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Earth System Dynamics Discussions

Interactive comment on "The problem of the second wind turbine – a note on a common but flawed wind power estimation method" *by* F. Gans et al.

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In our manuscript (GMK10) we claim that the common method to estimate wind power when applied at the large to planetary scale is flawed because it does not account for the removal of kinetic energy from the atmosphere. In their comment, Archer, Jacobson and Sta. Maria (AJS10) argue that our claim is incorrect and the model we use to demonstrate this flaw is unphysical. We find that much of the information included in the AJS10 comment is not controversial and more importantly, does not address the main message of our paper. To clearly illustrate the implicit assumption in previous estimates that results in the flawed estimates, we provide a brief step-by-step summary

while explicitly noting where we disagree with AJS10. We hope that by doing so we help to clarify the conflict and contribute to resolving this important issue.

The following bullets describe the steps from the generation of kinetic energy within the atmosphere by forces to the extraction of kinetic energy by turbines:

1. The kinetic energy associated with motion is generated by forces.
2. Surface-based wind turbines remove kinetic energy from the atmospheric boundary layer to generate electric energy.
3. As a result of kinetic energy removal, the wind velocity is decreased downwind of the wind turbine.
4. Kinetic energy is mixed in from above causing a replenishment of the kinetic energy in the flow downwind of the turbine.
5. If the transfer of kinetic energy from above is not limited, this would result in a linear dependence of extracted power P_{ex} from the number of turbines N_{turb}, such that $P_{ex} \propto N_{turb}$. Such a relationship was used by previous studies such as Archer and Jacobson (2005); Lu et al. (2009) to derive global estimates for wind power.
6. If the transfer of kinetic energy from above is limited, then $P_{ex} \not\propto N_{turb}$ but the extracted power must be less than the generation rate of kinetic energy $G(KE)$ in the atmosphere, so $P_{ex} < G(KE)$. In this limiting case, the turbine details do not enter into a global estimate of wind power since the limiting factor is the natural generation rate of kinetic energy within the atmosphere. We used our simplified 'tunnel setup' (GMK10, Eq. 1-6 and Fig. 1) to demonstrate the saturation of wind power extraction based on energy conservation (GMK10, Fig. 2).

7. Where we disagree with AJS10 is that we argue that at large scales, it is the natural generation rate of kinetic energy that is the limiting factor, and the approximation $P_{ex} \propto N_{turb}$ no longer holds. In other words, as the scale of wind power extraction is extended from a single wind turbine ($N = 1$) to the planetary scale ($N = planet$), the transition from the small scale to global scale behavior is observed by $P_{ex} \propto N_{turb}$ for a small number of turbines, but approaches $P_{ex} < G(KE)$ for large N_{turb} which is demonstrated in GMK10 Fig. 2. The importance of this understanding can be expressed using the following two examples:

   a. Current estimates for the generation rate of kinetic energy in the total atmosphere are $G(KE) \approx 900TW$ Peixoto and Oort (1992); Li et al. (2007). This is in contrast to the AJS10 derivation of a theoretical global wind power potential in the lowest 1km of the atmosphere to be 1,700TW, which suggests that this estimate is far too high unless the authors can describe an atmospheric feedback that would generate substantial amounts of additional kinetic energy. Furthermore, since 900 TW is the total dissipation rate, it does not only have to support wind power that is extracted but also the natural dissipation of winds that is unavoidably connected to atmospheric motion. This would indicate that the assumption of #5 is extremely unlikely at the planetary scale.

   b. If we extend the assumption of non-limiting kinetic energy generation and transfer and then apply the method described in Sta. Maria & Jacobson (2009) to the abstract case of reducing kinetic energy in the lowest 1km of the atmosphere by wind power extraction by turbines to zero, then this yields a generation rate greater than 164,000 TW to continually supply the downward flux of kinetic energy. Since this is very close to the solar constant at the top of the atmosphere, this estimate seems to clearly violate the limits on kinetic energy generation imposed by the first and second law of

thermodynamics.

   On the other hand, the recent discussion paper Miller et al. (2010) uses atmospheric energetics and thermodynamic limits on power extraction within a three-dimensional atmospheric general circulation model to derive surface wind power estimates that support our line of reasoning.

In order to focus the discussion of these outstanding issues, we would recommend that the authors of AJS10 focus on the items mentioned above, specifically the assumption of an unlimited generation rate of kinetic energy within the atmosphere, and then clearly expound on what we view as the pertinent disagreement points related to our line of reasoning.

Our detailed reply to all comments by AJS10 can be found in the first chapter of the supplement file. Chapter 2 deals with how the estimate in #7b was derived.

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Please also note the supplement to this comment:
http://www.earth-syst-dynam-discuss.net/1/C73/2010/esdd-1-C73-2010-supplement.pdf

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