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Scenarios for mitigating CO_2 emissions from energy supply in the absence of CO_2 removal

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ABSTRACT

This paper investigates the effectiveness of different energy scenarios for achieving early reductions in global energy-related CO_2 emissions on trajectories to zero or near-zero emissions by 2050. To keep global heating below 1.5°C without overshoot by 2050, global CO_2 emissions must decline by about half by 2030. To achieve rapid, early emission reductions entails substantially changing recent pre-COVID (2000–2019) observed trends, which comprise increasing total primary energy supply (TPES) and approximately constant fraction of TPES derived from fossil fuels (FF fraction). Scenarios are developed to explore the effects of varying future trends in these variables in the absence of substantial CO_2 removal, because relying on the latter is speculative and risky. The principal result is that, to reduce energy-related emissions to at least half the 2019 level by 2030 en route to zero or near-zero CO_2 emissions by 2050, either TPES must be reduced to at least half its 2019 value by 2050 or impossibly rapid reductions must be made in the FF fraction of supply, given current technological options. Reduction in energy consumption likely entails economic degrowth in high-income countries, driven by policies that are socioeconomic, cultural and political, in addition to technological. This needs serious consideration and international cooperation.

Key policy insights:

- If global energy consumption grows at the pre-COVID rate, technological change alone cannot halve global CO_2 emissions by 2030 and hence cannot keep global heating below 1.5°C by 2050.
- In the absence of substantial CO_2 removal, policies are needed to reduce global energy consumption and hence foster degrowth in high-income economies.
- Policies to drive technological and socioeconomic changes could together cut global energy consumption and thus total primary energy supply and associated emissions by at least 75% by 2050.

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climate mitigation scenarios; renewable energy; energy efficiency; total primary energy supply; fossil fuel fraction; degrowth; steady-state economy

1. Introduction

Anthropogenic climate change has become a crisis. IPCC SR15 found that ‘limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane (*high confidence*)’ (IPCC, 2018, p. 33). More recent research suggests that it may already be too late to keep average global heating below 1.5°C without overshoot (DNV-GL, 2020; Lenton et al., 2019; Steffen, 2022). Of particular concern about exceeding 1.5°C is the increased risk of crossing tipping points, especially the irreversible loss of the West Antarctic ice sheet and increases in frequency of extreme El Niño events (IPCC, 2018, section 3.5; Steffen et al., 2018; Lenton et al., 2019). Therefore, rapid, early reductions in emissions are needed – a key outcome of COP26 in November 2021 (UK COP26, 2021). More precisely, according to the IPCC, ‘In model pathways with no or limited overshoot of 1.5°C, global net

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anthropogenic CO2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range)' (IPCC, 2018, p. 12).

Because the probability of limiting global heating to 1.5°C is determined by cumulative emissions of CO_2 together with non-CO_2 radiative forcing (IPCC, 2018, pp. 5–6), time is of the essence in mitigating annual emissions. Therefore, this paper tests the hypothesis that, in the absence of substantial CO_2 removal, technological change alone may not be sufficient to achieve significant early reduction of energy-related emissions on trajectories to zero emissions by 2050 and, therefore, reductions in energy consumption, and hence total primary energy supply (TPES), may also be needed.

Previous climate mitigation scenario assessments that explored reducing emissions to net zero by 2050 include those of the Intergovernmental Panel on Climate Change Special Report on 1.5°C (IPCC, 2018), using Integrated Assessment Models, and the Net Zero Emissions 2050 (NZE2050) Scenario of the International Energy Agency (IEA, 2020a), using its own World Energy Model.[1] Both assessments rely on very rapid technological change to transition fossil fuels (FF) to zero-carbon energy sources and both assume continued economic growth, which is problematic on account of its correlations with increasing consumption of energy and materials (Haberl et al., 2020; Hickel & Kallis, 2020; Parrique et al., 2019). In addition, most scenarios rely on removing very large amounts of CO_2 from the atmosphere and flue gases using technologies that, apart from afforestation and reforestation, are not commercially available at scale. Relying on CO_2 removal is speculative and risky (Anderson et al., 2020; de Coninck & Benson, 2014; Creutzig et al., 2021; Larkin et al., 2018; Realmonte et al., 2019), as is relying on the possibility of other technological breakthroughs (see Section 4.1).

Identifying a gap in the climate mitigation modelling literature, Keyßer and Lenzen (2021) developed 1.5°C degrowth scenarios and compared them with IPCC scenarios. They found that 'the degrowth scenarios minimize many key risks for feasibility and sustainability compared to technology-driven pathways, such as the reliance on high energy-GDP decoupling, large-scale CO_2 removal and large-scale and high-speed renewable energy transformation'. Hickel et al. (2021) point out that post-growth approaches in high-income countries can improve social outcomes while making it easier to achieve rapid mitigation. So far, consideration of non-technological strategies for emissions reduction has not gained central stage, despite some valuable research (Grubler et al., 2020; Hickel et al., 2021; Keyßer & Lenzen, 2021), but this may have to change to allow for the risk that CO_2 removal cannot contribute significantly to mitigation. This is the concern motivating the present paper.

The energy sector contributes about three-quarters of global CO_2 emissions (Ge & Friedrich, 2020). Therefore, transitioning this sector to zero emissions is central to solving the climate crisis. The broad technological strategy for doing this, by transitioning to predominantly or entirely renewable energy (RE) supply together with increased energy efficiency (EE), and the electrification of most transport and heating, has a wide agreement in the energy scenario literature (Bogdanov et al., 2019, 2021; IEA, 2020a; IPCC, 2018; Jacobson et al., 2015, 2018).[2] Wind and solar photovoltaics are by far the cheapest technologies for bulk electricity supply, even after taking account of the cost of additional storage – neither nuclear power nor coal with carbon capture and storage can compete (Graham et al., 2021; IRENA, 2020; Lazard, 2020). Jacobson et al. (2015) found that the cost of electricity in their 100% renewable electricity (RElec) scenario for the United States is less than the cost of electricity, including externalities, in a projected conventional system based mainly on FF. More recently, Bogdanov et al. (2021) found that the cost of energy in 100% RE (for all energy use) is approximately the same as that of the present FF-dominated energy system, even when external costs are ignored.

This energy strategy can potentially remove the majority of CO_2 emissions and indeed the majority of all greenhouse gas (GHG) emissions, before other sectors, agriculture and non-energy industrial processes can transition to net zero GHG emissions. Unlike energy, it is likely that agriculture and non-energy industrial processes may never be able to be reduced to zero GHG emissions. Therefore, to achieve net zero for all GHG emissions by 2050, it may be necessary to achieve zero CO_2 emissions from the energy sector by 2040–2050.

Almost all the technologies for RE and EE scenarios are commercially available, the exceptions being hydrogen-based fuels for aviation and shipping, which together are responsible for about 5% of global GHG emissions (IEA, 2021a, 2021b), and for non-energy industrial processes such as steel-making. Research and development to reduce the costs of producing hydrogen by electrolysis is continuing and major projects are planned (e.g. Parkinson, 2021a, 2021b).

The aim of the present paper is to offer decision-makers and researchers policy options for rapid, early, climate mitigation to zero emissions in the energy sector that are not limited to technological change and, in particular, are not dependent on large-scale CO_2 removal. The focus is on trajectories that make very large reductions in energy-related emissions by 2040 and significant reductions by 2030. The study is designed to be simple and transparent, so that the impact on emissions of the future trajectory in energy consumption is revealed and the results can be easily communicated to a wider audience. Therefore, this paper constructs and analyses scenarios for mitigating CO_2 emissions from the energy sector driven by two driving forces: TPES and technological change represented by the fraction of TPES derived from fossil fuels (FF fraction). The study is intended to be complementary to the detailed, sector-specific modelling reported by the IPCC and the IEA. However, scenarios with comprehensive technological, sector-specific modelling must still satisfy the macro-level constraints exposed by considering TPES and FF fraction only. The present study exposes explicitly the impact on emissions of growth or decline in TPES in the absence of CO_2 removal, an aspect that tends to be obscured in the detailed models.

Section 2 outlines the method, reviews the basic data on the recent past evolution of the two drivers of emissions considered in this paper, and sets out scenarios for their future evolution, utilizing a simple equation for the time-evolution of the main drivers of energy-related CO_2 emissions in terms of TPES and FF fraction. The results are given in Section 3 and the policy implications are discussed in Section 4.

2. Method

The method is to create scenarios of changes over time in the direct driving forces of energy emissions, TPES and FF fraction, and to explore their respective impacts on CO_2 emissions. The scenarios do not involve GDP explicitly, which is not an end in itself (Keyßer & Lenzen, 2021), but rather an indirect driver of emissions via TPES, as is population. To introduce GDP would entail introducing additional assumptions. Actions to stop population growth (education of women, dissemination of contraceptive information and improved social security) are likely to be slow in effect.

As with all scenarios, these are not predictions of the future. However, they enable us to ask: If we continue on this or that pathway, what are the likely emissions? Which pathways should be avoided and which are likely to be effective? The qualification 'likely' is used because models are simplified versions of reality. Modelling is a low-cost method of exploring various options.

2.1 Basic equations

The IPCC AR5 report on climate mitigation (Blanco et al., 2014, p. 364) recognizes that:

> There is neither a unique method to identify the drivers of climate change, nor can the drivers always be objectively defined: human activities manifest themselves through a complex network of interactions, and isolating a clear cause-and-effect for a certain phenomenon purely through the lens of scientific observation is often difficult.

Unlike the Kaya Identity discussed in the IPCC AR5 report (Blanco et al., 2014; based on Raupach et al., 2007), we have chosen an equation in which the drivers of energy-related CO_2 emissions $C(t)$, where t is time in years, are independent of C. $C(t)$ can be expressed in terms of TPES $E(t)$,[3] the fraction $F(t)$ of TPES derived from FF, and an emissions factor $h(t)$ expressing the average emissions per unit of energy generation, as follows:

$$C(t) = E(t) \cdot F(t) \cdot h(t) \tag{1}$$

This can be simplified by recognizing that world $h(t)$ is approximately constant with value 69 megatonnes (Mt) of CO_2 per exajoule (EJ) of FF, as calculated from the observed data for 2000–2019 (see Table SM.1 in Supplementary Material). Any small improvements in the efficiency of converting FF to usable energy will produce a negligible emissions reduction compared with the magnitude of reductions needed by 2050 and indeed by 2030. Therefore, to a good approximation for the whole world,

$$C(t)/C_0 \cong [E(t)/E_0][F(t)/F_0] \quad (2)$$

where the subscript zero represents time $t = 0$.

The two drivers of emissions in Equation (2), *E* and *F*, are graphed for the period 2000–2019 in Fig. SM.1 (see Supplementary Material). Equation (2) is the basis of the scenarios for 2021–2050 presented in Section 2.3. Energy efficiency improvements are included in the trajectories chosen for *E(t)*.

Equations (1) and (2) represent territorial emissions and so cannot be applied directly to emissions embodied in exports and imports of an individual country or group of countries apart from the whole world.

2.2 Past data

Lamb et al. (2021) analyses recent trends in global and regional emissions in each of five economic sectors and many subsectors from 1990 to 2019. While this detail is valuable for the planning of end-use energy efficiency programmes, it is unnecessary for the purpose of the present paper. For past emissions and their possible drivers in less detail, IPCC AR5 (Blanco et al., 2014) considers the period 1970–2010. But since trends have changed substantially over the past several decades, we treat the recent period 2000–2019 as the basis for our business-as-usual (BAU) scenario and the starting point for other scenarios (see Table SM.1 and Fig. SM.1 in Supplementary Material).

Included in the 45% increase in TPES over the period 2000–2019 are the effects of the 76% increase in global GDP in constant US$ (World Bank, n.d.) and the 26% increase in population (United Nations, 2019). Although the quantity of global non-combustible[4] renewable *electricity* generation increased by 135% and the fraction of *electricity* generated by non-combustible renewables increased from 18% to 24% over 2000–2019 (IEA, 2021f), the fraction of TPES from FF was approximately constant over the same period. This was the result of the growth in TPES and the fact that, despite its high growth rate, the generation of non-combustible RElec is still responsible for a small fraction of TPES, 2.9% in 2000 increasing to 4.7% by 2019 (IEA, 2021f). From 2015 to 2019, RElec generation grew by 1391 TWh while total electricity generation grew by 2683 TWh. Thus RElec is chasing a retreating target (Diesendorf, 2022). To implement a future rapid decrease in the FF fraction would require the rapid electrification of FF transport and heating, where the energy is supplied by a greatly increased rate of growth of RElec (see Section 4.1).

2.3 Scenarios 2019–2050

Year 2019 has been chosen as the baseline year for scenarios to 2050, because it is the most recent pre-COVID year for which data are available for the driving forces. Although there was a 4% drop in global energy demand during 2020 resulting from the COVID-19 pandemic, there was an estimated increase of about 4.6% in 2021, resulting from a strong recovery in global economic activity (IEA, 2021c). Therefore, it appears reasonable to assume that emissions and TPES in 2019 and 2021 are approximately equal and to project forward from 2021, while ignoring the pause in 2020. The outputs of this analysis are the annual energy-related CO_2 emissions in 2030, 2040 and 2050. As explained in the introduction, the scenarios of interest are those that achieve zero (or near-zero), not net zero, CO_2 emissions[5] from the energy sector by 2050 and 2040.

The scenarios for energy-related, annual CO_2 emissions are set out in Table 1. In choosing scenarios, it has been assumed that the FF fraction *F* will not grow. This is based on the observations that *F* remained approximately constant in the range 0.80–0.82 in the period 2000–2019 (see Table SM.1 and Fig. SM.1 in Supplementary Material), and that renewable *electricity* supply has continued to grow rapidly, even during 2020. At worst, from the viewpoint of climate mitigation, *F* will remain constant and at best it will be reduced to zero by around 2040. In the scenarios, TPES is varied between 35% above and 75% below its 2019 value.

The 2030 and 2040 emissions provide an indication as to whether the cumulative emissions on the trajectory to 2040 or 2050 will be high, medium, or low. Scenario 1, the worst scenario in terms of climate mitigation considered here, comprises a linear increase in *E(t)* over 2021–2050 at the same rate as the average of the period 2000–2019 and the FF fraction *F(t)* remaining at its 2019 value of 0.81.

Table 1. Results for scenarios for global energy-related CO_2 emissions.

Scenario	Description	C/C_0 2030	C/C_0 2040	C/C_0 2050
1	*E* extrapolated to 2050; *F* constant at 2021 value	1.11	1.24	1.37
2	*E* extrapolated to 2050; *F* reduced linearly to 0 at 2050	0.77	0.43	0
3	*E* extrapolated to 2050; *F* reduced linearly to 0 at 2040	0.59	0	0
4	*E* extrapolated to 2050; *F* reduced exponentially, half-life 10 yr	0.60	0.33	0.18
5	*E* extrapolated to 2050; *F* reduced exponentially, half-life 7 yr	0.46	0.19	0.08
6	*E* constant; *F* reduced linearly to 0 at 2050	0.69	0.35	0
7	*E* constant; *F* reduced linearly to 0 at 2040	0.53	0	0
8	*E constant*; *F* reduced exponentially, half-life 10 yr	0.54	0.27	0.13
9	*E* constant; *F* reduced exponentially, half-life 7 yr	0.41	0.15	0.06
10	*E* reduced linearly to 50% at 2050; *F* reduced linearly to 0 at 2050	0.58	0.23	0
11	*E* reduced linearly to 50% at 2050; *F* reduced linearly to 0 at 2040	0.45	0	0
12	*E* reduced linearly to 50% at 2050; *F* reduced exponentially, half-life 10 yr	0.45	0.18	0.07
13	*E* reduced linearly to 50% at 2050; *F* reduced exponentially, half-life 7 yr	0.34	0.10	0.03
14	*E* reduced linearly to 25% at 2050; *F* reduced linearly to 0 at 2050	0.44	0.09	0
15	*E* reduced linearly to 25% at 2050; *F* reduced linearly to 0 at 2040	0.34	0	0
16	*E* reduced linearly to 25% at 2050; *F* reduced exponentially, half-life 10 yr	0.35	0.07	0.03
17	*E* reduced linearly to 25% at 2050; *F* reduced exponentially, half-life 7 yr	0.29	0.04	0.01

Notes: The scenarios are based on Equation (2). *E* is the total primary energy supply (TPES) and *F* is the fraction of TPES supplied by fossil fuels. '*E* extrapolated to 2050' means *E* is projected linearly from 2021 with the same slope as from 2000 to 2019. C_0 is *C* at 2021, assumed to be approximately the same as at 2019.

3. Results

The results are set out for 17 scenarios in Table 1 and graphed for four of these scenarios in Figure 1. Three of the graphed scenarios (S12, S14 and S16) may be compatible with both the requirements of climate science and credible technological change, as discussed in Section 4.1; S1 is business-as-usual.

The principal results are:

1. Scenario 1, which has a continuation of the trends in *E* and *F* from 2000–2019, results in an 11% increase in emissions by 2030 and a 37% increase by 2050.
2. The pathway to achieving zero emissions at 2050 matters, because the greater the cumulative emissions (approximated by the areas under the scenario lines), the greater is the risk of crossing climate tipping

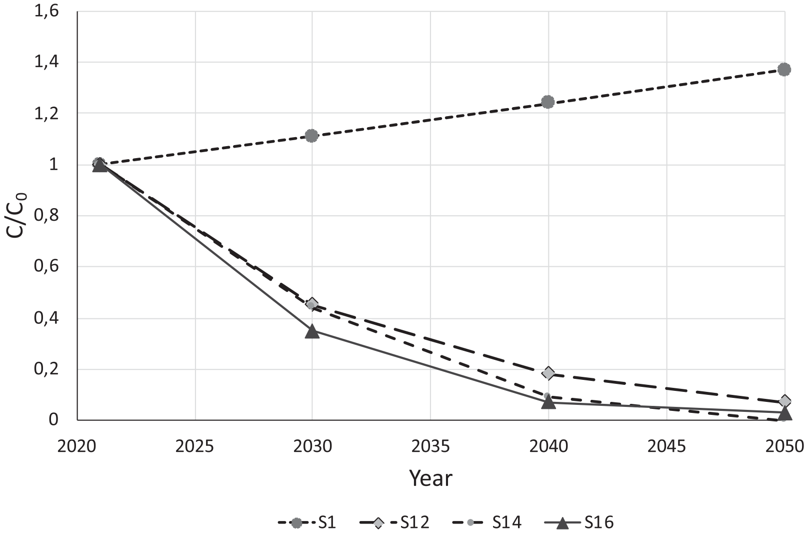

Figure 1. Four scenarios for global energy-related CO_2 emissions selected from Table 1.

Note: Scenario 1 is business-as-usual and is unacceptable in terms of climate science; the other three may be possible in terms of technology and policy.

points before zero emissions can be reached (IPCC, 2018, section 3.5; Steffen et al., 2018; Lenton et al., 2019).

3. The following nine scenarios obtain emission reductions of at least 50% by 2030, at least 80% by 2040, and zero or nearly zero by 2050: Scenarios 5, 9, 11–17. These are of particular interest in terms of the 1.5°C global heating aspirational target (see Section 4.1).

4. Discussion, policy implications, and future research

This section first discusses the credibility of the scenarios for TPES, then summarizes the well-known policies to drive technological change to reduce the FF fraction to zero on or before 2050, and finally discusses policies for socioeconomic and political change to reduce the demand for energy services and hence open the possibility of at least 50% reductions in emissions by 2030 and at least 80% reductions by 2040.

4.1 How credible are the modelled TPES reductions?

If we do not wish to rely on CO_2 removal, then we must attempt to achieve even faster emission reductions than the illustrative scenario SSP1-1.9 of IPCC (2021, Fig. SPM.4 and Table SPM.1), all of which assume CO_2 removal. The only scenarios of the present analysis that could in theory achieve energy-related CO_2 emission reductions of at least 50% by 2030 and at least 80% by 2040 *while TPES is increasing or constant* are Scenarios 5 and 9, respectively, but in both cases, *F* must be reduced exponentially with a half-life[6] of seven years. This requires policies to accelerate the retirement of FF power stations, motor vehicles and heating equipment, and simultaneously to accelerate the growth of RElec, EVs, and electrical heating equipment (see Section 4.2). While solar PV farms and wind farms can be planned and constructed in three years and utility-scale batteries in less than one year, the rate-limiting tasks for rapid RElec growth stem from the need to build new, high-voltage transmission lines and storage apart from batteries, and to reform electricity markets to be more suitable for systems where most electricity is generated by variable renewables. Nevertheless, a few countries (e.g. Australia, Denmark, United Kingdom) have doubled their non-combustible RElec generation over the past 7–8 years (IEA, 2021e) and this growth rate could be extended to other countries. However, transitioning transport and FF heating to electricity are slower processes (REN21, 2021; IEA, 2021e). Therefore, the exponential growth of RE (not RElec) with a doubling time of seven years (Scenarios 5, 9, 13) appears impossible, as does linear growth to 100% RE (not RElec) by 2040 (Scenarios 3, 7, 11, 15).

This leaves Scenarios 12, 14, and 16 as possibly compatible with both the requirements of climate science and credible technological change (Figure 1).

Apart from RElec and EE, are there any other low-carbon energy technologies that could accelerate the transition? Existing nuclear power stations are much slower to build than wind and solar (Koomey & Hultman, 2007; Schneider & Froggatt, 2021, pp. 53–56) and their electricity is more expensive than from wind and solar, even after including additional storage (Graham et al., 2020; Lazard, 2020). Small modular reactors, which are under development, are the subject of much debate and uncertainty. What is clear from the literature is that they have several potential benefits between which there are trade-offs; they are unlikely to become commercially available until the 2030s at the earliest, and that, unless they can be mass-produced (i.e. become truly modular), their electricity would be more expensive than from large conventional reactors (Ramana & Mian, 2014; IEA, 2019; Mignacca & Locatelli, 2020; Schneider & Froggatt, 2021, pp. 280–289). Proponents of nuclear fusion do not expect it to generate electricity on a commercial scale before 2050; the World Nuclear Association (2021) expects Demo, to demonstrate the first large-scale production of fusion electrical power on a continual basis, to be constructed 'after 2040'. The UK government (2021a) announced £220 million for the conceptual design of a fusion power station by 2040.

Fortunately, global scenarios in which TPES declines substantially are possible, because the transition from the combustion of FF to non-combustible RE technologies delivers huge improvements in the efficiencies of energy conversion from primary to end-use energy (Bogdanov et al., 2019, 2021; Jacobson et al., 2015, 2018). A RE future will be mainly an electrical energy future and one unit of electrical energy from RE, or one unit of FF electricity saved by demand reduction, can substitute for 2–4 units of FF primary energy and its emissions, depending on the FF replaced and the type of FF power station. Substituting electric heat pumps for low-temperature heating by FF combustion gives similar efficiency improvements. Electric vehicles with 75–90% energy conversion efficiencies can replace most internal combustion engine vehicles with 15–30% efficiencies. Taking account of these energy conversion efficiency gains, offset partially by the low efficiencies of Power-to-X processes[7], Bogdanov et al. (2021) calculate that the transition to 100% RE could provide 50% savings in TPES. Extrapolating the pre-COVID linear growth in TPES from 2021 to 2050 (see Table 1) gives an increase of 37%. Taking account of energy conversion efficiency halves this, giving a decrease of 21.5% in the estimated 2021 value of TPES. Additional large reductions can be obtained from improvements in the efficiency of energy use in buildings and industries (IEA, 2020a, section 3.5), reducing TPES in 2050 to more than 50% below the 2019 value. Behaviour changes, fostered by government policies, could reduce the demand for energy services in high-income countries (Section 4.3). Therefore, reductions in global TPES could possibly reach 75% below the 2019–2022 level by 2050. Such reductions may be necessary for stabilising anthropogenic climate change.

4.2 Policies for technological change

Following the broad strategy outlined in the introduction, the key policies to drive the rapid transition to large-scale RElec, its uses for transportation and heating, and end-use energy efficiency are summarized in Table 2.

Reducing energy demand will reduce the task of RE, especially in light of the uncertainty as to whether CO_2 removal will be able to contribute significantly to low-carbon energy supply. Demand reduction can be achieved by the increased energy conversion efficiency (Section 4.1), behaviour change to reduce non-essential energy services (Section 4.3) and increased end-use energy efficiency (this section):

While the policies for technological change are mostly straightforward, the policies needed for socioeconomic change will be more difficult to implement.

4.3 Policies for socioeconomic change

The IEA's NZE2050 scenario includes a reduction in energy-related CO_2 emissions by behaviour changes that reduce the demand for energy services (IEA, 2020a, pp. 142–143). However, this step forward by the IEA is still focused on types of behaviour changes that offer useful but minor additional reductions in energy consumption, such as reduced speed limits on roads, adjusting the temperature settings for heating and cooling of buildings, increased car sharing, replacing some long-distance air travel with video conferencing, washing clothes in cold water, line clothes drying and, outside the energy sector, different agricultural practices as well as shifts to a vegetarian diet. But 40% of these emission reductions rely on individual behaviour change independent of government policies. Much more could be done by appropriate government policies, given sufficient political will and community support.

Scenario modelling by D'Alessandro et al. (2020) supports the thesis of Schor and Jorgenson (2019) that 'economic policies ought to go beyond the stimuli for technological solutions and move away from the growth imperative to achieve large-scale reductions in emissions'. Not only do policy options have to be broadened beyond the energy sector and beyond technological change, they must also include socioeconomic, political and cultural changes to drive behaviour changes for degrowth. Examples of such policies, to be implemented initially in the high-income countries, are:

- Expanding public goods and services, such as public transport, public education, public housing, and free or low-cost basic medical care; more generally, Universal Basic Services (Coote et al., 2019; Hickel, 2020, chapter 5).
- Fostering the increased reuse of products and recycling of materials (Raworth, 2017; Schröder et al., 2021). Policies include regulations and standards to reduce planned obsolescence, facilitating leasing instead of buying products, caps on global production, and environmental tax reform.

Table 2. Policies for technological change.

Technology type or supporting issue	Policy
RElec and storage	Establish RElec zones with new and upgraded transmission links to the main grid (AEMO, 2020) Reverse auctions with contracts-for-difference (Buckman et al., 2019) Finance for energy storage,[9] for example, where policy can direct a national development bank to stimulate investment (Zhang, 2022) Reform of electricity markets to facilitate the growth of RElec and in particular, to maintain reliability of supply, increase flexibility in operation, and manage two-way flows of electricity, millions of power stations of various sizes, and demand response (Aggarwal et al., 2019; Ela et al., 2016; Milligan et al., 2016)
Transport	Grants for battery electric vehicles (BEVs) and fast charging stations; limits on motor vehicle emissions; replacement of government vehicle fleets with BEVs (IEA, 2021d) Funding of infrastructure for improved urban public and active transport
Heating	Incentives for replacing residential and industrial natural gas heating by electric heat pumps or 'green' gas (ACEEE, n.d.; IRENA, IEA & REN21, 2020; REN21, 2021, pp. 69–70; UK Government, 2021b)
Pricing	A carbon price whose value reflects to some degree the environmental and social costs of using FF as well as carbon pricing within its own borders. In a recent example, the European Union is planning to place a carbon tariff on imports from countries that do not already have a carbon price (European Parliament, 2021)
FF phase-out	Fossil Fuel Non-Proliferation Treaty where a step in this direction was taken at COP26 with the formation of the Powering Past Coal Alliance (PPCA, n.d. see also FFNPT, n.d. and Newell & Simms, 2020)
Social justice	International climate justice policies (Jafry, 2019; Timperley, 2021), where high-income countries, which are responsible for the vast majority of emissions, must assist and compensate low-income countries Social justice policies within countries, where policies are needed to assist workers in the FF and related industries by means of retraining, relocation, employment creation and pensions (Campbell, 2021; Mayer, 2018; Scottish Government, 2020)[10]
End-use energy efficiency	Mandatory energy audits, energy labelling and energy rating of buildings, and mandatory disclosure of energy ratings when the buildings are sold or rented (Brown, 2015; Economidou et al., 2020; Fekete et al., 2021; IEA, 2020b) Incentives (e.g. building regulations) for the use of low-energy, low-carbon, and recycled materials
Reductions in rebound	Rebound arises from increased, low-cost energy efficiency, energy conservation, and RElec; it can be reduced by carbon pricing, progressive taxation, regulations and standards for energy efficiency, consumption information, identity signalling, and feebates/rebates (Font Vivanco et al., 2016)
Reducing life-cycle emissions from low-carbon technologies	Grants for using RElec in the manufacturing of RE, energy efficient and energy storage technologies[11] Incentives to foster the implementation of particular energy storage technologies with high energy returns on energy invested (EROIs)[12]

- Shrinking environmentally and socially destructive industries in addition to FF industries (e.g. native forest logging, armaments, toxic chemicals) by environmental tax reform, caps on global production, international bans, regulations and removing subsidies (Hickel, 2020, chapter 5).
- A wealth tax to reduce consumption by the world's biggest consumers, the rich. Consumption by affluent households worldwide is by far the strongest determinant and the strongest accelerator of increases of global environmental and social impacts (Chancel & Piketty, 2015; Teixidó-Figueras et al., 2016; Wiedmann et al., 2020).
- Introducing a government-funded job guarantee to provide jobs at the minimum wage for everyone who wants to work (see Section 4.4 and Mitchell (1998)). This would provide jobs, with training, in environmental protection, community development and other socially beneficial projects, as well as a buffer for trade cycles.
- Urban planning to reduce intra-city travel and encourage public and active (non-motorised) transport (Newman & Kenworthy, 2006).
- Stabilising the population, since every additional person in the high-income and rapidly developing countries will have, on average, high per capita consumption and hence high climate impacts. A key

supporting policy is improving social security, so that people do not have to depend on their children for support in poverty, old age, disability or misfortune (Holm, 1975).

The barriers to these policies must be discussed openly and overcome. Economic growth is driven by the neoliberal economic system (see degrowth references below) and vested interests with enormous political power within and across nations. Both these forces exert pressure on governments to continue with business-as-usual (Klein, 2014; Moe, 2015; Pearse, 2007). The following policies would reduce the resistance by vested interests in particular to climate mitigation policies, at least in nominally democratic countries, and have benefits far beyond climate mitigation:

- a ban on political donations together with the introduction of publicly funded elections;
- establishment of national integrity commissions to reduce corruption in government decision-making;
- tighter restrictions on the revolving door in jobs between vested interests in business and politicians/political advisers;
- a review leading to the reduction of the legal powers of corporations; and, in particular,
- removal of mining and forestry industries' legal right to access land and other natural resources against the wishes of owners and traditional custodians.

To limit climate change and protect the environment more broadly, the case for degrowth to a steady-state economy, with throughput reduced to a level compatible with an ecologically sustainable society, is gaining wider discussion and the concept of 'sustainable prosperity' is emerging (Daly, 1977; Dietz & O'Neill, 2013; D'Alessandro et al., 2020; D'Alisa et al., 2014; Hickel, 2020; Hickel & Kallis, 2020; Jackson, 2017; Victor, 2019). Degrowth is defined here in biophysical terms as *equitable downscaling of throughput (that is, energy, materials and land-use) and stabilization of population numbers, while increasing social equity and wellbeing*.

One of the justifications for this proposed socioeconomic transition comes from the evidence that absolute decoupling between economic growth and GHG emissions is very rare in practice and, when it does occur, is limited geographically and temporally (Haberl et al., 2020; Parrique et al., 2019). In other words, 'green growth' is a contradiction in terms. Many proposals for a Green (New) Deal as part of the economic recovery from COVID-19 (e.g. Ocasio-Cortez & Markey, 2019; Simon, 2019) do not include explicit restrictions on consumption or economic growth. These, and many other 'green' scenarios by environmentalists and environmental organizations that support green growth, reassure decision-makers that technological change without socioeconomic change is sufficient for climate mitigation and environmental protection in general. Political resistance to reducing consumption, resulting from pressure by vested interests and the ideology of growth, is likely to be formidable. Nevertheless, the economic recovery from the COVID-19 pandemic offers an opportunity to implement this socioeconomic transition whose proponents reject decoupling and hence 'green growth' on the grounds that the former is not supported by evidence and the latter is environmentally inadequate (Agora Energiewende, 2020; Diesendorf, 2020; Haberl et al., 2020; Parrique et al., 2019; Taherzadeh, 2021).

4.4 Financing the transition

A major challenge is funding the transition while achieving full employment. Modelling by D'Alessandro et al. (2020) finds that policies to attain low-carbon emissions together with social equity require substantial levels of public expenditure. Modern Monetary Theory (Kelton, 2020; Mitchell et al., 2019) offers the macroeconomic framework in which sovereign states that issue their own fiat currencies[8] are not like households in being constrained to spend only their revenue. Instead, they can create debt-free money, so long as they manage their currency so that it retains its value. These countries could help finance the necessary post-COVID transitions to zero emissions and steady-state economies, as well as job guarantees in their own countries.

4.5 Limitations and suggested further research

One of the limitations of the present study is that, in expressing changes in energy-related CO_2 emissions at a macro level in terms of changes in TPES and FF fraction, it cannot examine impacts on emissions driven by growth in GDP and population. It also cannot examine the detailed impacts of various energy supply and demand policies and measures as done by comprehensive technological, sector-specific modelling. The value of the present approach is to complement the latter.

Another limitation is that the analysis is provided for the whole world and so does not identify where, geographically and politically, the drivers of emissions or emissions reductions are located. Energy-related CO_2 emissions and TPES are increasing rapidly in rapidly growing (RapidG) economies (see Table SM.2 in Supplementary Material). This is not surprising, because these economies are doing most of the manufacturing for the high-income economies. Energy embodied in traded goods must be addressed in developing climate mitigation policies (Wiedmann & Lenzen, 2018). For example, China is a net energy exporter in terms of embodied energy, and its embodied energy trade surplus was 21.4 EJ in 2007 (Cui et al., 2015); over the period 2009–2015, the energy embodied in China's exports was about 28.1 EJ (Zhu et al., 2020) or about 16% of China's TPES in 2015. The climate crisis opens up an opportunity for RapidG and other developing countries to produce zero- and low-carbon goods for export to high-income countries (Trollip et al., 2022). Further research is needed to model climate scenarios that take account of international trade while not assuming CO_2 removal.

Therefore, to reduce and reverse the growth in global TPES, high-income countries must reduce their consumption and assist developing countries to grow RE and EE through technology transfer and investment (Zhu et al., 2020). These countries will also need to become less dependent upon exports to, and finance from, high-income countries (Gadha et al., 2022).

5. Conclusion

Over the past two decades, renewable energy (RE), almost entirely in the form of renewable electricity (RElec), has grown rapidly, but so has demand and thus total primary energy supply (TPES). As a result, the fraction of global TPES supplied by fossil fuels (FF) has remained approximately constant over 2000–2019. At 2015–2019 rates of growth of TPES and RE, RE cannot replace all TPES and so energy-related emissions are expected to increase through 2050 and beyond. However, we can expect accelerated growth of RE supply as transport and, eventually, heating by FF, become electrified and thus increasingly powered by RElec. Furthermore, the rate of growth of TPES will be reduced automatically during the transition to RElec as a result of the increased efficiency of energy conversion between TPES and electricity, as discussed in Sections 2.2 and 4.1. This will assist the task of ending the growth in TPES.

Nevertheless, the energy scenarios developed in this paper, which exclude CO_2 removal and technological breakthroughs, indicate that, even if the FF fraction could be reduced to zero or near-zero by 2050, while energy demand grows or is held constant, energy-related emissions will still be high in 2030 and, in some cases, quite high in 2040. Therefore there is a high (unquantifiable) risk of crossing a climate tipping point before 2040. The limitations of a transition to RE are partly technological and partly non-technical, with the non-technical limitations, for example, relating to the need to reform electricity markets, and to people's reluctance to replace 'prematurely' working technologies, such as ICE vehicles and gas heating systems.

In the absence of compelling evidence that the gap between growing energy demand and RE supply can be closed by CO_2 removal or by other technological breakthrough, the technological transition to reduce the FF fraction to zero must be supplemented by the reduction in energy consumption, and hence a reduction in global TPES, especially by the high-income and rapidly growing (RapidG) economies. Technological change, in the form of improved efficiency of energy use and improved energy conversion efficiency, is necessary and could make a substantial contribution to reducing energy consumption and TPES, but it is unlikely to be sufficient to reverse energy demand growth in the high-income and RapidG economies that together produce three-quarters of today's global emissions. This analysis shows that Scenarios 12, 14, and 16 may satisfy both the requirements of climate science and technological change (see Table 1 and Figure 1).

In the absence of evidence of absolute decoupling between economic growth and GHG emissions over large regions and long periods of time, reduction in energy consumption beyond technological energy efficiency would have to be achieved in the high-income and RapidG economies. Beyond technological change, demand reduction could be achieved by socioeconomic and political change, which can be driven by policies designed to facilitate behavioural change. Because a large proportion of economic activity and hence energy consumption of the RapidG economies is devoted to manufacturing 'goods' for the high-income countries, the latter countries could reduce consumption and hence demand for such 'goods', thus reducing RapidG emissions and hence global emissions. At the same time, the high-income countries could assist the RapidG and less-developed economies generally to become less dependent upon exports with high embodied carbon to high-income countries.

The case for a transition to a steady-state economy with low throughput and low emissions, initially in the high-income economies and then in rapidly growing economies, needs more serious attention and international cooperation.

Notes

1. This is a large-scale simulation model designed to replicate how energy markets function and generates detailed sector-by-sector and region-by region energy projections.
2. However, there is debate about the possible timescale and whether there are significant roles for certain technologies, namely bioenergy, nuclear energy or large-scale CO_2 removal.
3. A consumption-based approach is also possible but not pursued here, because greenhouse gases from electricity supply are emitted from the combustion of primary energy.
4. We focus on non-combustible RE (e.g. wind, solar and hydro-electricity), because biofuels are unlikely to make a large contribution in the future on account of environmental concerns.
5. Reducing CO_2 emissions to zero or near zero will automatically reduce CO_2e to near-zero, because fugitive (methane) emissions will be greatly reduced.
6. Half-life is the time required for the decaying quantity to fall to half its initial value.
7. X represents such processes as electrolysis of water to produce hydrogen for many purposes including the manufacture of steel, fertilisers and chemicals; water pumping; and seawater desalination.
8. Government-issued currency that is not backed by a physical commodity such as gold, but rather by the government that issued it. States that are sovereign in currency include the USA, UK, Japan, China and Australia, but not individual members of the European Union.
9. Relevant types of storage technologies include grid-integrated batteries, pumped hydro, and compressed air. Financing policies are needed because, where banks and other financial institutions may hesitate to lend, a government-funded lender, such as Australia's Clean Energy Finance Corporation (CEFC, n.d.) can stimulate investment.
10. In addition to the ethical case for social justice, this policy has potential economic benefits and would assist in gaining worker and community support for the more radical climate and energy policies (see Section 4.3) to reduce energy demand substantially and, beyond that, to cut all GHG emissions.
11. At present, construction of RE and EE technologies requires some use of FF. Already RE is beginning to be used for mining and processing the raw materials and for the electricity used in manufacture, so that over time RE and EE technologies will be made increasingly with RE inputs (Diesendorf, 2022, section 3.6).
12. For example those that are net generators of electricity such as hydro-electricity (not pumped) and concentrated solar thermal power with thermal storage. (Diesendorf & Wiedmann, 2020)

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