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Can renewable energy power the future?

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HIGHLIGHTS

- Published estimates for renewable energy (RE) technical potential vary 100-fold.
- Intermittent wind and solar energy dominate total RE potential.
- We argue it is unlikely that RE can meet existing global energy use.
- The need to maintain ecosystem services will reduce global RE potential.
- The need for storage of intermittent RE will further reduce net RE potential.

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ABSTRACT

Fossil fuels face resource depletion, supply security, and climate change problems; renewable energy (RE) may offer the best prospects for their long-term replacement. However, RE sources differ in many important ways from fossil fuels, particularly in that they are energy flows rather than stocks. The most important RE sources, wind and solar energy, are also intermittent, necessitating major energy storage as these sources increase their share of total energy supply. We show that estimates for the technical potential of RE vary by two orders of magnitude, and argue that values at the lower end of the range must be seriously considered, both because their energy return on energy invested falls, and environmental costs rise, with cumulative output. Finally, most future RE output will be electric, necessitating radical reconfiguration of existing grids to function with intermittent RE.

1. Introduction

Underlying any binding and universal agreement on greenhouse gas emissions to limit the average global temperature increase since pre-industrial times to 2 °C is the belief that there is sufficient *carbon-free* energy to meet our future needs (Intergovernmental Panel on Climate Change (IPCC) 2015; Jacobson and Delucchi, 2011; Steinke et al., 2013).

Much has been made of the opportunity for continued use of fossil fuels to meet our future needs through use of carbon capture and sequestration (CCS) (IPCC, 2015). But declining fossil fuel reserves and the lower efficiency of CCS preclude it being a long-term solution. Nuclear energy's prospects are also uncertain; given its falling energy share (Table 1) and an ageing global reactor fleet that will need decommissioning in the coming decades (Froggatt and Schneider, 2015), its contribution may never be more than marginal. Renewable energy (RE) offers the strongest prospect for both mitigating climate change and replacing fossil fuels, and so we focus on it here. At present, RE's share of global commercial energy is less than 10%, although slowly rising (Table 1).

As Fig. 1 shows, many steps are involved in accessing, converting and supplying RE to the consumer. The five sources that dominate RE can be conveniently divided into two groups (Table 1). At a global level, these sources depend on, or exist as, Earth energy flows. Group I have much greater Earth energy flows than Group II, i.e. their theoretical potential is much greater. The energy available depends on the location, quality and variation of these flows. Land constraints can limit RE access: complex geography, alternative land use, or environmental sensitivity. Allowing for these constraints reduces the theoretical potential to the *geographical potential* (de Castro et al., 2013).

Further constraints arise from converting the RE flows into electricity, expected to be the dominant mode of future RE delivery. Accounting for these limits yields the *technical potential* (de Castro et al., 2013; Hoogwijk et al., 2004). Technical limits arise from the physics of the conversion processes used, and inefficiencies. For example, a wind turbine cannot extract all the

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Table 1
Global primary commercial energy by type, 2014.Source: (BP, 2015).

Energy group	Energy type	Primary energy (EJ)		Primary energy (%)	
		2004	2014	2004	2014
Group I RE	Wind, solar	0.8	8.5	0.2	1.6
Group II RE	Hydro, bioenergy, geothermal	29.8	41.6	6.7	7.7
Nuclear	Fission	26.6	24.0	5.9	4.4
Fossil fuels	Coal, oil, gas	385.2	467.2	87.2	86.3
All energy	All types	442.0	541.3	100.0	100.0

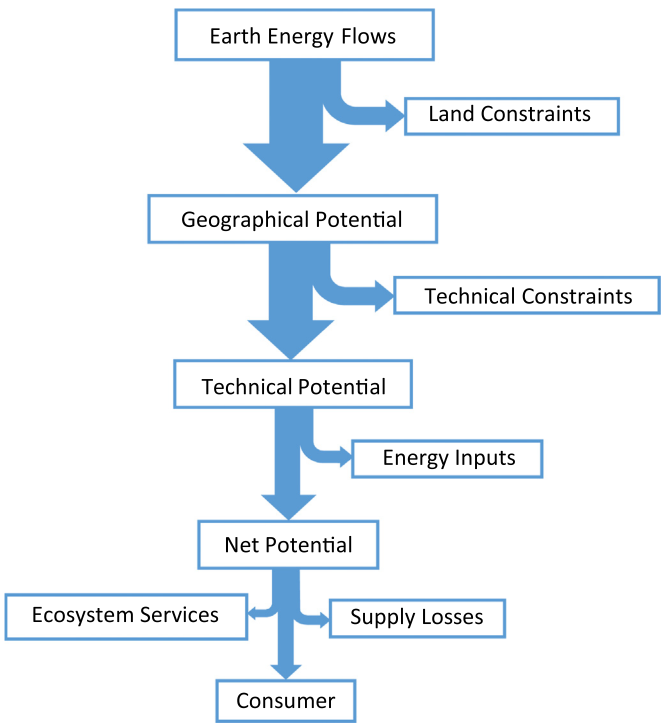

Fig. 1. Indicative constraints on the flow of RE from source to user.

energy in the wind, and thermal efficiency limits apply to bioenergy. Further, the important sources wind and solar, being intermittent flows, will eventually need energy storage, and perhaps partial conversion to non-electric energy, lowering the delivered energy and raising costs (Moriarty and Honnery, 2012a; Hall et al., 2014; Lund et al., 2015). And not all the technical potential may be economically feasible.

Subtracting the energy consumed to operate the RE system yields the net potential of the RE source. Energy inputs will vary depending on source and location. Finally, the electrical grid used to connect the consumer to the RE energy source has losses. Losses result from the often long distances separating the consumer from the land-intensive and possibly remote RE power plants, and from the need to match supply with demand.

Energy is also needed to maintain ecosystem services. Provision for Earth's ecosystems occurs both as a land constraint, and also through supply of energy to maintain land, water and air quality.

Given these extensive constraints in the RE system, are we certain that RE can meet our future energy needs? In exploring this question, we first review the literature on RE technical potential, finding large variations in published estimates. We then argue that consideration of both RE energy inputs compared with outputs, and the need to maintain ecosystem services, support estimates at the lower end of the range.

2. Conflicting published estimates for RE potential

Published estimates for individual RE technical potentials show a wide range of values (de Castro et al., 2011, 2013; Moriarty and Honnery, 2012a), except for hydropower, where most estimates are around 30–50 EJ. For combined RE sources, the upper limit is many times present energy consumption, suggesting no constraints on future energy use. Especially high estimates (each over 1500 EJ) have been published for solar energy, bioenergy, and geothermal heat. These high estimates are now increasingly being challenged as unrealistic (Buchanan, 2011; de Castro et al., 2011, 2013; Makarieva et al., 2008; Searle and Malins, 2014; Trainer, 2013). An overview of the arguments for tight constraints on RE is given below.

First, geographical constraints may be more limiting than generally thought. Areas unsuitable for solar and wind energy include the deep sea, icecaps, high mountains and forests. But criteria for geographical constraints are not applied consistently over different RE sources: hydroelectric dams have inundated forests, and in some cases entire cities have been relocated. Constraints on wind energy, for example, are much more restrictive (Hoogwijk et al., 2004). A further 'geographical' constraint on future RE output, particularly for wind energy, is public opposition. Such opposition is already significant in many OECD countries, not only because of perceived effects on visual amenity and property prices, but also because of concern for bird and bat deaths (Smallwood, 2013).

Although recently published values for geothermal electricity potential are small (1–22 EJ), for geothermal heat, estimates range up to 5000 EJ, or even far higher, but actual use is severely limited by another type of geographical constraint. In the US, for example, geothermal activity is concentrated in the western states. Because it is not feasible to transmit low-grade heat more than about 8 km, only a small percentage of this geothermal resource can be exploited (Lienau and Ross, 1996).

Second, the energy return on energy invested (EROI) may prove too low for viability as an energy source. The EROI of any energy conversion device is the ratio of gross output energy to the energy inputs needed for manufacture, erection, maintenance, operation, and decommissioning, with both inputs and outputs measured in comparable energy terms. The difference between output and input energy is the *net* energy (Fig. 1); only net energy can power the non-energy economic sectors. For example, the world's hot deserts cover more than 10 million km^2, giving rise to calls for massive solar energy farms there: the Desertec proposal (Chatzivasileiadis et al., 2013) plans to transmit solar (and wind) electricity from North Africa and the Middle East up to 5000 km to central and northern Europe. The solar farms would need large supplies of fresh water piped in for cleaning, supplying water to the necessary workforce settlements, and possibly, coolant for solar thermal electricity conversion (STEC) plants. For major output of electricity from Desertec, energy storage would be needed. If hydrogen was used as the energy carrier, further large amounts of water would be needed. All these factors would greatly reduce EROI (de Castro et al., 2013).

Third, energy security concerns are a further constraint on RE potential. Although two-thirds of crude oil and products cross international borders (BP, 2015), only 1.4% of global electricity generated does so, usually to a neighbouring country; countries may be reluctant to become heavily dependent on imported electricity, such as with Desertec (Lilliestam and Ellenbeck, 2011).

Fourth, estimates of RE output/m^2 are often over-optimistic. For solar energy this can occur because the total area needed for existing PV/STEC farms is much larger than that occupied by the solar arrays themselves (de Castro et al., 2013). For bioenergy, although published estimates (World Energy Council (WEC), 2013)