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Max-Planck-Institut
für Biogeochemie

Postfach 10 01 64
07701 Jena

Hans-Knöll-Straße 10
07745 Jena

Tel.: +49-(0)3641 57-60
Fax: +49-(0)3641 57-70
www.bgc-jena.mpg.de

Direktorium

Prof. Dr. Susan Trumbore
Tel.: +49 3641 57 6110
Fax: +49 3641 57 7100
susan.trumbore@bgc-jena.mpg.de

Prof. Dr. Martin Heimann
Tel.: +49 3641 57 6350
Fax: +49 3641 57 7300
martin.heimann@bgc-jena.mpg.de

Forschungskoordination

Dr. Eberhard Fritz
Tel.: +49 3641 57 6800
Fax: +49 3641 57 7860
efritz@bgc-jena.mpg.de

Öffentlichkeitsarbeit

Susanne Hermsmeier
Tel.: +49 3641 57 6801
Fax: +49 3641 57 7860
sherms@bgc-jena.mpg.de

Solar, wind, and wave power – natural limits of renewable energy

Using thermodynamic approaches, the natural limits of renewable energies and their possible impact on the climate system have been analyzed at the Max-Planck-Institute for Biogeochemistry in Jena, Germany. Their research suggests the availability of energy from wind and waves is renewable but limited and its extensive extraction might impede its own regeneration by the Earth system. However, the conversion of solar energy seems capable of fulfilling the growing demand for sustainable energy on Earth for quite some time.

Producing enough sustainable energy is a major challenge for the future of our civilization. While climate-friendly nuclear energy bears major safety risks, the burning of fossil fuels ultimately contributes to climate change. Alternative natural energy sources like sun, wind, and waves are considered risk-free, renewable, and without a climate impact. The latter two aspects have now been analyzed by scientists of the Max-Planck-Institute for Biogeochemistry in Jena, Germany, using a holistic approach. They used the well-established physical theory of thermodynamics to differentiate between energy and so-called free energy, the part of energy that is relevant for the availability of renewable energy.

“Free energy is a well-defined concept in physics”, says Dr. Axel Kleidon, head of the independent Max-Planck Research group ‘Biospheric Theory and Modelling’. It refers to the fraction of energy that is useful for performing physical work, such as lifting or accelerating mass, but also for energy conversion for human use. The natural limits on the rate of free energy generation are not often considered and discussion of them is practically absent in the fields of climatic change and renewable energy potentials. In two new publications (see references below), Kleidon and colleagues show that the natural ability of the Earth system to generate different forms of this useful energy is limited to roughly 1,000 terawatts (1 terawatt equals 10^{12} watt, the unit of energy use through time), compared to the massive solar influx of more than 160,000 terawatts. The physical theory of thermodynamics can explain this very low efficiency of conversion of solar radiation into free energy. “Indeed, only about 0.6 % of the huge energy from solar radiation can be transformed into usable free energy”, confirms Kleidon. Human energy consumption currently accounts for about 5% of the free energy available on Earth.

The implication of this new, thermodynamic look at renewable energy is that its different forms have different types of impacts. Incoming solar energy heats the Earth surface differently, generating wind, which then provides an energy input to waves. The efficiency for conversion of free energy into the physical work done by wind and waves is limited, with thermodynamics describing the mechanisms. Hence a renewable source of energy based on wind and waves is continually replenished by energy input from the sun, but ultimately finite. “We found that wind or wave power deplete the natural stock of free energy”, explains Kleidon. Thus, the extraction of wind and wave energy has an impact on the ability of the climate system to (re)generate these forms of energy.

The use of solar energy as a renewable energy form is different. When sunlight results in heating or is reflected back to space, its free energy is largely wasted. Photosynthesis and solar power technologies exploit sunlight directly and produce free energy before it is converted into heat, and hence allow the

Earth system to generate additional free energy. Even solar energy has free energy extraction limits, but its placement at the top of the free energy hierarchy makes the human extraction limits proportionally much higher.

Contact:
Dr. Axel Kleidon
Max-Planck-Institute for Biogeochemistry, Jena, Germany
Phone: +49 3641 576217
Fax: +49 3641 577217
Email: akleidon@bgc-jena.mpg.de

Background Information:

*The **Max-Planck-Institute for Biogeochemistry**, founded in 1997, is dedicated to the study of long-term interactions among the biosphere, atmosphere, geosphere and the oceans. The research aims of the Institute include:*

- quantifying the role of these interactions in the control of the Earth's climate in a time of increasing anthropogenic impact;

- developing a quantitative and predictive understanding of the regulation of processes in ecosystems and their attendant biogeochemical cycles in the face of climate change;

- and investigating feedback mechanisms at the Earth's surface that involve vegetation, atmospheric composition and climate. For more information see www.bgc-jena.mpg.de.

*The independent **Max-Planck Research Group „Biospheric Theory and Modelling"**, headed by Dr. Axel Kleidon, develops and uses theoretical approaches and numerical simulation models to investigate the role of the biota in driving the global geochemical cycles within the Earth system and how these affect the climatic conditions. It applies complex systems theories as well as thermodynamics to describe biotic effects on the environment. The group develops a range of simulation models to reproduce and explain the observed geographic variation of terrestrial vegetation, fluxes of energy, water, carbon, and other elements for the present-day and its past evolution. These approaches are used to evaluate the causes and consequences of human modifications to the Earth system (www.bgcjena.mpg.de/bgc-theory).*

***Further information** on the contents of this press release is available as "frequently asked questions" at www.bgcjena.mpg.de/bgc-theory. Original data are published in:*

- L.M. Miller, F. Gans, & A. Kleidon, 2011: Estimating maximum global land surface wind power extractability and associated climatic consequences; Earth Syst. Dynam. 2. 1-12, doi: 10.5194/esd-2-1-2011.

- A. Kleidon, 2011: How does the earth system generate and maintain thermodynamic disequilibrium and what does it imply for the future of the planet? Philosophical Transactions of the Royal Society (submitted), arXiv: 1103.2014v1.

(luigi giordano – Fotolia)

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The independent Max-Planck Research group ‘Biospheric Theory and Modelling’ at the Max-Planck-Institute for Biogeochemistry, Jena, Germany. (Picture: MPI-BGC)

Back row, for left to right: James Dyke, Lee Miller, Axel Kleidon, Ryan Pavlick, Darren Dreqry, Steffen Richter, Philipp Porada, Susanne Arens, Kerstin Sickel, Björn Reu, Corina Buendia, Kristin Bohn.
Front row, from left: Eugenio Simoncini, Fabian Gans, Stan Schymanski.
No picture from: Birgitta Wiehl, Corinne Sacher, Gerhard Bönisch, Natalia Ungelenk.