Review

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Review

The Energy Implications of Averting Climate Change Catastrophe

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Abstract: Conventional methods of climate change (CC) mitigation have not 'bent the curve' of steadily rising annual anthropic CO_2 emissions or atmospheric concentrations of greenhouse gases. This study reviews the present position and likely future of such methods, using recently published literature with a global context. It particularly looks at how fast they could be implemented, given that the limited time available for avoiding catastrophic CC (CCC). The study then examines solar geoengineering, an approach often viewed as complementary to conventional mitigation. The review next introduces equity considerations, and shows how this will shorten even further the time available for effective action for CC mitigation. The main findings are as follows. Conventional mitigation approaches will be implemented too slowly to be of much help in avoiding CCC, partly because some suggested technologies are infeasible, while others are either of limited technical potential, or, like wind and solar energy, cannot be introduced fast enough. Because of these problems, solar geoengineering is increasingly advocated as a quick-acting and effective solution. However, it could have serious side effects, and given that there will be winners and losers at the international as well as the more regional level, political opposition may make it difficult to implement. The conclusion is that global energy consumption itself must be rapidly reduced to avoid catastrophic climate change.

Keywords: climate change; climate equity; energy equity; energy reductions; fossil fuels; global sustainability; policy changes; renewable energy; technological optimism

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1. Introduction

Interest in climate change (CC) and means of CC mitigation is at an all-time high. According to the Scopus database, a total of over 426,000 papers have so far been published with the term 'climate change' in either the title, abstract, or keywords. In 2022 the figure was over 48,000, more than double the 2016 number. However, this vast number of reviewed papers has not led to any reduction in carbon emissions. On the contrary, CO_2 emissions from energy and industry have risen from 21.3 gigatonne (Gt) in 1990, the year of the first Intergovernmental Panel on Climate Change (IPCC) report to 33.9 Gt in 2021 [1]. This has been paralleled by the rise in overall greenhouse gas (GHG) emissions, which reached an estimated 59±6.6 $GtCO_2$ equivalent ($GtCO_2$-eq) in 2019 [2].

A further factor to consider is that Earth faces several other environmental challenges in addition to CC [3]. Steffen et al. [4] originally identified nine planetary boundaries, including CC, the crossing of any of which could prove catastrophic. These other global problems include deterioration of the ocean environment and ongoing acidification, biodiversity loss, and air, water and land pollution, especially by plastics [5-9]. Also, as Crist et al. [10] have warned, the world's present population, let alone projected further increases [11], will make achieving a sustainable future Earth even more difficult.

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What is novel in this paper is the stress on the crucial importance of the time factor in assessing the feasibility of the various possible responses to CC, and its interaction with equity considerations. For CC mitigation, the important factor is not the ultimate potential for each proposal, but whether they can be effectively deployed in time to avert, not only catastrophic CC [12], but also the other challenges to global sustainability. Synergistic interactions between these various threats can potentially shorten further the time we have available for effective action to avoid crossing a given threshold [13] Or, as the IPCC [2] put it, we can have high confidence that: 'Climatic and non-climatic risks will increasingly interact, creating compound and cascading risks that are more complex and difficult to manage.' A full discussion of this time dimension is lacking in virtually all of the many studies which address CC mitigation.

In Section 2, the frequency of published papers in Scopus on various possible approaches to dealing with climate change are presented and discussed, as well as the approach used for article selection in this paper. Section 3 stresses the crucial importance of timing: can any of these proposed solutions make a real difference in the crucial next decade or two? Section 4 examines in turn the various conventional mitigation methods from this time-based viewpoint. In Section 5, solar geoengineering (SG) is considered as an alternative to the slow shift to low-carbon fuels, but has known and possibly unknown serious risks. Section 6 examines the complex questions of equity in income, energy use, and CO_2 emissions, in both low- and high-income countries. Finally, Section 7 discusses all these methods and finds that none of them, singly or together can affect the reduction in climate forcing needed over the critical next couple of decades. The overall conclusion is that the needed changes will necessitate the end of global economic growth.

2. Materials and Methods

Figure 1 uses the Scopus database to show how annual publications on various methods of CC mitigation have changed over the years. Although not an energy-related CC mitigation approach, SG has been included since it has been regarded by many as an alternative (or at least a complement) to conventional mitigation approaches [14]. It is evident that interest in bioenergy with carbon capture and storage (BECCS), SG (also called solar radiation management (SRM)), and direct air capture (DAC) only took off after around 2010. In contrast, the more general term carbon dioxide removal (CDR), which includes BECCS and DAC as well as methods like reforestation, enhanced weathering (EW), and soil carbon sequestration, has had many annual publications for decades. As mentioned, the term 'climate change' returned a total of over 426 thousand papers, with annual numbers beginning to rise sharply in the late 1980s. Over the same period a further 70,400 included the term 'global warming' in place of 'climate change', lifting the combined total to almost half a million articles

In this paper, the various approaches to avoiding CCC are critically discussed. The emphasis on papers selected for discussion in general meet two criteria. First, they preferably should be global in scope, since CC is a global problem; local solutions may not be feasible elsewhere, and could even be globally counterproductive. Second, given the progress in both understanding the nature of CC, and the assessment of the viability of proposed mitigation solutions, very recent papers were preferred over older ones. The sixth assessment IPCC reports [15, 16], and particularly their 2023 Synthesis Report [2], are relied on for the science of global warming and up-to-date surveys of mitigation methods. The annual publications by BP [1] and International Energy Agency (IEA) [17] were used for global and national energy statistics.

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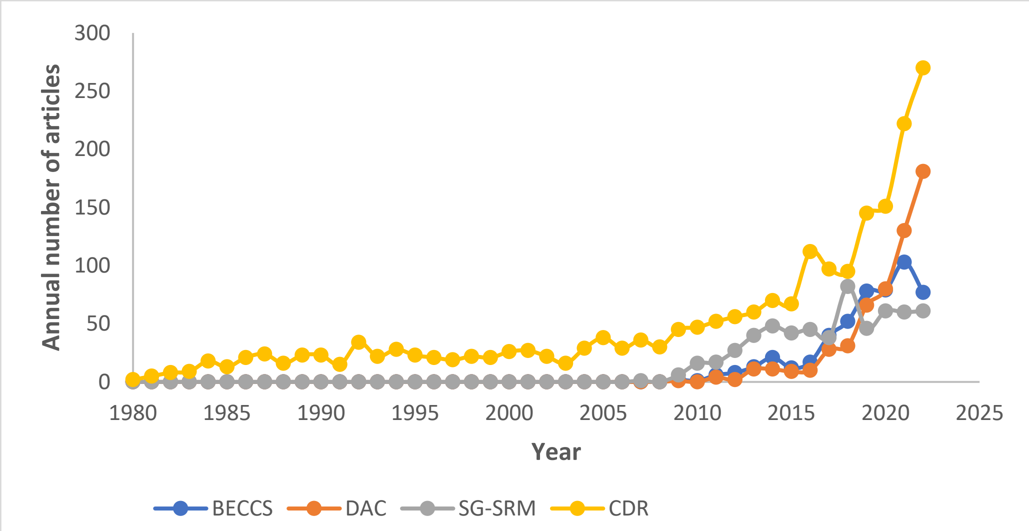

Figure 1. Plot of the annual number of annual publications in the Scopus database with the terms 'BECCS', 'DAC', 'SG OR SRM' and CDR in the title, abstract or keywords, 1980 to 2022.

3. The importance of timing for low-carbon energy

A complication for CC mitigation is the short time left for effective action. Already the world is experiencing a spate of record-breaking extreme weather events—floods, heat waves, droughts, and wildfires [18, 19]. Both their severity and frequency are anticipated to rise in a non-linear manner as temperature rises; the increase from 1.0 to 1.5 °C can be expected to produce more damage than the previous increase from 0.5 to 1.0 °C, just as this latter rise was more damaging than that from 0 to 0.5 °C. This does not mean that when the mean global temperature surpasses 1.5 or 2.0 °C above pre-industrial levels, we give up all attempts at mitigation. Even a 3.0 °C rise, while disastrous in its effects, will be much less severe than a 4 °C increase [2].

Different mitigation methods not only have different average costs and potentials, but also have different time frames for their implementation. For all forms of RE except bioenergy, lifetime energy input costs are dominated by energy for construction, as the annual operating energy costs are small. Because of this, the rate of introduction of new RE is important, as formalized in dynamic energy analysis (DEA).

Capellán-Pérez et al. [20] have examined the consequences of a complete global shift to 100% RE for electricity by year 2060. Their modeled results showed that the average energy return on investment (EROI) would fall from its current value of about 12 to about three by 2050, and would then stabilize at about five. The authors pointed out that these low values are well below those thought needed to maintain a (growth-oriented) industrial economy. The reason for these low EROI values is that much of the output from the RE plants is needed to build new RE plants, limiting the amount of energy available to run the rest of the economy. From another angle, Fizaine and Court [21] have argued that for the US 'growth is only possible if its primary energy system has at least a minimum EROI of approximately 11:1.' The conclusion is that if the aim is to keep industrial economies going, DEA/EROI considerations show that the rate of uptake of RE for electricity—and for primary energy generally—must be curtailed.

A further factor that could slow down the rate of non-carbon energy sources is that in many OECD countries, electricity production is falling. This is the case for major economies such as France, Germany and the UK [1]. With falling demand, there is less need for new electricity power capacity of any type, which again will hinder growth in RE electricity in these countries; growth in RE may be dictated by the replacement rate of aging generation infrastructure rather than growth in demand. For total commercial primary energy consumption, the decrease is even more pronounced, with the OECD overall, and especially the European Union (EU) countries, experiencing a peak around 2007 [1]. Table 1 shows the change in the share of total primary energy and total low carbon primary energy of the OECD and non-OECD over the period 2011 to 2022.

Table 1. OECD and non-OECD share of primary energy and low carbon fuel primary energy for 2011 and 2022.

Energy type\Year	2011	2022
OECD primary energy share %	46.5	38.8
Non-OECD primary energy share (%)	53.5	61.2
OECD low carbon primary energy share (%)	61.1	48.1
Non-OECD low carbon primary energy share (%)	38.9	51.9

Source [1].

If CO_2 was a short-lived gas in the atmosphere—with, say, an atmospheric lifetime of only one year—then any reduction in annual emissions would also reduce atmospheric CO_2 concentrations. The problem is, of course, that CO_2 has a very long atmospheric lifetime. Although the exact figure is disputed (see e.g. [22, 23]), full recovery to its pre-industrial atmospheric levels could take centuries. It follows that most of the CO_2 the world has emitted since the 1950s will still be present over the crucial next few decades.

The multiple challenges to sustainability discussed in the Introduction complicate the search for timely CC mitigation solutions in two ways, which adds to the urgency of rapid response to ongoing CC. Climate change—and how we respond to it—will affect other environmental problems such as biodiversity loss [6]. More generally, the various global limits can act synergistically, lowering the threshold, and thus the time available for effective action to avoid crossing a given threshold [13].

4. Assessment of conventional approaches

In 1990, the IPCC Intergovernmental Panel on Climate Change (IPCC) released its first report. At that time, the conventional methods for mitigation could have provided a feasible solution. These approaches include greatly increased use of the various forms of renewable energy (RE); nuclear power; increased energy efficiency; and CDR, both by biological and mechanical means. But as is shown here, these solutions, even taken together, cannot give the world much relief from climate change. Reasons include the following, with one or more applicable to each approach:

- They cannot deliver major CC mitigation in a timely manner
- Their mitigation potential is too small
- Feedback effects reduce their mitigation potential
- Political opposition limits their deployment at scale
- Their expansion conflicts with other important aims

The authors have discussed the difficulties facing these various approaches in previous publications (see, e.g. [24, 25]). Hence in this section, emphasis will be placed on the first of these points: how rapidly can each of these could reduce global climate forcing?

4.1. Non-fossil fuel energy sources

Solar and wind energy are not only the fastest-growing RE sources [26], but also those with the greatest expansion potential. Nevertheless, DEA indicates that their rate of growth could be limited if sufficient energy is to be available for the non-energy sectors of the economy [19]. As already discussed, the rate at which their output can grow is governed by their EROI [27]. A characteristic of all RE sources except biomass is that nearly all energy inputs—for materials mining and processing, for construction, and for access roads and for transmission and distribution power lines—must be made upfront, before any energy output can be obtained. Maintenance energy costs are relatively minor. Only dismantling and site cleanup energy costs must be postponed until the plant's end of life.

If EROI for wind and solar energy is high, then only minor energy inputs are needed, and the net energy available for the non-energy economy sectors is high. But if low—below a value of about

5 - 10—an 'energy cliff' [27] is encountered, such that input energy costs are significant, and a DEA analysis is needed. The problem is that the EROI values for wind, and especially for photovoltaic (PV) systems, are strongly contested (see, e.g. [28-30]), with some researchers giving very high values for PV and other very low values.

The key explanation for this divergence is the inclusion or otherwise of important input costs, especially what have been termed Ecosystem Maintenance Energy (ESME) costs [31]. These include the energy costs of avoiding pollution from mining of the often-scarce materials needed for wind and PV energy systems. All too often, such mining in tropical African countries and elsewhere ignores the local pollution generated. Even when tailing dams are constructed, they often fail [32]. This suggests that input energy costs for RE electricity systems (which have much higher materials input per gigawatt (GW) of capacity than fossil fuel (FF) plants [33]) are often significantly under-estimated, which means that their EROI values are inflated. Lower EROI values also mean that emission savings are also lower than expected. Further, while adding energy storage systems such as batteries to smooth supply in RE networks can recover curtailed energy, they ultimately act to reduce EROI and came with considerable ESME costs [31].

Hydro, bioenergy, and geothermal electricity are expected to exhibit only slow growth in all the IEA [26] scenarios, and together to be several times smaller than wind and solar combined. Despite their minor potential, it is still useful to look at their GHG emissions profile over time. Tropical hydro systems emit high levels of CO_2 and methane gas over their early years of operation. Geothermal plants also emit CO_2, and only achieve carbon balance after several centuries [34]. For bioenergy plantations, Sterman et al. [35] have stressed the many decades are needed for regrowth, so that the CO_2 drawdown from plantations will not be available in the coming decades. Development of RE projects can impact not only local biodiversity [36] but also many globally significant biodiversity areas [37], even beyond the area occupied by the RE plant [38].

For hydro, bioenergy, and geothermal electricity, time considerations show that over the early years of operation, GHG reductions are far less than expected. A further complication for hydropower is that ongoing CC could change river flows and their timing, and lead to faster reservoir siltation rates; all of which could reduce lifetime TWh and so EROI. Glacier loss in the Himalayas could lead initially to higher hydro potential, but decreased potential as glaciers shrink. There is also increased risk to Himalayan hydropower projects from 'Glacial Lake Outburst Floods' [39]. For bioenergy, competition for food could push bioenergy production out of prime farmland (such as is used in the US for corn ethanol production), again lowering EROI, because of increased need for water and fertilizer inputs.

Nuclear energy's share of global electricity production is expected to fall further, having peaked at 14.6% in 2006—well before the 2011 Fukushima accident—before falling to 9.8% in 2012 [1]. There are several reasons for this market share decline. Nuclear plants take a long time to plan and build, particularly compared with wind or PV solar farms. This is especially true for plants in the major OECD countries, where political opposition has led to moratoriums on new plants in a number of countries, and long construction times for plants being built. A related point is that many plants are nearing the end of their service lives, so that closures will hinder net nuclear output growth, even if new plants are built. The end result is that nuclear power is most unlikely to play more than a minor role in energy production over the coming decades [24].

The IEA [26] presented three future energy scenarios, and gave the expected contribution of all RE sources, as well as nuclear energy, to global primary energy supply up to 2050. Table 1 shows their percentage contributions in 2010 and 2021, and expected values in the years 2030, 2040 and 2050 for the Announced Pledges Scenario (APS). This scenario is actually an optimistic one, given that the world is not on track to reach this target. Even so, less than half of global energy in 2040 is projected to come from non-carbon sources. In the IEA's back-casting exercise to see what would be needed for 'Net Zero Emissions by 2050' (NZE 2050) scenario, RE and nuclear together would still provide less than 40% of global primary energy in 2030.

Table 1. Share of RE and nuclear energy in global primary energy in 2010, 2021, and the EIA's APS scenario for 2030, 2040, and 2050.

Energy type\Year	2010	2020	2021	2030	2040	2050
RE (all types) %	8.3	11.7	11.9	23.8	38.2	50.7
RE (all types) EJ	*45*	*69*	*74*	*141*	*239*	*319*
Nuclear energy %	5.6	4.9	4.8	6.1	7.8	8.9
Nuclear energy EJ	*30*	*29*	*30*	*39*	*49*	*56*

Source [26].

4.2. Carbon dioxide removal (CDR)

Carbon dioxide removal can take many forms, both biological and mechanical. Biological approaches include reforestation and sequestration in soils, and a technology untried at scale, bioenergy with carbon capture and storage (BECCS). The various approaches are described in detail in [40]. Their climate mitigation potential over the next two decades appears minor. Carbon capture and storage (CCS), needed for CO_2 capture from FF power stations, as well as for BECCS and DAC, despite its discussion for three decades, presently sequesters only a few tens of million tonnes CO_2, compared with the tens of billions needed to be a major CC mitigation solution. CO_2 utilization is attracting increased attention, but is presently insignificant. Table 2 gives the values for GtC emissions avoided for each of the listed scenarios for the years 2030, 2040, and 2050. Even in these optimistic scenarios, in 2030 only 0.4-1.2 Gt of CO_2 was captured, compared with the nearly 23 Gt still released in the IEA NZE 2050 scenario.

Bastin et al. [41] calculated that a global tree planting program could sequester a total of 205 Gt of CO_2, largely by increasing soil carbon, and afforestation in grasslands and scrublands. Veldman et al. [42], in their critique of the Bastin et al. paper, claimed that their estimate was too high by a factor of five, and that a more realistic—but still useful—value was 42 Gt. The far lower estimate was partly caused by over-estimating soil organic carbon gains, failing to account for warming from boreal forests because of reduced albedo, and neglected existing human use of savannas, grasslands, and shrublands. In an earlier review, Boysen et al. [43] argued that such global terrestrial carbon fixation could only counteract business-as usual warming at the expense of nearly all natural ecosystems.

Figure 2 outlines the various technical approaches that can be taken to reduce CO_2 emissions to the atmosphere. The already-discussed low-carbon energy sources (RE and nuclear), while already well-established, continue to benefit from technical improvements (e.g. in solar PV cell efficiency), whereas CO_2 removal methods are in their infancy or yet to be attempted. A key advantage seen for CDR is that it enables the present fossil fuel economy to continue—at least until readily exploitable reserves of FF, particularly oil, are depleted, with the likely consequence of delayed implementation of low carbon alternatives. Aside from the moral hazard attached to this approach, the question of when 'peak oil' will occur is unclear, with some arguing for only a few years left before it occurs (e.g. [44]) and others for decades in the future (e.g. [45]). A recent view is that the question is irrelevant, since 'peak demand' will come well before 'peak supply' [46], but if SG is adopted, peak oil could be a limiting factor.

Table 2. CCUS (including BECCS and DAC) in various zero emissions by 2050 scenarios (in annual Gt CO_2 avoided).

Scenario	**2021**	**2030**	**2040**	**2050**
IEA 2022 (NZE)	0.04	1.22	4.42	6.23
BP 2023	0.04	NA	NA	6.05
DNV 2022	0.04	0.4	3.6	5.8

Sources [26, 47, 48].

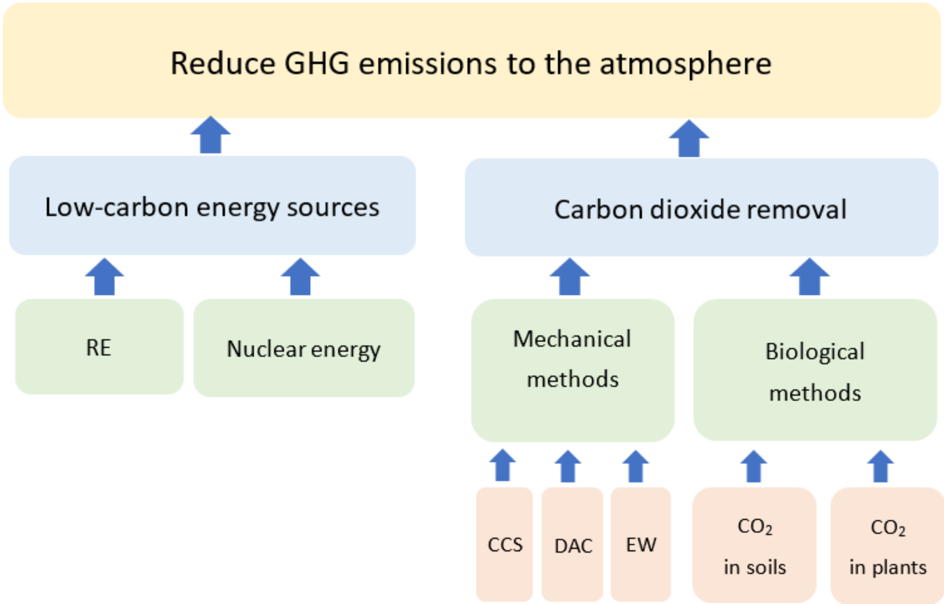

Figure 2. Diagram of conventional approaches for reducing GHG emissions to the atmosphere.

4.3. Energy efficiency

The theoretical potential for energy efficiency improvements is large [49, 50], but several obstacles stand in the way of rapid efficiency gains, even though it is likely the cheapest method of CC mitigation. One obstacle to rapid change is the existence of a large and still growing generating capacity of FF power stations, and a large and still growing global vehicle fleet [51]. Most efficiency improvement methods rely on new equipment replacing inefficient old ones.

Energy savings from efficiency improvements are also reduced by the well-known energy rebound effect [52]—lower fuel costs of (say) vehicle operation can induce extra travel. Furthermore, the desire for private vehicles in countries with low present ownership levels will tend to swamp any efficiency gains. Deep energy/carbon reductions from efficiency gains are also offset by both the widespread introduction of new energy-using equipment or practices, such as ride-on lawnmowers, mechanical hedge clippers and leaf blowers for gardens. A recent innovation, Bitcoin mining, is very energy intensive; a 2023 study found that its global electricity use exceeded that of many countries, including Norway [53]. Another example is bottled water, which is first collected from the source, then distributed from bottling plants in small trucks, replacing the far more energy-efficient tap water.

In the case of vehicular transport, three developments negate efficiency gains. The first is the desire for faster travel—time efficiency (speed) can conflict with energy efficiency. Hence public transport is replaced by car travel, and aircraft dominates long-distance travel. The second development is the increase in non-propulsion energy needs in vehicles, for entertainment, driver aids, or environmental control. The third is the global shift to larger sports utility vehicles replacing cars. In the US in 2021, such vehicles formed 77% of all four-wheel private vehicle sales of 14.57 million [54]. Rapid reductions in GHGs from energy efficiency improvements seem unlikely in a market-based global economy.

5. Solar geoengineering: Impact on low-carbon energy

The above discussion has shown that none of the conventional methods for CC mitigation look capable of delivering major reductions in carbon emissions any time soon, let alone reducing atmospheric levels of GHGs. To be clear: conventional approaches have failed, as shown by rising annual GHG emissions, as discussed in the Introduction. Thus, early advocates envisaged SG as a way of completely counteracting climate forcing without the need to change either global energy consumption or the energy mix.

In its most discussed form, SG involves the annual placement of several Mt of sulphate aerosols in the lower stratosphere to increase Earth's albedo. It is acknowledged, however, that deploying SG to counter (say) a doubling of atmospheric CO_2 ppm compared with the pre-industrial value of around 280 ppm could lead to unacceptable side effects, worsening climate impacts (such as precipitation decreases) in some regions [14] in an already water-stressed world [55]. Instead, it is proposed that SG be used to counteract perhaps 50% of global warming [14].

One possible important effect of SG (and also all CDR methods) is that they could discourage uptake of low-carbon sources of energy. Proponents for SG claim that it will be far cheaper for a given reduction in climate forcing than low-carbon energy, and further, can be rapidly implemented in a year or two. It can also be rapidly terminated should the side effects prove unacceptable. Above all (again like CDR) it enables the continuation of the fossil fuel economy, which has strong support from industry—and FF exporting economies such as the Organization of the Petroleum Exporting Countries (OPEC) countries. [56].

One localized form of SG—painting urban roofs and pavements with a high albedo coating—avoids the freeloader effect that bedevils meaningful reduction efforts, since the benefits accrue solely to the urban residents, and, further, does not need any new technology. Under certain climate conditions, this approach can lower energy use by reducing the need for summer air conditioning. Such energy savings, however, will be at least partly offset by possible higher heating energy in winter, because of lower heat absorption by reflective roofs. Nor is this approach cheap: even in 2009, the UK Royal Society [57] estimated the annual costs as USD 0.30 per m^2, and stated that repainting would be needed every 10 years. For an estimated 1.5 million km^2 of global urban surface, the first-year cost would be USD 450 billion. The energy costs of the coatings also need to be set against the energy savings.

6. Global equity in energy and climate change impacts

So far, this review—in line with the great majority of papers on energy—has not factored in equity considerations. As an editorial in Nature, referring to the enormously influential 2009 paper by Rockström et al. [58] 'A safe operating space for humanity' put it: 'A gap in the original concept was that it lacked environmental justice and equity—it needed to take into account the fact that everyone, especially the most vulnerable, has an absolute right to water, food, energy and health, alongside the right to a clean environment' [59]. The original 2009 paper found that three of the nine planetary boundaries had been crossed. However, the authors now list eight boundaries, namely 'climate, natural ecosystem area, ecosystem functional integrity, surface water, groundwater, nitrogen, phosphorus and aerosols' and when equity considerations are factored in, argued that seven of these thresholds have already been crossed [60]. Why is there an increase in the number of planetary thresholds considered to have been breached? The answer lies in the fact that different geographical regions, and even different groups of people in the same region, for instance an urban area, can experience the impacts of climate change very differently.

Equity has many aspects, and the ones relevant to energy use and subsequent GHG emissions include income, energy use and CO_2 emissions distribution, both at the national and household level. Chancel and Piketty [61] examined world income distribution over the past century. They found that on the international level, inequality was falling, but at the household level it was increasing. Energy inequality is also still high, even at the international level, particularly if only commercial fuels are considered [17]. Kartha et al. [62] have shown that CO_2 emissions are very unequally distributed among the world's households. The top 10% of households accounted for 49% of emissions in 2015, with the bottom 50% only emitted 7%. When split into sectorial emissions, the poorest 50% of the world's population emit less than 20% of total GHG emissions from transport and energy, but an almost equal share from agriculture. On an average per capita basis, IEA statistics [1] show that emissions from the highest emitting country are 200 times those of the lowest. As the IPCC [2] have stated: 'Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected.'

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Another form of inequity is revealed when cumulative emissions of CO_2 are considered. Since CO_2 is a long-lived gas in the atmosphere, cumulative as well as annual emissions are important. In 1965, the OECD countries accounted for 68.8% of global CO_2 emissions from fossil fuel use and industry. By 2021, the much-enlarged list of OECD countries accounted for only 33.3% of such CO_2 emissions, although the average emissions per capita in OECD countries was almost twice as high as the global average [1]. But when cumulative emissions are considered, 55.6% of all energy-related emissions since 1850 have been from OECD countries, the figure dropping to 45.9% when all GHG emissions are considered [63].

6.1. Inequality in low-income countries, especially in the tropics

Low-income countries, particularly those in tropical Africa, Asia, and South America, are anticipated to experience the negative effects of CC both earlier and more severely than those in high-income nations. There are several reasons for this difference:

- Tropical ecosystems are near their upper thermal limit, so rising temperatures could exceed optimum plant germination temperature, or even exceeding the upper limit for germination [64]. (Further, [65] have argued that many tropical ecosystems have adapted to a narrow temperature range, although Sentinella et al. [64] dispute this claim.) Thus, temperature rises could have adverse consequences for agriculture. In contrast in more temperate climates, rising temperatures will shift more species closer to their optimum germination temperature [64].
- Even for similar extreme weather events like floods or droughts, the risks for low-income communities and households are much higher than in wealthier countries, as poorer communities have less resources, both material and administrative, for coping and recovery, and tend to lose a bigger share of their wealth. Even worse, a vicious circle can occur, between disasters losses—whatever the cause—and poverty: '(…) poverty is a major driver of people's vulnerability to natural disasters, which in turn increase poverty in a measurable and significant way [66]. Cappelli et al. [67] even argued for a vicious cycle that 'keeps some countries stuck in a disasters-inequality trap.'
- Further, there are significant differences in the human mortality from extreme weather events depending on the level of vulnerability. As the IPCC [2] noted: 'Between 2010 and 2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability.'

The question to ask here is how already-adopted conventional policies for CC mitigation—and proposals such as SG—will affect prospects for more equality in an unequal world. The example of traditional biomass fuel is instructive. A possible conflict exists between the 'simplistic' desire by many CC mitigation advocates for low-income countries to move directly to RE and forego FFs. As Ramachandran [68] has argued, for cooking meals in places like India, FFs such as liquid petroleum gas (LPG) should greatly reduce the damaging health effects of particulate pollution that occurs with traditional biomass fuels. Vital health concerns can and should sometimes override CC mitigation.

An important example will illustrate the difficulties involved in trying to balance CC mitigation and equity. One heavily-favored adaptation to rising global temperatures and heat waves, conflicts with CC mitigation efforts; the use air conditioner (A/C) units. Globally, A/C numbers have very closely followed an exponential curve since at least 1990, and in 2021 they numbered over two billion. If this exponential growth pattern persists, the IEA [69] have forecast this figure to rise to over 5.5 billion units by 2050. Even as early as 2016, A/C units consumed 10% of global electricity, or more than 2000 terawatt-hr (TWh) [70].

There is no easy solution to this dilemma. The need for A/C units is evident from the work of Raymond et al. [71] who documented how, in some regions of the world, wet bulb temperatures on occasion exceed 35 °C, which marks an upper physiological limit for human tolerance. Humans can become acclimatized to lower temperatures [72], but beyond 35 °C wet bulb temperatures, A/C appears to be the only solution. Even so, a mixture of acclimatization and A/C could be used, with A/C only used for higher temperatures, and not just for room temperatures above 20 °C. As Hanna and Tait [72] have argued, both 'behavioral and technological adaptations' will be necessary for adaptation to rising global warming.

Although 90.4% of the global population had access to electricity in 2020, households without electricity were heavily concentrated in tropical African countries [73]. Residents of many such countries are still mainly engaged in agriculture, requiring prolonged periods outside. Most of their fuel is still from traditional biomass, which also needs much time outside for its collection. Further, at present, apart from sleeping, many of the other human activities take place outside the house [74]. So, even if electricity was available, and the cost of the A/C units and power consumption could be afforded, it may not help such tropical residents to avoid life-threatening temperatures.

6.2. Inequality in high-income countries

A few years ago, it could be argued that although poor countries would be the first to experience the full brunt of CC, high-income countries such as those in the core OECD, would not experience much adverse change until global temperatures reached 3 °C above pre-industrial [75]. We now know better, as evidenced by the record-breaking heat waves in Europe [76] and forest fires in California [77].

It is important to consider equity problems, not only between high- and low- income countries, but also within high-income countries as well, as shown for the US by Polonik et al. [78]. Large cities often exhibit a pronounced urban heat island (UHI) effect. The UHI has several contributory factors, including heat release from vehicles, buildings etc., the 'canyon effect' of tall buildings blocking back-radiation from escaping, and reduced evapo-transpiration from paved surfaces [79]. Chakraborty et al [80], based on a study of the distribution of UHI and income in 25 cities around the globe, found that the UHI—together with its deleterious health effects—disproportionately affected low-income groups. The main reason was that low-income areas in cities tended to have a much smaller area given over to parks and vegetation—and conversely, a higher share of paved areas—which reduces evapo-transpiration from their surfaces. Risks in all countries from extreme temperatures are higher for urban dwellers [81].

7. Discussion and conclusions

The discussion above has shown that technical solutions for mitigating climate change have not been successful so far. Further, given the limited time we have to avoid extremely disruptive CC, these methods, even together, cannot be relied on as the dominant approach to tackling CC over the next decade or so. This conclusion has even more force when inequality—of incomes, energy use, and climate change damages—are factored into CC mitigation policies. As already discussed, Gupta et al. [60] and Rockström et al. [82] have argued on equity grounds that no further temperature increase should be allowed—even a 1.5 °C rise is too high.

The limitations of this review mainly arise from the extreme uncertainty surrounding how the future climate will evolve, both regionally and globally. Witze [76] has summed up this uncertainty as follows: 'Unprecedented temperatures are coming faster and more furiously than researchers expected, raising questions about what to anticipate in the future.' This in turn is partly the result of uncertainty about whether (and when) the world's nations will implement policies which seriously tackle CC. Another uncertainty is the possibility of some breakthrough technology which can quickly mitigate CC. However, given the multiple environmental problems we face, experience shows that any innovation could well exacerbate these other risks to our future.

What options are left for avoiding CCC, given the failure of existing and proposed approaches? The only approach is rapid reduction in GHG emissions, not by low-carbon or CDR methods, but by rapid reductions in energy use itself, initially in the high energy-use nations. As shown, large energy efficiency improvements cannot be expected in the context of a continuing global growth economy. Jason Hickel and colleagues [83] have stressed the urgent need for what is lacking in the IPCC and other official documents: CC mitigation scenarios that do not assume the continuation of global economic growth. Such global economic 'degrowth' would not be uniform, in that reductions would

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first need to apply to OECD and other high-income countries—or better, high income households in every country.

In a later paper, Hickel and colleagues [84] have given some ideas for how such degrowth could be achieved in high-income countries, mainly by more focus on satisfying human needs. In particular, they advocated cutting production in sectors such as animal products, private transport, aviation, fast fashion, and ending planned obsolescence of goods. They also advocated providing high-quality public health care, housing and education, where human welfare can be improved with low resource use. At the same time, equity demands some growth in presently low-income countries—or households. Here the UN's Sustainable Development Goals (SDGs) [85] could be used as a starting point in meeting basic human needs.

Deep emission reductions from rapid reduction in FF use will prove very difficult to implement politically in high-income countries, and there is no guarantee of success. In fact, the model results of van Ruijven and colleagues [86] indicated that energy use would grow strongly out to 2050. Although most would come from assumed economic growth, the changing climate led to further energy growth of between 11-58%, depending on the scenario.

Although the majority of the population in OECD countries think that CC is a serious problem, one that needs to be urgently addressed, this support may be predicated on their being a relatively painless solution like a massive shift to low-carbon fuels, or use of CDR, particularly if promoted as a means of providing more time for deploying low-carbon technologies. As this review has argued, such technological optimism is likely unwarranted, so that fundamental social and political changes will be needed. But to echo the words of UK's former prime minister, Margaret Thatcher: 'There is no alternative.'

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Nomenclature

A/C air conditioner

APC Announced Pledges Scenario

BECCS bioenergy with carbon capture and storage

CC climate change

CCC catastrophic climate change

CCS carbon capture and storage

CDR carbon dioxide removal

CO_2 carbon dioxide

CO_2-eq carbon dioxide equivalent

DAC direct air capture

DEA dynamic energy analysis

EIA Energy Information Administration

EJ exajoule (10^{18} joule)

EROI energy return on investment

ESME Ecosystem Maintenance Energy

ESS Earth System Science

EU European Union

EW enhanced weathering

FF fossil fuels

GHG greenhouse gas

Gt gigatonne = 10^9 tonne

GW gigawatt (10^9 watt)

IEA International Energy Agency

IPCC Intergovernmental Panel on Climate Change

Mt megatonne (10^6 tonne)

OECD Organization for Economic Cooperation and Development

OPEC Organization of the Petroleum Exporting Countries

ppm parts per million (atmospheric)

PV photovoltaic

RE renewable energy

SDG Sustainable Development Goal

SG solar geoengineering

SRM solar radiation management

t CO_2/cap tonnes CO_2 per capita

TWh terawatt-hour (10^{12} watt-hr)

USD US dollars

UNEP United Nations Environment Program

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