^{o}N to 70 ^{o}N. The world case is with 1.146 billion 5-MW turbines at 100 m over the world's land and oceans. The land case is with 324.5 million 5-MW turbines over the world's land, including Antarctica. The 50 percent 2030 demand case is with 4 million 5-MW turbines over the world's land from 15 ^{o}S to 60 ^{o}S and from 15 ^{o}N to the Arctic Circle. In all cases, the turbines have 126-m blade diameters. From Jacobson and Archer (2012).



References

Jacobson, M.Z., and C.L. Archer, Saturation wind power potential and its implications for wind energy, *Proc. Nat. Acad. Sci.*, *109*, 15,679-15,684, doi:10.1073/pnas.1208993109, 2012.

Jacobson, M.Z., M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, Alphabetical: C. Bozonnat, L. Chobadi, H.A. Clonts, P. Enevoldsen, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, E.M. Hennessy, J. Liu, J. Lo, C.B. Meyer, S.B. Morris, K.R. Moy, P.L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, A.S. Yachanin, 100 percent clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, *Joule, 1*, 108-121, doi:10.1016/j.joule.2017.07.005, 2017.