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*Review*

# The limits of renewable energy

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**Abstract:** Planet Earth is simultaneously approaching a number of ecological and resource limits. The resulting uncertainties will heavily impact future energy choices, both the level of primary energy used globally and the shares of fossil, renewable and nuclear fuels in the energy mix. This paper reviews the possible futures for the various types of renewable energy. To be viable, all potential energy sources must be assessed on their energy return on energy invested (energy return). Given that renewable energy RE growth is considered important for sustainability reasons, renewable energy must be assessed on its ecologically sustainable or 'green' energy return, which includes the energy costs of ecosystem maintenance as input energy costs. The green energy return is accordingly much lower than the conventional value, so that ecologically sustainable renewable energy is unlikely to deliver anything near existing global energy use. The paper further argues that such constraints on renewable energy growth rates mean it cannot be a timely response to global climate change. The paper concludes that energy reductions will be essential, mainly in high energy use countries.

**Keywords:** bioenergy; climate change; energy forecasts; geothermal energy; hydropower; renewable energy; solar energy; wind energy; tidal energy

**Abbreviations:** BECCS: bioenergy carbon capture and sequestration; CCC: catastrophic climate change; CCS: carbon capture and sequestration; $CO_2$: carbon dioxide; $CO_2$-e: carbon dioxide equivalent; DAC: direct air capture; EIA: Energy Information Administration; EROI: energy return on energy invested; ESME: ecosystem maintenance energy; EW: enhanced weathering; FF: fossil fuels; GHG: greenhouse gas; IEA: International Energy Agency; IPCC: Intergovernmental Panel on Climate Change; IRENA: International Renewable Energy Agency; LCA: life cycle analysis; NET: negative emission technology; OECD: Organization for Economic Cooperation and Development; RE: renewable energy; USD: US dollar

**Units:** EJ: exajoule ($10^{18}$ joule); GJ: gigajoule ($10^9$ joule); Gt: gigatonne ($10^9$ tonne); Gtoe: gigatonne oil equivalent; GW: gigawatt ($10^{18}$ watt); MJ: megajoule ($10^6$ joule); Mt: megatonne ($10^6$ tonne); MW: megawatt ($10^6$ watt); TW: terawatt ($10^{12}$ watt)

## 1. Introduction

The world faces a variety of biophysical limits; in the latest iteration, the authors of the 'planetary limits' concept list 10 of them [1,2]. For energy use, climate change (CC) is very relevant, and the authors give a limit for $CO_2$, the main greenhouse gas, in the range 350–450 parts per million (ppm), compared with a 2021 value of over 415 ppm [3]. But the other limits are also important, particularly for the various forms of renewable energy (RE). For example, biodiversity integrity, both for land and fresh water, is clearly important for the future of bioenergy and hydropower. Limits for freshwater use and biogeochemical flows (P and N) are likewise relevant for bioenergy.

Not only does the existence of these various limits impact on the prospects for RE, but we are dangerously close to exceeding several of these limits, including biodiversity integrity and CC, as the above values for $CO_2$ ppm demonstrate. Hoegh-Guldberg et al. [4], in their eponymous paper, have stressed 'The human imperative of stabilizing global climate change at 1.5 °C'. They showed that the adverse effects from CC have risen non-linearly with each 0.5 °C global temperature rise. The various Earth limits might also exhibit abrupt change or 'tipping points' [5,6]. Even worse, the various tipping points might act synergistically, lowering the threshold for any one limit [6]. In recognition of this, the terms 'catastrophic climate change' (CCC) and 'climate emergency' are being increasingly used in specialist journals and more generally [7].

Biodiversity loss prevention is just as urgent as CC, and the two problems 'overlap both in their causes and their solutions' [8]. CC can also cause biodiversity and ecosystem services loss [9]. According to a report by Swiss Re [10] 'A fifth of countries worldwide [are] at risk from ecosystem collapse as biodiversity declines […]'. In summary, $CO_2$ emissions are not the only criterion for assessing the environmental impacts of energy use. Just as important, the urgency of ameliorating these various effects means that the *time* taken for RE to become the dominant energy source is also critical in evaluating its effectiveness in preventing CCC.

When we think of future global renewable or overall energy use, several questions come to mind. What will be the global primary energy consumption in, say, 2040 or 2050? At least one researcher, Modis [11] thinks that global (commercial) energy use in 2050 can be predicted between very narrow limits, based on the close fit of a logistic curve to the 1860 to 2017 data. He estimated a 25% rise from 2018–2050, with a 90% probability of falling between 639 EJ (EJ = exajoule = $10^{18}$ joule) and 758 EJ. The coronavirus pandemic, which became global in early 2020, has now shown how unforeseen events can overturn predictions even for only one year ahead, but only time will tell whether the drop in global energy use in 2020 was a temporary blip, or signalled the beginning of a new energy regime.

A second question: what will be the *sources* of this energy—how many EJ of fossil fuels (FF), RE, and nuclear energy? Marchetti [12] has demonstrated that, in the past at least, energy sources replaced each other in a regular manner. Thus, coal accounted for 50% by around 1880, displacing wood, the dominant energy source up until then. Global shares for both coal and oil have now declined, but the share for natural gas (NG) is still rising [13]. Historically, such energy transitions have taken decades [12,14–16], and have occurred either because new energy sources have been discovered in large quantities, or because technical advances have made once largely ignored energy sources (such as wind) viable. As shown by Hansen et al. [17], an increasing number of studies are looking at the prospects for 100% RE systems, either nationally or globally.

Although wood, and then coal, accounted for most energy use at their peak, the same was not true for oil, and is unlikely for nuclear or NG. Further, earlier fuels do not disappear or even decrease in absolute quantity, they just lose some of their share. However, the Marchetti approach may be of little use in forecasting future fuels, since it merely suggests that it may be a mix of solar and fusion energy. Some researchers [see e.g., 18,19] believe that it is at least possible that biomass could once again become a major energy source, with output several times existing levels.

A third question: how will global energy consumption be divided up between the various global regions or individual countries? At present, an enormous disparity in primary energy use per capita exists between countries [20], which is even greater if only commercial energy is counted [13]. This disparity would matter less if future global energy use was unconstrained by either resource availability or adverse environmental effects of energy use [21]. Lu [22] discussed one example of how poverty affects biodiversity: in the Congo basin bush meat is hunted at twice the sustainable rate, with much of this hunting being done to provide basic sustenance.

This review has the following structure. In section 2, the review methodology is briefly addressed, and the bias toward very recent articles for review explained. Section 3 discusses the general questions that must be considered when examining RE, and also briefly reviews how major energy organizations view the future of RE. Sections 4 to 7 discuss in turn hydro; bioenergy; geothermal and ocean energy; and finally, the intermittent energy sources, solar and wind. Section 7 synthesises the data and findings of the review, and suggests that only deep global energy reductions, combined with a more equitable energy use distribution, can give a timely and effective response to the multiple environmental challenges Earth faces.

## 2. Review methodology

Using the Elsevier Scopus database, the number of published papers with the chosen term in either the title, keywords or abstract over the period 1991–2020 is given in Table 1. As can be seen, the numbers of papers on each RE source discussed here is vast, and has risen rapidly over the past decade. It is also evident that the most promising and rapidly growing sources (wind and solar) lead in papers published. (Despite the reasonable criticisms levelled at the term 'renewable energy' [23], for convenience the term is retained in this review.) For a review such as this, which covers the prospects for each of the various RE sources as well as an overall assessment, a selection of the published literature obviously had to be made. The selection made here heavily favoured papers from 2018 onwards, with many published in the years 2020 or 2021, to reflect the change in thinking in the light of the global pandemic which began to affect the global economy early in 2020. In some ways, this review can be considered an update of our 2018 AIMS Energy paper [24], which reviewed the literature up to the end of 2017.

Further, preference was given to recent papers with a *global* emphasis, since biophysical and resource problems (such as CC) tend to be global in scope. (As an example, bats in China are thought to provide a vital link to the coronavirus causing covid-19, now a global problem.) Selected papers from earlier years were sometimes included either to give a sense of how the views (and forecasts) on a given RE source has changed over time, or because no relevant research after 2018 was available.

As well as research papers, the review relied on data sources from energy organizations for global energy statistics, ideally classified by year, region/country, and magnitude for each energy source. To the authors' knowledge, the most reliable sources published periodically in English are:

- BP (*Statistical review of world energy*)
- EIA (*International energy outlook*)
- IEA (*Key energy statistics*)
- IRENA (*Renewable energy statistics*)
- REN 21 (*Global status report*)

Similarly, there are some regularly published *forecasts* (including forecast scenarios) for energy, again usually classified by year, region/country, and energy source. Those relevant to this RE review and discussed briefly in Section 3 (especially Table 3) include those from BP [25], the EIA [26], the IEA [27], as well as from ExxonMobil [28] and OPEC [29]. Also included is the detailed one-off forecast from DNV GL [30].

**Table 1.** Numbers of papers in Elsevier Scopus database by RE type, for selected years.

| RE source | 1991–2000 | 2001–2010 | 2011–2020 |
|---|---|---|---|
| Geothermal energy | 1342 | 3932 | 12,742 |
| Hydropower or hydroelectricity | 1936 | 5446 | 17,078 |
| Solar energy or PV | 15,642 | 47,414 | 173,610 |
| Ocean energy[1] | 3176 | 9373 | 21,343 |
| Bioenergy or biofuel | 1920 | 17,356 | 73,895 |
| Wind energy | 7112 | 27,014 | 85,316 |

[1] includes tidal energy

Source: Elsevier Scopus database

## 3. Renewable energy: general considerations

RE sources in 2019 constitute only 11.4% of all *commercial* primary energy used globally, according to BP data [13]. Even when non-commercial energy was included—nearly all of which is fuel wood and crop/animal wastes burnt in low-income countries—the share in 2018 was only 13.8% [20]. Given both that statistics for wood fuel are not reliable, and that different methodologies are in use for converting renewable electricity to primary energy, the focus here will be mainly on RE electricity. Table 2 shows electricity generation by various RE sources for years 2000 and 2019, along with IEA projections for year 2025. Comparison with Table 1 data indicates that the present dominance of hydro is not reflected in research paper numbers, perhaps because it is a mature technology, with few likely technological advances to come. In contrast, the vast number of solar energy papers recently published reflect recent breakthroughs in PV cell materials. Table 2 also shows that wind and solar electricity outputs are fast-increasing, and look set to overtake hydro in the coming decades. According to the IEA [31]: 'Overall, renewables are set to account for 95% of the net increase in global power capacity through 2025'.

The 2025 IEA projections are short-term forecasts reflecting various national RE incentive plans (and their likely near-term future) and projects in the pipeline. Much more ambitious projections are also available for years up to 2040 or 2050 from the various energy organizations. Table 3 shows the estimates both for total primary energy in 2050 and for RE % share. The upper values for BP and EIA project a higher share for RE than the other forecasters. For BP, at least, the higher values may be the result of their electricity accounting methodology, although the exclusion of non-commercial biomass will act to reduce the RE value [34].

**Table 2.** Electricity generation (in TWh) by various RE sources, 2000 and 2019, and IEA projections for 2025.

| RE source | 2000 TWh | 2019 TWh | 2025 TWh[1] |
|---|---|---|---|
| Hydro | 2652.0 | 4222.2 | 4650 |
| Wind | 31.4 | 1429.6 | 2550 |
| Solar | 1.1 | 724.1 | 1650 |
| Geothermal | 49.5 | 92.8 | |
| Bioenergy | 136.1 | 558.0 | 900 |
| Tidal | 0.5 | 1.0 | |
| All RE | 2870.6 | 7027.7 | 9750 |
| All energy sources | 15,555.3 | 27,004.7 | NA |

[1] Forecast values

Sources: [13,20,31–33].

The ‘business-as-usual scenario’ for BP achieves a 29.1% share by 2050, but their ‘rapid transition’ and ‘net zero’ scenarios see RE’s share growing to 53.1% and 69.1% respectively. These upper values are best viewed as normative scenarios: like the four ‘illustrative model pathways’ in IPCC [35] they give possible energy mixes which would give zero emissions by 2040 or 2050, but without specifying paths by which this result could be feasibly achieved.

The IEA total primary energy forecast for its Sustainable Development Scenario, at 299.3 EJ in 2040, is far lower than that for any other organization. Like BP, EIA also has a Net Zero Emissions by 2050 scenario, with no FF energy at all, but no values for 2040 were given. (Interestingly, non-commercial bioenergy was predicted to decrease significantly). Oei et al. [36] have discussed in detail the shortfalls of present energy modelling—the presumed basis of these forecasts—in the context of 100% RE. The values in Table 3 can be compared with the far larger 1979 forecasts of Haefele [37], who forecast total energy use by 2030 as in the range 826–1303 EJ.

All RE production projects must pass one vital test: the energy produced over the life of the project must exceed the energy needed to manufacture, erect, operate, and finally decommission the energy-producing devices and their necessary infrastructure, such as access roads and transmission lines. For economic viability, this ratio, termed the energy return on energy invested (EROI), has been variously estimated as needing to be in the range 3–11 [38]. But this is not the whole story. Although the various RE sources are promoted as being ecologically sustainable, they, like the other energy sources, can also cause ecological damage over their life cycle. Those for hydroelectricity are well-known, but even wind and solar energy require minerals in short supply for their manufacture [39,40]. Their distribution is also important: China has an effectively monopolistic status ‘in the mining, refining, and technical knowledge for the production of rare earth elements. This has generated conflicts with the European Union, the USA and Japan due to their dependence on these raw materials' [41].

**Table 3.** Energy organization forecasts for global primary energy (EJ) and % RE, 2050.

| Organization | 2050 (EJ) | 2050 RE (%) | Reference |
|---|---|---|---|
| BP | 625–725 | 29.1–68.9 | [25] |
| DNV GL | 571 | 45.0 | [30] |
| EIA[1] | 905 | 27.8 | [26] |
| ExxonMobil[2] | 678 | 17.0 | [28] |
| IEA[2] | 299–525 | 10.1–27.0[3] | [27] |
| OPEC[4] | 757 | 21.4 | [29] |

[1] Base Case only

[2] Data from 2040

[3] Includes nuclear energy

[4] Data from 20404

The mining of these minerals can result in ethical problems; in the DR Congo, for example, the world's leading cobalt producer, children work in the mines [42]. Mining is also often accompanied by serious environmental damage, such as tailings dam failures [43]. Even in high-income countries, the high production of waste such as tailings has become a problem that at the moment does not have concrete solutions in terms of the disposal of this waste. For example, in copper mining, for every ton of copper concentrate obtained, 151 tons of tailings are generated, and in addition, in some cases they are deposited on the seabed, causing environmental damage near the marine coast [44].

RE development can also adversely affect areas that are important for preserving global and local biodiversity [45,46]. Sovacool et al. [47] have given recent global monetary estimates for these 'negative externalities' for electricity production from various RE as well as fossil fuel and nuclear sources, finding a total cost of USD 11.6 trillion for 2018, or 7.2 c/kWh. For RE electricity, the highest mean costs were for bioenergy (5.9 c/kWh) and PV 5.4 c/kWh). The range of values for bioenergy electricity was very large, as it is very location dependent. For hydropower, the mean cost was appreciably less, at 1.76 c/kWh. For all RE sources, the unweighted mean was about 2.7 c/kWh.

The authors have previously argued for the inclusion of these costs in EROI calculations [48,49], by assessing the energy needed to restore ecosystems to their undamaged state. As an illustration, consider emissions of $CO_2$. Several methods are available for dealing with $CO_2$ emissions from FF plants, and a number of studies have provided estimates of the energy costs of carbon sequestration after $CO_2$ capture from FF plant exhaust stacks, direct air capture (DAC), enhanced weathering (EW), or biological carbon sequestration. The cheapest of these methods can serve as an estimate of what the authors have termed the ecosystem maintenance energy (ESME) cost.

Including these energy costs can lead to significant reductions in the ecologically sustainable or *green* value for EROI, here termed EROIg [49]. EROIg includes the energy costs of ecosystem maintenance as input energy costs. The published literature does contain many examples of Life Cycle Analyses (LCAs) for various RE types and some (e.g., [50]) even compare different RE sources. However, attempting to assign energy costs to the environmental damages reported is very difficult. The papers thus merely rank the energy sources on each category, such as GHGs or acidification. Even without considering these ESME costs, Dupont et al. [51] have shown that globally, the gross EROI for all energy is 9.4, and for net EROI, 8.5, values below those usually reported.

The inclusion of ESME costs is particularly important when dynamic energy analysis (DEA) is considered. DEA is relevant when most energy inputs must be made before any energy is produced, as is the case for most RE sources, and when the EROIg is comparatively low, as is likely the case for intermittent renewable sources [52]. Further, EROIg will probably decline as gross RE output rises [38], leading to rising energy input costs for a given net green energy output. Under these circumstances, rapid capacity expansion results in much energy output being diverted to building increased capacity, leading to less energy available to run the non-energy sectors of the economy [38,53]. The only alternatives then are either to use less final energy, or to increase FF production—which of course increases GHG emissions. Cutting energy use in the non-energy sectors may be the only way forward for both climate stability and environmental sustainability in general.

## 4. Hydroelectricity

Hydroelectricity accounted for 4222 TWh, or 15.6% of world electricity production in 2019 [13], and is by far the leading source of renewable electricity. Most estimates of EROI for hydro are much higher than for other RE sources [40], partly because of the long life of hydro projects—up to a century. Another advantage is that hydroelectricity is dispatchable, given that—except for run-of-the-river schemes—gravitational energy is stored in the reservoir behind the dam.

Nevertheless, hydro's future as a leading RE source is in doubt. First, unlike most RE sources, researcher estimates for global hydro technical potential span a comparatively narrow range from around three to four times present output [53–55]. Even this value is probably far too high because of hydro's increasingly well-documented ecological and social impacts. Zarf et al. [56] have discussed the disproportional impact future hydropower development will have on regions of high large-size fish species richness such as South America and South/East Asia. Williams [57] has shown in detail the adverse ecological, social, economic, and political consequences of dam development in the Mekong river basin. A different problem is fresh water evaporation from hydro reservoirs [58].

Hydro dams, like geothermal schemes, can also directly enhance global climate forcing. Dams in tropical regions emit GHGs because of rotting vegetation, and the reservoir surface can also decrease local albedo. Wohlfahrt et al. [59] found, for a globally distributed sample of hydro reservoirs compared with the surrounding landscape that '19% of all investigated hydropower plants required 40 years or more for the negative radiative forcing from the fossil fuel displacement to offset the albedo effect'.

A further uncertainty concerns the impact of on-going climate change on the performance of existing hydro schemes and planning for new ones. All hydro reservoirs lose storage capacity through sedimentation, but any increase in intensive storm frequency in catchments—expected in a warmer climate—will lead to higher soil erosion rates, and thus sedimentation. Hydro output is expected to rise in some regions under continued global warming, but to decrease in others. In colder regions, earlier snowmelt will skew the seasonal distribution of stream flow volumes. In mountainous areas such as the Himalaya-Karakoram system, considered the most important of the so-called 'mountain water towers' [60], glacial melt will increase stream flows for a decade or two. After the glacial ice has largely melted, streamflow will be precipitation-driven, leading to more temporarily skewed river flows. Hydro capacity will likely be adversely affected. All these uncertainties will make it difficult to evaluate new hydro proposals, as crucial parameters will become increasingly uncertain over the coming decades. This uncertainty is far more important than it is for wind or solar energy, where lifetimes are only 20–30 years.

Even without considering the present ecological costs of hydro schemes, there is evidence that the EROI for hydro is declining globally over time. The global ratio of output increase (in TWh) divided by the increase in output power (in GW) has declined over recent decades [13,61]. Since input energy costs will be roughly proportional to GW capacity, this *capacity factor* decline suggests a progressive decline in global hydro EROI. Further, a recent paper found that for two hydro schemes in Ecuador, 'the net environmental performance' was negative: \$0.98/kWh for dam-based hydropower, and \$0.08/kWh for the run-of-river case study [62]. It is thus possible that the high conventional EROI for hydro will not be reflected in hydro EROIg values.

## 5. Bioenergy

Although bioenergy accounted for around 9.3% of global primary energy in 2018 [20], only a small share of this bioenergy is used for modern purposes such as liquid biofuels or electricity generation. Nevertheless, the IPCC [35] and many other energy analysts see a huge role for bioenergy in future in the form of bioenergy with carbon capture and sequestration (BECCS). The IPCC report [35] discussed four 'illustrative model pathways'. Pathways P1-P3 had no, or limited, 1.5 °C overshoot, while P4 had higher overshoot, but, like P1-P3, still achieved zero net $CO_2$ emissions by around year 2050. While all four pathways relied on FF reductions and land use change, P3, and especially P4, also relied heavily on BECCS. Pathway P4 assumes that cumulative CCS would total 1218 Gt $CO_2$ by 2010. Nearly all of this (1191 Gt) would be from BECCS. Rogelj et al. [19] have suggested that RE could provide about 1000 EJ of primary energy in year 2100, of which 400 EJ would come from bioenergy with CCS, with 300 EJ by 2050. These values should be compared with the 1900 EJ energy equivalent of the entire terrestrial Net Primary Production of all plant matter [63].

Bioenergy is very different from most other RE sources in that it is a solid fuel and so can be stored. It can also be converted into liquid or gaseous fuels. Bioenergy can even be transported over long distances—wood pellets are exported to Europe as a power station fuel, just like fossil fuels. Unlike oil or gas, it is widely available in all inhabited continents. Further, no technological breakthroughs are needed for its widespread implementation.

But bioenergy is different from other RE sources in another way: unlike wind or solar, biomass for bioenergy faces increasing competition from other uses for biomass. The global population is not expected to peak before the year 2100, when the UN mean estimate is just under 11 billion [64]; *ceteris paribus*, global demand for food (and fiber) will rise in step. Satisfying the food needs for all the world's people is an ethical imperative. However, the use of biomass for materials, including construction timber, should also be placed ahead of biomass for bioenergy, because, for a given mass of biomass, it leads to greater reductions in $CO_2$ emissions [63]. The competition from other uses means that it is not possible to give a value for its technical potential, even assuming a given EROIg cut-off value. Stenzel et al. [65] have stressed another aspect of this competition: given the lack of rain-fed land, irrigation is likely needed for greatly expanded bioenergy crops, further lowering EROI—and increasing global water stress.

Bioenergy is regarded not only as a RE source, but also a key component in climate mitigation, because it is assumed that replanting and growth of biomass will fully offset the $CO_2$ emissions from bioenergy combustion. Sterman et al. [66] have, however, argued that bioenergy used for electricity production could exacerbate $CO_2$ emissions compared to the coal it displaces, at least until year 2100. As they state: 'The result arises because (1) wood generates more $CO_2$/kWh than coal, creating an initial carbon debt; (2) regrowth of harvested land can remove $CO_2$ from the atmosphere, but takes time and is not certain; and (3) until the carbon debt is repaid, atmospheric $CO_2$ is higher, increasing radiative forcing and worsening climate change long after the initial carbon debt is repaid by new growth'.

Biomass is not subject to the problem facing rapid expansion of other RE sources. The upfront energy costs are a smaller share than is the case for wind or solar, and operating energy costs are a larger share of total input energy over the plant's lifetime. *Ceteris paribus*, expanding biomass output could be faster than it is for other RE sources. But, as shown above, when climate mitigation is considered, the time aspect is just as important as for intermittent renewable energy. To avoid a climate emergency, climate mitigation needs to be rapidly implemented in a decade or so. Waiting until the second half of this century for climate benefits will not be a solution.

## 6. Renewable energy from non-solar sources

The minor RE sources considered here include geothermal energy and tidal energy. These two sources together in 2019 only produced 652 TWh of electricity, or 2.45% of the global total. A key advantage of both is that they are climate independent and predictable, unlike wind and solar. For geothermal electricity, Huttrer [67] gave installed capacity at 15.95 GWe in 2020, producing 95.1 TWh, a small increase over 2019 (Table 2). The three leading countries for geothermal electricity are the US, Indonesia and the Philippines [13]. The global technical potential for electricity production from conventional geothermal systems is seen as minor, with most estimates about 1–3 EJ [24]. However, very high technical potential is claimed for so-called Enhanced Geothermal Systems (EGS). As summarized by Aghahosseini and Breyer [68]: 'The findings indicate that around 4600 GWe of EGS capacity can be built at a cost of 50 €/MWh or lower'. At 50 to 150 €/MWh, this figure increased tenfold. However, the sustainable potential was much lower, estimated at 256 GWe in 2050, or 16 times the 2020 installed geothermal capacity. The 256 GWe value is still less than 25% of installed wind/solar capacity in 2019 [13].

Another optimistic view is espoused by van der Zwaan and Dalla Longa [69], who projected that, under their assumptions, geothermal electricity production would grow to around 800–1300 TWh/yr by 2050, 'depending on assumptions regarding climate ambition and cost reductions for enhanced geothermal resource systems'.

The environmental damages arising from geothermal energy production include various harmful emissions which can impact groundwater quality and human health, seismic tremors, and land subsidence [70,71]. Chen et al. [70] have cautioned against using GHG reductions as the sole yardstick for environmental assessment for geothermal energy. Nevertheless, considering only $CO_2$ emissions, Fridriksson et al. [72] have shown that full fuel cycle emissions (measured as gm $CO_2$/kWh) can overlap with those from FF power plants.

In addition to electricity from higher temperature resources, geothermal energy can also provide low temperature heat for direct use. In 2019, installed capacity was 107.7 GW thermal, producing 1.0 EJ heat energy [73]. The potential for direct use appears vast, given the amount of heat stored in the upper few kilometres of Earth. However, the *exploitable* potential is only a very small fraction of this amount, for two reasons. First, too great an annual withdrawal risks depleting the heat source. Global geothermal terrestrial heat release is only 280 EJ annually, yet annual geothermal heat potential estimates are as high as 300,000 EJ. Evidently, such heat releases could not be sustained for long [24]. For direct heat, mainly for residential and commercial applications, one otherwise optimistic forecast [69] foresaw only about 3300–3800 TWh/yr (or roughly 12–14 EJ) in 2050. Second, low grade heat can only be carried a few km before heat losses make it uneconomic as a thermal energy source. Further, regions of good geothermal heat potential, which tend to be near tectonic plate boundaries, are often sparsely inhabited, further restricting its use.

At present, the only ocean source being utilized is tidal energy, a technology that is at least 1000 years old [74], and possibly much older. Tidal energy in 2019 had a negligible total installed capacity of only 0.53 GW and output of a little over one TWh, compared with 623 GW for wind [13]. No forecasting group expect ocean energy to be more than a very marginal energy source, even in 2050. The IEA have projected global capacity rising to around 15 TWh by 2030 [75]. Even so, its share of global electricity would be negligible. Given the serious environmental concerns facing new projects Van Haren [76] estimates a maximum theoretical potential of 100 GW, and the practical exploitable potential much lower.

## 7. Intermittent renewable energy

In terms of Earth energy flows, solar and wind energy dwarf all other RE sources, at estimated annual flows of 3,900,000 EJ and 28,400 EJ respectively [53]. If RE is to become the dominant energy source, the intermittent RE sources, solar, wind, and perhaps wave and ocean current energy, and ocean thermal energy conversion (OTEC), will have to supply most energy [48]. In 2019, no energy was generated by the latter three sources, although field tests on prototypes stretch back a century or more; they will not be considered further. For energy levels at or above the present, wind and solar output must increase by 1–2 orders of magnitude, given that other RE sources can only supply minor amounts. In support of this argument, the IEA [31] anticipate wind and solar combined to account for about 90% of RE electricity capacity added in their 'main case', even in the near-term 2022–2025 period. The IEA also predict that installed wind and PV capacity together will surpass coal generating capacity by 2024 [31].

It follows that for a reliable electricity supply, and also to meet non-electrical energy needs, conversion of intermittently-generated electricity into some energy form that can be stored, such as hydrogen, will be necessary [38]. The energy output will be lowered because of energy losses through conversion and storage, while the need for conversion/storage equipment will raise input energy costs. The EROIg of the energy system will accordingly be further lowered. To the extent that FFs have higher conventional EROI values than RE sources, an energy subsidy to RE is involved, which will decline to zero as FFs are phased out [38].

Since solar and wind presently have such a low share of global electricity (Table 2), let alone total energy, it is easy to overlook some input energy costs which will become more important in future. RE sources can only be considered 'technically feasible' as well as ecologically sustainable if their EROIg value exceeds unity by some margin.

Solar and wind growth are subject to two constraints peculiar to intermittent sources of electricity. First, Blazquez et al. [77] have pointed to a paradox for intermittent RE electricity: '[…] the incompatibility between electricity liberalization and renewable policy, regardless of the country, location or renewable technologies. The Paradox holds as long as market clear prices with short term marginal costs, and renewable technology's marginal cost is close to zero and not dispatchable’. The authors do suggest several ways out of this paradox, including subsidies to FF generation and even reversing the move to 100% RE electricity.

Second, intermittent RE encounters a further problem, in that transmission capacity will need to be greatly increased. Not only are new transmission lines necessary to service, for example, offshore wind farms, but line capacity for a given annual energy flow must be much higher that for the same energy flow from fossil or nuclear plants. This follows from the much lower capacity factor for wind or solar farms compared with the latter electricity plants. DNV GL [30] accordingly foresaw a 170% expansion will be needed in global grid capacity by 2050. The IEA [31] regard this transmission line capacity problem as hindering a rapid rise in RE capacity in a number of regions.

Solar and wind energy conversion devices also require a variety of exotic materials for their construction—in addition to large quantities of copper, which is also needed for transmission lines. Many of these minerals are mined in countries with minimal environmental standards, so that their monetary and energy costs are a poor indicator of their actual costs.

The remainder of this section considers in turn the special circumstances of solar, then wind energy.

### *7.1. Solar energy*

Since the first modern PV cells were developed in 1954, great progress has been made in both reducing monetary and energy costs for cell manufacture, and in insolation conversion efficiency [78]. PV technology dominates the solar energy market, with nearly 98% of the total solar electricity output in 2018 [32]. De Castro and Capellán-Pérez [79] have shown that the performance of installed concentrated solar power (CSP) plants falls well below that forecast. For PV cells, Tawalbeh et al. [80] have stressed that the technical advances in efficiency may be at the expense of adverse environment effects.

In general, the energy return is higher for regions with higher annual insolation levels. But it is not enough for solar energy farms to have good insolation levels—and available land, which can be a problem for Europe and Japan. Dhar et al. [81] have shown that both PV arrays and CSP plants can have high demands for fresh water. This water is needed to clean the surfaces of both PV cells and CSP reflector mirrors to avoid output deterioration. But they noted that the largest water use is often to supress dust from the ground surface; this use will evidently be very necessary in hot arid areas. Dust deposition can lead to serious deterioration of PV cell performance [82].

Additional fresh water is needed if solar farms are located in regions very remote from load centres, such as the ‘Desertec’ project and other proposals to utilize the solar energy resources of North Africa and the Middle East for the energy needs of those regions and Europe [83]. The desert area of northern Chile is also a region of very high insolation [84]. If the solar electricity in these high insolation regions was converted to hydrogen, fresh water would also be needed for hydrolysis.

### *7.2. Wind energy*

As for solar energy, wind energy is already being deployed in many countries on all continents, with the leading producers being China and the US [13]. Also, like solar energy, wind energy has no direct GHG emissions. Wind energy is also land-sparing compared to other RE sources, in that agriculture and grazing can coexist with wind turbines. Nevertheless, wind energy faces a number of environmental and other challenges [85,86], which have resulted in citizen opposition to wind farms in both high- and low-income countries. To the extent that local opposition is environmentally-based, it pits local environmental values against global (climate change mitigation) values [87]. However, this local opposition may also be partly based on the decline in house prices near wind turbines. Because of this and other economic factors, Dorrell and Lee [88] have even argued that for many wind power projects, the economic costs can exceed the benefits.

Bird deaths from turbine collisions may be minor compared to bird deaths from collisions with buildings and road vehicles, or from domestic pets. Nevertheless, they are large: Smallwood and Bell [89] estimated that for the US alone in 2012, between 234,000 and 573,000 birds were killed by turbines—as well as 600,000 to 888,000 bats. But they concluded that many bat deaths, at least, could be avoided: 'Because the migration season is relatively brief and corresponds with reduced wind speeds, a seasonal curtailment strategy would greatly reduce bat fatalities without giving up a large proportion of a wind project's annual energy generation'. This reduced energy output is a good illustration of an ESME cost. Both birds and bats provide valuable pollination services [8].

Abbasi et al. [90] have even argued that wind energy can affect climate: 'large-scale windfarms with tall wind turbines can have an influence on the weather, possibly on climate, due to the combined effects of the wind velocity deficit they create, changes in the atmospheric turbulence pattern they cause, and landscape roughness they enhance'. Miller and Keith [91] have argued that if all present US electricity demand of 0.5 TW was generated by wind power, the 'continental US surface temperatures' would be warmed by 0.24 °C. As an illustration of the effects of large turbines, slower wind speeds and increased turbulence have been measured 'extending 50–75 km downwind of Germany's offshore wind plants' [92]. For this reason, Veers [93] has advocated that a systems approach be adopted for both tower design and turbine layout in an era of tall turbine structures.

## 8. Discussion and conclusions

It is evident from the preceding sections that although RE sources in general are promoted for their low environmental costs, and are often termed zero-carbon emissions fuels, they can cause substantial environmental harms, either directly, or indirectly from the mining and manufacture of input materials/components. The direct effects on climate for the main RE sources, given in sections 4 through 7, are summarized in Table 4 (where a tick represents a direct effect—even if minor, and a cross represents no direct effect.) No attempt is made to indicate the relative severity of the effects, which in any case will vary from installation to installation.

**Table 4.** Direct climate change effects of various RE sources.

| RE source | Direct $CO_2$ | Other GHGs | Albedo change | Temp Rise |
|---|---|---|---|---|
| Hydro | ✓ | ✓ | ✓ | ✕ |
| Wind | ✕ | ✕ | ✕ | ✓ |
| Solar | ✕ | ✕ | ✕ | ✓ |
| Geothermal | ✓ | ✓ | ✕ | ✕ |
| Bioenergy | ✓ | ✓ | ✓ | ✕ |

It follows that rather than FFs and RE sources being considered as polar opposites, they should be seen as lying on a continuum, just as FFs themselves do. In terms of grams of $CO_2$ or other pollutants per MJ, there is much overlap between the different energy sources. Although for convenience, typical values are often given for the EROI for each RE type, these values too can overlap, as each RE source will have a range of EROI values, depending on such parameters as resource quality (eg, insolation level for solar energy) and distance to load centres. EROI values will also change over time as the most suitable sites are progressively utilized.

Increasing RE in the energy mix is only one possible way of combatting CC. Others include a greater share of NG in the remaining FF mix, increased use of nuclear energy, energy reductions through unprecedented energy efficiency improvements, CCS for large FF plants, and carbon dioxide removal (CDR) approaches [7,21]. One popular suggestion is for reforestation or afforestation. Although this does withdraw $CO_2$ from the atmosphere, growing forests have other CC effects that can lower its mitigation impact [94]. On a different note, Anderegg et al. [95] have warned that: 'Climate-driven risks may fundamentally compromise forest carbon stocks and sinks in the 21st century'. A number of authors have argued that negative emission technologies (NETs) are an essential part of effectively combatting CC [e.g., 96,97]. Particularly in the 2018 IPCC report [35], NETs in the form of bioenergy combined with CCS (BECCS) has been seen as a vital part of response to the $CO_2$ emissions of FFs.

Another proposed solution is geoengineering, especially in the form of solar radiation management (SRM), which involves the placement of millions of tonnes of aerosol in the lower stratosphere to reflect insolation and thus increase Earth's albedo. Although SRM could be implemented rapidly and appears far cheaper than other CC mitigation approaches, there are major uncertainties regarding effectiveness, known and unknown ecological side effects and political acceptability [7,98]. It may even have adverse effects on biodiversity if terminated too abruptly [99]. There are also doubts as to whether it will work as planned—at least at high $CO_2$ levels [100].

If a variety of approaches are used, it might appear that each one would only need to be a minor part of the solution. However, this multi-pronged approach may be less effective than envisaged, because of the conflicts that can occur between these approaches, both for climate change mitigation, and for global environmental sustainability in general. As Papadimitriou et al. [101] have stressed in the context of adaptation, trade-offs are inevitable, given the existence of conflicting goals. For RE, the main conflicts are:

- SRM, because it produces more diffuse light, will lower the output from focused solar energy devices, and will reduce the effectiveness of passive solar energy systems. If SRM also reduces precipitation in some regions, output from hydropower and bioenergy plantations could fall.
- Implementation of tech fixes such as SRM or CDR could reduce incentives for the shift to low-carbon sources, or for energy conservation.
- Afforestation, reforestation, or bioenergy plantations in northern latitudes will reduce the surface albedo, thus tending to offset the mitigation effect of carbon drawdown from tree growth in those regions [102].
- RE resources themselves can have significant adverse climate change and general environmental consequences [48,49]. Both hydro and geothermal energy can even directly emit significant quantities of GHGs (see Table 4).
- Deep energy reductions, such as those in the IEA Sustainable Development Scenario, will lead to spare FF capacity in high-energy countries, which will lower both incentives and need for new

RE energy infrastructure. As Tong et al. [103] have shown, the 'committed emissions' from existing FF plants, if they are allowed to operate until the end of their useful lives, will push the planet well beyond the 1.5 ℃ limit. Although most OECD coal plants are near retirement age, the same is not true of NG plants.

In conclusion, it is doubtful if RE can ever provide for even current levels of primary energy use, especially if RE is to help avoid the many biophysical limits the planet is rapidly approaching. As discussed in Section 3, EROIg for RE will likely fall if RE becomes the dominant energy source. For a given level of net green output, progressively greater gross RE output would then be needed. When the limited time frame for action to avoid crossing biophysical limits is also factored in, it is clear that RE can no longer be considered a major means of avoiding CCC. Instead, primary energy reductions, particularly in high energy-use countries, appears to be the main remaining option.

## Conflict of interest

The authors declare that there are no conflicts of interest related to this study.

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