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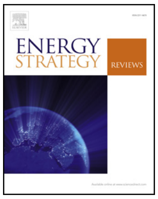

Energy system changes in 1.5 °C, well below 2 °C and 2 °C scenarios

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ABSTRACT

Meeting the Paris Agreement's goal to limit global warming to well below 2 °C and pursuing efforts towards 1.5 °C is likely to require more rapid and fundamental energy system changes than the previously-agreed 2 °C target. Here we assess over 200 integrated assessment model scenarios which achieve 2 °C and well-below 2 °C targets, drawn from the IPCC's fifth assessment report database combined with a set of 1.5 °C scenarios produced in recent years. We specifically assess differences in a range of near-term indicators describing CO2 emissions reductions pathways, changes in primary energy and final energy across the economy's major sectors, in addition to more detailed metrics around the use of carbon capture and storage (CCS), negative emissions, low-carbon electricity and hydrogen.

1. Introduction

The Paris Agreement has ignited intense interest in the goal of limiting global temperature increase to 1.5 °C, through the formulation of its Article 2.1a) which states the Paris Agreement's aim of "Holding the increase in global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit temperature increase to 1.5 °C above pre-industrial levels, …" [1]. To date there has been relatively limited analysis of how energy systems might have to transform in order to make this goal achievable. One such analysis [2] detailed the differences between 2 °C and 1.5 °C scenarios on the basis of 10 macro-level metrics, including a range of costs metrics (near- and long-term mitigation costs, carbon prices and electricity prices) as well as emissions metrics (cumulative CO_2 removal, rates of decarbonisation and rates of CO_2 reduction in the electricity, industry, transport and buildings sectors). The lower temperature goal implies faster decarbonisation, higher carbon prices and electricity costs, as well as an earlier and greater role for net negative emissions technologies such as bioenergy with carbon capture and storage (BECCS).

However, there has so far been no systematic assessment of the differences between 2 °C, well below 2 °C and 1.5 °C pathways across a wide ensemble of scenarios, with a view to understanding the underlying drivers of change in the energy system, for example by analysing how the different sectors' mix of energy vectors and energy intensity changes over time. Such an assessment, as presented here, should help businesses, governments and other stakeholders concerned with addressing climate change to identify which sectors and energy vectors to focus on in order to achieve the more challenging goal of a 1.5 °C temperature change limit, as opposed to the 2 °C limit which has formed the focus of the vast majority of recent low-carbon pathways analytical studies (see for example Dessens et al. (2016) in this journal [3] for a recent meta-analysis of the implications of such 2 °C pathways).

The rest of this paper is structured as follows: Section 2 outlines the methods used to construct a database of below 2 °C scenarios to analyse the implications of different levels of mitigation stringency on energy system transformations; Section 3 reports on a wide range of indicators intended to give an in-depth picture of how the energy system transforms over the 21st century in the different groups of scenarios; Section 4 provides a contextual discussion, identifies limitations of the analysis and points towards where further research on well below 2 °C and 1.5 °C scenarios would add further insights into energy transformation pathways; Section 5 concludes.

2. Methods

The study combines scenarios from the IPCC AR5 database [4], which has a large number of scenarios achieving a median temperature change as low as 1.7–1.8 °C (and a very limited number achieving less than this), with a group of 1.5 °C scenarios from a separate set of mitigation studies [2]. The AR5 database contains a total of 1184 scenarios, 524 of which are associated with probabilistic estimates of long-term temperature change. The others are not associated with such changes because they do not represent all systems which emit greenhouse gases, but rather focus on the emissions of CO_2 from the global

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energy system. Only those scenarios with associated probabilistic estimates of long-term temperature changes are used here. These are categorised into 3 different groups: the first group, referred to as “below 1.5 °C”, contains scenarios which result in a median 2100 warming of below 1.5 °C (which means there is a 50% chance of limiting warming to less than 1.5 °C); the second group, referred to as “below 1.75 °C”, contains scenarios which result in a median warming of between 1.5 °C and 1.75 °C; and the third group, referred to as “below 2 °C”, contains scenarios which result in a median warming of between 1.75 °C and 2 °C.[1] This provides a perspective on how 1.5 °C, “well below 2 °C” (here interpreted as those which achieve between 1.5 °C and 1.75 °C in 2100) and below 2 °C (here interpreted as 1.75–2 °C in 2100) scenarios differ. Our interpretation here does not imply any recommendation of what “well below 2 °C” should mean in the context of the Paris Agreement.

The grouping results in 5 “below 1.5 °C” scenarios, 73 “below 1.75 °C” scenarios and 125 “below 2 °C” scenarios from the AR5 database. The small number of 1.5 °C scenarios reflects the context in which scenario analysis has been undertaken in previous years – namely that the dominant climate goal discussed in international policy circles was the 2 °C limit, with little attention to even more stringent climate objectives. It is thus useful to bolster the AR5 database with 1.5 °C scenarios from existing model runs which produce comparable metrics, so as to allow a more detailed comparison of 1.5 °C with higher temperature pathways. These come from the analysis undertaken using the MESSAGE and REMIND integrated assessment models in a number of analyses [6–8] as summarised in Rogelj et al. (2015) [2]. In total they increase the number of “below 1.5 °C” scenarios from 5 to 42.

The AR5 database includes a variety of output metrics on the energy system, including the primary, secondary and final energy for the principal energy vectors at these levels, split by major economy sector, and with associated emissions. The Supplementary Material Table S1 contains the full list of metrics analysed in this assessment and Fig. S1 shows how these are categorised in a primary to final energy hierarchy, including emissions from the different transformation and final use processes. The same metrics are used for the additional 1.5 °C scenarios from Rogelj et al. (2015) [2], with the exception of mitigation cost metrics which are unavailable as their quantification requires a reference scenario in the absence of climate mitigation measures, which was not available.

It should be noted that the scenario dataset used here is an “ensemble of opportunity”. It is not a random sampling of future possibilities of how the world economy should decarbonise, but rather a dataset consisting of a large number of scenarios which have been run with varying objectives, such as timing of mitigation action, technology availability and degree of energy efficiency improvement, and which have either been deliberately designed to achieve specific temperature change objectives, or which happen to achieve them as a result of the mitigation options implemented in the models.

Fig. 1 shows the range of models used in each grouping of scenarios, whilst Table S2 shows the full scenario name and model used in each of the 240 scenarios explored in this study. The 5 models that make up the scenario dataset (GCAM, IMAGE, MESSAGE, MERGE and REMIND) are all considered to be models of the “high” low-carbon supply technology variety, whilst, across a large range of integrated assessment models, they all consistently show the highest levels of abatement relative to baselines, the lowest carbon intensity relative to energy intensity and the lowest fossil fuel and industrial CO_2 emissions levels under high carbon tax scenarios ($200/t$CO_2$ in 2005 US$) associated with deep mitigation [9]. It is therefore perhaps unsurprising that these models can achieve and provide the lowest temperature change scenarios from the broader group of integrated assessment models. The dominance of MESSAGE and REMIND in the below 1.5 °C and below 2 °C scenarios (they constitute 88% and 85% of these scenario groups respectively), compared to their relative under-representation in the below 1.75 °C scenarios (where they constitute 32% of scenarios) requires some further analysis and discussion of the results of the below 1.75 °C temperature category, as is undertaken in Section 3.

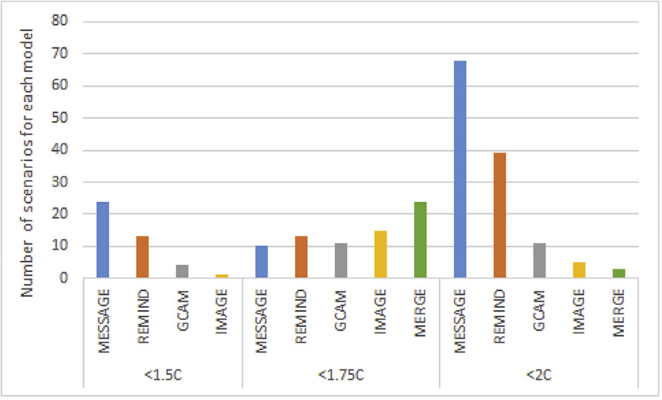

Fig. 1. Number of scenarios for each integrated assessment model across scenario groupings.

In addition to Fig. 1, Fig. S3 (Supplementary material) highlights the different numbers of scenarios in each temperature category which fall into different sub-categories (immediate versus delayed action, full versus partial technology portfolio, and lower versus standard energy intensity). For the below 1.5 °C temperature category, the vast majority of scenarios are immediate action and full technology portfolio, whilst the scenarios are evenly split between lower and standard energy intensity. By contrast, for the below 1.75 °C temperature category, only about 1/3rd of scenarios are for immediate action, and a small minority are for lower energy intensity, although as with the below 1.5 °C scenarios, the majority are for full technology portfolio. The below 2 °C temperature category, like the below 1.75 °C category, is dominated by standard energy intensity reduction scenarios, whilst being fairly evenly split between the immediate and delayed action as well as the full and partial technology scenarios.

These caveats aside, the scenario database used in this analysis constitutes a readily-available, easily interrogated and usefully large set of scenarios which can be used to gain a first set of insights into how integrated assessment and energy systems models respond to differing levels of stringency in below 2 °C mitigation goals. Fig. S1 demonstrates that the scenarios are broadly speaking similar in terms of their assumed GDP and population growth levels, which also aids the validity of comparing the energy system transformations across them.

3. Results

In the following sub-sections, all indicators are presented using box and whisker plots, with the boxes representing the interquartile range and including the median value. Whiskers show the extreme values of the range excluding outliers, here using Tukey's method of defining outliers as any values which are greater than a distance of 1.5 times the interquartile range from the edge of that range. Each Figure in the results section also shows the number of scenarios in each scenario group for which data for each indicator is available.

3.1. CO_2 emissions

Global CO_2 emissions from the combustion of fossil fuels as well as from industrial processes (principally cement production) are significantly lower in the below 1.5 °C scenarios compared to the below 1.75 °C and below 2 °C scenarios, as shown in Fig. 2a). It is useful to

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[1] Note that these scenarios have not been selected according to a specific climate forcing class as specified by the IPCC's fifth assessment report [5], but rather according to the achieved median increase in global mean temperature by 2100 as reported in the AR5 database.

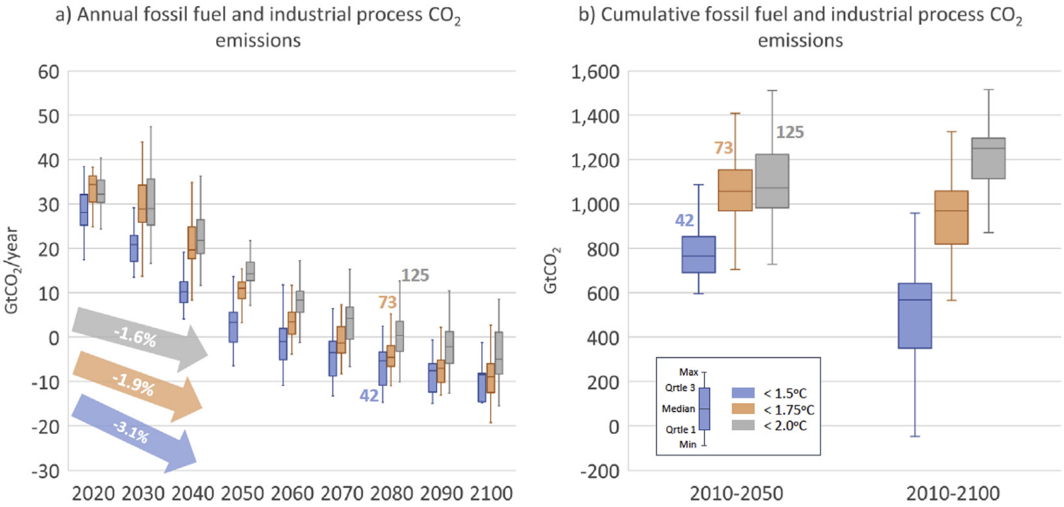

Fig. 2. Annual and cumulative global CO_2 emissions from fossil fuel combustion and industrial processes Arrows on Fig. 2a) refer to linear average annual reduction in CO_2 over the 2020–2040 period, expressed as a median value across each group of scenarios. Numbers on chart areas refer to number of scenarios in each group for which indicator data is available.

focus on near-term emissions reduction rates as these will have a critical role in determining the feasibility of meeting the long-term temperature goals. Over the period 2020–2040, the below 1.5 °C scenarios require far quicker annual average emissions reductions, at 3.1% per year (median) in linear terms.[2] This is significantly higher than the rate of the median below 1.75 °C scenarios (at 1.9% per year) and almost twice as fast as the median of the below 2 °C scenarios (at 1.6% per year).

Owing to the strong linear proportionality between cumulative CO_2 emissions and long-term temperature change (see Fig. 10 of [10]), it is also useful to understand how this cumulative CO_2 metric differs between scenarios. This relationship has been assessed to be of the order of 0.2–0.7 °C per 1000 $GtCO_2$ [11]. Fig. 2b) shows that in the climate model setup applied by the IPCC AR5 assessment, the cumulative 2010–2100 CO_2 in the below 1.75 °C scenarios is ~300 $GtCO_2$ lower than the below 2 °C scenarios, with the below 1.5 °C scenarios a further 400 $GtCO_2$ lower than the 1.75 °C scenarios. This difference – of about 700 $GtCO_2$ to achieve a median warming of 1.5 °C compared to 2 °C - is about half the total available 21st century cumulative CO_2 emissions allowance for the 2 °C goal. This follows from the linear proportionality between cumulative CO_2 emissions and long-term warming and the fact that warming to date is already about 1 °C relative to pre-industrial levels [12]. Looking at the 2010–2050 period, cumulative CO_2 is virtually the same in the below 1.75 °C and below 2 °C scenarios, but significantly lower in 1.5 °C scenarios. This is potentially an important indicator that, according to the models, there may be relatively insignificant differences between near-term emissions reductions if aiming for a below 1.75 °C versus below 2 °C goal, but that if the more stringent below 1.5 °C goal is sought, then near-term more drastic emissions reductions are likely to be required.

For the 1.75 °C category which is least dominated by the MESSAGE and REMIND models, the median emissions reduction rate is 2.0% per year for just these two models' scenarios, compared to 1.9% per year for all models in this temperature category. In addition, Fig. S3 shows how the 2020–2040 CO_2 average annual emissions reduction rates vary across the immediate/delayed action, full/partial technology portfolio and standard/low energy intensity criteria. The Figure demonstrates that, whilst there is some variation across these criteria within each temperature sub-category, lower temperature targets are associated with higher average annual emissions reductions than for higher temperature targets.

3.2. Mitigation costs

Fig. 3a) shows GDP losses for only the below 1.75 °C and below 2 °C scenarios. The majority of below 1.5 °C scenarios, as reported in Rogelj et al. (2015) [2] were not run against a baseline counterfactual scenario, so no mitigation cost metric was generated for them. Median GDP losses (as a share of total global GDP) are about 1–1.5% points greater in the 1.75 °C scenarios over the period 2030–2080 when compared to the below 2 °C scenarios, though after this the difference in median losses diminishes. The headline findings of the IPCC's fifth assessment report WGIII on mitigation, are that across the range of models the economic costs (in terms of consumption losses) of achieving “450 ppm” pathways are approximately 1–4% in 2030, 2–6% in 2050 and 3–11% in 2100 (with the range reflecting the 16th – 84th percentiles of results) [13]. This is broadly reflected by Fig. 3a), even though it shows the slightly different cost measure of GDP loss. The present value GDP loss over the period 2020–2100, using a discount rate of 5%, is also shown (the right-most bar on the left hand pane), indicating a median GDP loss of 4.5% for the below 1.75 °C scenarios, versus 3.5% for the below 2 °C scenarios.

Fig. 3b) shows that the carbon price in the below 2 °C scenarios rises to a median level of $1600/t$CO_2$ by 2100, with the below 1.75 °C scenarios seeing a similar level by this time. However, in the first half of the century the below 1.75 °C scenarios' carbon prices tend to be higher than those of the below 2 °C scenarios. The below 1.5 °C scenarios have markedly higher carbon prices, more than twice as high as those of the below 1.75 °C and below 2 °C scenarios in the first half of the century, with the multiple increasing beyond 2050. By 2100 the median carbon price of the below 1.5 °C scenarios is almost $4500/t$CO_2$, about three times that of the other scenarios' medians, and rising in the last two decades at more than $1000/t$CO_2$, a previously-identified marker of extreme challenge in achieving the low-carbon transition [8,14]. In terms of near-term indicators, these scenarios suggest that by 2030 we might expect to see global average carbon prices in excess of $100/t$CO_2$ (median $145/t$CO_2$) if we are on a below 1.5 °C pathway, with prices in the range $50–100/t$CO_2$ (median $69/tCO2) and less than $50/t$CO_2$ (median $45/t$CO_2$) for below 1.75 °C and below 2 °C scenarios respectively.

Considering the 1.75 °C category, the median 2030 carbon price for just the MESSAGE and REMIND scenarios is $88/t$CO_2$, which is almost

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[2] Where ultimately zero and negative emissions levels are reached, linear reductions are more appropriate than compound rates [2].

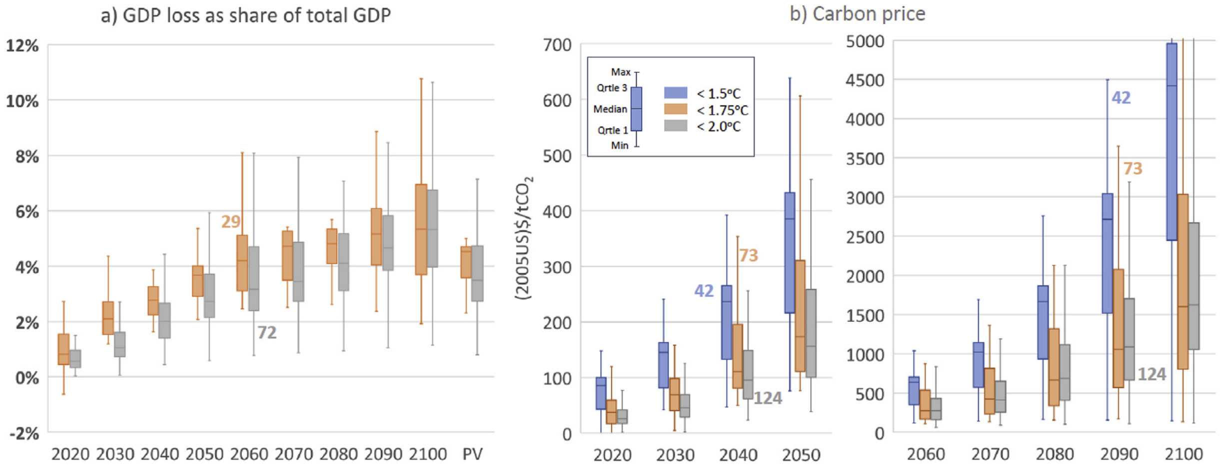

Fig. 3. Mitigation costs and carbon prices "PV" in Fig. 3a) refers to the present value of GDP losses over the period 2020–2100, using a discount rate of 5%. Numbers on chart areas refer to number of scenarios in each group for which indicator data is available.

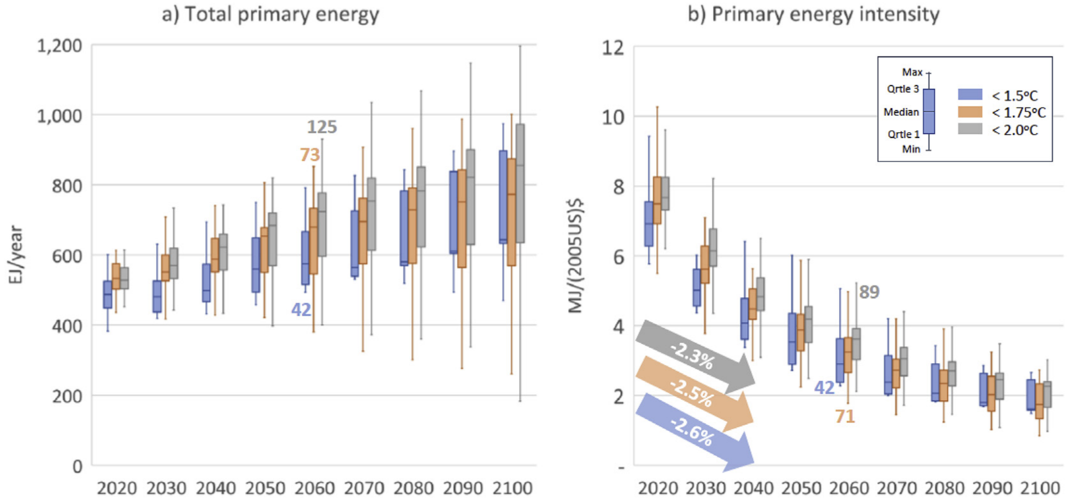

Fig. 4. Global primary energy demand and primary energy intensity of GDP Arrows on Fig. 4b) show compound average annual reduction in primary energy intensity of GDP over the 2020–2040 period, expressed as a median value across each group of scenarios. Numbers on chart areas refer to number of scenarios in each group for which indicator data is available. Whilst total primary energy is available for all models, global GDP is only reported for 71 of 73 models in the below 1.75 °C group and for 89 models in the below 2 °C group (as shown in Figure S2b, Supplementary Material). Hence primary energy intensity of GDP can only be shown for this reduced number of scenarios.

30% higher than the median across all scenarios, though within the \$50–100/tCO$_2$ range indicated above.

3.3. Primary energy demand

As shown in Fig. 4a), primary energy demand increases globally across all scenarios when considering the median and interquartile ranges, although in some extreme cases global primary energy actually starts to fall from mid-century. Total primary energy (Fig. 5a)) and primary energy intensity of global GDP (Fig. 4b)) are both lower in the below 1.5 °C scenarios compared to the below 1.75 °C scenarios, and lower in the 1.75 °C versus 2 °C scenarios, as would be expected. This is particularly noticeable in the early decades of this century. For example as soon as 2030, median primary energy intensity in the below 1.5 °C scenarios is 11% lower than the median for the below 1.75 °C scenarios, which is in turn 9% lower than the median for the below 2 °C scenarios.

It should be noted that the below 1.5 °C scenarios already have significantly lower primary energy intensity by 2020, given that the majority of these begin global mitigation action from 2010, whereas the below 1.75 °C and below 2 °C scenarios contain a mix of mitigation pathways starting from 2010, 2020 and some cases 2030. As such, rather than comparing absolute primary energy intensity, a more suitable indicator is the change in intensity. Here we compare the compound average annual reduction, which, as shown in Fig. 5b), sees the below 1.5 °C scenarios reducing global primary energy intensity by 2.6% per year on average (in median terms) over the period 2020–2040, compared to 2.5% and 2.3% for the below 1.75 °C and below 2 °C scenarios respectively. This reinforces Rogelj et al. (2015)'s [2] assertion that energy efficiency improvements are likely to be a central part of deeper mitigation scenarios. To compare this indicator to historical progress, there has been an approximate 1.5% compound annual reduction in primary energy intensity over the recent period 2000–2014 [15], and a 0.8% compound annual reduction over the longer period of 1970–2010 [13], so each of the scenario groups explored here represents a significant increase on this rate – a feat that will not materialize without dedicated measures to overcome known barriers to energy efficiency improvements [16].

When accounting for only the MESSAGE and REMIND scenarios in the 1.75 °C group, the median primary energy intensity reduction rate over the period 2020–2040 is 2.4% compared to the median of 2.5% across all scenarios in this group.

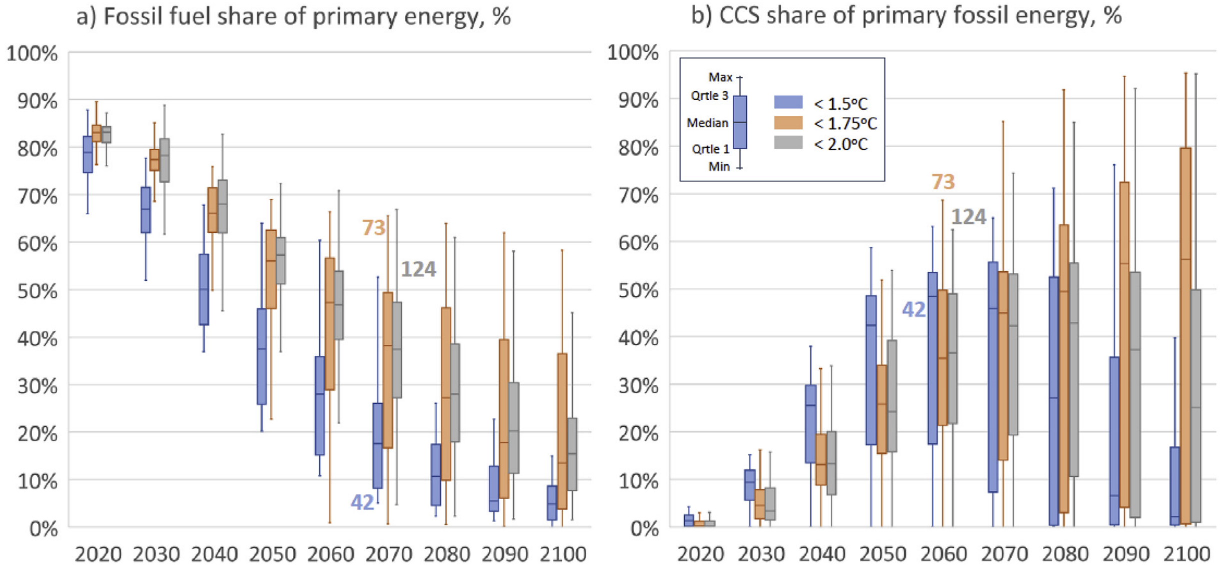

Fig. 5. Fossil fuel share of primary energy and CCS share of fossil fuels Numbers on chart areas refer to number of scenarios in each group for which indicator data is available. Scenarios with 0% share of CCS in primary fossil energy are for restricted technology portfolio scenarios where CCS is specifically not allowed in the energy system mix.

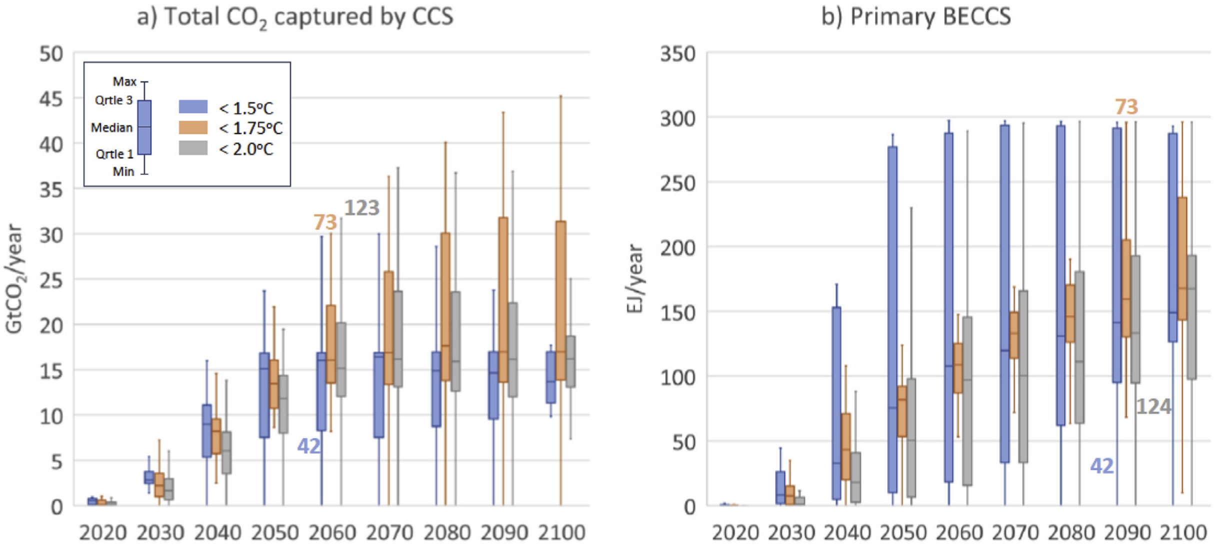

Fig. 6. Global CO_2 captured by Carbon Capture and Storage technologies and global energy supply from bio-energy with carbon capture and storage Numbers on chart areas refer to number of scenarios in each group for which indicator data is available.

3.4. *Role of fossil fuels*

The median fossil fuel share of global primary energy in the below 1.5 °C scenarios is less than the 1.75 °C scenarios throughout the period to 2100, with a very wide difference of more than 15% points in 2040, as shown in Fig. 5a). Compared to the recent (2014) fossil fuel share of primary energy of 81% [17], the median of the 1.5 °C scenarios sees only 67% of primary energy supplied by fossil fuels in 2030 and only 50% in 2040. By contrast, the below 1.75 °C scenarios have a median of 77% in 2030 and 66% in 2040, with the below 2 °C scenarios at 78% (2030) and 68% (2040). This not only underlines the continuing importance of fossil fuels in the global primary energy mix, but also the relatively static share of fossil fuels in the below 1.75 °C and below 2 °C scenarios to 2030 at least. Fossil fuel share could thus, as indicated in this scenario set, be an important indicator of the global temperature pathway trajectory being followed.

It should be noted, however, that rapid phase-out of fossil fuels, though a marker of fast decarbonisation towards stringent mitigation targets, could also foment economic and political instability as a result of stranded assets and scrapped capital [18–20], thereby threatening or undermining some of the states and institutions required to deliver rapid decarbonisation and making such pathways more challenging. One important determinant of the continuing use of fossil fuels even in deep mitigation scenarios is the degree to which CO_2 emissions from their combustion can be captured and sequestered (i.e. combined with carbon capture and storage – CCS – technology). Fig. 5b) shows the share of primary fossil fuel energy which is used in conjunction with CCS. Up to 2070, the CCS share of primary fossil energy is higher in the median of the below 1.5 °C scenarios than in the 1.75 °C scenarios (except 2060), and higher in 1.75 °C than 2 °C scenarios (except in 2060). However, the CCS share of primary fossil energy is significantly higher in 1.75 °C scenarios after 2070, with 1.5 °C and 2 °C scenarios share actually decreasing after 2080. Considering just the MESSAGE and REMIND scenarios, which dominate the 1.5 °C and 2 °C categories, the 1.75 °C group has a CCS share of fossil primary energy of just 3% or less after 2070, reflecting these models' longer-term preference for

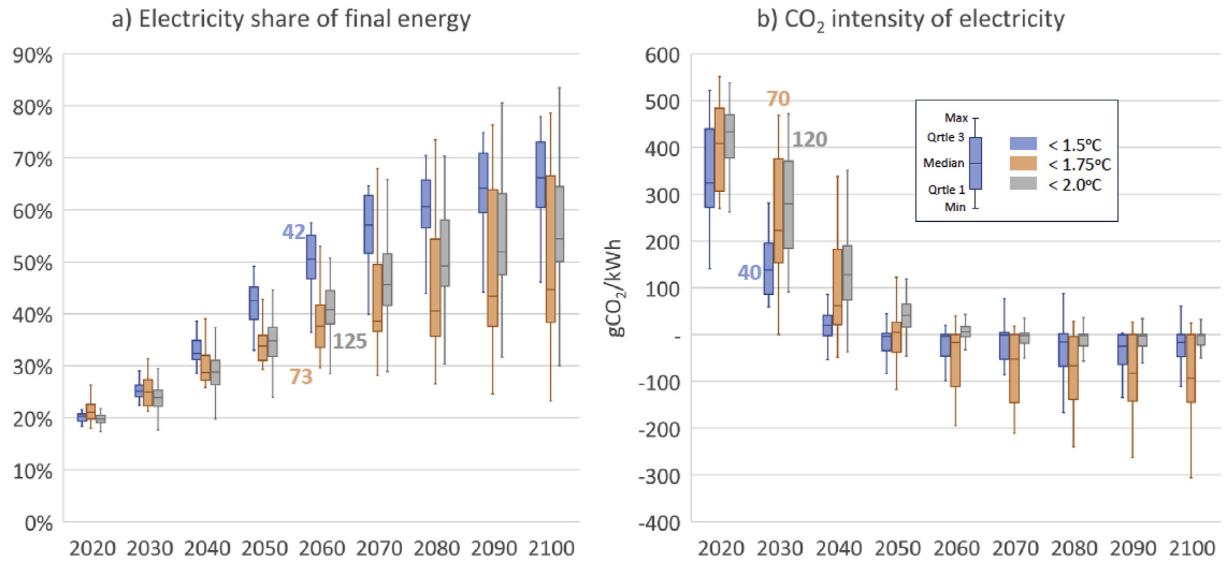

Fig. 7. Global electricity share of final energy and electricity CO_2 intensity Numbers on chart areas refer to number of scenarios in each group for which indicator data is available. Note that electricity CO_2 is not reported for all scenarios in each temperature group.

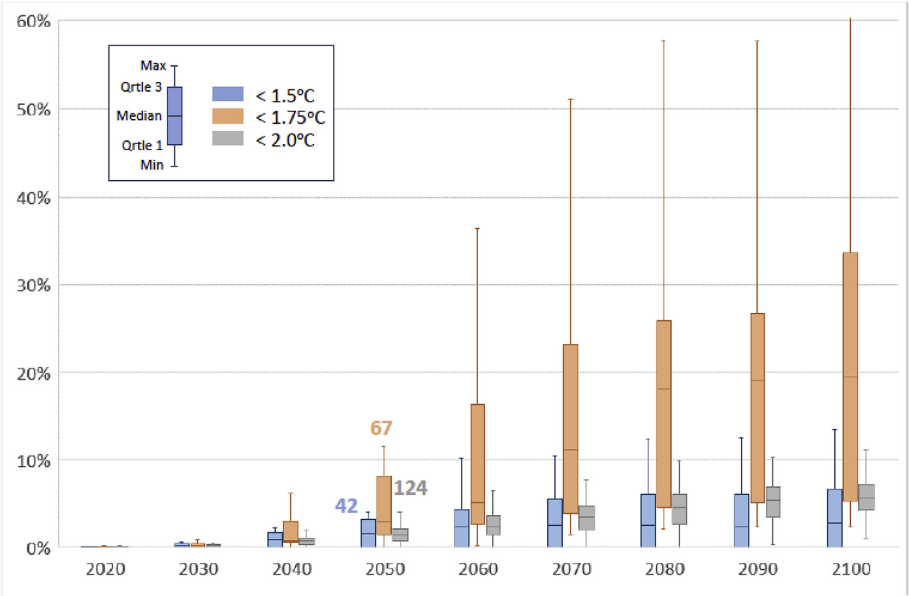

Fig. 8. Hydrogen as share of final global energy Numbers on chart areas refer to number of scenarios in each group for which indicator data is available.

renewables compared to CCS [21]. However, for the consideration of near-term indicators, the MESSAGE and REMIND scenarios have similar values to the all-model grouping for 1.75 °C, as shown in Table S3 (Supplementary material).

3.5. Role of BECCS and CO_2 capture

As shown in Fig. 6a), in the period to 2050 more CO_2 is captured in the median of the below 1.5 °C scenarios compared to the below 1.75 °C scenarios, and in the below 1.75 °C compared to the below 2 °C scenarios. After 2050, the median CO_2 captured is similar across scenarios. The median of the total cumulative CO_2 captured over the period 2020 to 2100 is 990 $GtCO_2$ in the below 1.5 °C scenarios, 1030 $GtCO_2$ in the below 1.75 °C scenarios and 887 $GtCO_2$ in the below 2 °C scenarios, in other words not dissimilar across all groups of scenarios (see Fig. S4, Supplementary Material, for ranges per temperature group). Considering just the MESSAGE and REMIND scenarios for the below 1.75 °C category, the cumulative CO_2 captured is 901 $GtCO_2$, between the 1.5 °C and 2 °C and an indication of the other models' greater reliance on CCS throughout the century (again as already noted in other analysis [21]). This compares to estimates of available CO_2 storage capacity in a wide range, from as low as 600 $GtCO_2$ to more than 10,000 $GtCO_2$ [22,23], so is technically feasible so long as available storage sites can be effectively exploited. Nevertheless, the ramp-up of a technology group which has few demonstration or pilot projects to a level where almost half the world's current level of CO_2 is captured remains a considerable challenge.

Bioenergy with carbon capture and storage (BECCS) is the sole negative emissions energy technology in the vast majority of previous studies of climate change mitigation in the global energy system. Other technologies that can deliver negative emissions, like direct air capture technologies or large-scale afforestation, have either not been included in integrated assessment modelling scenario exercises, or have been included to a much lesser degree. A specific focus on bioenergy with carbon capture and storage (BECCS) is thus essential in any comparison of deep mitigation scenarios. Fig. 6b) shows that there is significantly

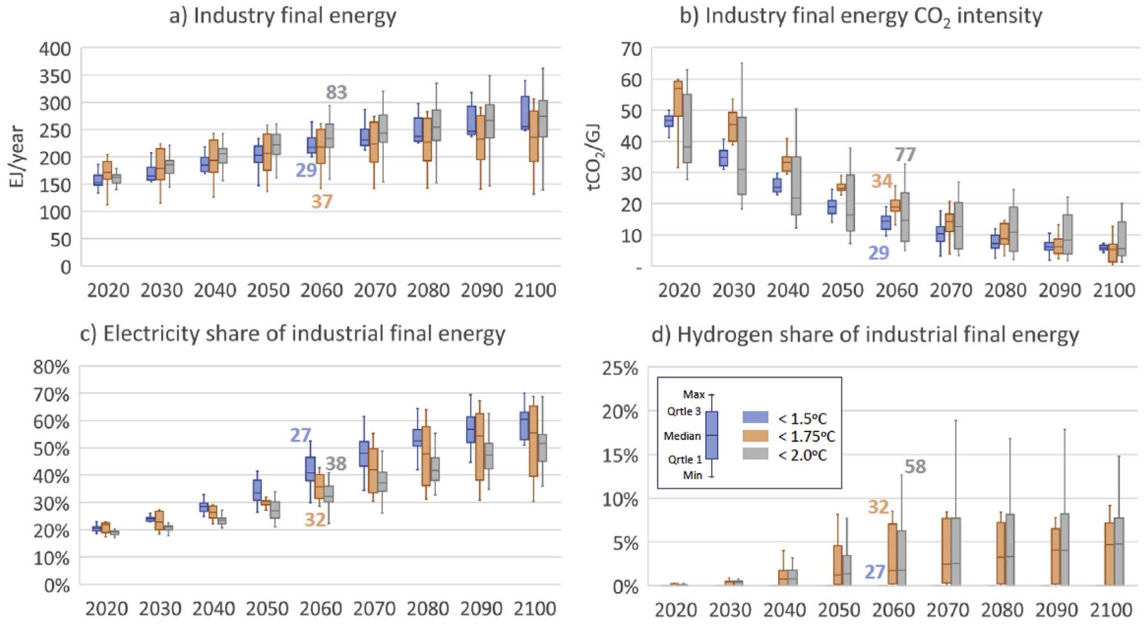

Fig. 9. Industrial sector final energy demand, CO_2 intensity, share of electricity and hydrogen Numbers on chart areas refer to number of scenarios in each group for which indicator data is available. Number of available scenarios differs for each metric depending on availability of industry CO_2, industry electricity final energy and industry hydrogen final energy data.

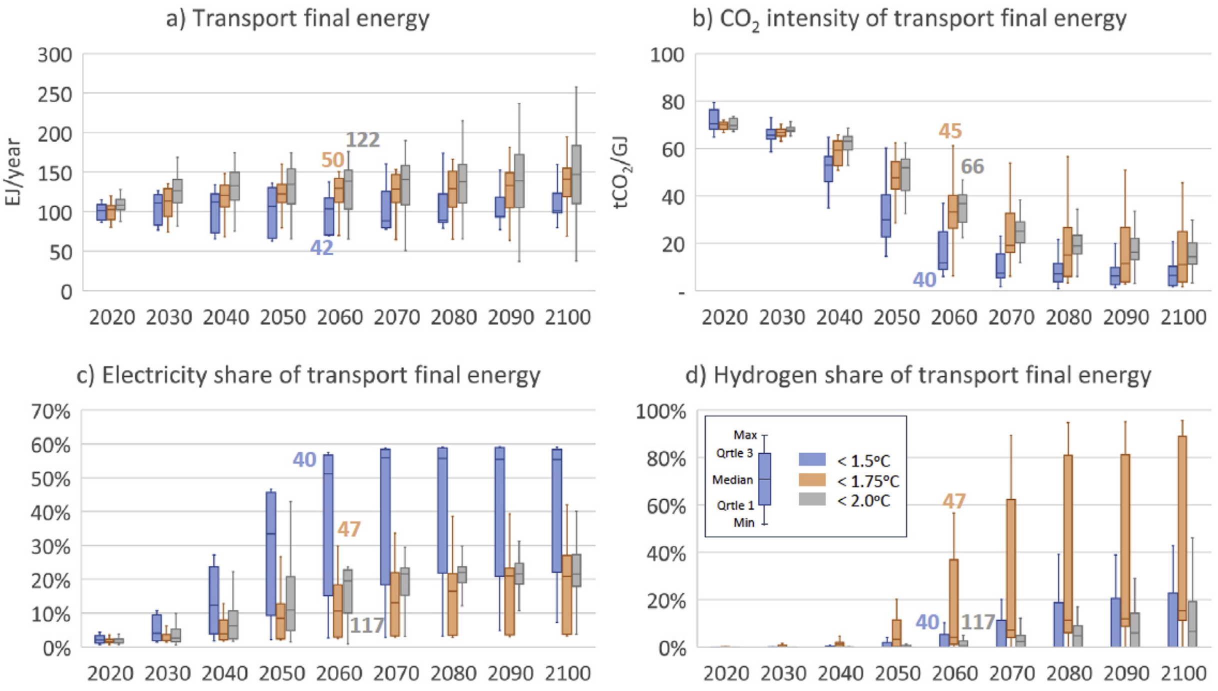

Fig. 10. Transport sector final energy demand, CO_2 intensity, share of electricity and hydrogen Numbers on chart areas refer to number of scenarios in each group for which indicator data is available. Number of available scenarios differs for each metric depending on availability of transport CO_2, transport electricity final energy and transport hydrogen final energy data.

higher ((50–100% greater) use of BECCS in the median case of the below 1.75 °C scenarios compared to the below 2 °C scenarios until 2050, after which the gap narrows such that by 2100 the median of both scenario groups are similar. There is a slightly lower median level of BECCS usage in the below 1.5 °C compared to below 1.75 °C scenarios throughout the century, somewhat contrary to expectations. Considering just the MESSAGE and REMIND scenarios in the 1.75 °C and 1.5 °C temperature categories, however, reveals that the median usage of BECCS is virtually identical for both temperature categories, indicating that the 1.75 °C all-model median is "pulled up" by those models that favour CCS and bioenergy more than MESSAGE and REMIND, but which do not have such influence in the other temperature change categories [21]. Of particular note, however, is the very wide range of BECCS primary energy usage across the 1.5 °C scenarios, a facet of the range of scenarios represented, with (at the lower end of the range) one GCAM scenario which has no CCS allowed ("GCAM 3.0 - EMF27-450-NoCCS") but also with a number of MESSAGE scenarios that focus on advanced non-CO_2 mitigation options and which therefore deploy little BECCS in the first half of the century. The wide variation of BECCS usage is thus a result of (at the higher end) the level of maximum bioenergy assumed to be available, and (at the lower end) a reflection of which other mitigation technologies and measures are also available aside from BECCS. In terms of indicators, a key differentiator between the below 2 °C and more stringent scenario groups is that in the former, there is a median of 50 EJ/year of BECCS primary energy by 2050, whereas in the latter, the figure is closer to 75–80 EJ/year (i.e. 50% more).

It is notable that none of the scenarios shown have in excess of 300 EJ/year of BECCS primary energy and in each group of scenarios the median by 2100 is around 150 EJ/year, reflecting other evidence that there is a high agreement across studies of a sustainable technical potential of bioenergy supply of 100 EJ/year by 2050, but that beyond 200 EJ/year there are increased of risks (to ecosystems, biodiversity and livelihoods) without specific technological and governmental preconditions [24,25].

3.6. Role of electricity

Decarbonisation of the electricity sector has long been a central tenet of low-carbon pathways [26], given the range of commercial and pre-commercial (i.e. pilot or demonstration phase) technical options (renewables, CCS, nuclear) with which this is achievable, as well as the potential for electrification of end-use sectors such as building heating and transport. As shown in Fig. 7a), each of the groups of scenarios here see very significant increases in electrification of final energy throughout the century, with the current levels of around 20% at least doubling in all groups of scenarios. In the below 1.5 °C scenarios, the electrification rate rises the fastest, such that by 2050 it is 43%, compared to less than 35% in the below 1.75 °C and below 2 °C cases. This seems to be a critical indicator of the pace with which the world is decarbonising as a whole, although somewhat curiously, electricity actually constitutes a 5–10% point smaller share of final energy in the 1.75 °C versus below 2 °C scenarios in the latter half of the century. As illustrated in Sections 3.7 and 3.9, this is primarily a result of the higher median share of hydrogen in the final energy mix, particularly the transport final energy mix, compared to the below 2 °C scenarios. This is a clear facet of model selection bias due to the ensemble of opportunity at our disposal rather than any fundamental facet of the tightening of the mitigation target from 2 °C to 1.75 °C, with the MERGE and IMAGE models (which tend to select a high degree of hydrogen in final energy) forming a large share (39 of 73 scenarios, or 54%) of the 1.75 °C scenarios. Considering just the MESSAGE and REMIND scenarios across this temperature group, the median share of electricity in final energy is, as expected, between the values for the 1.5 °C and 2 °C groupings, at 39% in 2050, growing to about 50% by 2070 and then to about 55% by 2100.

Fig. 7b) shows that to 2050, the below 1.5 °C scenarios have a significantly lower median CO_2 electricity intensity than the below 1.75 °C scenarios, and the below 1.75 °C scenarios in turn have significantly lower CO_2 intensity of electricity than the below 2 °C scenarios. The below 1.75 °C scenarios have the most carbon-negative electricity post-2050, which corresponds to their greater use of BECCS as shown in Fig. 6b). In the coming years electricity sector carbon intensity is likely to be a key indicator of the pace with which the world is decarbonising, given broad agreement across the different groups of scenarios that the electricity sector is more or less carbon-free by 2050. By 2030, the below 1.5 °C scenarios have a median carbon intensity of electricity of 140gCO_2/kWh compared to 230gCO_2/kWh for the below 1.75 °C scenarios and 280gCO_2/kWh for the below 2 °C scenarios. This compares to 2014 global average levels of 570gCO_2/kWh [17].

3.7. Role of hydrogen

Fig. 8 shows that in all groups of scenarios the median share of hydrogen is below 10% of final energy throughout the period to 2100. Hydrogen actually constitutes a higher share of final energy in the available below 1.75 °C scenarios compared to the below 2 °C and below 1.5 °C scenarios, owing to the greater share of runs in this group from the MERGE and IMAGE models, which as discussed in Section 3.6, see a much higher share of hydrogen compared to the other models. The MERGE model in particular tends to favour a hydrogen economy by 2100, with in some cases more than 50% of final energy supplied by this energy vector, including almost all of final transport energy demand (see Section 3.9).

In terms of indicators, the role of hydrogen in these groups of scenarios is in general not consistently associated with more or less stringent mitigation pathways, which suggests that there is no clear role for a specific hydrogen-related indicator at this time. There has been a tailing off of interest in a hydrogen economy over the last decade, following a period of relatively intensive focus on this energy carrier over the late 1990s to early 2000s, with barriers to the widespread implementation of hydrogen including the need for extensive infrastructure, its high cost and technological immaturity [27]. However, it is important to keep open the possibility that hydrogen could yet play a very significant role in the low-carbon economy, with initiatives such as increased use of hydrogen in low-carbon heat [28], including to decarbonise gas grids [29], as well as in heavy freight, shipping and aviation sectors [30] where it might still represent a more technically and economically viable option compared to electrification.

3.8. Industry sector

The median final industrial energy demand, as shown in Fig. 9a), can be seen to grow in a broadly similar manner across the three scenario groups. The 2020 share of electricity in industrial final energy increases in all scenario groups, from about 20% in 2020 to 21% (below 2 °C), 23% (below 1.75 °C) and 24% (below 1.5 °C) by 2030, and to 23% (below 2 °C), 26% (below 1.75 °C) and 29% (below 1.5 °C) by 2040. The share of electricity in industrial manufacturing (Fig. 9c)) is therefore potentially a key differentiating indicator between the different groups of scenarios. However, whether this increasing share is achievable will depend on a number of factors, including: the share of energy-intensive industrial manufacturing (principally iron and steel, cement and chemicals) in the overall industrial sector, since these sectors tend to require high temperature processes which are not easily electrified [31]; the share of steel production that occurs through electric arc furnace-based recycling of steel [31]; and the electrification of processes in other energy-intensive sectors [32].

In spite of having the lowest share of electricity in final energy, some below 2 °C scenarios actually have the lowest overall CO_2 intensity of final energy in industry until 2060, as shown in Fig. 9b). This could be in part because hydrogen's share in final energy (Fig. 9d)) is greater than in the 1.5 °C scenarios (though on average it is approximately the same as the below 1.75 °C scenarios). Alternatively it could be due to varying levels of CCS in the industrial manufacturing sector. The 1.75 °C scenario grouping is dominated by the GCAM and IMAGE models (together making up 27 of 37 industry final energy scenarios, with the remaining 10 from MESSAGE) which have similar final industry energy to MESSAGE, but significantly higher industry CO_2 than MESSAGE, contributing to this temperature category having the highest median industry CO_2 intensity of final energy until 2070. It is notable that the GCAM model consistently has much higher BECCS primary energy throughout the century compared to MESSAGE, whilst the IMAGE model has somewhat higher BECCS but deploys this earlier in the century when compared to MESSAGE. This additional reliance on negative emissions in GCAM and IMAGE is likely to explain the greater CO_2 intensity of industrial energy until 2070 in the 1.75 °C group.

The AR5 scenario database does not provide detailed underlying activity drivers for each energy end-use sector, such as building floor area, transport vehicle-km travelled, or tonnes of iron, cement or other industrial output. It is therefore not possible to compare the underlying energy intensity of the industrial manufacturing sector across scenarios.

In addition, there are relatively few data points for the industry energy output metrics. Of the 240 scenarios across all groups, 60% have data for total CO_2 from industry and total final industrial energy demand, 40% have electricity final energy and 27% have hydrogen final energy outputs. This is because many integrated assessment models do not have an explicit or detailed representation of the industrial manufacturing sectors. The indicators for industry must therefore be treated with caution as they are not fully representative of the entire scenario ensemble. Furthermore, it is to be recommended that where possible integrated assessment modelling groups prioritise the disaggregation of the industry sector where possible, given that it is a major source of CO_2 emissions (approximately 8–9 $GtCO_2$ or 30% of total fossil fuel combustion and industrial process CO_2 emissions in 2010, according to the scenarios analysed in this study).

3.9. Transport sector

Fig. 10a) shows that the median final energy demand from transport is higher for the higher temperature mitigation scenarios. In fact by 2100, median transport final energy in the below 1.75 °C scenarios is about 40% higher than in the below 1.5 °C median scenario, with the below 2 °C median almost 50% higher than the below 1.5 °C median. This is likely to reflect the large necessity for modal shifts away from private motorised transport to active modes such as walking and cycling, as well as increased use of public transport, for passengers. For freight, it is likely to reflect more efficient use of transport through improved logistics, as well as shifts from road freight to more efficient rail freight [33,34].

In addition, the CO_2 intensity of transport final energy (Fig. 10b)) is lower for the more stringent mitigation scenarios – significantly so in the case of the below 1.5 °C scenarios, which are 30–40% below 1.75 °C and 2 °C scenarios by 2050. This is in part a result of the higher median electrification rate of the below 1.5 °C scenarios (Fig. 10c)), with a median share of more than 50% of final energy provided by electricity from 2060 onwards. The below 1.75 °C scenarios have the lowest electrification rate. As discussed in Section 3.7, these scenarios are dominated by two models (IMAGE and MERGE) that see a much higher share of hydrogen in the energy system as a whole. Fig. 10d) reveals that this is driven largely by hydrogen penetration in the transport sector, with a median penetration of 15% of transport final energy by 2100, although with the upper quartile extending to almost 90% by 2100. This is not unexpected given energy system models' choice of hydrogen fuel cell vehicles in the transport sector in low-carbon scenarios, in spite of current trends pointing towards a likely dominance of electric vehicles in the low-carbon transport mix. In fact electrification of transport provides a potential differentiating indicator between these three groups of scenarios, with the below 1.5 °C scenarios at a greater-than-10% share of electricity by 2040, and the below 1.75 °C and below 2 °C scenarios around 5% at this time.

As with the industrial manufacturing sector discussed in Section 3.8, there is no straightforward way to compare the underlying activity drivers of energy demand in the transport sectors across the three groups of scenarios. As such, it is not possible to comment on the degree to which the energy efficiency of transport activity differs across these groups.

3.10. Buildings sector

Fig. 11a) and Fig. 11b) show that buildings sector median final energy and median CO_2 intensity of final energy are both noticeably lower in the below 1.5 °C scenarios compared to the below 2 °C scenarios. However, the picture is less intuitive for the below 1.75 °C scenarios, with median final energy and CO_2 intensity of final energy both significantly higher than both the below 1.5 °C and below 2 °C scenarios for most of the period to 2100. The scenarios in this temperature group are dominated by IMAGE (15 of 34 CO_2 intensity of buildings final energy scenarios), GCAM (10 of 34 scenarios) and MESSAGE (9 of 34 scenarios). The former models (particularly GCAM) tend to have higher (by about 30–50% in 2030) final energy in buildings compared to MESSAGE, but significantly higher (by over 100% in 2030) buildings CO_2 emissions, which makes their CO_2 intensity of final buildings energy also significantly higher. As noted in Section 3.8, GCAM and IMAGE rely more on negative emissions from BECCS compared to MESSAGE, which is likely to partly explain their greater CO_2 intensity of final buildings energy.

The share of electricity in buildings (Fig. 11c)) is similar in the below 1.75 °C and below 2 °C scenarios in the first half of the century, with the share higher in the below 1.75 °C scenarios after 2050. The electricity share is highest in the below 1.5 °C scenario. By 2040 it is greater than 40% compared to just below 40% for the below 1.75 °C and below 2 °C scenarios, whilst by 2050 it is greater than 60% in the below 1.5 °C scenario, compared to 53% in the below 1.75 °C and below 2 °C scenarios. Near-term electricity share is therefore a potential differentiating indicator which broadly shows as-expected differences between the different scenario groups, reflecting the already-identified requirement to electrify heating demand in buildings via heat pumps [35]. The hydrogen share of final energy in all groups of scenarios (Fig. 11d)) is less than 1.5% throughout the century in all cases, although as discussed in Section 3.7 this could change with an increasing role for hydrogen in low-carbon heating [28].

4. Discussion

The comparison of the three groups of scenarios presented in Section 3 yields in most cases expected differences (in terms of ordering) between the different indicators, with the exceptions being primarily for the 1.75 °C temperature grouping, which reflects a broader range of models and whose results are highlighted and discussed where they differ from the expected ordering between temperature groupings. The comparison also highlights differences in the costs of mitigation, carbon prices and the cumulative CO_2 levels associated with each 2100 median temperature change level. A number of useful comparison indicators may be drawn from the analysis, as general characteristics of scenarios available in the literature. Table 1 summarises the near-term indicators derived from each sub-section in Section 3 above. Table S2 (Supplementary Material) repeats the analysis in Table 1 for the below 1.75 °C group, focusing on how the metrics differ when comparing the all-model range of scenarios to those that are based purely on the MESSAGE and REMIND scenarios. This demonstrates that in most cases the metrics do not differ significantly, although the MESSAGE and REMIND scenarios tend to have higher electrification and lower carbon intensity of electricity in the near-term, which may indicate a bias towards these trends in the other temperature groups.

Mitigation cost is not included because it cannot easily be measured on an annual basis, but is rather a result of all energy system incurred costs in the mitigation scenario, compared to the counterfactual baseline. As a real world indicator it is also impractical, as it cannot be measured due to the absence of observations of what costs under a counterfactual development would be. Hydrogen share of final energy is not recommended as in this analysis it is relatively insignificant in the below 1.5 °C and below 2 °C scenarios, and appears to suffer from model selection bias in these scenarios, owing to their reliance on the MESSAGE and REMIND models which do not have significant use of this energy vector. CO_2 intensity of end-use sectors could be captured, but the results shown in Figs. 9 and 11 do not follow intuition for the below 1.75 °C scenarios, in this case owing to their over-reliance on other models (in the case of transport, IMAGE and MERGE, and in the case of industry and buildings, IMAGE and GCAM). As such, these metrics are not included in Table 1.

It should be noted that the metrics in Table 1 only provide a partial picture of the required rates of change for the global energy system to

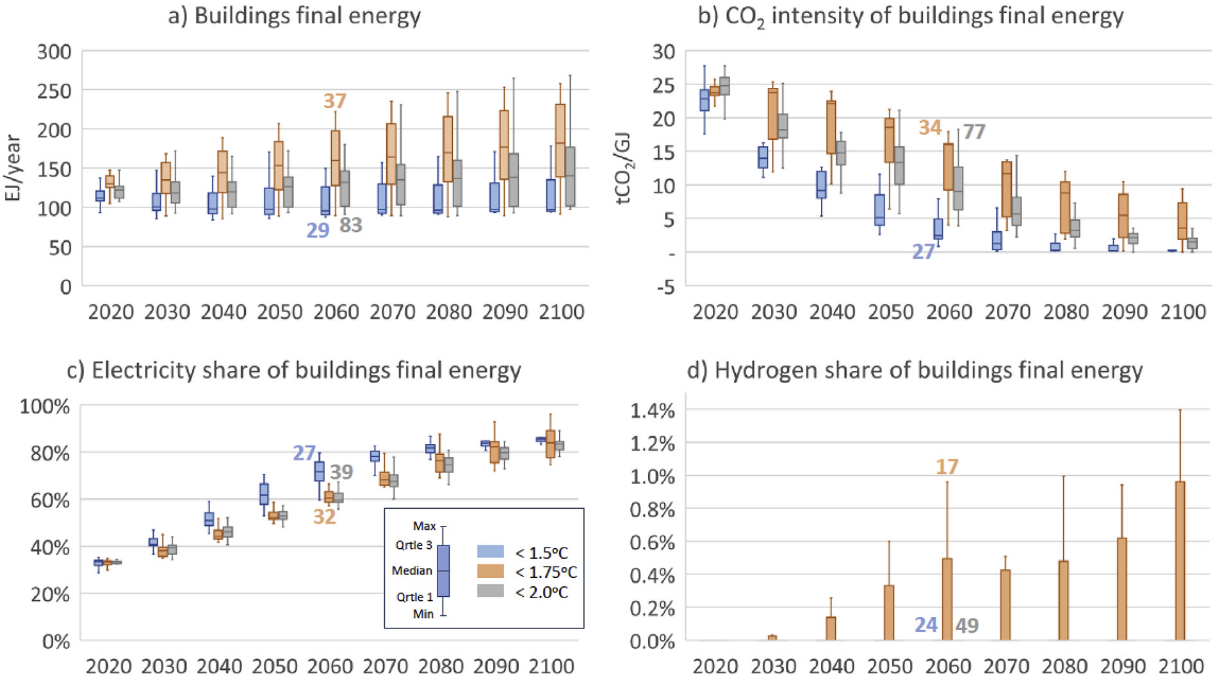

Fig. 11. Buildings sector final energy demand, CO_2 intensity, share of electricity and hydrogen Numbers on chart areas refer to number of scenarios in each group for which indicator data is available. Number of available scenarios differs for each metric depending on availability of buildings CO_2, buildings electricity final energy and buildings hydrogen final energy data.

achieve the different temperature change ranges. One important reason is that the below 1.5 °C scenarios have mitigation action starting from 2010, with median levels of fossil fuel and industry CO_2 significantly lower than currently-projected outturn figures. For example, IEA projections see 2020 emissions across all of its scenarios at 31–34 $GtCO_2$, from fossil fuel combustion alone [21], with projected cement process emissions adding approximately a further 2 $GtCO_2$ by 2020 [36]. This compares to 28 $GtCO_2$ for the *total* fossil fuel and industry emissions in the median below 1.5 °C scenario available at the time of this study. In spite of uncertainties around actual CO_2 emissions being of the order ± 2 $GtCO_2$ [37], this nevertheless means that the required rate of decarbonisation would be greater than indicated here. Indeed, analysis suggests that if mitigation action follows a level consistent with the current Paris pledges to 2030, then even a 5% annual rate of decarbonisation post-2030 would provide a less than 5% probability of limiting global temperature increase to below 1.5 °C [38], one reason why scientists have called for an increase in ambition with respect to these initial pledges [39]. However, it should also be noted that the scenario classification used here reflects the relationship between greenhouse gas emissions and temperature change as reflected at the time of the IPCC fifth assessment report, with more recent evidence [40] suggesting that the available cumulative CO_2 budget to achieve a

Table 1
Differentiating indicators for energy system changes in below 1.5 °C, 1.75 °C and 2 °C mitigation scenarios.

	< 1.5C	< 1.75C	< 2C
CO_2 emissions	> 3%/yr linear reduction (average 2020–2040)	1.5–2%/yr linear reduction (average 2020–2040)	1.5%/yr linear reduction (average 2020–2040)
Carbon prices	> $150/$tCO_2$ by 2030 > $200/$tCO_2$ by 2040	$50–100/$tCO_2$ by 2030 > $100/$tCO_2$ by 2040	< $50/$tCO_2$ by 2030
Primary energy intensity	> 2.5%/yr reduction (average 2020–2040)	2.5%/yr reduction (average 2020–2040)	< 2.5%/yr reduction (average 2020–2040)
Fossil fuel share of primary energy	< 70% by 2030 < =50% by 2040	< 80% by 2030 < =70% by 2040	< 80% by 2030 < =70% by 2040
CCS share of fossil fuel primary energy	~10% by 2030 > 20% by 2040	~5% by 2030 > 10% by 2040	~5% by 2030 > 10% by 2040
CO_2 captured	0-5 $GtCO_2$ by 2030 ~10 $GtCO_2$ by 2040	0-5 $GtCO_2$ by 2030 5-10 $GtCO_2$ by 2040	0-5 $GtCO_2$ by 2030 ~5 $GtCO_2$ by 2040
BECCS primary energy	> 5 EJ/yr by 2030 > 25 EJ/yr by 2040	> 5 EJ/yr by 2030 > 25 EJ/yr by 2040	0-5 EJ/yr by 2030 10-20 EJ/yr by 2040
Electricity share of final energy	> 25% by 2030 > 30% by 2040	> 25% by 2030 ~30% by 2040	20–25% by 2030 ~30% by 2040
Electricity carbon intensity	< 150gCO_2/kWh by 2030 < 50gCO_2/kWh by 2040	200-250gCO_2/kWh by 2030 50-100 gCO_2/kWh by 2040	250-300gCO_2/kWh by 2030 100-150 gCO_2/kWh by 2040
Electricity share of industry final energy	~25% by 2030 ~30% by 2040	20–25% by 2030 25–30% by 2040	20–25% by 2030 20–25% by 2040
Electricity share of transport final energy	~5% by 2030 > 10% by 2040	0–5% by 2030 5–10% by 2040	0–5% by 2030 5–10% by 2040
Electricity share of buildings final energy	> 40% by 2030 > 50% by 2040	35–40% by 2030 40–50% by 2040	35–40% by 2030 40–50% by 2040

below 1.5 °C target could be somewhat larger than previously estimated, yet not larger than the levels that currently characterise the median of the below 1.75 °C scenarios in Fig. 2b). In summary, the required carbon budget to achieve 1.5 °C and the consequent required rates of decarbonisation are broadly known, but will need continuous updating based on how much emissions we continue to emit each year and will hence remain a question requiring continued tracking and research.

There are no historical analogues for sustained emissions reductions at any of these scenario groups' global average rates for the period 2020–2040. Historically emissions reductions have been achieved at the country scale, but largely as side-effects of policies that aimed at reducing dependence on oil rather than reducing CO_2 emissions [41]. The most rapid of these was in Sweden due to energy security policies that fostered a switch away from fossil fuels, with an annual compound average 4% emissions reduction over the decade 1974–1984, equivalent to a 3% linear reduction rate [42]. Repeating this for a 20 year period at a global level, as consistent with the median 1.5 °C scenario, is likely to require more than energy security and energy independence policies. A further challenge will entail upscaling the CO_2 capture industry, with about 5GtCO_2 by 2040 in the below 2 °C scenarios and about twice this in the below 1.5 °C scenarios.

Table 1 only presents a partial view of the decarbonisation challenge. For example, CO_2 capture with BECCS in particular is likely to be an important long-term option for achieving all of these temperature goals cost-effectively according to the scenarios explored here, which suggests further analysis of the implications of utilising the significant bioenergy required is critical. However, it should be noted that some scenarios able to achieve even the below 1.5 °C temperature goal can do so without BECCS, with low energy intensity (including behavioural and lifestyle changes) a critical facet of doing so, as highlighted in more recent analysis [43,44]. In addition, although some scenarios include a significant role for hydrogen, particularly in the transport sector, it remains unclear how significant a role this energy vector will have in practice in the longer-term. At the current time it appears hydrogen may not feature heavily in low-carbon transportation, particularly for light duty vehicles, given recent industry announcements over electric vehicles and the associated heralding of the "death of the internal combustion engine" at the hands of electric cars [45]. In summary, the near-term metrics in Table 1 are useful for understanding the degree to which the global energy system is decarbonising in the near-term in line with different long-term temperature goals, but there are long-term uncertainties around the deployment of technologies and fuels like BECCS and hydrogen, that also require further consideration in determining the overall feasibility of achieving these goals.

A number of additional metrics could be important in helping further characterise the energy system changes in different temperature pathways. Ideally further detail in underlying activity drivers is required, in order to establish carbon intensity and energy intensity of activity in each of the industry, transport and buildings sectors. As already noted in Section 3.8, a representation of the industry sector across a greater share of integrated assessment models would help to characterise low-carbon pathway metrics in this sector with greater confidence. In addition, it is likely that forthcoming integrated assessment model scenarios will encompass a greater range of technology options, particularly around negative emissions technologies which tend to be represented primarily by BECCS in this ensemble. This, combined with updated assumptions on technology costs and their implications for the penetration of such technologies in least-cost pathways, as recently demonstrated for solar PV and electric vehicles [46,47], is likely to yield some changes in the range of values of the metrics as presented here.

5. Conclusions

It is already apparent from initial integrated assessment modelling analysis that the international goal of limiting temperature change to well below 2 °C and pursuing efforts towards 1.5 °C is likely to require a more rapid and deeper energy system decarbonisation than meeting the already-challenging 2 °C target. This study uses a large ensemble of existing scenarios to provide a detailed characterisation of how below 1.5 °C decarbonisation pathways compare to pathways holding warming in 2100 between 1.5 and 1.75 °C and 1.75–2 °C, respectively. It highlights the degree to which deeper mitigation is associated in the next two decades with more rapid reductions in primary energy intensity, a faster phasing out of fossil fuels, a greater share of CCS in remaining fossil fuels, a greater deployment of BECCS, a more rapid decarbonisation of electricity and a greater share of decarbonised electricity in end-use sectors, with higher carbon prices. Comparing the development of global decarbonisation pathways with these indicators will prove useful for understanding the degree to which the world is on a trajectory consistent with the Paris Agreement, as countries revise their pledges and level of ambition.

The results presented here stem from an available ensemble that was not constructed to sample models and scenario types evenly across the various groups. Rogelj et al.'s (2015) [2] earlier study to some extent addressed these problems by dedicated like-with-like comparisons of selected scenario subsets comparing 2 °C and 1.5 °C scenarios. It is recommended that further such comparisons are undertaken to allow a richer within-model understanding of energy system pathway differences, to complement the ensemble comparison undertaken here.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2018.12.006.

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