

## **Solar, wind and waves: Natural limits to renewable sources of energy within the Earth system**

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Renewable sources of energy, such as solar, wind, wave, or hydropower, utilize energy that is continuously generated by natural processes within the Earth system from the planetary forcing. Here we estimate the limits of these natural energy conversions and the extent to which these can be used as renewable energy sources using the laws of thermodynamics. At most, wind power in the order of 1 000 TW (1 TW =  $10^{12}$  W) can be derived from the total flux of incoming solar radiation of 175 000 TW, which is consistent with estimates based on observations. Other generation rates that are derived from the kinetic energy of wind are in the order of 10 - 100 TW. In comparison, the human primary energy demand of about 17 TW constitutes a considerable fraction of these rates. We provide some further analysis on the limits of wind power using a combination of conceptual models, observational data, and numerical simulation models. We find that many current estimates of wind power substantially overestimate the potential of wind power because the effect of kinetic energy extraction on the air flow is neglected. We conclude that the only form of renewable energy that is available in substantial amounts and that is associated with minor climatic impacts is solar power.