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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

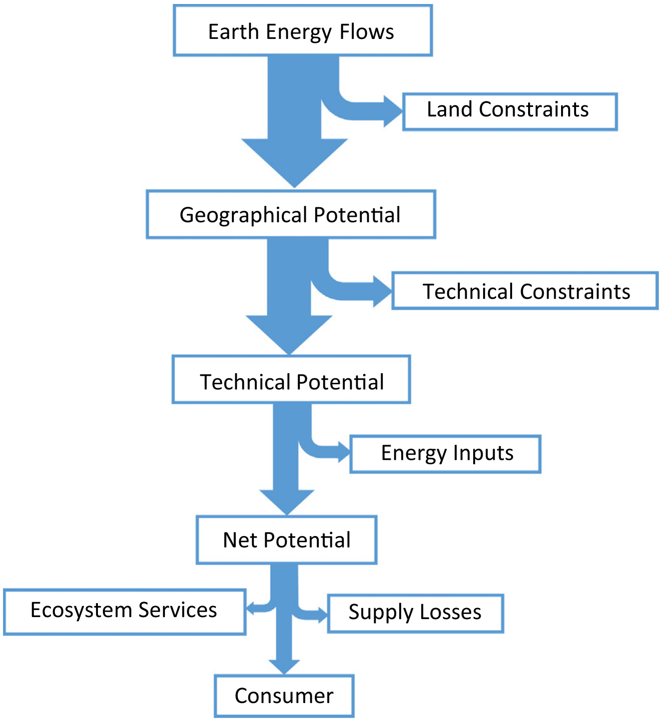

Fig. 1. Indicative constraints on the flow of RE from source to user.

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) for potential range up to 1500 EJ, the entire terrestrial net primary production is only around 2000 EJ annually (Schramski et al., 2015). Recent research has found that for bioenergy plantations, actual field yields fall far short of those from experimental plots. As Searle and Malins (2014) stated, the lower yields are 'due to biomass losses with drying, harvesting inefficiency under real world conditions, and edge effects in small plots.' Even for food crops presently used for biofuels, yields are likely over-estimated by 100–150% (Johnston et al., 2009).

Consideration of these constraints act to greatly reduce RE technical potential. In contrast to the high estimates given above, estimates as low as about 30 EJ (electric) for wind (de Castro et al., 2011), 60–120 EJ (electric) for solar (de Castro et al., 2013) and 27.5 EJ for biomass (Field et al., 2008), have been reported. In summary, published estimates span two orders of magnitude. (Of course, fossil fuel reserves are also uncertain, but this does not directly affect their *annual* production.) The following sections present further support for the need to take these lower estimates seriously.

3. Declining EROI limits RE potential

For RE project viability, a hard constraint is that EROI > 1.0, and ideally should be much greater, if only because EROI calculations are uncertain (Murphy et al., 2011). Despite uncertainty, it is still the case that, *ceteris paribus*, EROI for solar is greater in higher insolation areas, and for wind in high wind speed areas.

The EROI for any RE type will fall as its annual output rises for several reasons. First, resource quality (e.g. average wind speeds, or geothermal steam temperatures) will decline with output as premium sites are used up. Even for a given wind turbine, EROI will decline as the turbine ages: in Europe average output declines of 12% over a 20-year lifetime have been documented (Staffell and Green, 2014). Also, EROI could well change over the life of the project (25–30 years for most RE systems and much more for hydro), because of adverse on-going land-use and climate changes. For instance, the Amazon basin hydro potential could be reduced to 25% of maximum plant capacity if 40% of the forest is lost (Stickler et al., 2013).

Second, fossil fuel EROIs are usually much higher than those for RE (Hall et al., 2014), giving a hidden energy subsidy to RE inputs that will decline as fossil fuel use declines. Third, as already noted, for Group I RE, the need for very large energy storage systems will progressively arise as grid penetration increases (Pickard, 2014).

Fourth, for bioenergy, the EROI will decline as municipal, agriculture and forestry biomass wastes are fully utilised, and it becomes necessary to rely more on lower EROI bioenergy plantations. Further, to avoid competition with food production, bioenergy should be grown on marginal land. The resulting higher need for energy-intensive fertiliser and irrigation water inputs will further reduce EROI. This example shows that the input energy costs for bioenergy cannot be considered in isolation from those for food. A system approach is needed, one that examines inputs and outputs from the entire biomass system—food, energy, fibre, forage, and forestry. If all humans adopted a vegetarian diet, bioenergy potential could accordingly be greatly increased (Powell and Lenton, 2012).

A counter-trend to decreasing EROI and technical potential is technological progress, which promises to both decrease input energy and increase output from RE energy conversion devices. Many RE technologies, however, are now mature, such as biomass combustion for heat and electricity, hydropower, high temperature geothermal electricity, and most wind turbine components. But technology is still evolving rapidly for PV cells and STEC mirrors, important since solar energy accounts for most RE potential. Even here, further advances are unlikely to greatly improve EROI because such receivers are only part of the energy costs of such systems. The balance of system (b.o.s.) items (eg support structures for PV or solar thermal arrays in large solar farms, transmission infrastructure etc.) are largely mature technologies and will not see much further energy cost reduction. Much of the present PV capacity has been installed on rooftops, greatly reducing structural support costs, but such installations can never play a major role in PV output expansion (de Castro et al., 2013). So even with energy cost reductions for receiver technology, overall input energy costs would still be substantial.

Some empirical evidence implies declines in EROI for hydro globally, and for geothermal energy in several OECD countries. For global hydropower, available data (WEC, 2013) allow comparison of annual gross electricity generated to installed generating capacity (TWh/GW) for various years. In 1993, this ratio was 3.75, but for the incremental capacity added over the years 1994–2011, the ratio had fallen to 1.43 (Moriarty and Wang, 2015). The most likely explanation is that EROI has fallen for new hydro projects, even though 2011 installed capacity was only about one-third of commonly assessed global potential. Geothermal data are less reliable than hydro data, and fields are subject to depletion. But for Italy, Japan, NZ and the US, all countries with at least 50 years of geothermal exploitation, TWh/GW ratios appear to have peaked between 1990 and 2011 (BP, 2015; International Energy Agency (IEA), 2003; WEC, 2013). Yet the technical potential for electricity generation in each country is given as many times higher than present output. The (minor) technical advances in hydro and geothermal electric plants seem unable to stem these declines.

4. Maintaining ecosystem services further limits RE potential

An important reason for replacing fossil fuels with RE is to promote ecological sustainability—in particular to minimise further climate change. The natural world provides many ecosystem services, such as provision of food, fresh water, and climate regulation, but land-intensive RE systems, particularly hydroelectricity and bioenergy, inevitably reduce such service provision. Further, different important ecosystem services—food, forestry products, livestock pastures—can compete with bioenergy. Major expansion of bioenergy could curtail their output.

In some cases, ecosystem services could be maintained by diverting some of the RE energy output, further reducing the net output to the economy (Moriarty and Honnery, 2011; Sheldon et al., 2015). An example would be proper treatment and disposal of toxic wastes from PV cell manufacture. RE installations can also themselves either directly cause greenhouse gas emissions, as with CO_2 from geothermal plants, and both CO_2 and CH_4 from tropical hydro dams (much of the still-undeveloped hydro potential is in the tropics (WEC, 2013)). High-latitude bioenergy plantations could even decrease local albedo (Keller et al., 2014). Offsetting the climate forcing from this albedo change could involve air capture of CO_2, with it heavy energy costs (Sheldon et al., 2015). In other cases, some areas otherwise geographically suitable for RE may have to be simply excluded, again reducing net RE output. This is particularly true for maintaining biodiversity, given that the present rate of global species loss is roughly 100–1000 times the natural background rate (Steffen et al., 2015).

Solar and wind energy are indeed more land-sparing and less environmentally disruptive than hydro and bioenergy, but they increasingly rely on exotic materials for their manufacture. The mining of these low-concentration minerals will increase both the energy and environmental costs of wind and solar energy with both costs rising as these ore grades decline (Jeffries, 2015). Hence there is a danger of 'environmental problem shifting', of reducing CO_2 emissions, but worsening other environmental problems elsewhere (van den Bergh et al., 2015).

Energy inputs for manufacture and erection of RE installations must be made before any energy output can be achieved, and so are obvious and widely acknowledged. In contrast, energy diverted for ecosystem maintenance is not so needed; such energy costs, if they are recognised at all, can be postponed, in some cases for many decades. These costs are not negligible—for hydro one estimate is six times conventional inputs (Sheldon et al., 2015), There is thus a danger of RE *overshoot*—of producing short-term net energy, but with further energy debts in the longer term.

5. Delivering future RE

So far we have emphasised the possible constraints on RE potential production, but also important is getting this energy to consumers. Here we focus on the electricity grid, as most RE will be produced as electricity. In present fossil fuel-dominated grids, daily and seasonally variable demand is met by standby plants which can rapidly come up to full power. If Group I RE dominates future grids, a further source of variability is introduced: the power output from such plants. Three approaches are possible for reducing the back-up power needed: building RE overcapacity, expanding the grid, and providing energy storage. Providing overcapacity is not only expensive, but actually reduces annual net RE energy, because energy will have to be dumped during times of excess output.

A recent study (Steinke et al., 2013) showed that a European-wide grid expansion could reduce the backup energy needed for a 100% Group I European grid from 40% to 20% of annual use. Greatly expanded grids (as in Desertec) would also enable RE from remote regions to be utilised. Even more ambitious are proposals for a global grid (Chatzivasileiadis et al., 2013) or solar power satellites (Seboldt 2004). Although either could potentially eliminate Group I output variability, neither would address *demand* variability. Further, major grid expansion faces technical difficulties, and would take several decades, whereas constructing new solar or wind farms only takes a few years, imposing a limit on future RE output *growth rates.* Intermittent systems also need greater capacity in high voltage lines than do fossil fuel systems for the same energy transfer (Buijs et al., 2011; Van Hertem and Ghandhari, 2010).

Although storage and grid expansion are to some extent substitutes (Steinke et al., 2013), major energy storage is unavoidable with an RE-dominated grid, if the need for fossil fuel backup plants is to be avoided. California has recognised this by mandating 1.32 GW of storage capacity in the state by 2020 (Lemmon, 2015). Storage possibilities include pumped hydro, batteries, compressed air, or synthesis of fuels such as hydrogen, methane or even liquid hydrocarbon fuels (Lemmon, 2015; Pickard, 2014). Since not all final energy demand is for electricity, fuel synthesis could be favoured for powering ships and planes and some industrial processes. All storage methods are expensive (Pickard, 2014), and full cycle inefficiencies (especially for fuel synthesis) will lower the net energy available from RE.

A very different idea for overcoming the intermittency problem is to move away from the fossil fuel era notion of energy available at any level demanded, at any time. With strong *energy demand management*, energy use could be concentrated on periods of high RE supply, such as summer daytime for solar energy. Transmitting large amounts of energy over long distances could also be partly avoided by shifting industry (and even population) to regions of high RE potential, as already happens today with aluminium smelters located near hydro plants. Also, more of the world's low-temperature geothermal energy potential could be exploited by such relocation.

6. Conclusions and policy implications

Because of the many problems facing continued fossil fuels use, RE is often seen as offering the best prospects for their long-term replacement. The most important RE sources, wind and solar energy, are intermittent, which will necessitate major energy storage if these sources are to dominate total energy supply in future. Literature estimates for RE technical potential vary by two orders of magnitude; values at the lower end of the range must be seriously considered, because their energy return on energy invested falls as cumulative output rises. Likewise, the energy costs for maintaining ecosystem services also rise with RE output, particularly for bio and hydro energy. Further, most future RE output will be electric, so radical reconfiguration of existing grids will be needed to supply intermittent RE to consumers.

So, in meeting the challenges of the 21st century, the world now faces a triple uncertainty: in the timing and severity of climate change, in the future supply of fossil fuels, and—as argued here—in future RE availability. Fossil fuel use may have to be reduced to near zero in the coming decades, and future RE output could be far below present energy use. Thus a prudent course would involve major energy reductions (Anderson, 2015; Moriarty and Honnery, 2012b). Not only will we need to maximise the energy services obtained from each unit of energy (for instance, through gains in technical energy efficiency), but we will likely also need to re-evaluate all energy-consuming tasks, discarding those that are less important.

References

Anderson, K., 2015. Duality in climate science. Nat. Geosci. . http://dx.doi.org/10.1038/ngeo2559

BP, 2015. BP Statistical Review of World Energy 2015. BP, London.

Buchanan, M., 2011. The fantasy of renewable energy. New Sci. 2, 8–9.

Buijs, P., Bekaert, D., Cole, S., van Hertem, D., Belmans, R., 2011. Transmission investment problems in Europe: going beyond standard solutions. Energy Policy 39, 1794–1801.

Chatzivasileiadis, S., Ernst, D., Andersson, G., 2013. The global grid. Renew. Energy 57, 372–383.

Field, C.B., Campbell, J.E., Lobell, D.B., 2008. Biomass energy: the scale of the potential resource. Trends Ecol. Evol. 23 (2), 65–72.

Froggatt, A., Schneider, M., 2015. Nuclear power versus renewable energy—a trend analysis. Proc. IEEE 103, 487–490.

Hall, C.A.S., Lambert., J.G., Balogh, S.B., 2014. EROI of different fuels and the implications for society. Energy Policy 64, 141–152.

Hoogwijk, M., de Vries, B., Turkenburg, W., 2004. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energy Econ. 26, 889–919.

Intergovernmental Panel on Climate Change (IPCC), 2015. Climate Change 2014: Synthesis Report. Cambridge University Press, Cambridge, UK.

International Energy Agency (IEA), 2003. Renewables Information, 2003 edition. IEA/OECD, Paris.

Jacobson, M.Z., Delucchi, M.A., 2011. Providing all global energy with wind, water and solar power, part 1: technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy 39, 1154–1169.

Jeffries, E., 2015. Coming clean. Nat. Clim. Change 5, 93–95.

Johnston, M., Foley, J.A., Holloway, T., Kucharik, C., Monfreda, C., 2009. Resetting global expectations from agricultural biofuels. Environ. Res. Lett. 4 (014004), 9.

Keller, D.P., Feng, E.Y., Oschlies, A., 2014. Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. Nature Commun. 5 (3304). http://dx.doi.org/10.1038/ncomms4304.

Lemmon, J.P., 2015. Reimagine fuel cells. Nature 525, 447–449.

Lienau, P.J., Ross, H., 1996. Final Report: Low-Temperature Resource Assessment Program. Available at 〈http://geoheat.oit.edu/pdf/db7.pdf〉.

Lilliestam, J., Ellenbeck, S., 2011. Energy security and renewable electricity trade—Will Desertec make Europe vulnerable to the 'energy weapon'? Energy Policy 39, 3380–3391.

Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew. Sustain. Energy Rev. 45, 785–807.

Makarieva, A.M., Gorshkov, V.G., Li, B.-L., 2008. Energy budget of the biosphere and civilization: rethinking environmental security of global renewable and non-renewable resources. Ecol. Complex. 5, 281–288.

Moriarty, P., Honnery, D., 2011. Is there an optimum level for renewable energy? Energy Policy 39, 2748–2753.

Moriarty, P., Honnery, D., 2012a. What is the global potential for renewable energy? Renew. Sustain. Energy Rev 16, 244–252.

Moriarty, P., Honnery, D., 2012b. Preparing for a low energy future. Futures 44, 883–892.

Moriarty, P., Wang, S.J., 2015. Assessing global renewable energy forecasts. Energy Procedia 75, 2523–2528. http://dx.doi.org/10.1016/j.egypro.2015.07.256.

Murphy, D.J., Hall, C.A.S., Dale, M., Cleveland, C., 2011. Order from chaos: a preliminary protocol for determining the EROI of fuels. Sustainability 3, 1888–1907. http://dx.doi.org/10.3390/su3101888.

Pickard, W.F., 2014. Smart grids versus the Achilles' Heel of renewable energy: can the needed storage infrastructure be constructed before the fossil fuel runs out? Proc. IEEE 102 (7), 1094–1105.

Powell, T.W.R., Lenton, T.M., 2012. Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. Energy Environ. Sci. 5, 8116–8133.

Schramski, J.R., Gattie, D.K., Brown, J.H., 2015. Human domination of the biosphere: rapid discharge of the earth-space battery foretells the future of humankind. Proc. Natl. Acad. Sci. USA . http://dx.doi.org/10.1073/pnas.1508353112.

Searle, S.Y., Malins, C.J., 2014. Will energy crop yields meet expectations? Biomass Bioenergy 65, 3–12.

Seboldt, W., 2004. Space- and earth-based solar power for the growing energy needs of future generations. Acta Astron. 55, 389–399.

Sheldon, S., Hadian, S., Zik, O., 2015. Beyond carbon: quantifying environmental externalities as energy for hydroelectric and nuclear power. Energy 84, 36–44.

Smallwood, K.S., 2013. Comparing bird and bat fatality-rate estimates among North American wind-energy projects. Wildlife Soc. Bull. 37 (1), 19–33.

Staffell, I., Green, R., 2014. How does wind farm performance decline with age? Renew. Energy 66, 775–786.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223), 1259855 10 pp..

Steinke, F., Wolfrum, P., Hoffmann, C., 2013. Grid vs. storage in a 100% renewable Europe. Renew. Energy 50, 826–832.

Stickler, C.M., Coe, M.T., Costa, M.H., Nepstad, D.C., McGrath, D.G., Dias, L.C.P., 2013. Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales. Proc. Natl. Acad. Sci. USA 110, 9601–9606.

Trainer, T., 2013. Can the world run on renewable energy? A revised negative case. Humanomics 29 (2), 88–104.

Van Hertem, D., Ghandhari, M., 2010. Multi-terminal VSC HVDC for the European supergrid: obstacles. Renew. Sustain. Energy Rev. 14, 3156–3163.

World Energy Council (WEC), 2013. World Energy Resources: 2013 Survey. WEC, London. (Also earlier surveys.).

de Castro, C., Mediavilla, M., Miguel, L.J., Frechoso, F., 2011. Global wind power potential: physical and technological limits. Energy Policy 39, 6677–6682.

de Castro, C., Mediavilla, M., Miguel, L.J., Frechoso, F., 2013. Global solar electric potential: a review of their technical and sustainable limits. Renew. Sustain. Energy Rev. 28, 824–835.

van den Bergh, J., Folke, C., Polasky, S., Scheffer, M., Steffen, W., 2015. What if solar energy becomes really cheap? A thought experiment on environmental problem shifting. Curr. Opin. Environ. Sustain 14, 170–179.