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Review

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 the recently published literature with a global context. It particularly looks at how fast they could be implemented, given the limited time available for avoiding catastrophic CC (CCC). This study then critically examines solar geoengineering, an approach often viewed as complementary to conventional mitigation. Next, this review introduces equity considerations and shows how these even further shorten the available time for effective action for CC mitigation. The main findings are as follows. Conventional mitigation approaches would 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. Due to these problems, solar geoengineering is increasingly advocated for as a quick-acting and effective solution. However, it could have serious side effects, and, given that there would be winners and losers at the international level as well as at the more regional level, political opposition may make it very difficult to implement. The conclusion is that global energy consumption itself must be rapidly reduced to avoid catastrophic climate change, which requires strong policy support.

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 rose from 21.3 gigatonnes (Gt) in 1990, the year of the first Intergovernmental Panel on Climate Change (IPCC) report, to 33.9 Gt in 2021 [1]. This was paralleled by the rise in overall greenhouse gas (GHG) emissions, which reached an estimated 59.0 ± 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, for which the crossing of any could prove catastrophic. These other global problems include the 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] warned, the world's present population, let alone projected further increases [11], make achieving a sustainable future Earth even more difficult.

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 it can be effectively deployed in time to avert not only catastrophic CC [12] but also the other challenges to global sustainability. Synergistic interactions among these various threats can potentially further shorten 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 that address CC mitigation.

In Section 2, the frequency of published papers in Scopus on various possible approaches to dealing with climate change, as well as the approach used for article selection in this paper, are presented and discussed. 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, in turn, examines 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 it 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 that is needed over the critical next couple of decades. The overall conclusion is that the changes needed—including energy reductions and the need to sustain biodiversity and cut land, air, and water pollution—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 was included since it is 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 426,000 papers, with annual numbers beginning to rise sharply in the late 1980s. Over the same period, a further 70,400 papers 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 IPCC's sixth assessment reports [15,16], particularly its 2023 Synthesis Report [2], were relied on for the science of global warming and the up-to-date surveys of mitigation methods. The annual publications by BP [1] and the International Energy Agency (IEA) [17] were used for global and national energy statistics.

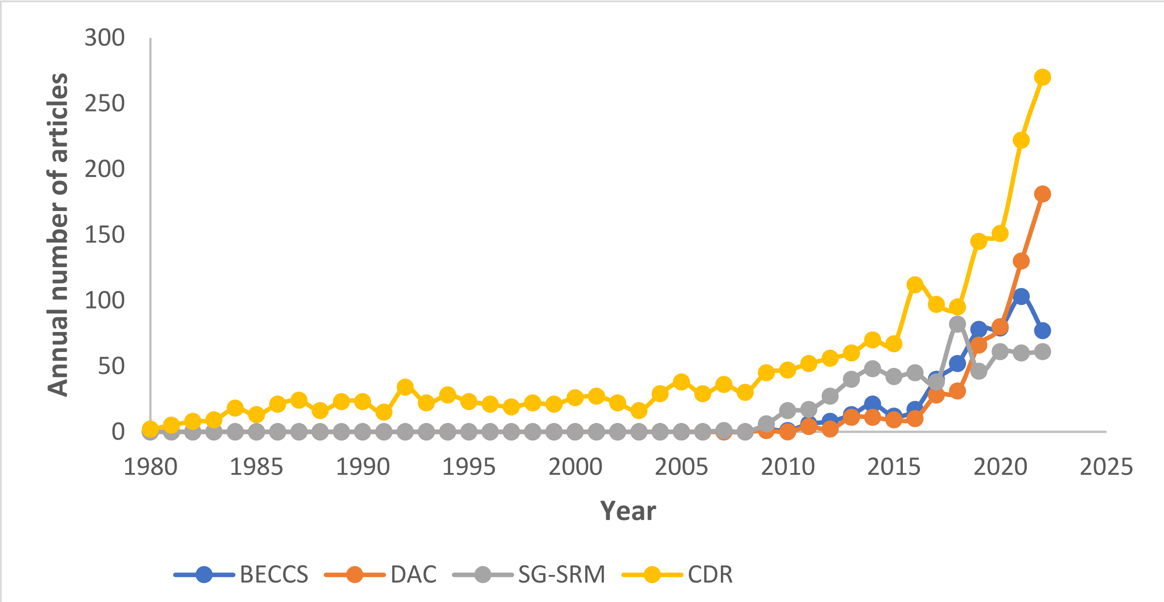

Figure 1. Plot of the annual number of annual publications in the Scopus database with the terms 'BECCS', 'DAC', 'SG OR SRM', and CDR in the title, abstract, or keywords, from 1980 to 2022.

3. 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 the 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 [2]. This does not mean that, when the mean global temperature surpasses 1.5 or 2.0 °C above pre-industrial levels, we should give up all attempts at mitigation. Even a 3.0 °C rise, while disastrous in its effects, is 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 renewable energy (RE) except bioenergy, lifetime energy input costs are dominated by energy for construction, as the annual operating energy costs are small. Due to this, the rate of introduction of new RE is important, as formalised in dynamic energy analysis (DEA).

Capellán-Pérez et al. [20] examined the consequences of a complete global shift to 100% RE for electricity by 2060. Their modelled results showed that the average energy return on investment (EROI) would fall from its current value of about 12 to about 3 by 2050 and would then stabilise at about 5. 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] 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 [1]. This is the case for major economies such as Germany and the UK, where usage peaked a decade or more ago [1]. With falling demand, there is less need for new electricity power capacity of any type, which again hinders growth in RE electricity in these countries. Although the output of wind and solar is increasing in both Europe and the Organization for Economic Cooperation and

Development (OECD) overall [1], further growth in RE may be dictated by the replacement rate of ageing 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, 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 2011–2022.

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 a rapid response to ongoing CC. Climate change—and how we respond to it—affects other environmental problems such as biodiversity loss [6]. More generally, various global limits can act synergistically, lowering a threshold and, thus, the time available for effective action to avoid crossing a given threshold [13]. Unfortunately, it is not possible to give any dates for when the various approaches would be able to play a dominant role in CC mitigation. Only for RE are estimates available for various scenarios, with the IEA [24] forecasting RE as just over half of global primary energy by 2050 in their Announced Pledges Scenario (APS).

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. The 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 discussed the difficulties facing these various approaches in previous publications (see, e.g., [25,26]). Hence, in this section, emphasis is placed on the first of these points: how rapidly could each of these reduce global climate forcing?

4.1. Non-Fossil Fuel Energy Sources

Solar and wind energy are not only the fastest-growing RE sources [24] but also those with the greatest expansion potential. Nevertheless, DEA indicates that their rate of growth could be limited if sufficient energy is 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, for access roads, and for transmission and distribution power lines—must be made upfront, before any energy output can be obtained. The maintenance energy costs are relatively minor. Only dismantling and site cleanup energy costs must be postponed until the plant's end of life.

If the 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 it is low—below a value of about 5–10—an 'energy cliff' [27] is encountered, such that input energy costs are significant, and 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 others giving very low values.

The key explanation for this divergence is the inclusion or otherwise of important input costs, especially those termed Ecosystem Maintenance Energy (ESME) costs [31]. These include the energy costs of avoiding pollution from the 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 that is generated. Even when tailing dams are constructed, they often fail [32]. This suggests that the 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 the supply in RE networks can recover curtailed energy, they ultimately act to reduce EROI and come with considerable ESME costs [31].

Hydro, bioenergy, and geothermal electricity are expected to exhibit only slow growth in all the IEA [24] scenarios, and together are 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] stressed that many decades are needed for regrowth, so the CO_2 drawdown from plantations would not be available in the coming decades. The 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, leading to faster reservoir siltation rates, all of which could reduce lifetime TWh and, thus, EROI. Glacier loss in the Himalayas could initially lead to higher hydro potential, though there would be 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 fertiliser 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 led to moratoriums on new plants and long construction times for plants being built in a number of countries. A related point is that many plants are nearing the end of their service lives, so closures would 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 [25].

The IEA [24] presented three future energy scenarios and gave the expected contribution of all RE sources, as well as nuclear energy, to the global primary energy supply up to 2050. Table 2 shows their percentage contributions in 2010 and 2021 and the expected values in 2030, 2040, and 2050 for the 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 the 'Net Zero Emissions by 2050′ (NZE 2050) scenario, RE and nuclear energy together would still provide less than 40% of global primary energy in 2030.

Table 2. Share of RE and nuclear energy in global primary energy in 2010, 2020, and 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 [24].

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). These various approaches are described in detail in [3]. 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 millions of tonnes of CO_2, compared with the tens of billions needed to be a major CC mitigation solution. It is also more costly than other approaches [40]. CO_2 utilisation is attracting increased attention but is presently insignificant. Table 3 gives the values for the GtC emissions avoided for each of the listed scenarios for 2030, 2040, and 2050. Even in these optimistic scenarios, in 2030 only 0.4–1.2 Gt of CO_2 would be 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 [41], claimed that their estimate was too high by a factor of five and that a more realistic—but still useful—value was 42 Gt. This 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 neglecting 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 into 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 are yet to be attempted. A key advantage 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 the 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 that there are only a few years left before it occurs (e.g., [44]), while others argue that it will occur decades in the future (e.g., [45]). A recent view is that the question is irrelevant, since 'peak demand' would come well before 'peak supply' [46]; but, if SG is adopted, peak oil could be a limiting factor.

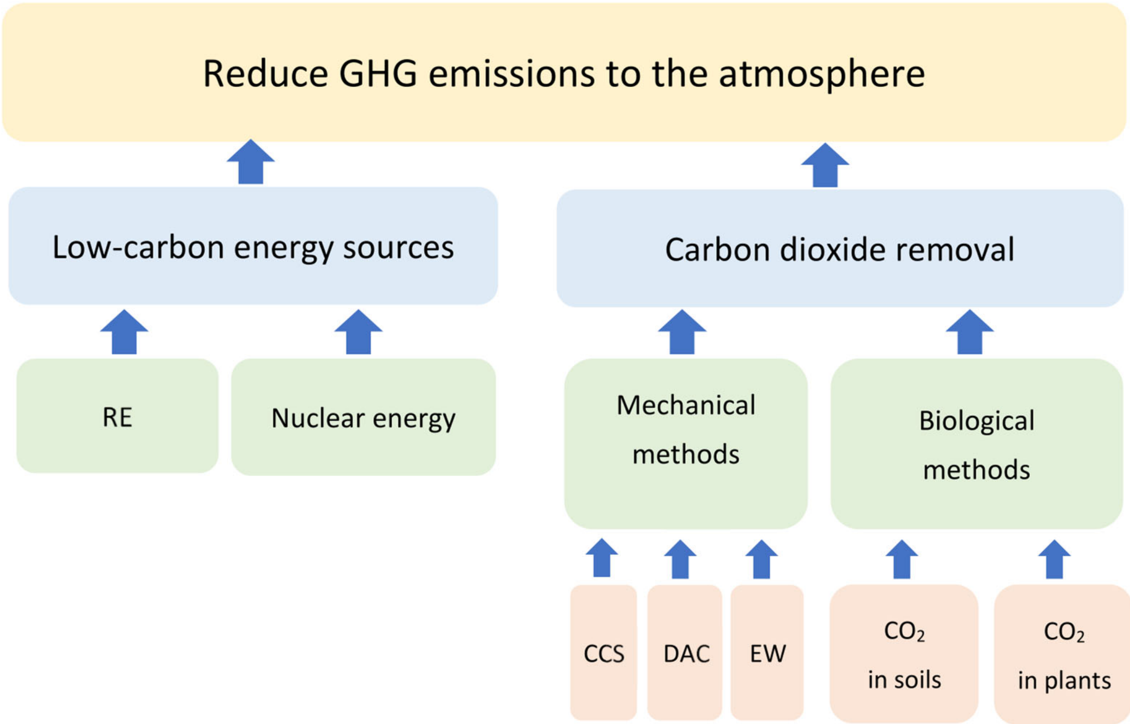

Figure 2. Diagram of conventional approaches for reducing GHG emissions into the atmosphere.

Table 3. CCUS (including BECCS and DAC) in various zero emissions scenarios by 2050 (in annual Gt of 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 [24,47,48].

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 energy efficiency is likely the cheapest method of CC mitigation. One obstacle to rapid change is the existence of the large and still-growing generating capacity of FF power stations, as well as a large and still growing global vehicle fleet [51]. Most efficiency improvement methods rely on new equipment replacing inefficient old equipment.

Energy savings from efficiency improvements are also reduced by the well-known energy rebound effect [52]—the lower fuel costs of (say) vehicle operation can induce extra travel. Furthermore, the desire for private vehicles in countries with low present ownership levels tends to swamp any efficiency gains. The deep energy/carbon reductions from efficiency gains are also offset by 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 and 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 dominate long-distance travel.

The second development is the increase in non-propulsion energy needs in vehicles, for entertainment, driver aids, and 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, at USD 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 shows 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, unless strong supporting policies are introduced. To be clear: conventional approaches without the strong policy support needed have failed so far, 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.

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].

In its most discussed form, SG involves the annual placement of sulphate aerosols in the lower stratosphere to increase Earth's albedo. In order to offset half the climate forcing from anthropogenic CC, a radiative forcing of about -2 W/m^2 is needed. This could be achieved by the annual placement of 12 Mt of sulphur into the lower stratosphere, perhaps using airplanes. Annual costs were estimated as anywhere between USD 20 and 200 billion [56].

One possible important effect of SG (and also all CDR methods) is that it could discourage the uptake of low-carbon sources of energy. Proponents for SG claim that it is far cheaper for a given reduction in climate forcing than low-carbon energy and, further, can be rapidly implemented in a year or two [57,58]. It can also be rapidly terminated should the side effects prove unacceptable. However, Trisos et al. [59] warned of the 'potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination'.

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 Organization of the Petroleum Exporting Countries (OPEC) countries [57].

Another problem with CO_2 atmospheric emissions into the atmosphere is that oceans absorb 25–30% of this CO_2, where it causes ocean acidification (OA), a serious threat to ocean ecosystems [8]. This OA would continue unabated under SG, though not if, for example, RE is used for CC mitigation, since atmospheric CO_2 emissions are avoided. For a fair comparison, the monetary, energy, and environmental costs of countering OA must be included for SG. Slaked lime is one option for such ocean alkalinity enhancement (OAE). Slaked lime could be relatively cheaply spread by freight ships, but its unavoidably high local concentrations could have serious adverse effects on ocean ecosystems [60].

Aircraft would enable more uniform spreading, but Gentile et al. [61] found that depending on aircraft height and dispersal time, aircraft energy use would involve a 28–77% energy penalty, with the cost per tonne of CO_2 neutralised between USD 31 and 1920. Since each extra molecule of ocean CO_2 must be neutralised, the quantities involved are very large; Fakhraee et al. [62] found that 6–30 Gt of CaO or MgO would be needed annually, depending on the assumptions made. In summary, when the need for OAE is factored in, SG may well be more expensive than more conventional options and would also entail additional ecological risks, which are still poorly understood.

Due to these serious problems, many scientists even opposed further research into SG [63–65]. In the words of McGuire [64], it is simply 'the wrong answer to the wrong question'.

One localised 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 solely accrue for the urban residents, and, further, does not need any new technology. Although its radiative forcing is negligible at -0.01 W/m^2 and, hence, is useless for global cooling, it is being implemented and has no adverse effects elsewhere. In contrast, any globally effective SG initiatives would have potentially serious ecological effects, as well as facing political opposition from nations perceiving themselves to be disadvantaged.

6. Global Equity in Energy and Climate Change Impacts

So far, this review—in line with the great majority of papers on energy—did not factor in equity considerations. As an editorial in *Nature*, referring to the enormously influential 2009 paper by Rockström et al. [66], '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' [67]. 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, they argue that seven of these thresholds have already been crossed [68]. 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 levels. Chancel and Piketty [69] examined world income distribution over the past century. They found that at 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. [70] showed 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 emitting 7%. When split into sectorial emissions, the poorest 50% of the world's population emitted less than 20% of the 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] stated, 'Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected'.

Another form of inequity is revealed when the 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, OECD countries accounted for 68.8% of global CO_2 emissions from fossil fuel use and industry. By 2022, the much-enlarged list of OECD countries accounted for only 33.7% 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, with the figure dropping to 45.9% when all GHG emissions are considered [71].

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 high-income countries. 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 exceed the upper limit for germination [72]. (Further, [73] argued that many tropical ecosystems have adapted to a narrow temperature range, although Sentinella et al. [72] dispute this claim.) Thus, temperature rises could have adverse consequences for agriculture. In contrast, in more temperate climates, rising temperatures shift more species closer to their optimum germination temperature [73].

- 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 fewer resources, both material and administrative, for coping and recovery and tend to lose a bigger share of their wealth. Even worse, a vicious cycle can occur between losses from disasters—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' [74]. Cappelli et al. [75] even argued for a vicious cycle that 'keeps some countries stuck in a disasters-inequality trap'.
- Further, there are significant differences in 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—affect the prospects for more equality in an unequal world. The example of traditional biomass fuel is instructive. A possible conflict exists between the 'simplistic' desire of many CC mitigation advocates for low-income countries to move directly to RE and forego FFs. As Ramachandran [76] 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 occur with traditional biomass fuels. Vital health concerns can and should sometimes override CC mitigation.

An important example illustrates the difficulties involved in trying to balance CC mitigation and equity. One heavily favoured adaptation to rising global temperatures and heat waves conflicts with CC mitigation efforts: the use of 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 [77] forecasts this figure to rise to over 5.5 billion units by 2050, with especially large increases in A/C units expected for both China and India. Even as early as 2016, A/C units consumed 10% of global electricity or more than 2000 terawatt hr (TWh) [78]. However, solar electricity output, with its peak during the hottest hours, is well-matched to provide power for A/C units.

There is no easy solution to this dilemma. The need for A/C units for most but not all countries is evident from the work of Raymond et al. [79], who documented how, in some regions of the world, wet bulb temperatures on occasion exceed 35 °C, which marks the upper physiological limit of human tolerance. Humans can become acclimatised to lower temperatures [79], but, beyond 35 °C wet bulb temperatures, A/C appears to be the only solution. Even so, a mixture of acclimatisation and A/C could be used, with A/C only used for higher temperatures and not for room temperatures above 20 °C. As Hanna and Tait [80] argued, both 'behavioral and technological adaptations' are 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 [81]. Furthermore, it is important that electricity companies are publicly owned, as energy in the hands of private companies is not a guarantee of access for everyone. Residents of many such countries are still mainly engaged in agriculture, requiring prolonged periods of being outside. Most of their fuel is still from traditional biomass, which also requires much time outside for its collection. Further, at present, apart from sleeping, many other human activities take place outside the house [82]. So, even if electricity was available, and the cost of A/C units and power consumption could be afforded, it may not help such tropical residents 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 levels [83]. We now know better, as evidenced by the record-breaking heat waves in Europe [84] and the forest fires in California [85].

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. [86]. Large cities often exhibit a pronounced urban heat island (UHI) effect. The UHI effect has several contributory factors, including heat release from vehicles, buildings, etc.; the 'canyon effect' of tall buildings blocking back radiation from escaping; and reduced evapotranspiration from paved surfaces [87]. Chakraborty et al. [88], based on a study of the distribution of the UHI effect and income in 25 cities around the globe, found that the UHI effect—together with its deleterious health effects—disproportionately affected low-income groups. The main reason was that low-income areas in cities tend to have a much smaller area given to parks and vegetation—and, conversely, a higher share of paved areas—which reduces evapotranspiration from their surfaces. The risks in all countries from extreme temperatures are higher for urban dwellers [89].

7. Discussion and Conclusions

The discussion above shows that the technical solutions for mitigating climate change have so far not been successful. Further, given the limited time we have to avoid extremely disruptive CC, these methods, even together, can only be a complementary 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. [68] and Rockström et al. [90] 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 [84] 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 that seriously tackle CC. Another uncertainty is the possibility of some breakthrough technology that 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 a rapid reduction in GHG emissions, not only by low-carbon or CDR methods but also by rapid reductions in energy use itself, initially in high-energy-use nations. The response to the COVID-19 crisis in the form of stringent lockdowns and the resulting emissions reductions indicates the importance of strong policies [91]. This conclusion is at odds with the continued growth in global energy use, as forecast by various government and energy organisations [2,24,47,48,51]. In a previous review, the authors [3] detailed the possible policy changes that are needed to support RE introduction and energy and GHG reductions.

As shown, large energy efficiency improvements cannot be expected in the context of continuing global economic growth. Jason Hickel and colleagues [92] stressed the urgent need for what is lacking from the IPCC and in 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 first need to apply to the OECD and other high-income countries—or, even better, high-income households in every country.

In a later paper, Hickel and colleagues [93] gave some ideas for how such degrowth could be achieved in high-income countries, mainly by focusing more on satisfying human needs. In particular, they advocated for cutting production in sectors such as animal products, private transport, aviation, and fast fashion and ending the planned obsolescence of goods. They also advocated for providing high-quality public health care, housing, and education, so human welfare can be improved with low resource use. At the same time, equity demands some growth in low-income countries—or households. Here, the UN's Sustainable Development Goals (SDGs) [94] could be used as a starting point in meeting basic human needs.

In an earlier paper, the authors showed how large reductions in GHG emissions are possible, particularly in agriculture worldwide, with crop pests being a key problem in low-income countries and food waste in high-income nations. Also, for passenger transport, especially in high-mobility countries, large GHG reductions are possible by shifting the emphasis from vehicular mobility to access and by promoting non-motorised modes of transport and public transport [3].

Deep emission reductions from a rapid reduction in FF use will prove very difficult to politically implement in high-income countries, and there is no guarantee of success. In fact, the model results of van Ruijven and colleagues [95] indicated that energy use would strongly grow until 2050. Although most energy growth would come from assumed economic growth, the changing climate led to further energy growth of 11–58%, depending on the scenario.

This review identifies a number of shortcomings and gaps in the published literature. A vital one is a better idea as to how the climate—especially the frequency, duration, and severity of extreme weather events—will respond to further increases in atmospheric GHGs. More work is also needed to produce realistic costs for the various options and for when they could be deployed.

Although the majority of the population in OECD countries thinks that CC is a serious problem, one that needs to be urgently addressed, this support may be predicated on there being a relatively painless solution like a massive shift to low-carbon fuels or the use of CDR, particularly if it is promoted as a means of providing more time for deploying low-carbon technologies. As this review argues, such technological optimism is likely unwarranted, so fundamental social and political changes are 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 (1018 joules)
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 = 1^9 tonnes
GW	gigawatt (10^9 watts)
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
Mt	megatonne (10^6 tonnes)
OA	ocean acidification
OAE	ocean alkalinity enhancement
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 of CO_2 per capita
TWh	terawatt hours (10^{12} watt hrs)
USD	US dollars
UNEP	United Nations Environment Program

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