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Interactive Comment

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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Interactive Discussion

Discussion Paper

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Response to Reply to Response to Comment on "The problem of the second wind turbine – a note on a common but flawed wind power estimation method" by F. Gans, LM Miller and A Kleidon (ESDD 1:103-114, doi:10.5149/esdd-1-103-201-, 2010

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1 Summary

The main disagreement between our paper Gans et al, 2010 (hereafter GMK10) and the comments made by Archer et al., 2010b concern the limits of how much the atmosphere can compensate for the extraction of kinetic energy by wind turbines with an enhanced generation rate of kinetic energy.

In GMK10, we assume that the ability of the atmosphere to generate kinetic energy is fixed. This assumption is justified as several lines of research show that the atmosphere operates near the maximum rate of kinetic energy generation that is thermodynamically possible. We mentioned this explicitly in GMK10:

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> "Less known thermodynamic derivations show that this rate of power generation is at a maximum value given the present-day radiative forcing gradients, as demonstrated by simple theoretical considerations (Lorenz, 1960), box models (Paltridge, 1978; Lorenz et al., 2001) and general circulation model simulations (Kleidon et al., 2003, 2006)."

but this critical aspect has not been addressed in any of the comments by Archer et al., 2010a (hereafter ASJ10a) or Archer et al., 2010b (hereafter AJS10b). The implication of this maximum rate of kinetic energy generation by the natural atmosphere is that any extraction of momentum by wind turbines must decrease kinetic energy within the atmosphere. This, as a consequence, results in lower global wind power availability and estimates.

On the other hand, AJS10b essentially assume an infinite capacity of the atmosphere to generate kinetic energy, as illustrated by the following quotes:

> "[GMK10 ignored] ... sources of new kinetic energy (KE) due to enhanced vertical and horizontal pressure gradients upon extraction"

> "This does not stop the pressure gradient force and vertical turbulent flux from acting to refill the lost momentum downwind (completely by the end of the wake volume), ..."

and

> "In fact, much of the PE [potential energy] converted to KE [kinetic energy] during wind-turbine extraction of KE should be regenerated by the internal energy (IE) produced from the additional KE dissipation due to the turbines."

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Specifically, the last quote by AJS10b should raise red flags. AJS10b essentially propose a perpetual motion machine of the second kind, defined by Kondepudi and Prigogine (1998) as "an engine, which will work in a complete cycle and convert all the heat it absorbs from a reservoir into mechanical work." Kondepudi and Prigogine (1998) later state that "...the Second Law [of Thermodynamics] is the statement that such a machine is impossible." Hence, for global estimates of wind power potential, it is critical to understand what the thermodynamic limits on wind power generation within the atmosphere are. When these fundamental limits are ignored, this must inevitably result in exaggerated global wind power estimates.

In the following, we will give a more detailed explanation of these thermodynamic limits on how much kinetic energy can be generated within the atmosphere, as these are critical and fundamental for any estimate of global wind power potential. It is important to emphasize that these limits are independent of the complexity and detail of the numerical models or methods being used and the details of wind turbine design specifications, as these fundamental limits relate to the radiative forcing of the global atmosphere rather than engineering specifications of turbines.

2 Thermodynamic limits to wind power generation by the atmosphere

Thermodynamics provides the fundamental basis to understand and quantify how much work can be extracted at maximum from heating gradients. Typically, the Carnot limit provides the basis of maximum work that can be performed by a heat engine. This limit does not provide us with the actual power of the engine, but sets the theoretical maximum power an engine can generate. The actual power of the engine, *e.g.* a car engine, depends on many engineering details, such as the number of cylinders, how well the computer controls the ignition process, the efficiency by which the fuel is burned in the cylinder, and so on. We can make a long list of items that affect the actual power of a car engine. Ultimately though, the maximum possible power of the car engine is given by the well established and fundamental Carnot limit, dependent on the engine temperature, the temperature of the environment, and the combustion rate. In other words, we can put a whole lot of engineering details into a better estimate in how much power the car engine can deliver, but inevitably, we know it cannot exceed the Carnot limit even with the best engineering advances.

This analogy directly relates to the discussion between AJS10b and ourselves. One can point out the many details of wind turbine design / layout and the role of model resolution in estimating global wind power potential. This is the approach that AJS10b have been utilizing. We take the alternate approach that is much simpler, but rooted in the fundamental laws of thermodynamics. By doing so, we show that AJS10b developed methodologies that do no longer account for these thermodynamic limits on wind power generation and thereby result in substantially higher estimates compared to our own.

The derivation of the Carnot efficiency, as the maximum efficiency by which heat can be converted into work, however, makes some critical assumptions that do not hold for the Earth's atmosphere. When these assumptions are relaxed, it results in much lower maximum efficiencies (Kleidon , 2010). Since wind power generation by the atmosphere is a critical component in any upper estimate of wind power availability, we quickly describe the lines of reasoning and the associated implications. For details, the reader is referred to (Kleidon , 2010).

First, the derivation of the Carnot efficiency assumes that the gradient in heat that allows for the extraction of work is not affected by how much work is being extracted. This assumption cannot be made for the atmosphere, because the large-scale motion of the atmosphere that is driven by this extracted work transports sensible and latent heat, thereby acting to deplete the difference in radiative heating between the tropics and the extratropics, and therefore the thermodynamic driving force for large-scale atmospheric motion. This heat transport results in the outgoing longwave radiative

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flux at the top of the atmosphere showing much less variation between the equator and the poles than incoming solar radiation at the top of the atmosphere and is a well established fact in climatology. This depletion of the heating gradient by atmospheric motion results in a lower maximum efficiency than the Carnot limit.

Second, the derivation of the Carnot efficiency assumes that no other irreversible processes deplete the radiative heating gradient that is used to extract work. This also requires relaxation, as the gradient that is generated by solar radiative forcing is also depleted by the emission of longwave emission. Because of the competition of these irreversible processes, the maximum power that can be extracted from the solar radiation gradient is reduced further.

When these thermodynamic limits are applied to the maximum generation rate of kinetic energy within the Earth's atmosphere, we need to start with the difference in solar radiative forcing between the tropics and the extratropics. This difference, expressed in Terawatts, is about 40 % of the total absorbed solar radiation, or $\Delta J_{sw} = 46000$ TW. If the atmosphere were to transport half of this heat flux, the latitudinal temperature gradient would be depleted and no power could be generated to draw the flow. Because of this tradeoff between atmospheric heat flux and latitudinal temperature gradient, a distinct maximum exists at which power is maximized. This maximum occurs approximately at $\Delta J_{sw}/4$. At this heat flux, the temperature gradient between the tropics and the extratropics reduces the radiative equilibrium temperature gradient of about 45K down to half its value. These simple estimates taken together yield a maximum power or maximum generation rate of kinetic energy of $46000/8 \cdot 45/288$ TW ≈ 900 TW (Kleidon , 2010). Even though this simple estimate is rough and leaves out many details that may affect this number to some extent, its magnitude corresponds very closely to the observed generation rate of kinetic energy of the atmosphere (*Peixoto and Oort*, 1992). In other words, the ability of the Earth's atmosphere to generate large-scale motion from the solar radiation gradient is close to being maximized. This notion that the atmosphere runs at maximum thermodynamic efficiency is not new, and supported by

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a body of previous studies of maximum generation of kinetic energy (Lorenz , 1960), or, almost equivalently, maximization of entropy production (Paltridge , 1975, 1978, 1979; Lorenz et al. , 2001; Kleidon et al. , 2003, 2006)). The assumption of a maximum thermodynamic efficiency of generating atmospheric motion has been shown to yield realistic predictions not just for the Earth's atmosphere, but also for other planetary atmospheres (Lorenz et al. , 2001; Lorenz , 2010) as well as other turbulent and complex processes (Ozawa et al. , 2003; Martyushev , 2006).

The relevance of these rather theoretical insights is that modifications of momentum dissipation or extraction at the surface – for instance, by substantial momentum extraction by large-scale installations of wind turbines – can only decrease the ability of the atmosphere to generate motion unless the gradient in solar radiative forcing is enhanced. AJS10b, to the contrary, argue that *"[GMK10 ignored] ... sources of new kinetic energy (KE) due to enhanced vertical and horizontal pressure gradients upon extraction"*. Given that the atmosphere converts the large-scale solar radiation gradient that exists between the tropics and the extratropics into kinetic energy near maximum efficiency, this argument would need to imply that the large-scale solar radiation gradient is enhanced. AJS10a and AJS10b, however, provide no argument for why this should take place. If the large-scale solar radiation gradient is unaffected, then the argument that more kinetic energy is generated violates the fundamental limits of kinetic energy generation that are given by thermodynamics. In GMK10, we made the conservative assumption that the generation of kinetic energy was fixed, hence total kinetic energy within the atmosphere needs to decrease with any extraction of momentum by wind turbines. The reduced momentum in the wake of the turbine builds up a gradient in momentum between the wake and the surrounding flow that drives the mixing of momentum and the replenishment of momentum in the wake. However, this comes at the expense of an inevitable, overall reduction of momentum in the surrounding flow, and reduces the overall efficiency of work extraction from the flow.

In terms of our use of an equation from Sta. Maria & Jacobson, 2009 (hereafter SJ09) to show that estimates based on this equation violates thermodynamic limits, AJS10b state that *"the equation in SJ09 represents energy (or power) extracted minus that regenerated"*, that *"GMK10b confuse P_{ex} for $P_{ex} - P_{reg}$" and that "they [GMK10b] ignore the kinetic energy regeneration term"* . This aspect was not explained in the original paper in SJ09. There is nothing to be ignored as $P_{reg} = 0$ because of the near maximum efficiency by which the global atmosphere generates motion. What AJS10b refer to as regeneration of power is merely a redistribution of momentum from the atmosphere aloft into the wake area. This redistribution does not add to the ability of the atmosphere to generate motion. When AJS10b claim that the dissipation of the extracted power would create more kinetic energy, they essentially propose a perpetual motion machine of second kind, as also pointed out by Bergmann, 2010 and we know very well that perpetual motion machines violate the fundamental laws of thermodynamics and can not exist.

3 Conclusion

In conclusion, any global estimate of wind power potential needs to take into account the thermodynamic limits of kinetic energy generation within the atmosphere. If these limits are ignored, this can easily result in exaggerated estimates of wind power potential that violate the fundamental laws of thermodynamics. These fundamental limits and their implications have already been demonstrated to be sound and valid. In (Kleidon et al. , 2003) and (Kleidon et al. , 2006) we confirmed with an atmospheric general circulation model that the capacity of the atmosphere to generate kinetic energy is close to being maximized. In (Miller et al. , 2010) we then quantified that large-scale, land-based near-surface removal of momentum is limited and reduces the overall generation of kinetic energy by the atmosphere. These studies can certainly be improved by accounting for more details of wind turbine design and the accuracy of the model simulations. However, even when more details are accounted for, the resulting estimates must not contradict the fundamental limitations imposed by thermodynamics.

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