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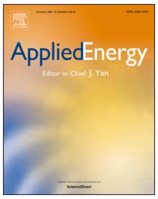

Global available wind energy with physical and energy return on investment constraints

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HIGHLIGHTS

- A novel methodology to estimate global wind energy potential is proposed.
- Wind park suitability is constrained by land use and water depth.
- Power production density is derived from energy conservation laws.
- Maximum wind potential is dependent on minimum Energy Return on Investment.
- Total potential is established between 700 and 100 EJ/year at $\mathrm{EROI}_{\mathrm{min}}$ from 5 to 12.

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ABSTRACT

Looking ahead to 2050 many countries intend to utilise wind as a prominent energy source. Predicting a realistic maximum yield of onshore and offshore wind will play a key role in establishing what technology mix can be achieved, specifying investment needs and designing policy. Historically, studies of wind resources have however differed in their incorporation of physical limits, land availability and economic constraints, resulting in a wide range of harvesting potentials. To obtain a more reliable estimate, physical and economic limits must be taken into account.

We use a grid-cell approach to assess the theoretical wind potential in all geographic locations by considering technological and land-use constraints. An analysis is then performed where the Energy Return on Investment (EROI) of the wind potential is evaluated. Finally, a top-down limitation on kinetic energy available in the atmospheric boundary layer is imposed.

With these constraints wind farm designs are optimized in order to maximize the net energy flux. We find that the global wind potential is substantially lower than previously established when both physical limits and a high cut-off EROI > 10 is applied. Several countries' potentials are below what is needed according to 100% renewable energy studies.

1. Introduction

Economic growth since the industrial revolution has been possible thanks to abundant sources of affordable energy, in the form of coal, oil and gas. However to mitigate climate change, we must urgently move away from fossil fuels. According to a study in Nature [1], a significant part of remaining fossil fuel reserves should remain unused in order to limit the increase in average global temperature to 2 °C. A rapid transition to a sustainable energy system is therefore the only option.

At the same time, energy demand will continue to increase significantly in the coming decades. According to some predictions it will reach 700–830 EJ by 2040 [2,3], up to 550 EJ in 2015 [4]. Renewable energy sources therefore will not only have to substitute for fossil fuels but will also have to supply growing energy needs to support economic and population growth. Given these challenges it is essential to accurately take into account their future production potential in a low-carbon energy system.

Wind power achieves a prominent share in the power generation mix in many techno-economic future energy studies of countries and regions [5–7]. Without an evidence-based upper-bound based on geographic potential however, overestimates can occur resulting in unrealistic transition scenarios. Moreover, with the pace of wind energy

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expansion being increasingly determined by government and companies via auctions, where capacities instead of prices are the fixed instrument of control, the provisioning of accurate long term capacity planning potential is even more important [8].

A major challenge to impose realistic potentials in planning scenarios is the large discrepancy between studies on the global and regional wind energy potential (Table 1). The difference in wind potential estimates results in a wide range of possibilities for the future role of renewables. A large group of researchers evaluate that with the right policies we will be able to grow our level of consumption and support economic growth with a 100% renewable energy system, thanks to technological progress, performance improvement, and cost reduction [9–12].

Other authors are less optimistic, arguing that the renewable energy potential is overestimated and that the analysis of potential share includes significant uncertainties in physical requirements. They argue that key physical and geographic constraints, which limit energy availability and accessibility, have not been taken into account [19,23–29].

In this study a novel methodology is described and implemented that to our knowledge is the first to combine physical, geographic, and economic constraints, derived from setting a minimum Energy Returned on Investment (EROI) as a limiter to the harvestable wind resource. Thereby we gain a more precise value for the maximum offshore and onshore wind potential at a global and country level. These can be utilised to create more realistic future energy systems scenario studies to underpin policy decisions and investment need assessments.

In Section 2 key considerations to be taken into account in the analysis of wind energy potentials are discussed. They are followed by the methodology employed in this study in Section 3, results are presented in Section 4 and discussed in Section 5. Finally, the study ends with a set of conclusions and the implications for energy strategy policies in Section 6.

Table 1
Global wind power potential estimates.

Authors	Estimated potential [EJ/year]	Scope	Wind regime constraints	Land use constraints?	Installed capacity density [MW/km^2]
Hoogwijk [13]	346	Onshore	$\bar{v}_{80m} \geqslant 6.9$ m/s	Yes	4
Archer and Jacobson [14]	2256	World	$\bar{v}_{80m} \geqslant 6.9$ m/s	No	9
Honnery and Moriatry [15]	229	Onshore	$\bar{v}_{70m} \geqslant 6$ m/s	Yes	2
EEA [16]	153	Europe	$\bar{v}_{10m} \geqslant 4$ m/s	Yes	*Onshore*: 10, *Offshore*: 6.4
Lu et al. [17]	3024	World	$C_f \geqslant 20\%$	Yes	*Onshore*: 9, *Offshore*: 5.85
Miller et al. [18]	570–2150	World	Top-down	No	–
de Castro et al. [19]	32	World	Top-down	Yes	–
GEA [20]	250–1200	World	$\bar{v}_{80m} \geqslant 6.9$ m/s	Yes	–
Bosch et al. [21]	2112	Onshore	$C_f \geqslant 15\%$	Yes	6.52
Eurek et al. [22]	2720	World	$C_f \geqslant 18\%$	Yes	5

2. Background

2.1. Net energy availability

The field of net energy analysis studies the energy surplus available to society after subtracting input energy needed to construct and operate an energy supply chain. To account for energy available on a net basis, Net Energy Ratios, such as the Energy Return on Investment (EROI) or Energy Returned on Energy Invested (ERoEI), are calculated [28–36]: these yield the ratio of energy delivered by an energy technology or system to the total amount of energy invested for its manufacture, transportation, construction, operation, maintenance, and decommissioning. This dimensionless factor enables a comparison between energy sources if the same boundaries for calculating inputs and outputs are used. First, it allows for an evaluation of the energy made available to society net of the energy self-consumption of the sector itself, so as to assess - in an absolute manner - the net potential that energy technologies can deliver to the economy. Second, it allows to evaluate in energy transition scenarios how the scale of the energy sector would need to change to deliver the same or changing energy needs. For example, if the baseline EROI of the energy sector is 8 and if this is halved to 4 over time due to a switch to different energy technologies, this would result in a 2.3 times greater energy sector size to supply the same end energy service, and a drop from 8 to 2 implies a 7 times larger energy sector for the same end service. The weight of scaling in terms of the size of the energy sector versus the rest of the economy starts to matter at an EROI below 15 and becomes increasingly relevant as the value drops below 10. Because of this scaling effect, studies indicate that there is a minimum EROI value to maintain our current standard of living [37–39].

Static evaluations of EROI for a given energy technology are widely present in the literature [40–43]. However, few studies exist on the potential of technologies globally or regionally on a net energy basis, nor on the future evolution of EROI of renewable energy technologies and energy systems. As renewable resources and energy consumption are not equally distributed on earth, it is plausible that the EROI of renewable energy sources declines with spatial expansion [30]. Renewable energy projects will primarily be built on the best sites (i.e. the sites with the highest resources or that are close to end-users), subsequently, in order to significantly increase capacity, lower quality sites will have to be exploited.

So far few studies on renewable energy potentials take into account EROI dynamics, despite its importance to assess the feasibility to rapidly expand renewable energy technology in the future, except to the knowledge of the author's the work of Dale et al. [28,29] and Moriatry and Honnery [26,27,44].

2.2. Maximum wind energy potential

The amount of wind energy that is available at a global scale is constrained by physical factors including incoming solar radiation, heat gradient, geography, and electricity transport distance. A considerable number of studies estimate the technical potential of wind energy via a bottom-up approach neglecting energy conservation laws that are in effect at a global scale [13,14,16,17,21,22]. Global potential is in these studies calculated from the sum of local potentials, based on the implicit assumption that the extraction of a large amount of wind power has no impact on global wind generation. However, wind power potential is not only limited by our ability to build and install more a more wind turbines, but also by the power generated by the sun. Therefore a global estimate of maximum kinetic energy extraction rates is needed, and should be taken into account as a physical constraint to the sum of