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Review

Energy policy and economics under climate change

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Abstract: Most anthropogenic greenhouse gas emissions are the result of the combustion of fossil fuels. Proposals for mitigating climate change thus include various carbon dioxide removal technologies, replacement of fossil fuels by non-carbon alternatives (renewable and nuclear energy), and reduction in energy use overall by improving energy efficiency. We argue here that deep controversy surrounds the efficacy and likely costs of all these technical fix proposals. Optimistic conclusions are often drawn for these technical solutions partly because many of the analyses do not follow an Earth Systems Science approach. Instead, we argue that in future solutions based on non-technical solutions will need to be a key approach for mitigating climate change in the short time frame we have left.

Keywords: carbon dioxide removal; climate mitigation; fossil fuels; energy costs; energy policy; energy return; Earth System Science; nuclear energy; precautionary principle; renewable energy; uncertainty

Abbreviations: BECCS: bioenergy carbon capture and sequestration; CCS: carbon capture and sequestration; CDR: Carbon dioxide removal; CO_2: carbon dioxide; CO_2-e: carbon dioxide equivalent; EJ: exajoule = 10^{18} joule; EROEI: energy return on energy invested; ESS: Earth System Science; GHG: greenhouse gas; GJ: gigajoule = 10^9 joule; Gt: gigatonne = 10^9 tonne; HANPP: human appropriation of Net Primary Production; IEA: International Energy Agency; IPCC: Intergovernmental Panel on Climate Change; LCA: Life Cycle Analysis; MJ: megajoule = 10^6 joule; NPP: Net Primary Production; OPEC: Organization of the Petroleum Exporting Countries; SCC: social cost of carbon

1. Introduction

The December 2015 Paris agreement committed the world's nations to limiting global temperature increases above the pre-industrial value to well below 2.0 °C, with an aspirational target of 1.5 °C increase. However, based on research reported in *New Scientist* [1], the world could breach the 1.5 °C limit as early as 2026. Anderson [2] has similarly argued that even 2 °C will be very difficult to achieve. But according to an analysis by climate scientists Xu and Ramanathan [3], any rise above 1.5 °C should be classed as "dangerous"—and increases above 3 °C as "catastrophic". A 2017 report [4] discussed the likely adverse consequences: for every 1.0 °C global temperature rise, wheat and rice yields are expected to decline by 6% and 10% respectively, and by 2050, a billion people, additional to the 125 million in 2016, will be exposed to deadly heat waves. Recent findings do not suggest that governments are taking climate change seriously, despite the rhetoric: according to Peters and his colleagues [5], annual carbon dioxide (CO_2) emissions from energy sources will rise by a projected 2% in 2017 to 37 gigatonnes (Gt), after no net growth from 2014 to 2016. Total CO_2 emissions, including net deforestation, are likely to be 41 Gt. The IEA, in their latest *World Energy Outlook* [6] have projected that global fossil fuel consumption will continue to grow until 2040, fuelled by population and economic growth.

Very clearly, we are entering uncharted and dangerous climate territory, and deep reductions in anthropogenic greenhouse gases (GHGs) are urgently needed. Since most of these emissions are related to fossil fuel energy production and combustion, the obvious question is: "What is the best way to greatly reduce energy GHGs, especially the dominant and long-lived one, CO_2?"

A key problem for energy policy is that the field of energy research relevant to climate change mitigation is beset by pervasive uncertainty. There are profound disagreements among reputable researchers on almost all topics of importance for making energy policy decisions. This disagreement is in marked contrast to the question of the reality of anthropogenic climate change itself, about which there is an overwhelming consensus among climate scientists [7]. An incomplete list of energy—related controversies would include the items presented in Table 1.

Table 1. Key energy controversies, and reference papers giving higher or lower values.

Energy controversy	Higher values	Lower values
Recoverable reserves for fossil fuels, especially oil	[8]	[9,10]
The technical potential for the various renewable energy (RE) sources	[8,11–14]	[15–24]
The Energy Return on Energy Invested (EROEI) and relative climate change benefits for the various RE sources	[25]	[26–30]
The time frames needed for these alternative fuels to replace fossil fuels	[31–35]	[36]
The likely monetary costs of these alternative fuels, compared with fossil fuels	[19,37]	[11,14]
Estimates of the social cost of carbon (SCC)	[38,39]	[40]
The technical potential for both biological CO_2 reductions and for various carbon capture and mechanical sequestration (CCS) methods, including from bioenergy (BECCS)	[41,42]	[43–46]
Costs for both biological CO_2 reductions and for various CCS methods, including BECCS	[47,48]	[41,42]

One way that can at least partly help resolve many of these controversies is to use an Earth System Science (ESS) approach [49]. In the context of climate change, this approach attempts to understand how all elements of the Earth system—atmosphere, biosphere, cryosphere, hydrosphere, biosphere, geosphere—interact to produce climate changes in the short- and long-term. More ambitiously, it also attempts to include human actions and responses into ESS modelling. In energy research and analysis, a parallel, if more restricted, approach is Life Cycle Analysis (LCA), which tries to document, for example, all the environmental and resource consequences of introducing a new energy technology compared with existing ones. Accordingly, this review mainly discusses papers with a global rather than a national or regional focus. Climate change is a global problem, and too often what looks like a solution at a national level merely displaces the problem elsewhere. As an example, the reduced energy-related CO_2 emissions in some OECD countries are largely the result of energy-intensive industry being shifted to Asia, particularly China.

This review is necessarily selective: entering in just the phrase “energy policy” into Google Scholar turned up nearly 800,000 hits. We thus focus on recent papers, since these in general will be based on the most up-to-date cost estimates, policy decisions (such as US withdrawal from the Paris climate agreement), and energy technology advances.

The rest of this review examines in turn the future prospects for each of the three competing energy sources: Fossil fuels, nuclear energy, and RE in its various forms. Each section examines the controversies given in Table 1, and attempts to reduce the areas of uncertainty. In the final, Discussion section, the implications of the preceding analysis are drawn out for energy policy, teasing out definite policy conclusions for global energy in a climate-constrained—and more generally, environment- and resource-constrained—world. Given that few of the controversies can be resolved with certainty, we urge an approach that is best able to deal with these. Accordingly, we advocate policies which rely less on technical fixes such as alternative fuels replacing fossil fuels and more on non-technical approaches based on re-examining the question of whether OECD countries in particular need to use so much energy at all.

2. Energy future: Fossil fuels

In attempting to forecast future energy, we need to look at present global energy production, given the decades it takes to change the energy production and distribution system [32]. Globally, fossil fuels still dominate primary energy, as they have for over a century. Although their share of electricity production is somewhat less, fossil fuels still generate nearly two-thirds of global electricity output (Table 2) (Electricity rather than primary energy data is presented here because of uncertainties regarding global bioenergy use, and conflicting methods for accounting for direct electricity production from, for example, hydro or wind [50]).

The table shows that despite rising concern about climate change, fossil fuels’ share of electricity production actually increased slightly over the period 1985–2016. Both hydro and nuclear power lost share over the period, with non-hydro RE, especially wind and solar, gaining share. However, the global figures conceal vast differences between various countries. Some countries still generate all electricity from fossil fuels (e.g. Saudi Arabia and other Gulf states); some are already close to 100% from renewable energy (Iceland, Norway); in a few others nuclear power presently dominates electricity production (Belgium, France) [51].

As already mentioned, fossil fuels are the backbone of our primary energy system, with a share in 2015 of 81.4%, according to the IEA [52]. Most researchers believe that fossil fuel depletion is unlikely to produce dramatic cuts in overall fossil fuel use, because unconventional resources of these fuels appear to be large [8,51]. Nevertheless, some have argued that the coming years will see increasing constraints on annual fossil fuel production [9,10]. Although EROEI has fallen for fossil fuels, Weißbach et al. [27] have argued their EROEIs are an order of magnitude higher than alternative energy sources. The energy return on energy invested (EROEI) is the ratio of energy output from a device over its service life compared to the energy inputs for construction, maintenance and dismantling at the end of its life (Non-conventional fossil fuels such as oil sands and shale gas have much lower EROEIs than conventional sources, implying a higher level of GHG emissions per unit of delivered fuel than conventional fossil fuels. Nevertheless, their exploitation requires few changes to the large and expensive existing energy infrastructure, and they do not need energy storage. But they are costly to produce; Shell oil is withdrawing its investment in the Alberta oil sands, and has written off $2.5 billion in its quest for Arctic oil [53]. So it is still possible that, even given unconventional oil resources, production could soon plateau and then decline [9,18]). But if governments make climate change a key concern, peak oil consumption may occur much earlier than geologically or economically constrained peak oil production.

Table 2. Global electricity (in TWh) energy mix, 1985 and 2016.

Energy source	1985 Output (TWh)	1985 Output (%)	2016 Output (TWh)	2016 Output (%)
Fossil fuels	6352	64.4	16322	65.8
Nuclear	1482	15.0	2617	10.5
Hydro	1979	20.1	4023	16.2
Other renewables	53	0.5	1854	7.5
All sources	9866	100	24816	100

Source: [51].

2.1. Carbon dioxide removal

Carbon dioxide removal (CDR) has been proposed as a means of continuing fossil fuel use while limiting CO_2 emissions to the atmosphere. It can take two forms: biological or mechanical. Biological carbon removal would draw down CO_2 from the atmosphere by increasing carbon fixation in soils and biomass, especially forests. As with other proposed solutions to the climate change problem, its efficacy is strongly contested. On the optimistic side, Griscom et al. [42] have argued that such "natural climate solutions", even "when constrained by food security, fiber security, and biodiversity conservation" can make a major contribution. They estimated that such carbon sequestration "can provide 37% of cost-effective CO_2 mitigation needed through 2030", or 23.8 Gt of CO_2-e, assuming that carbon is taxed globally at above $US100 per tonne CO_2 by year 2030.

Other researchers, however, have doubts about biological sequestration as a major approach for carbon mitigation [43,45]. Smith and Torn [43] have examined the ecological consequences of carbon removal by using afforestation and bioenergy carbon capture and sequestration (BECCS), and concluded that even if limited to 1 Gt C/year (or 3.66 Gt CO_2/year), "either strategy represents a major perturbation to land, water, nitrogen, and phosphorous stocks and flows". From a very different, ESS, perspective, Keller and colleagues [44] have cautioned that forests in boreal areas (and such forests are set to expand naturally as temperatures rise) will decrease the albedo (the share of insolation that is reflected directly back into space) and thus promote local warming, offsetting the climate benefit of increased carbon fixation.

The second approach is to use mechanical means to either capture CO_2 emitted from large sources such as power stations using amine solutions (termed carbon sequestration and storage (CCS)), or to capture it directly from the air, by passing ambient air over a sorbent. In both cases the sorbent is regenerated to use again [47]. Also, in either case the collected CO_2 would then need to be compressed, transported, and stored deep underground, perhaps in saline acquifers, or in disused oil and gas fields. Because of the low concentration of CO_2 in ambient air (0.04%) air capture is much more energy intensive than capturing CO_2 from power station exhaust streams, where CO_2 concentration is closer to 10%. An alternative approach to air capture would be to mine, crush, and finely grind minerals such as olivine to greatly increase their surface area for CO_2 absorption [54]. The environmental effects, however, could be severe.

In a *New Scientist* article, Marshall [41] has published a table giving both the potential for the various CDR methods—both biological and mechanical—as well as summary cost estimate ranges for each method. The data suggest that global CDR—mainly in the form of air capture and BECCS—could not only capture 10–20 Gt of CO_2 annually, but could do so at costs possibly as low as US$10–50 per tonne CO_2. On the other hand, a study from an American Physical Society panel [47] reported that for air capture: "With optimistic assumptions about some important technical parameters, the cost of this system is estimated to be of the order of $600 or more per metric ton of CO_2". Even the generally optimistic paper by Grissom et al. [42] assumed a US$100 per tonne CO_2 carbon tax would be needed by 2030. Honegger and Reiner [48] further point out that in addition to high costs, negative emission technologies offer few benefits apart from emissions reduction.

CDR by any method, including biological carbon removal and mechanical CCS, is more acceptable to the fossil fuel industry and its supporters than large-scale reductions in fossil fuel energy use. Globally agreed limits on CO_2 emissions, such as that emerging from the climate meeting in Paris in late 2015, are seen as a key factor that could encourage its introduction. But CCS, first proposed over two decades ago, presently only sequesters around 40 million tonnes of CO_2 annually, whereas several billion tonnes annually are needed for CCS to be a significant carbon reduction method. Furthermore, interest in mechanical CDR appears to be waning. After a spurt in investment in pilot plants and R & D in the early years of this decade, little expenditure has occurred globally since 2013 [55]. And if the decarbonisation of electricity production were to proceed at a more rapid pace, an ever-shrinking tonnage of CO_2 would be annually available for CCS.

The problems facing mechanical carbon sequestration are thus several-fold. It is energy intensive, particularly air capture, is likely expensive, and would take decades to implement on a large scale. The annual rate at which CO_2 can be safely sequestered may be small compared with projected year 2017 CO_2 production from fossil fuels of 37 Gt [5], even if global storage capacity is high. Above all, studies which have modelled CO_2 underground storage on the huge scale needed found over-pressures extending over tens of thousands of km^2 [56]. Both pre-existing seismic activity and that induced by the change in effective pressures could compromise the integrity of storage, allowing CO_2 to intrude into potable water aquifers and even to the surface [46,49]. Elliot and Celia [57] have pointed out another problem: There will be substantial overlap between the sedimentary basins needed for carbon sequestration and those containing tight natural gas which can only be recovered by fracking. Fracked basins are not suitable for carbon storage. Overall, these difficulties, and the resulting legal problems and citizen opposition to large-scale projects would seem to largely rule out this expensive method for carbon mitigation in the coming decades.

2.2. Fossil fuel costs and subsidies

Although all energy sources are presently subsidised to some extent, subsidies for fossil fuels dominate [18]. According to the World Bank, in 2015, the total subsidy to fossil fuels amounted to US$5.3 trillion. About 20% of this total was accounted for by subsidies to consumers; the remainder was in the form of negative externalities, particularly for GHG emissions and air pollution [58]. These externalities are subject to large uncertainties, but their values for GHG emissions could be far greater, given that estimates for the social cost of carbon (SCC) could be very high: Ackerman and Stanton [38] have suggested values could rise to as high as US$1500 per tonne CO_2 by 2050, although Nordhaus has calculated far lower values [40].

One way of reducing the climate change externality associated with fossil fuel combustion is to impose a tax on the carbon content of such fuels. To be most effective in reducing carbon emissions, such a tax should be imposed in all countries, to avoid an unfair trade advantage for countries either not imposing, or having a lower carbon tax than other countries. The latest Intergovernmental Panel on Climate Change (IPCC) report [8] considered four scenarios, or Representative Concentration Pathways (RCPs): 2.6, 4.5, 6.0 and 8.5. The numbers (with units of W/m^2) refer to the “approximate total radiative forcing in year 2100 relative to 1750” [12]. To achieve the carbon reductions needed by RCP 2.6, the only one of the four scenarios that could ensure climate stability before year 2100, van Vuuren and colleagues [12] estimated that by 2050 a carbon tax would need to rise steadily to $US600 per tonne carbon (or US$160/tonne CO_2) and thereafter be maintained at around the $US700–900 range. Yet today, only a very small share of global emissions are covered by carbon taxes or emissions trading schemes, and prices are very low compared to what is needed [8].

Table 3 shows how energy use and energy-related CO_2 emissions (both on a per capita basis) vary with energy costs, as reflected in premium petrol and domestic electricity costs for various high income OECD countries. It is clear that the US, with its much lower energy prices, has correspondingly much higher energy use and CO_2 emissions per capita than the other OECD countries listed. This suggests that carbon taxes would be effective in cutting energy use and its related CO_2 emissions, and such taxes are supported by the IPCC [8]. Baranzini et al. [59] have discussed seven reasons to support such carbon pricing. Nevertheless, high carbon taxes as presently conceived would increase inequality. As Eisenstein [60] has stressed, a minority of the world’s population—many living in low average emission countries—are responsible for the bulk of global emissions. High carbon taxes could make it difficult for very low emitters to improve their living standard.

Table 3. Energy prices, energy use and CO_2 per capita for various OECD countries.

Country	Gasoline price (2017 $US/litre)	Domestic elec price (2017 $US/kWh)	Energy (2016 GJ/capita)	CO_2 (2016 tonne CO_2/capita)
France	1.491	0.183	152.6	4.88
Germany	1.475	0.330	164.8	9.29
Japan	1.158	0.222	145.9	9.32

Continued

Country	Gasoline price (2017 $US/litre)	Domestic elec price (2017 $US/kWh)	Energy (2016 GJ/capita)	CO_2 (2016 tonne CO_2/capita)
Sweden	1.572	0.174	222.2	4.99
UK	1.479	0.208	119.7	6.17
US	0.683	0.125	295.4	16.61

Sources: [51,52,61].

2.3. Reduced fossil fuel energy use: Energy efficiency and conservation

We have argued that CCS is unlikely to be important for climate change mitigation any time soon. A high carbon tax would evidently help CCS overcome its higher costs compared with fossil fuel use without CCS, but CCS would then need to compete against other mitigation alternatives which would also benefit from a carbon tax. Here we discuss energy efficiency and (very briefly) conservation; non-carbon energy sources are discussed in the following two sections.

Carbon avoidance methods can be ranked in terms of their cost per tonne of carbon avoided. When this is done various energy efficiency and conservation measures are found to be among the cheapest, and could allow much carbon reduction to be achieved at negative cost [62]. Further, the potential for energy and consequent carbon reductions appears to be very large. Cullen et al. [63] concluded that “73% of global energy use could be saved by practically achievable design changes” to end-use devices such as space heating/cooling systems and vehicles. Further energy savings could be made by improving power station efficiencies. Noted energy researcher Amory Lovins has coined the term “negawatts” to describe the energy freed up for use elsewhere by energy efficiency improvements [62].

However, in a detailed study of the possibilities of the EU achieving a 60% reduction in transport GHG emissions over the 1990 values by 2050, Dray et al. [64] estimated that an annual improvement of only 1.0% was possible for new passenger vehicles and light trucks. They concluded that an overall 60% reduction in all EU transport would be difficult to achieve “due primarily to limitations in biofuel production capacity and a lack of technologies that would drastically reduce CO_2 emissions from heavy trucks and intercontinental aviation”.

When we consider the huge unmet demand for both car ownership and air travel in non-OECD countries (and achieving parity with the present OECD levels would mean roughly a four-fold rise in car numbers and air travel [65]), it is clear that technical advances cannot play more than a minor role in global transport emission reductions. In a similar manner, global numbers of energy intensive domestic appliances—washing machines, dishwashers, air conditioners, high definition TV sets—would also multiply several-fold if OECD ownership levels were achieved globally. The real monetary cost of large domestic appliances (such as washing machines and refrigerators) has been falling for several decades, both in the US [66] in the Netherlands [67] and, presumably, globally as well. Falling costs will encourage global take-up of these goods.

Even given the potential for theoretical energy efficiency improvements, there are, of course, many barriers to their implementation, including sunk costs in existing equipment such as power stations, vehicles of all kinds, and domestic appliances, and the short-term focus by consumers in recouping costs from energy-saving investments. Further, for most households, energy costs are a small share of their total expenditure, and householders are poor at assessing the energy use of various appliances. They therefore tend to use energy in an unreflective way, and are reluctant to alter household routines in order to make minor monetary savings [68,69]. Also, for private vehicles, advances in engine efficiency are often at least partly negated by motorist demands for high performance vehicles, and higher energy demands for auxiliary equipment such as power steering and entertainment systems.

Energy conservation has been increasingly discussed, often under the term energy demand management, but official studies [8] consider that its potential is of only minor importance. Breukers et al. [70] have pointed out the barriers to effecting permanent reductions in energy use. We dispute this pessimistic conclusion, and return to this important topic in Section 5.

3. Energy future: Nuclear energy

Non-fossil fuels sources include nuclear energy and the various RE sources, both usually considered as low GHG emission sources. Despite the problems that face rapid growth of nuclear energy, some have argued that with new reactor types, nuclear power will be essential for climate change mitigation [8,71]. But other observers in recent years have not seen a major future role for nuclear power. The modelled results of Rogner and Riahi [72] suggested that a strong nuclear program is not essential: deep GHG reductions can occur even with a phase-out of nuclear power. The US Energy Information Administration (EIA), in their latest *International Energy Outlook* [73] foresaw very little rise in the share of nuclear power in global electricity production by 2040: In their Reference Case scenario, nuclear power's share of the global electricity market was forecast to rise to only 12.4% from its 2014 level of 10.5% [51]. Similarly, the oil company BP [74] have forecast only a minor electricity share increase for nuclear power out to 2035, with any future growth of global nuclear resting heavily on China.

The outlook for nuclear power seems particularly bleak in the OECD countries, which in 2016 generated more than 75% of the global total [51]. France, the leading country for nuclear power in terms of market share, now aims to reduce nuclear's share from about 75% to 50% by 2025 through "the closure of 'up to 17' reactors" [75]. South Korea, which in 2016 generated over 30% of its power from nuclear energy was planning to cut this share back to around 18% by 2030 [76]. In the US, Westinghouse, which is constructing the only new nuclear plants there for more than three decades, filed for bankruptcy in March 2017 [77].

It thus seems likely that nuclear power will at best maintain its present modest share of global electricity, a share which has fallen from 17.5% in 1993 to 10.5% in 2016 [51]. An obvious reason is its high capital costs, partly the result of its long lead times for reactor planning and construction, particularly in countries with strong and effective environmental legislation. Or as Koomey et al. [78] put it: "A key aspect of nuclear reactors that makes them such high-risk investments are that they are large scale, complex, and predominantly site-built. Hence construction takes years (even in the best case) and can extend over a decade or more". They also stressed that real costs have generally risen over time. Government financial support is less likely in the continuing aftermath of the global financial crisis, and very few reactors are constructed without such support. Popular support for nuclear power will be harder to mobilise in the wake of the Fukushima nuclear accident. And because the reactor fleet is ageing, a significant global construction program would be needed just to maintain present nuclear electricity output [77].

4. Energy future: Renewable energy sources

Some researchers have considered that as a group, RE sources can effectively mitigate climate change by replacing fossil fuel use at little or no additional cost [11,13,79], while others doubt that this is possible [19–22,24,26,80,81]. Here we first examine the future prospects for the various renewable energy sources in general. We then look at individual RE sources, particularly bioenergy, presently the largest source of RE, and solar energy, which has far and away the greatest potential of any RE source.

4.1. General considerations

Earlier we stressed that it is important in global energy research to use an Earth System Science approach. Failure to follow this approach explains much of the variation in the energy literature for both the technical potential of the various RE sources, and their EROEI values. EROEI assessments are an important input into technical potential determination, since if the EROEI of a particular proposed RE resource is not at least unity, it cannot be an energy source [17]. It may need to be much higher, perhaps three or even five, to be a viable energy source.

As is clear from the exchange between Weißbach et al. [17,82] on the one hand, and Raugei et al. [83,84] on the other, there is disagreement about what items should be included as input energy costs for EROEI assessments of various energy sources, and what assumptions should be made about their useful lifetimes, and the need for storage for intermittent wind and PV electricity. Because they do not include the energy content of the fossil fuels, Raugei has argued that the much higher values obtained by Weißbach et al for fossil (and nuclear) power generation are seriously over-estimated. But if, as seems likely, most of the remaining fossil fuel reserves must be left in the ground if we are to achieve climate stability [85], then including their energy content as energy input makes little sense.

According to the IEA [52], all forms of RE in 2015 accounted for 78 EJ, or 13.7% of global primary energy use, mostly in the form of fuel wood. We now have sufficient experience with the various forms of RE and their growth to place some bounds on their production over the next few decades. Smil [31] showed that for several new energy sources in the US, reaching 5% of the total energy market took at least several decades, and then several more decades to get from 5% to 25%. Höök et al. [86] undertook a detailed study of the long-term world growth rates for fossil, nuclear, and renewable energy types. They found that many projections for future RE assumed future growth rates far in excess of what the historical record suggested is feasible. Le Page [87] has documented the growth in renewables, and argued that progress is far too slow.

The rate at which RE can replace fossil fuels is not only limited by technical potential, availability of scarce input materials or the vast sunk investments in existing fossil fuel energy infrastructure, such as vehicles and power plants. It is also constrained because most lifetime energy input costs for RE electrical sources (bioenergy is an exception) are upfront costs, which must be made before any electricity can be generated at all. Under certain circumstances, for wind power, a rapid expansion program for wind turbines can lead to low or even negative net energy output for some time [88], depending on such factors as the expected lifetime of the turbines, their EROEI value and whether storage infrastructure is needed for this intermittent energy source. Countries that have significant installed wind capacity relative to total electric power capacity, such as Germany and Spain, have experienced only linear wind energy growth for a decade or more [51]. Global wind output also appears to have already left its exponential growth phase: over the past decade growth has only been linear [51], with the trend suggesting that gross wind electricity production in 2040 will be of the order of 10 EJ.

Globally, geothermal electricity and hydro power (outside China) have also seen only linear annual growth for several decades. Perversely, attempts to regain exponential growth in RE electricity generation, if at a sufficiently large scale, could lead to significant growth in production and installation GHG emissions, and since much of the installed equipment has a limited life, cyclic dips in net generation governed by replacement life times [88]. In short, problems similar to those for wind power could be expected for other primary RE electricity sources.

4.2. Bioenergy

A number of factors can influence calculation of global technical potential for bioenergy. Many studies do not consider the full environmental impacts of a major bioenergy program. Evaluations should consider all of the following:

- Emissions of GHGs in addition to CO_2, especially N_2O from fertilised soils [89]. In fact, so important are emissions of reactive nitrogen becoming for the environment that Battye and colleagues [90] ask in their eponymous article: “Is nitrogen the next carbon?”
- The effects of bioenergy crop expansion on biodiversity [91,92], water availability, and phosphorus availability [93].
- As already discussed, the albedo decrease effects of forest growth in high latitudes [44].
- The effects of bioenergy expansion on global food availability and prices. This introduces an ethical dimension into technical potential assessments. Although global moves toward a more vegetarian diet would, ceteris paribus, increase bioenergy potential even with a global “food first” policy, current dietary trends are in the opposite direction [94].
- Using crop residues for biofuel can reduce soil carbon retention and increase CO_2 emissions [95], so there is a need for limits on their use [96].
- Estimates of likely global biomass potential should be based on the yields on the marginal lands likely to be all that is available, not on prime farmland. Also, actual field yields will be much lower than those obtained from experimental plots [97].

The latest IPCC report [98] placed a large emphasis on bioenergy for climate mitigation. Estimates for bioenergy technical potential range from around 30 EJ to 1500 EJ [94]. The upper value for these estimates is 75% of the entire terrestrial net primary production (NPP) of about 2000 EJ [99]. Since this NPP must sustain all heterotrophic life, not just humans, the value is unrealistically high. When the full environmental and other impacts of biofuels are taken into account, the low end of the above range for bioenergy potential seems more likely to be realistic.

4.3. Solar energy

The fastest growing RE source is solar energy, mainly electricity produced from PV cells. As is also the case for bioenergy, researchers profoundly disagree about the EROEI values for PV electricity. Although the insolation received by Earth is vast, a vital question concerns the relative EROEI values for PV cells. Clearly, local insolation is important, and for Switzerland and Germany (the latter country is a major producer of PV electricity), Ferroni and Hopkirk [28] calculated an EROEI of only 0.82. In other words, at least up until now, PV electricity production in this region has been an energy sink. The input energy values for PV cells are independent of insolation level, but their survey found large variation in this value, ranging globally from 300 to 2000 kWh_{elec} per square metre of PV cell arrays. An important reason for their low EROEI value was that they included the input and installation energy costs of failed cells in their analysis. Despite their input costs, these failed PV cells have zero electricity output.

A global analysis of PV electricity [29] suggested that before 2010, global PV electricity production did not cover its energy inputs, although the situation was improving. Nevertheless, it could be 2020 before any cumulative net energy will be produced. A more recent analysis by Louwen et al. [30] reached a similar conclusion, although given the uncertainties in analysis they gave the breakeven year for net cumulative energy output as anywhere between 1997 and 2018. At the other extreme, Espinosa et al. (2012) titled their article “Solar cells with one-day energy payback for the factories of the future”. And Creutzig and colleagues have argued that solar energy could cost-effectively supply between 67 and 130 EJ by 2050, making it the dominant global power source.

4.4. Conclusions on renewables

There are several reasons why the growth in RE is likely to be modest in the coming decades:

- Output of some RE sources, such as hydro and geothermal electricity, may be nearing technical limits in many countries, particularly those in the OECD [26]. For other sources such as wind and solar, the near-term problem is likely to be limited sites with high-quality resources (e.g. high average wind speeds) that are close to load centres [26,49,100].
- RE sources need much more land per unit of energy produced than do fossil or nuclear energy, which can lead to conflicts. Wind farms have already met significant opposition—reasons include visual intrusion, noise pollution with its possibly adverse health effects [101], and bird and bat deaths. Yet wind power will need to be scaled up by one to two orders of magnitude (and solar energy by two to three) if business-as-usual energy consumption projections are to be met largely by RE. It will become progressively more difficult to avoid environmental conflicts as output grows.
- RE sources, particularly solar energy, are still far more expensive than fossil fuel electricity [37] and (like fossil fuels) have often received government subsidies to encourage their growth. But as their output rises, so does the total subsidy cost, resulting in governments reducing the subsidies, as in Germany and Spain for solar energy, and in the US possibly for both wind energy and biofuels.
- It is becoming clear that RE sources, particularly hydro, biomass, and even wind, can have their own substantial climate change effects, which could delay or even stop many RE projects [26,49]. Barros et al. [102] have assessed the sustainability index of various energy sources. With 0 being the least sustainable, and 1.0 the most sustainable possible values, the index varied between 0.39 and 0.80 for RE sources. For conventional power plants the index ranged from 0.29 to 0.57. Clearly there is substantial overlap.

Large declines in fossil fuel use from carbon pricing and resulting energy efficiency and conservation measures would lead to substantial unused capacity in fossil fuel infrastructure, including power generation. Further, large cuts in fossil fuels would give correspondingly large emission cuts, reducing pressures for the introduction of non-carbon sources. Declining fossil fuel use would thus raise the relative share of alternatives in the total fuel mix, but would not necessarily do much to raise the absolute level of alternative energy output.

5. Discussion and conclusion

Not all countries face the same level of uncertainty as to what energy source to stress in future. For Kuwait and other Gulf states, hydro is not an option, but solar energy has a large technical potential. Conversely solar energy will never be a major option for Iceland, but hydro and geothermal are obvious choices there, and indeed already provide nearly 100% of electricity generated. But for countries with large areas and varying climatic zones, such as China and the US, choosing which energy sources to develop in a major way will be more difficult. However, sometimes definite conclusions can be reached regarding the use to which a particular fuel is put: if climate change mitigation is the reason for developing biofuels, it will always be more effective to use available biofuels for electricity generation than as a liquid fuel replacement for oil-based transport fuels [103].

This review has argued that technical fixes for the climate change problem that arise from the global fossil fuel-based economy—carbon capture technologies to enable fossil fuel use to continue, or their replacement by alternative energy sources, or by energy efficiency improvements—will be of decreasing effectiveness in the coming decades. Steffen and colleagues [104] have discussed the implications of nine “planetary boundaries” such as global climate change and global loss of biodiversity, which if crossed could have serious implications for Earth’s future. With perhaps the sole exception of ozone layer depletion, the world is moving closer to these limits and may even have crossed some. Additional limits, either regional or even global, are possible. The possibility of transgressing one or more of these multiple limits is the main reason why technical fixes are less useful for tackling environmental or resource challenges than was the case decades ago. This “multiple limits” analysis is also consistent with the ESS approach advocated in this review.

In many applications, diesel, for example, is a more efficient fuel than petrol and various countries have encouraged its use for this reason, but air pollution concerns are leading to a reversal of this policy [105]. Also, Li and colleagues [106] have found that in China, air pollution can lower the output of PV arrays. In eastern China the modelled reduction in output averaged 21% for fixed arrays, but rose to 34% for two-axis tracking systems. They unsurprisingly advocated for air pollution reduction to improve PV output—as well as improving the health of the population. But there is a downside to air pollution reduction: Globally, atmospheric aerosols act to lower average surface temperatures by reflecting insolation and thus increasing Earth’s albedo [107]. We do need to cut air pollution, but also we need to recognise the negative impacts on climate change mitigation. “Unintended consequences” will be an increasingly common feature of tech fixes in a finite world.

Air travel also illustrates the trade-off between pollution and energy efficiency. Aircraft will use less fuel on take-off if they can gain altitude slowly, but noise problems around busy airports require them to rise at a faster rate. Van den Bergh et al. [108] have discussed an important example of what they have called “environmental problem shifting”: A large-scale shift to RE sources to mitigate climate change could lead to depletion of important minerals needed for manufacturing RE components. Finally, we have already discussed how a tech fix can even have direct adverse effects on the very problem it is meant to solve: high latitude forests fix carbon and reduce atmospheric CO_2 ppm, but at the same time lower albedo, thus raising temperatures [44].

Furthermore, several of the technologies which official studies heavily rely on for climate mitigation are only in the early stages of development, and may never achieve feasibility on a large scale. This appears to be the case for CCS and other schemes for mechanically reducing CO_2 emissions to the atmosphere. The energy costs of air capture, the environmental effects of mineral CO_2 capture, and the real potential for underground CO_2 storage (and the annual rate at which it could be safely and permanently sequestered) are all subject to deep uncertainty.

Any solution to the climate change risk from fossil fuel use must recognise the following problems:

- Reversals in policy direction cannot be ruled out. Leaded petrol, diesel fuels, and chlorofluorocarbons (CFCs) were all earlier seen as environmentally beneficial. Biofuels for transport could be the next casualty. Andersen [109] has detailed the unintended consequences that can arise from a shift to each of the various RE sources.
- Time for change is limited. Compared with the many decades it normally takes for a global change in energy or transport systems [32,33], the time left is very short.
- Global inequality—in per capita income, energy consumption, ownership of cars and the more energy-intensive domestic appliances—means that there is a potentially huge unmet demand for energy-intensive equipment. Even unprecedented rates of energy efficiency improvement risk being swamped by increased global ownership, if other nations aspire to OECD levels of affluence.
- Proposed solutions that may give minor reductions in energy-related GHGs in the near term may prove counter-productive in the long run by focussing efforts on marginal improvements while ignoring less obvious but more effective solutions. For transport, an example would be stressing fuel efficiency and alternative fuels while downplaying access as the fundamental purpose of passenger transport.

If, as just argued, technical fixes at best can only be of minor value for climate change amelioration, what can be done? The answer, we argue, is that only deep social changes and a rapid transition to a less energy-intensive mode of living can deliver the large GHG reductions needed if the world is to avoid catastrophic climate change [110]. For transport, this would mean a new emphasis on providing access—to workplaces, schools, shops, and services—rather than mobility (as measured by pass-km). It would also mean a reversal of present transport mode priorities, with non-motorised modes the leading means of access, followed by motorised modes.

Degrowth proponents (e.g. Kallis [111]) have argued that “decarbonisation and dematerialisation” will inevitably have a negative effect on GDP growth. Kallis suggests three economic policies that might be needed for degrowth: “Work-sharing, green taxes and public money”. He and other degrowth researchers do not under-estimate the formidable political obstacles to such a path, but they point out that the easy political path—continuation of the present inaction—is not an option.

Schindler and Hilborn [112] have discussed general policy approaches in the context of environmental conservation. They advocated that policies be flexible, which makes sense given both the uncertainties surrounding the efficacy of the various climate mitigation approaches outlined in this review, and the uncertain trajectory of future climate change. Even non-technical approaches cannot be expected to be exempt from unintended consequences, and some may need to be discontinued. Above all we will need to adopt the precautionary principle in the context of climate change. This principle has been criticised for being vague and even incoherent. However it is only a new name for the age-old wisdom embodied in expressions like “better safe than sorry” and “hope for the best, prepare for the worst”. As Taleb and colleagues [113] have stressed, in line with the already-discussed dire warnings of Xu and Ramanathan [3], the possibility of catastrophic damage renders ordinary economic calculation of costs and benefits meaningless.

Conflicts of interest

Both authors declare that there are no conflicts of interest in this paper.

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