

Questions and Answers on human activity and natural limits of renewable energy within the earth system:

Humans only consume 0.1% of the solar energy that the Earth receives. So what's the big deal in the research of Kleidon and colleagues?

The big deal is that not all energy is useful. In physics, this difference is described by the concept of free energy, which is the fraction of energy that can be used to perform work, such as lifting or accelerating mass. Of the 160 000 TW of incoming sunlight, most of it is reflected back to space or converted into heating the Earth's surface. Once converted into heat, the conversion to free energy is strongly limited by the laws of thermodynamics and yield maximum rates in the order of 1000 TW. Humans, on the other hand, primarily rely on free energy and not surface heating to survive. We cannot meet our metabolic needs by the heat stored in a glass of warm water, but we need the calories that are contained in food. Hence, humans rely on the consumption of approximately 30 TW of chemical free energy (food), an approximation based on a variety of estimates, but generally of the same magnitude as the current human energy consumption rate of approximately 17 TW. Together, this consumption rate is about 47 TW. This consumption rate is therefore sizable compared to the generation rates of natural processes (about 5 % of the above quantity of 1000 TW).

The 47 TW of human energy consumption is much larger than the 17 TW of primary energy consumption generally used. Why does Kleidon and colleagues use the larger number?

The 17 TW refers to primary energy consumption, which is mainly associated with the consumption of fossil fuels such as coal, natural gas and oil, as well as electricity generation by nuclear energy. What this number does not include is that humans use a great deal of free energy by using photosynthesis products for food production. This number corresponds to about 30 TW. Both numbers reflect the use of free energy and hence have been added together to yield the total of 47 TW. While there are clearly uncertainties surrounding these numbers, specifically regarding the 30 TW, the importance of this number is its magnitude, not its precise value.

There is so much wind and waves out there. Why should this not be enough for the all future needs?

For a sustainable use of renewable energy, it is not the stock of free energy (i.e. the amount of wind or waves) that is relevant, but rather the rates at which these are generated. These generation rates are associated with natural processes. For instance, wind is generated from differences in pressure gradients that were generated by differences in heating. Waves are primarily generated by winds at the surface. The limits can be quantified by thermodynamics and show that these generation rates are typically only a small fraction of the incoming sunlight. Wind power with about 1000 TW is the largest power source, wave power only involves about 63 TW and tidal power less than 5 TW. These limits do not depend on the details of the employed technology or their future enhancements.

Why should the atmosphere not just compensate and generate even more wind?

Because it cannot. Thermodynamics sets strict and fundamental limits on how much work can be extracted from a heating gradient. Observation-based estimates of how much the atmosphere generates and destroys wind energy naturally are very close to theoretical estimates of maximum generation rates and also correspond to what climate model studies tell us. What this implies is that the atmosphere generates as much wind as possible. So removing substantial amounts of wind can only result in less wind left behind and a reduced ability to generate wind.

So windmills reduce wind and generate heat. The wind would have been dissipated by forests, mountain slopes etc, anyway. So what?

It should be noted that the heating generated by friction is very small to the heating generated by the absorption of solar radiation and can therefore be neglected. And yes, wind is naturally destroyed near the surface due to friction. As a result of the friction, turbulence is generated which is associated with efficient ways to cool the surface and to transport moisture into the atmosphere. When wind is removed by turbines, this efficient way to cool and transport moisture is reduced, resulting in climatic effects. Hence, the wind removal by wind turbines directly affects atmospheric dynamics and the ability of the surface to cool, thereby resulting in climatic changes.

So does this mean that wind power is not renewable after all?

Of course not. Wind power is renewable. What we say and what our research shows is that extracting wind power by wind turbines at the large-scale leaves less behind less wind and degrades the ability of the atmosphere to generate wind. These atmospheric effects are critical for the natural limits of wind power generation, and these natural limits are the ones we quantified. Other researchers have found similar effects (e.g. David Keith at the University of Calgary, Chien Wang and Ron Prinn at MIT).

Do the results imply that wind power has no future?

In our study, we considered the hypothetical, maximum limit of how much wind power one could extract from the atmosphere by covering the whole land surface with wind turbines in a climate model. Our estimates suggest that wind power is unlikely to meet the growing energy needs of humans in the long-term and that its use has climatic impacts. The current use of wind power is far below the limit we estimated, so wind power can still play an important role in the next decades during the transition to renewable energy.

So is solar energy the ultimate and ideal renewable energy?

Absolutely. Other renewables such as wind, waves, and hydropower are indirectly derived from sunlight, but result from a sequence of energy conversions. This sequence of energy conversions is driven by differences in solar heating, which generate winds. Winds drive waves and the global water cycle. Thermodynamics, a fundamental theory in physics, tells us that these conversions cannot take place with 100% efficiency. Most of the useful part of energy (called "free energy", see also answer above) is lost when sunlight heats the ground. Photosynthesis by plants and solar power technologies (photovoltaic and concentrated solar) exploit sunlight directly and produce free energy in electrical and chemical form before it is converted into heat. In contrast, the other forms (wind, wave, hydropower) are driven by differences in heating, and therefore must be much less efficient in using solar energy. And to sum this up, life uses solar energy for the last billion years, so why shouldn't we?

Are the climatic effects of wind power as severe as global warming?

To look at the climatic effects of withdrawing wind from the atmosphere by wind turbines, we used climate model simulations. Removing wind affects atmospheric dynamics, but also results in more complex effects on temperature and other climatic variables. To compare the total change in climate, we looked at averaged absolute differences and compared these to a climate model simulation with doubled atmospheric concentrations of carbon dioxide. The simulations showed that when the maximum wind power is removed from the atmosphere in a hypothetical example in which all land is covered by wind turbines, the absolute climatic differences are comparable to those associated with doubled carbon dioxide concentration. With this comparison we intend to show that substantial removal of wind by wind turbines has substantial effects on climate and reduces the ability of the atmosphere to generate wind. Present levels of wind power generation are far below such level of impacts.

Kleidon often cites Lovelock in his research, who proposed the controversial Gaia hypothesis. Isn't Kleidon's research more of a quasi-religious account of how the Earth functions as a system rather than hard science?

Viewing the Earth as a thermodynamic system far from equilibrium is a fundamental perspective grounded in well-established laws of physics, and not quasi-religious. The research of James Lovelock in the 1960ies first proposed the use of chemical disequilibrium within the Earth's atmosphere as a quantitative sign of widespread life and pioneered the view of the Earth as being an interconnected and interacting system. Even though his accounts were mostly qualitative, these can be formulated in rigorous thermodynamic terms and hence can result in quantitative science. Furthermore, thermodynamic limits, such as the Carnot limit or the maximum power principle in engineering, are well established, fundamental limits to how engines and systems operate. No engineer would seriously challenge the Carnot limit as the fundamental limit on how much heat can be converted into work by an engine. Relatively little attention is given to how these thermodynamic limits apply to processes within the earth system and what this implies for the natural potential of different forms of renewable energy. In contrast, some atmospheric scientists have even proposed nearly infinite supply of wind power even though this clearly violates these fundamental, thermodynamic limits. This demonstrates

how important such a thermodynamic view is to establish the upper limits of different forms of renewable energy within the earth system.

Kleidon's group is called "Biospheric Theory and Modelling". Why are they qualified to make statements regarding renewable energy?

Our research is motivated by Lovelock's vision of the Earth as one interconnected thermodynamic system that is heavily influenced by life and we work towards formulating the thermodynamic basis of such a vision. We do this to understand the fundamental role that the biosphere plays within the Earth system, but also to better understand human impacts on the system. In more practical terms, our research focuses on quantifying free energy transfer rates by different earth system processes as well as their limits so that we can relate free energy generation to the strength of the biogeochemical cycles of water, carbon and other elements as well as their effects on the earth system. And since human activity is driven by free energy consumption, the quantification of free energy generation rates within the earth system is directly related to the natural, upper limits of renewable energy. Hence, our research allows us to make a highly relevant contribution to establishing the natural limits of renewable energy.

Who is funding this type of research?

The research is funded entirely by the Max-Planck Society (www.mpg.de), a German federal research organization devoted to conduct basic research. This source of funding with 'no strings attached' allows us to investigate the rather important question of how different forms of renewable energy are generated within the Earth system as well as fundamental limitations without prejudices, preconceptions, or personal, financial, or political conflicts of interest.