The Structure of a Scientific Article

Saturation wind power potential and it implications for wind energy

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nes convert kinetic to electrical energy, which returns to the atmosphere as heat to regenerate some potential and kinetic energy. As the number of wind turbines increases over large geographic regions, power extraction first increases linearly, but then converges to a saturation potential not identified previously from physical prindples or t ne properties. These saturation potentials are >250 terawatt at 100 m globally, approximately 80 TW at 100 m ow plus coastal ocean outside 10 km in the jet streams. Antarctica, and approximately Thus, there is no fundament obtaining half (approximately 5.75 TW) or several t it's all-purpose power

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tarbines further does not increase the generated power further. At the SWPP winds still occur because individual turbines can extract no more than 59.3 % of the kinetic energy in the wind (Betz's limit). This paper also defines the fund wind power potential (FWPP), which is the maximum power that can be extracted by a fixed number of wind turbines at decreasing installed density and increasing geographic area. The SWPP is calculated here at 100 m above ground, the hub height of most modern wind turbines, assuming conventional wind turbines distributed everywhere on Earth, including over the oceans (simulation named "global-SWPP") and, separately, over land only but excluding Antarctica ("land-SWPP"). The SWPP is also calculated at 10 b above ground in the jet streams assuming airbome wind devices ("jet stream-SWPP"). Capturing jet stream winds presents greater technological challenges than capturing surface winds but is still of interest (1, 2).

The main purpose of these simulations is to use a physical model to determine the theoretical limit of wind energy available at these altitudes, particularly because some recent studies that accounted for energy extraction by turbines, but not physically, have suggested that available wind energy is small (2, 3). Previous theoretical estimates of the power in the wind (4-9) are similarly not based on a physical model of energy extraction so cannot give estimates of wind potential at the height of turbines. As found here, energy extraction at a given altitude does not deplete energy at all altitudes above or below it; so an estimate of wind potential in the whole atmosphere does not answer the practical question about wind turbine potential at typical hub heights.

More relevant for practical applications, the FWPP of four million turbines at 100 m in three different configurations is quantified here to determine if this number is sufficient for powering half the world's all-purpose power demand in a 2080 clean-energy economy (10).

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realistic met are accounted for. This information is critical for determining the feasibility of a worldwide renewable energy future. Calculating the SWPP for large penetrations of wind (≥1 TW) is not currently possible from data analysis, because penetrations are still low (239 gigawatts (GW) installed worldwide at the start of 2012). The most accurate method available to analyze this issue is with a complex 3D atmospheric-ocean-land coupled model.

Previous global simulations of wind fams have assumed that wind farm effects on the atmosphere can be represented by changing surface roughness or adding a drag coefficient (2, 13-17). Roughness parameterizations, though, incorrectly reduce wind speeds the most in the bottom model layer, whereas in reality a surface wind turbine reduces wind speed the most at hub height, approximately 100 m above ground (Fig. 1). Because soughness lengths and drag coefficients are approximate, it is also difficult to ensure they extract the correct amount of energy from the wind. Calaf, et al. (18) demonstrated the inaccuracy of standard roughness parameterizations against large-eddy simulation results and developed a multiple layer roughness parameterization for ground-bases

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pollutants (10, 19). As such, wind turbines reduce direct heat and pollutant emissions compared with conventional generators. However, the electricity use still needs to be accounted for because the heat is a source of some regenerated kinetic energy (via conversion of internal energy to some available potential energy to kinetic energy). To date, only ref. 1 has calculated the heat from electricity returned to the air, but they focused on airborne rather than ground-based wind turbines.

Author contributions MZ1 and CLA, designed research; MZ1 and CLA performed research; M.Z.J. contributed new reagents analytic tools; M.Z.J. and C.L.A. analyzed data and MZ1 and CLA wrote the paper. The authors declare no conflict of interest

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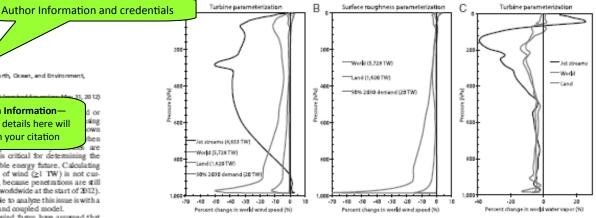


Fig. 1. Comparison of heights and magnitudes of globally averaged percent winds peed reduction averaged over one year from (A) the turbine momentum sink parameterization presented here vs. (8) the latteu (33) surface roughness parameterizations. In both case, the world is covered with either 1.146 billion (blue, world), 324.5 million (green, land), or four million (red, 50% of 2030 power demand) (

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speed 0.44 km² each. A jet stneen case is also shown in (A) for 931 million (black) 5-MW vapor mata mixing ratio vertical profiles between the world (Simulation B) land (0, and let at 4"x 5" horizontal resolution. Numbers in parentheses are installed wind power in

Materials and Methods

Here, the GATOR-GCMOM global model (20, 21) is used to examine satury tion and fixed wind power potentials. The model is modified to be 4°-67 sig turbines as an elevated momentum sink, where the kinet the extinction from the wind is determined from a turbine power curve at the instantare ous model wind speed. The treatment of turbines developed is conceptually similar to that in (22, 23) but differs as follows: (0) it assumes each wind turbine occupies multiple vertical atmospheric layers, rather than one layer, (i) it is applied to numerous wind farms worldwide simultaneously rather than one local farm. (W) it is applied in a global model where momen tum extraction feeds back to global dynamics rather than a limited-area model with only regional feedbado, and (iv) it accounts for energy conserve-

tion due to both electricity use and turbulent discipation of kinetic energy. In addition, the new treatment allows distributed wind turbines in a grid gell to extract energy from four points on a staggered Anakawa C grid, thereby impacting five cells simultane ously, rather than from the center of the cell, affecting only that call The SI Materials and Methods describes the model treatment of wind tur-

bine ki nat eo ab ca "The results section...contains all 10.00 the data from the experiments." mut This section might include charts, tables, graphs, and written descriptions. roughness to turbulence, then he

Table 1 summarizes the simulations. Acontrol with turbines at 100 m hub height but no momentum extra In this case, the global capacity factor was about 31% based on im modeled wind speeds applied to the power curve for a 5-MW turbine

fee wind speeds with data. To deter-Author Information and credentials 4" x 5" horizontal resolution sensitivity extraction, as do with day assing installed power density, were run, Simulations (G) (25" x 2.5") and (10 (1.5" x 1.5").

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"The materials and methods section gives the technical details of how the experiments were carried out."

 $1.5^{\circ} \times 1.5^{\circ} =$ To determine the PWPP of four million 5-MW turbines, the number estimated to supply half the world's all-ourpose power in a dean energy economy in 2030 (10), the turbines were distributed in three configurations: over all and 155-605 and 15N-66.50N, and below 3 km altitude (Simulation N): over eight land and coastal sites (Table 1, foot note) (O); and over three land sites (Table 1, footnote) (P).

Really to determine the SWPP of the jets treams (10-70N and 10-70S) at 10 km, a 4" x 5" simulation (C) with the maximum power density as in simulation (0) was run. A 1.5" x 1.5" simulation (10) was also run to scale results with resolution.

All simulations included 66 vertical sigma-pressure layers up to 0.219 hP at (u60 km), including 15 layers from 0-1 km and 500-m resolution from 1-21 km. The genter of the lowest model layer was 15 m above ground. The rotor of each surface turbine (simulations 8-P) intersected five model layers. That of each jet-stream turbine (simulations Q-R) intersected two layers. The model was run forward from January 1, 2005 with no data animllation. Because this study does not focus on temperature response and due to the long computer time required for rediative, cloud, serous, and ges processes, only five-year simulations were run. Wind power extraction in all five years was similar and convergent in all simulations.

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Fig. 2.4 shows that, up to about 715 TW (1.4 W/m2) of installed power, the output from power-extracting wind turbines first increases linearly. The linearity is demonstrated by comparing the initial slope of the "global-SWPP curve" (with power extraction) with the slope of the "global-no power extraction" line. The latter is the line between zero and the power output from Simulation A, hich is the reference case with turbines but without power

action. At higher penetrations, power output increases with shing returns until it reaches global saturation (approximately 253 TW, also Fig. S3B for coarse-resolution results) at about 2,870 TW (5.65 W/m2) installed. Higher penetrations of wind serve no additional benefit. Thus, for the first 715 TW

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total power in that region (100 TW) multiplied by the fraction that could interact with wind turbine rotors (<0.3), the fraction in the range of turbine cut-in and cut-out speeds (0.75), and the fraction converted from kinetic to electrical energy (0.5). These factors were all accounted for in time and space in the simulations here. The large difference highlights the importance of using physical calculations.

The SWPP over land outside Antarctica here was approximately 72 TW (Fig. 24 and Fig. S3C). Based on the high-resolution global-SWPP calculations here, another approximately 8 TW was available offshore at depths <200 m, giving a land plus coastal SWPP estimate of 80 TW. Like with the global case, the land-SWPP curve (Fig. 2.4) shows a linear portion at low turbine penetrations. Beyond approximately 185 TW of installed power, diminishing returns set in. However, the full land-SWPP was not obtained until approximately 1,500 TW (11.3 W/m²) of installed power. The result here suggests that bottom-up approaches for calculating wind power potentials over land are justified for <185 TW installed power.

The land-SWPP is not much lower than the 125 TW of onshore power from a study (25) that assumed a fixed percentage energy loss due to turbine interference but not increasing competition for wind with increasing turbine penetration. Results from (25 fall near the linear "global-no extraction" curve in Fig. 24, above the land-SWPP.

Another study (26) estimated the world land plus coast potential based on world sounding and surface data a Similarly, ref. 25 estimated a land potential of 78 TW factors of 20% or higher. Both studies accounted tions with mean annual wind speeds before ext 7 m/s and did not account for increasing competitio wo offsetting factors caused their results to be simila d-SW PP (72 TW) and the land plus near-shore est oximately 80 TW) found here. cally viable

If only 50% of land-based wind we locations (3), the feasible wind not

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just available energy potentials, thus include losses and efficiencies. Airborne jet-stream turbines would require energy to ascend and descend and may not operate all year. This analysis does not quantify such losses, only extractable energy.

The extractable power globally at 100 m and, separately, at 10 km in the jet streams, are both independently less than the total extractable power in the wind at all altitudes, estimated broadly as 450-3,800 TW (4-9). These previous studies, though, did not consider extraction at a single altitude, such as the height of modern wind turbines nor did they use a 3D model to make their estimates. Extraction of power at each 100 m and at 10 km does not give the same discipation as complete extraction of kinetic energy from the atmosphere, as seen in Fig. 1; instead, each results in wind reduction over a vertical segment of the atmosphere, decreasing with distance from the height of extraction. Simulations N-P examine whether approximately four million

5-MW turbines (20 TW installed) can provide at least 5.75 TW of delivered power, enough to supply 50% of all-purpose enduse power demand in 2030 for a world energy infrastructure converted to wind, water, and sunlight (WWS) and electricity/ hydrogen (10). Fig. 2B shows that the power output of four illion turbines increases with decreasing wind turbine spacing, When turbines are packed at an installed density of 11.3 W/m into three sites worldwide, the power output is too low (approximately 1.6 TW-Table 1 and Fig. S3F) to match power demand. At eight locations (5.6 W/m2 installed), the output improves to pproximately 4 TW (Fig. S3E) but

However, when turbines are spread References: The numbers away from the poles, and in all (0.11 W/m2 installed), the output j connect to the citations (Fig. S3D), much more than need an installed density of approximately included at the end of the to spread turbines evenly across such can have installed densities of 5.6article. able spreading between faims occi density within and between farms is

Discussion It is well known that spreading nes in a farm increases a interference of one turbine nn array ett. with the next (11, 12) ne results here suggest that staggering farms then raphically, improves the overall power output. In other words the power potential of a fixed number of turbines (FWPP) increases with increased spreading of fams. The addition of surface wind turbines reduced horizontal wind speeds in their wake the most and below and above the wake centerline to a lesser extent (Fig. 1.4). The reduction in wake wind speed reduced shearing stress below and increased it above the wake centerline, cons istent with large-eddy-simulation results (18). Greater shearing stress above the wake increased subgrid-scale turbulent kinetic energy (TKE) there, increasing the downward transport of horizontal momentum from above to the turbines. Downward transport of horizontal momentum to a turbine wake was also increased in the model by subgrid-scale thermal turbulence and grid-scale gravity waves when they were present. Lesser shearing stress below the wake decreased TKE and downward momentum fluxes near the surface, as in ref. 18. Evaporation rates are proportional to both surface wind speed and surface shearing stress, and both decreased in all surface turbine simulations, reducing evaporation and water vapor (e.g., Fig. 1C). These calculations were all made with the model resolving the bottom kilometer with 15 vertical layers, including five layers intersecting turbine rotors.

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the form Drag from blade rotation also creates turbulence in of small-scale vortices that can enhance mixing. This mechanism has been suggested by ref. 27 to explain why wind turbin crease downwind surface temperatures during the day, when lapse rate is generally unstable, and slightly increase them night, when the lapse rate is generally stable but winds at hu height are stronger. However, blade-generated turbulence under neutral conditions is observed to be transported and dissipate downwind in a spiral motion (28), with greater turbulence intensity above the turbine centerline than below (28, 29). While such turbulence reduces mean wind speeds in the wake, it also increases the downward transport of faster winds from aloft into the wake. Blade-generated turbulence is transported ventically due to shear turbulence generated by the velocity deficit in the wake and ambient turbulence rather than on its own (28). As such, bladegenerated turbulence decreases substantially between its peak above the centerline and surface and little may get to the surface. as indicated by at least some measurements and high-resolution modeling (figure 1 of ref. 29). This result may differ under very unstable conditions. Even when blade-generated turbulence reaches the ground, it may largely be offset by reduced shearing stress below the turbine caused by reduced wind speed in the wake, resulting in little net surface turbulence, consistent with the aforementioned measurements (29). Both the reduced wind

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speed and small turbulence change near the surface due to turbines contributed in the model to reducing surface evaporation. Uncertainties in the treatment of turbulence still exist due to both the coarse horizontal resolution of the model and the simplification of no turbine-rotor generated turbulence.

Reduced evaporation reduced evaporative cooling of the surface, first warming the surface. However, because evaporated ter vapor normally recondenses in the atmosphere to form ads, releasing latent heat there, the reduction in water vapor uced latent heat release in the air, cooling the air due as a alt of this process. Because water vapor contributes to air prese, reducing water vapor also reduced globally averaged air sure by approximately 0.3 and approximately 0.1 hPa in the bal (Simulation B) and land (I) cases, respectively. Because er vapor is a greenhouse gas, reducing it increased thermalradiation escape to space, cooling the surface further. Howver. less water also reduced cloudiness, increasing solar radiation to the surface during the day but increasing outgoing thermal-IR at night, thus causing a slight warming at night, as observed (27, 30). The net effect of all five changes (air cooling due to lower atmospheric latent heat release, ground warming due to lower surface water evaporation, air and ground cooling due to a reduced water vapor greenhouse effect, ground warming due to reduced daytime cloudiness, and ground cooling due to reduced nighttime cloudiness) was a globally averaged surface-air temperature decrease in 15 out of the 16 surface-turbine simulations. This result is expected because water vapor is known to cause net warming of the atmosphere, so reducing it should cause cooling (31). Temperature results, though, are still uncertain, particularly due to the uncertainty of clouds and the transient nature of the simulations and could change over longer simulations because full temperature responses take decades to realize. A certain henefit of the slower winds, though, is the reduction in wind-driven soil dut; sea spray; and spore, pollen, and bacteria emissions, reducing human exposure to small particles that penetrate deep into the lungs

Globally distributed turbines decreased zonal winds; however, they increased meridional winds in the pole-ward direction in both hemispheres (Fig. S4 A and B). The pole-ward transport of air increased the pressure gradient between the poles and Equator by approximately 15-25 hPa, supporting the contention that the atmosphere responded to the increased dispiration of kinetic energy by increasing some of its available potential energy via enhanced pole-to-Equator pressure gradients. Reduced water vapor partial pressure at low latitudes contributed slightly to the enhanced pressure gradient.

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Global warming increases temperatures at the poles more than lower latitudes. The temperature gradient reduction could reduce global mear-surface wind resources in the future although ocean wind resources over the last 25 years have increased in the global average according to multiple datasets (32). Higher water vapor due to future warming will also likely offset reduced water vapor due to wind turbines.

Jet-stream turbines reduced mean wind speeds at altitudes above and below them, but increased boundary-layer wind speeds (Fig. 1C). Like in the surface case, turbines decreased zonal wind speeds substantially (Fig. S5.4), but increased mendional wind speeds (Fig. S5B), moving air pole-ward at 10 km but equatorward near the surface in both hemispheres, following the respective pressure gradients (Fig. S5C). Lower surface pressure in the tropics through midlatitudes caused air to rise, expand, and cool adiabatically, decreasing temperatures at all altitudes (Fig. S5D) and increasing both cloud liquid helow 5 km (Fig. SSE) and cloud ice above that. Enhanced cloudiness increased precipitation, and both, together with net divergence, decreased water vapor in the trooks and subtrooks and increased it toward the poles (Fig. S5F). Compressional heating over the poles increased temperatures there, but the net effect of jet stream turbines was surface cooling by >1 K (Fig. S5F), as cold air advection from the Poles prevailed near the surface. Interestingly, the higher houndary-layer wind speeds (Fig. 1C and Fig. S54) increased evaporation there, but enhanced condensation of that vapor decreased column vapor at low latitudes (Fig. S5F).

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