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All options, not silver bullets, needed to limit global warming to 1.5 °C: a scenario appraisal

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Abstract

Climate science provides strong evidence of the necessity of limiting global warming to 1.5 °C, in line with the Paris Climate Agreement. The IPCC 1.5 °C special report (SR1.5) presents 414 emissions scenarios modelled for the report, of which around 50 are classified as '1.5 °C scenarios', with no or low temperature overshoot. These emission scenarios differ in their reliance on individual mitigation levers, including reduction of global energy demand, decarbonisation of energy production, development of land-management systems, and the pace and scale of deploying carbon dioxide removal (CDR) technologies. The reliance of 1.5 °C scenarios on these levers needs to be critically assessed in light of the potentials of the relevant technologies and roll-out plans. We use a set of five parameters to bundle and characterise the mitigation levers employed in the SR1.5 1.5 °C scenarios. For each of these levers, we draw on the literature to define 'medium' and 'high' upper bounds that delineate between their 'reasonable', 'challenging' and 'speculative' use by mid century. We do not find any 1.5 °C scenarios that stay within all medium upper bounds on the five mitigation levers. Scenarios most frequently 'over use' CDR with geological storage as a mitigation lever, whilst reductions of energy demand and carbon intensity of energy production are 'over used' less frequently. If we allow mitigation levers to be employed up to our high upper bounds, we are left with 22 of the SR1.5 1.5 °C scenarios with no or low overshoot. The scenarios that fulfil these criteria are characterised by greater coverage of the available mitigation levers than those scenarios that exceed at least one of the high upper bounds. When excluding the two scenarios that exceed the SR1.5 carbon budget for limiting global warming to 1.5 °C, this subset of 1.5 °C scenarios shows a range of 15–22 Gt CO_2 (16–22 Gt CO_2 interquartile range) for emissions in 2030. For the year of reaching net zero CO_2 emissions the range is 2039–2061 (2049–2057 interquartile range).

1. Introduction

The 1.5 °C scenarios presented in the IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways (hereafter SR1.5, Rogelj *et al* 2018) evoke two lines of questioning: (a) how realistic are the pathways that enable limiting global warming to 1.5 °C? (regarding for example over-reliance on individual emission-reductions technologies or abrupt shifts in energy demand); and (b) do the scenarios truly exhaust all available realistic technologies, measures and portfolios to reduce emissions (e.g. shifts in behaviour or nature-based solutions), or do they over-rely on individual 'silver bullet' solutions? In addition, the inclusion of a scenario from Shell, labelled a 'sectoral study', in the SR1.5 has been met with confusion and criticism. Although this scenario does not fulfil the special report's criteria for holding 1.5 °C by the end of the 21st century, it was presented as 1.5 °C consistent in some of the ensuing discussions in the non-scientific literature (Scott 2018). Given the dissonance in the reactions from the scientific community, the prominence of these scenarios in the political discussion, and the urgent need to communicate clearly with policy makers, here we address two key questions in response to the lines of questioning given above, based on a novel quantitative analyses of the SR1.5 1.5 °C scenarios: (a) in light of the latest scientific literature on the potential of different emissions-reductions measures, just how difficult is limiting global warming to 1.5 °C when considering the SR1.5 scenarios?; (b) do the SR1.5 scenarios comprehensively cover all mitigation options that could enable limiting warming to 1.5 °C?

Of the 414 emissions pathways included in the analysis in the SR1.5, 53 were categorised as holding global warming above pre-industrial levels to 1.5 °C by the end of the century with low (<0.1 °C) or no overshoot of 1.5 °C throughout the century (Rogelj *et al* 2018). Whilst the SR1.5 touches upon 'the question of whether it is feasible to limit warming to 1.5°C' (see SR1.5 cross-chapter box 3, chapter 1), and elaborates on the dimensions along which feasibility should be considered (technological, economic, institutional, socio-cultural, environmental/ecological, geophysical; see also chapter 4.5.1 of the SR1.5), no attempt is made to distinguish between feasible and infeasible pathways to 1.5 °C on a scenario-by-scenario basis. The feasibility of mitigation pathways is discussed in a growing body of literature (Riahi *et al* 2015, Gambhir *et al* 2017, Rogelj *et al* 2018, Kriegler *et al* 2018a, 2018b, Jewell and Cherp 2020), in which the ambiguity of the term 'feasibility' is a central theme. For example, Kriegler *et al* (2018b) emphasise that feasibility is subjective and different experts may come to different conclusions. They therefore use a heuristic approach to estimate what might constitute a limit to feasibility. Jewell and Cherp (2020) draw attention to the dynamical nature of feasibility, in particular political feasibility, which could alter dramatically in the face of unexpected political and/or technological transformations. And Rogelj *et al* (2018) note that scenarios are a valuable source of insights into the conditions under which 1.5 °C can or cannot be achieved, but shy away from providing an 'absolute statement on (scenario) feasibility'. The question of feasibility is deserving of its own research agenda, and will be essential to building a robust and more-detailed vision for stabilising global average temperature increase at or below 1.5 °C.

In this letter we do not attempt a comprehensive feasibility assessment, but rather discuss the attainability of 1.5 °C scenarios by dissembling the mitigation options embodied in them into five aggregate levers and compare these to current estimates of the potentials of mitigation technologies and measures found in the literature. The questions of technological, economic and political feasibility and resource competition between different mitigation levers are only considered in so far as they are accounted for in the mitigation potentials for these levers drawn from the literature. Within these limitations we attempt to create a bridge between the scenario community and the debate around specific mitigation technologies and measures, drawing attention to potential contradictions and scenario implications that are somewhat hidden within the scenario data. The results of our analysis should serve as a contribution to the discussion on scenario feasibility in the post-SR1.5 debate.

The SR1.5 Summary for Policymakers itself concludes that '…1.5 °C (pathways) with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure and industrial systems…(which are)…unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options' (SR1.5 SPM C.2). Our analysis contributes to quantifying and qualifying these conclusions.

2. Methods

2.1. The 1.5 °C scenarios

The emissions scenario ensemble considered in this analysis are a subset of the emissions scenarios assessed in the SR1.5 (Rogelj *et al* 2018) and hosted at data.ene.iiasa.acat/iamc-1.5c-explorer (Huppmann *et al* 2019). The scenarios in this database are categorised according to the median end-of-century global temperature rise, and the maximum global temperature reached during the century as calculated by the simple climate model MAGICC6 (Meinshausen *et al* 2011). The scenario ensemble for the present analysis

comprises those scenarios categorised as '1.5 °C no overshoot' and '1.5 °C low overshoot (<0.1 °C)', where overshoot refers to the amount by which 1.5 °C global warming is exceeded, before returning below 1.5 °C any time before the end of the 21st century. The three scenarios from the model C-ROADS-5.005 that fall into these categories are excluded from our analysis due to a lack of data on the energy-sector transformations, leaving 50 scenarios in our ensemble (see table S1 for a full list).

2.1.1. Scenario dimensions: emissions targets and mitigation levers

All of the emissions scenarios presented in the SR1.5 as 1.5 °C scenarios rely on deep mitigation portfolios comprising some combination of (a) far-reaching decarbonisation of the global energy, transport, industry and buildings and construction systems; (b) massive scaling up of technologies to remove carbon dioxide (CO_2) from the atmosphere; (c) the transformation of global agricultural and land-use practices; (d) major changes in global consumer behaviour; and (e) reduction of non-CO_2 greenhouse gases and other short-lived climate forcers (note that these can have heating and/or cooling effects, depending on the particular forcing agent and the time scale of interest). These purported solutions face many barriers and associated trade-offs (Smith *et al* 2016), not all of which are considered by the models with which the scenarios were developed.

Using different combinations of these mitigation levers (not including the non-CO_2 lever), the scenarios arrive at different levels of cumulative CO_2 emissions, known as the carbon budget, as per equation (1):

$$\sum_{t=2018}^{y} C_y = \sum_{t=2018}^{y} [\mathrm{CI}_t \times E_t + C_{\mathrm{IP},t} + C_{\mathrm{AFOLU},t} - \mathrm{CDR}_{\mathrm{geo}}] \quad (1)$$

where CI_t is the carbon intensity of final energy demand in a given year, t; E_t is the final energy demand; $C_{\mathrm{IP},t}$ is the annual rate of CO_2 emissions from industrial processes; $C_{\mathrm{AFOLU},t}$ is the annual rate of CO_2 emissions from agriculture, forestry and land-use change (AFOLU), which can be expressed as the difference between residual positive AFOLU emissions and CO_2 that is removed from the atmosphere through AFOLU (i.e. $C_{\mathrm{AFOLU},t} = C_{\mathrm{AFOLU,res}} - \mathrm{CDR}_{\mathrm{AFOLU}}$); and $\mathrm{CDR}_{\mathrm{geo},t}$ is the annual rate at which CO_2 is removed from the atmosphere and stored geologically using human-made technologies.

The left-hand side of equation (1) describes cumulative CO_2 emissions. Peak cumulative CO_2 emissions, and to a lesser degree cumulative CO_2 emissions at the end of the century, provide a proxy for peak and end-of-century global mean temperature (GMT) rise (Zickfeld *et al* 2016, Tokarska *et al* 2019). Our selection of the '1.5 °C no overshoot' and '1.5 °C low overshoot' scenarios from the SR1.5 ensemble is analogous (but not exactly equivalent) to placing limits on peak and end-of-century cumulative CO_2 emissions.

The decomposition on the right-hand side of equation (1) therefore identifies a set of broad mitigation 'levers' for staying within carbon budgets, and by extrapolation temperature limits (e.g. 1.5 °C with no or low overshoot). Here we focus on four of the five levers described in equation (1). For each lever we define a parameter characterising the use of the lever in the scenarios in the year 2050. The premise of the analysis is that the attainability of a particular scenario decreases with increasing use of the mitigation levers. This allows us to decompose the overall assessment of scenario attainability into an assessment of to what extent available mitigation levers are used, which can be compared with information on the mitigation potential of those levers from the literature.

Although non-fossil fuel emissions from industrial processes ($C_{\mathrm{IP},t}$ in equation (1), around 60% of which result from cement production) are a decarbonisation bottleneck in the industry sector, in the analysis that follows we have chosen not to turn it into an explicit mitigation lever to evaluate the attainability of mitigation measures associated with industrial process emissions. Firstly, the technological and institutional challenges associated with decarbonisation of industrial processes are very specific and so will be the solutions to overcome decarbonisation bottlenecks in this area. This does not lend itself to a broad brush assessment of mitigation bounds from the general literature. Secondly, unlike decarbonisation of the energy sector, which would result in emissions reductions across the board, industrial process emissions only represent a small amount of overall emissions. Hence, should some mitigation bottlenecks in this area arise, there is the potential to compensate this with only a modest increase in the use of other levers. Figure S1 (available online at stacks.iop.org/ERL/16/064037/mmedia) shows the emissions from industrial processes for the scenario ensemble used for this analysis. It can be seen that most 1.5 °C scenarios assume a strong reduction in industrial process emissions.

We also do not include mitigation levers associated with carbon dioxide removal (CDR) options associated with ocean fertilisation, carbon storage in industrial products (e.g. wooden building materials) and solar radiation management, owing to their absence from the scenarios studies.

The temperature impact of non-CO_2 greenhouse gases (GHGs) and short-lived climate forcers can modulate the relationship between warming and cumulative CO_2 emissions. In deep mitigation scenarios, non-CO_2 warming typically increases in the

short term due to a rapid reduction of aerosol cooling and then peaks and declines when the increasing cooling impact of deep reductions in short-lived GHG emissions, particularly methane, overtake the decline in aerosol cooling (Rogelj *et al* 2018). Therefore, short-lived GHG emission reductions is an important additional mitigation lever to the mitigation levers highlighted in the right hand side of equation (1). We add it as fifth lever to our analysis. The resulting five mitigation levers are listed in table 1, schematically depicted in figures 1(a) and (b) and are the object of our analysis.

2.2. The mitigation levers

Each of the levers defined in section 2.1.1 represents a collection of measures and technologies with somewhat related feasibility properties when deployed at large scale. However, as discussed in more detail in the supplement, individual levers encompass technologies and measures for which the current scale of deployment and technological proof-of-concept differ significantly. In table 1 we define medium and high upper bounds on mitigation potential based on our assessment of the scientific literature. For the purposes of discussion, we classify use of the levers up to the medium upper bound in the year 2050 as 'reasonable', beyond the medium upper bound but within the high upper bound as 'challenging', and beyond the high upper bound as 'speculative'. Further explanation and justification of the upper bounds can be found in the supplement. We use these upper bounds in our assessment of whether the scenarios have a reasonable chance of attaining mitigation targets aligned with limiting global warming to 1.5 °C, based on their compatibility with attainable development and roll-out of mitigation measures and technologies.

Based on these upper bounds, potential relative contributions of the different mitigation levers to meeting the IPCC emissions targets for 1.5 °C with no or low overshoot can be estimated (see table S2). Given the large ranges in potential, depending on assumptions of roll-out speed, technological advancement, storage capacities and resource competition, the contribution of CDR_{geo}, CDR_{AFOLU} and non-CO_2 mitigation is relatively comparable in terms of annual emissions reductions. However, the potential of energy-system transformations, combining reduction in carbon intensity of energy production and reduction of energy demand, is significantly larger (3–4 times) in absolute terms. This serves as a reminder that deep decarbonisation of the energy sector is a necessary prerequisite for achieving the 1.5 °C targets, which cannot be substituted with carbon-dioxide removal strategies or reductions in non-CO_2 mitigation, and relies to a great extent on relatively mature technologies.

2.3. Coverage indicator (V)

In the analysis that follows we make use of a coverage indicator, V, developed for this analysis, which quantifies the extent to which the scenarios make use of the 'mitigation space' up to the medium upper bounds on the levers. A scenario for which all parameters exhaust or lie beyond the medium upper bounds (U_{med}) will have $V = 1$ (full coverage). Scenarios with values of V close to 1, i.e. with high coverage, exhaust or come close to exhausting all mitigation levers up to the potential enabled by the medium upper bounds. Scenarios with lower coverage do not make full use of the medium potential of some mitigation levers. The coverage indicator combines the two energy levers (carbon-intensity reduction and energy-demand reduction) to consider overall supply and demand-side mitigation in the energy sector. This also allows the levers to be compared quantitatively, since the upper bounds can then all be expressed in terms of emissions reductions in 2050 (in units of $GtCO_2eq$). A more detailed description of the coverage indicator can be found in the supplement.

3. Results

3.1. Discussion of hypotheses

We now compare the state of the art in scientific research on the potential of different mitigation levers with the use of these levers in the IPCC 1.5 °C emissions scenarios. We use the results of this analysis to address the question of under which assumptions is 1.5 °C attainable, and whether or not all relevant mitigation portfolios (i.e. combinations of mitigation levers) to limit GMT at or below 1.5 °C are represented in the SR1.5 ensemble.

To structure this analysis, we position the different perspectives in the post-SR1.5 debate within the hypothesis space described in table 2. Along one dimension, hypotheses 'A', 'A*' and 'not (A or A*)' differentiate between levers being used at reasonable, challenging and speculative levels (e.g. based on different estimates—and interpretations thereof—in the published scientific literature). Along the other dimension hypotheses 'B' and 'not B' address whether or not the SR1.5 1.5 °C scenario ensemble covers, at least implicitly, all available mitigation portfolios. This would not be the case if (a) an important mitigation lever is completely missing from all scenarios, or (b) no scenario fully exploits all available levers to the extent permissible. We emphasise that hypothesis B (full coverage) does not require that every scenario in the ensemble includes every possible mitigation technology and measure, or fully exploits all available levers. The existence of one scenario suffices. Moreover, due to the grouping of individual mitigation measures into five broad levers, our analysis is qualified to meaningfully assess hypothesis B.

Table 1. Definition of the five levers and the medium and high upper bounds used in this analysis. The high upper bounds are provided in brackets.

Dimension	Lever	Definition	Medium (high) upper bound, $U_{med(high)}$	Source
Carbon-dioxide removal (CDR)	$CDR_{geologic}$	The annual CO_2 removal rate in 2050 via direct air capture (DAC), enhanced weathering (EW) and captured from bioenergy use and stored in geological deposits (BECCS). Competition for land resources is not considered.	3 $GtCO_2$/yr (7 Gt CO_2/yr)	Fuss *et al* (2018) Fuss *et al* (2018)
	CDR_{AFOLU}	The annual CO_2 removal rate in 2050 via agriculture, forestry and other land use (AFOLU). Technologies considered: afforestation and reforestation (AR) and soil carbon sequestration (SCS). Competition for land resources is not considered. CDR_{AFOLU} should be considered a lower bound on CO_2 removal via AFOLU, since C_{AFOLU} may still include residual positive AFOLU emissions, which are not accounted for in this analysis (see supplement for more information).	2.5 Gt CO_2/yr (8.6 Gt CO_2/yr)	Fuss *et al* (2018) Fuss *et al* (2018)
Carbon intensity of energy production	CI_{2050}	Relative reduction in carbon intensity of final energy demand in 2050 compared to 2018 (global average).	75% (93%)	Kriegler *et al* (2018b) Kriegler *et al* (2018b)
Energy demand	E_{2050}	Relative reduction in final energy demand in 2050 compared to 2018.	0% (40%)	Grubler *et al* (2018) IEA (2018)
Non-CO2 emissions	$CH4_{2050}$	Relative reduction in methane emissions in 2050 compared to 2018.	54% (67%)	Höglund-Isaksson *et al* (2020) van Vuuren *et al* (2018)

Table 2. Hypothesis space for the attainability of 1.5 °C. The rows consider different levels of use of the mitigation levers and the columns address the completeness of the scenario ensemble considered. The fractions denote the number of scenarios that confirm the hypothesis given in the row headings. The filtered ensemble discussed in the text corresponds to the cell highlighted in grey, which allows levers to be used at challenging levels (i.e. up to the high upper bounds).

		Completeness of mitigation portfolios and levers	
		Hypothesis B The scenario ensemble includes scenarios that utilise all relevant mitigations levers and attainable combinations thereof. Based on this analysis: **B could be true** because the ensemble includes scenarios that make broad use of the mitigation levers considered.	**Hypothesis Not B** Relevant combinations of mitigation levers are missing from the scenario ensemble and/or relevant levers have not been considered. Based on this analysis: **Not B could be true** because it cannot be ruled out that relevant combinations of mitigation levers are missing from the scenario ensemble and/or relevant levers have not been considered (see section 3.1.4).
Level of potential	**Hypothesis A** Some of the SR1.5 scenarios are attainable with mitigation levers used at reasonable levels Based on this analysis: **A is not true** because 0/50 scenarios achieve 1.5 °C with low overshoot with all mitigation levers used at reasonable levels.	Meaning of hypothesis: A and B: 1.5 °C is attainable with mitigation levers used at reasonable levels. Based on this analysis: **A and B is not true**	Meaning of hypothesis: A and Not B: 1.5 °C is attainable with mitigation levers used at reasonable levels. Based on this analysis: **A and Not B is not true**
	Hypothesis A* None of the scenarios are attainable with all mitigation levers used at reasonable levels, but some are attainable with mitigation levers used at 'challenging' levels. Based on this analysis: **A* could be true** because 22/50 scenarios achieve 1.5 °C with low overshoot with all mitigation levers used at reasonable or challenging levels.	Meaning of hypothesis: A* and B: 1.5 °C could be attainable, but requires some mitigation levers to be used at 'challenging' levels. Based on this analysis: **A* and B could be true**	Meaning of hypothesis: A* and Not B: 1.5 °C could be attainable, and potentially with more limited use of the mitigation levers considered in this analysis. Based on this analysis: **A* and Not B could be true**
	Hypothesis Not (A or A*) None of the scenarios achieve 1.5 °C without using at least one of the mitigation levers at 'speculative' levels. Based on this analysis: **Not (A or A*) is not true** because 22/50 scenarios do achieve 1.5 °C with low overshoot with all mitigation levers used at reasonable or challenging levels.	Meaning of hypothesis: Not (A or A*) and B: 1.5 °C is no longer attainable unless some mitigation levers are used at 'speculative' levels Based on this analysis: **Not (A or A*) and B is not true**	Meaning of hypothesis: Not (A or A*) and Not B: 1.5 °C might still be attainable with levers used within reasonable or challenging levels, if new levers emerge or all relevant combinations of levers were exploited. Based on this analysis: **Not (A or A*) and Not B is not true**

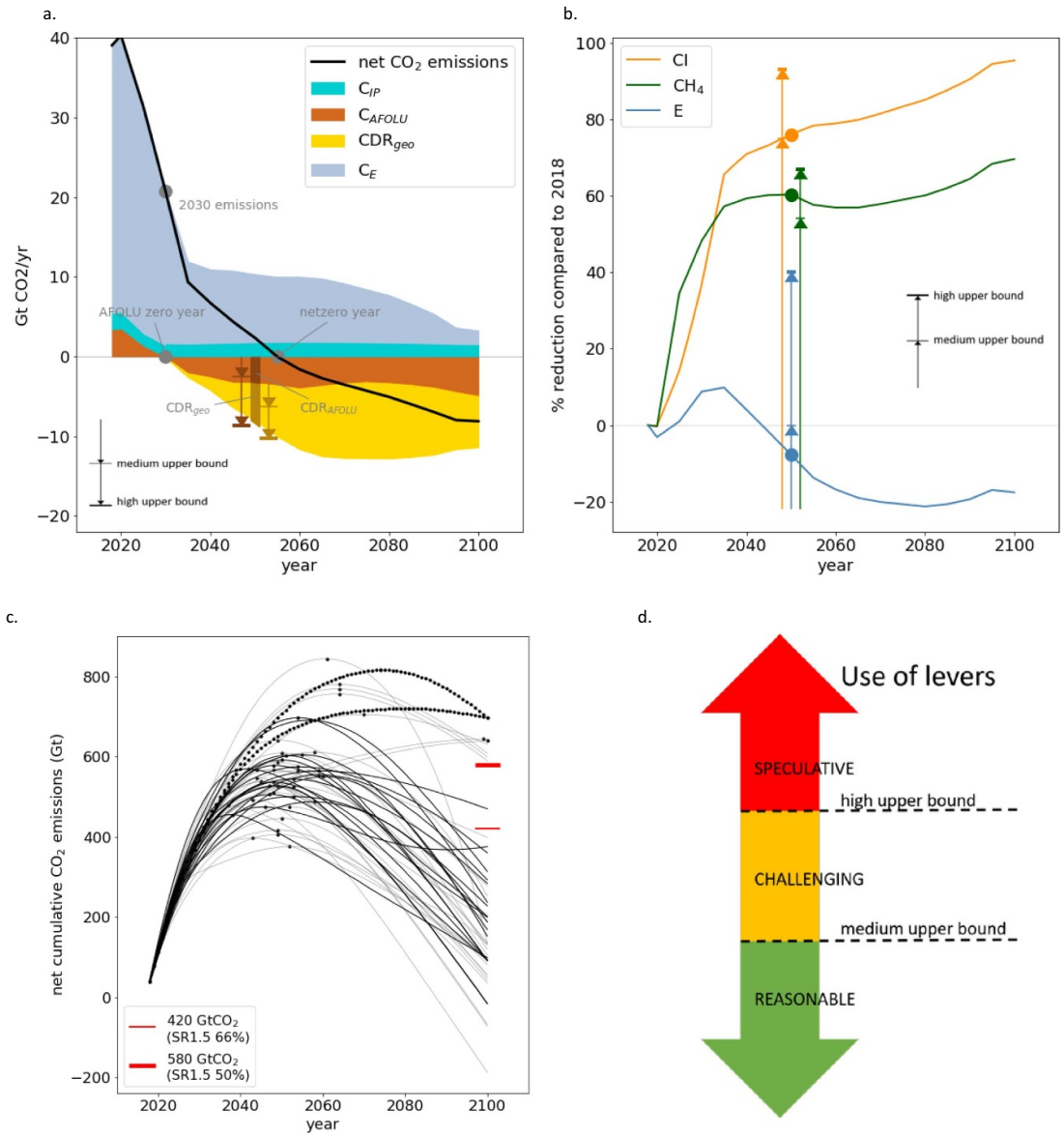

Figure 1. (a) Schematic of the scenario dimensions measured in Gt CO_2/yr used to analyse the emissions scenarios. The solid black curve shows net annual CO_2 emissions for an illustrative pathway. The shaded areas are a stacked plot of the contribution to net CO_2 emissions from CO_2 removal with geologic storage (CDR_{geo}, yellow), agriculture, forests and other land use (C_{AFOLU}, brown), industrial processes (C_{IP}, turquoise) and other emissions (light blue) for the same scenario. The height of the darker brown (CDR_{AFOLU}) and yellow (CDR_{geo}) columns depict the value of the chosen lever for the illustrative pathway (in our analysis the CDR_{geo} and CDR_{AFOLU} parameters are positive in the case of CO_2 *removal*, i.e. the opposite sign as to what is shown in the schematic). The thin and thick short horizontal bars show the medium and high upper bounds respectively (CDR_{AFOLU} in brown, CDR_{geo} in yellow). Note that the upper bounds for CDR_{geo} are shown relative to the C_{AFOLU} curve. The grey points show the value of the three emergent parameters for the illustrative pathway considered (see section 3.2). (b) Schematic of the levers measured in percentage change compared to 2018. The yellow curve shows percentage reduction in relative carbon intensity of energy production for the same illustrative pathway as shown in figure 1(a). The green and blue curves show the percentage reduction in methane emissions and final energy demand respectively for the same pathway. The points depict the value of the chosen lever for the illustrative pathway and the think and thick short horizontal bars show the medium and high upper bounds respectively. (c) Net cumulative CO_2 emissions for all scenarios considered for 2018–2100. The bold and faint red horizontal lines show the remaining carbon budget quoted in the SR1.5 for a 50% and 66% likelihood of limiting global warming to 1.5 °C. The small black points show the position of carbon neutrality (i.e. peak cumulative CO_2 emissions) for each scenario. The black curves correspond to the 22 scenarios that lie within all five high-potential upper bounds, of which the scenarios depicted as dotted black curves exceed the remaining carbon budget for staying below 1.5 °C with 50% likelihood and are discussed further in section 3.2. (d) How to interpret the upper bounds: Use of a particular lever up to the medium upper bound is considered within reasonable expectations; use of the lever between the medium and high upper bounds is considered challenging; and any use of the lever above the high upper bound is considered speculative.

This is because it does not necessitate a detailed check of the availability of individual technologies and measures to lower energy demand, decarbonise energy use, remove CO_2 from the atmosphere and reduce methane emissions, but rather only looks at to what extent these options are used in these scenarios. If evidence is found to support hypothesis B, our analysis can be used to comment on the

attainability of the 1.5 °C target; if evidence is found to support negation of hypothesis B, we may conclude that the SR1.5 scenario ensemble is not sufficient to comment robustly on the attainability of the target.

Our analysis responds to the questions emerging from the hypothesis space in three steps:

(a) Does the SR1.5 scenario ensemble contain scenarios that stay within the medium and upper bounds on mitigation levers? We emphasise that in this first step we are most interested in identifying scenarios that *are* consistent with estimates of mitigation potential found in the literature, rather than commenting on scenarios that exceed these potentials for one or more levers. We acknowledge that the scenarios have not been designed to fulfil the criteria against which we are testing, suggesting that the scenario ensemble will not necessarily cover all possible paths to fulfilling these criteria. In this step we test hypothesis A and A*.
(b) What are the characteristics of the scenarios that stay within our upper bounds?
(c) Does the SR1.5 ensemble include all possible portfolios to 1.5 °C within our upper bounds, or are there missing mitigation portfolios or mitigation levers? In this step we test hypothesis B.

3.1.1. 1.5 °C is not attainable with mitigation levers allowed to be used at reasonable levels

We begin by applying upper bounds on the five aggregate mitigation levers to our ensemble of scenarios taken from the SR1.5. Of the 50 scenarios considered, none can achieve 1.5 °C with no or low overshoot whilst keeping all the mitigation levers at reasonable levels (i.e. hypothesis A is not true). This means that all SR1.5 scenarios with no or low overshoot of 1.5 °C use at least one mitigation lever beyond reasonable levels. The scenarios appear to be most excessive in their use of CDR_{geo}, with only 20% (10/50) of all scenarios using this lever at reasonable levels; at least 40% of the scenarios use all other levers at reasonable levels (see table S3; figure S2(a) provides an overview of how the scenarios are distributed within each of the five parameters and includes alternative bounds for the mitigation levers found in the literature and used in this analysis). Only six scenarios use all but one lever at reasonable levels. In three of these cases, CDR_{geo} is used at challenging levels, in two it is CDR_{AFOLU} and in one it is CI_{2050}. This suggests that in particular CDR_{geo} is employed as the ultimate means, i.e. the 'silver bullet', for achieving 1.5 °C while using other mitigation levers at reasonable levels.

3.1.2. 1.5 °C could still be attainable if mitigation levers allowed to be used at challenging levels

22 scenarios stay within all high upper bounds on the levers (we refer to these scenarios hereafter as the 'filtered ensemble'), leading to the conclusion that 1.5 °C could still be attainable, but will require that some mitigation levers be used at challenging levels (i.e. hypothesis A*). The scenario parameters of each of these 22 scenarios are depicted in figure 2 in increasing order of the coverage indicator, *V* (the same figure for all scenarios is available in the supplement), allowing for a deeper analysis of the use of the individual mitigation levers in these scenarios to stay below 1.5 °C (with no or low overshoot).

A closer look at the filtered ensemble reveals the kind of trade-offs that result from respecting the upper bounds: the scenarios with no temperature overshoot make use of at least one lever at speculative levels. If a low temporary overshoot in limiting warming to 1.5 °C is permitted, carbon-dioxide removal technologies and measures can be exploited at challenging levels in order to limit the extent of the transformation of the energy system to within reasonable expectations. This approach is followed for example by REMIND-MAgPIE 1.7–3.0: SMP_1p5C_Def, REMIND-MAgPIE 1.7–3.0: SMP_1p5C_lifesty and WITCH-GLOBIOM 4.2: ADVANCE_2020_1.5C-2100. Even when combining large-scale CDR deployment with a relatively large reduction in energy demand (IMAGE 3.0.1: SSP1-19), or with a relatively rapid and large reduction in carbon intensity (REMIND-MAgPIE 1.7–3.0: PEP_1p5C_red_eff), a low overshoot of the 1.5 °C target some time in the 21st century appears inevitable.

Nevertheless, highly ambitious transformation of the energy system (both carbon intensity and energy demand) relaxes the pressure on CDR technologies to achieve the necessary mitigation. One scenario stays within all high upper bounds without any geologic-CDR (P1; MESSAGEix-GLOBIOM 1.0: LowEnergyDemand), accompanied by large reductions in energy demand by 2050 (40% relative to 2018) and considerable reduction in methane emissions (56% relative to 2018). This strong decoupling of emissions and energy production explains how large reductions in climate forcing are achieved, while staying within the high-potential upper bounds for CDR and methane reductions.

The characteristic pathways P1 and P3 from the SR1.5 belong to the filtered ensemble; P2 and P4 do not. P2 (based on a population scenario that stabilises at just over 7 billion in 2100) assumes reduction of methane emissions until 2050 at speculative levels (80% reduction compared to 67% reduction high upper bound). P4 more than doubles the

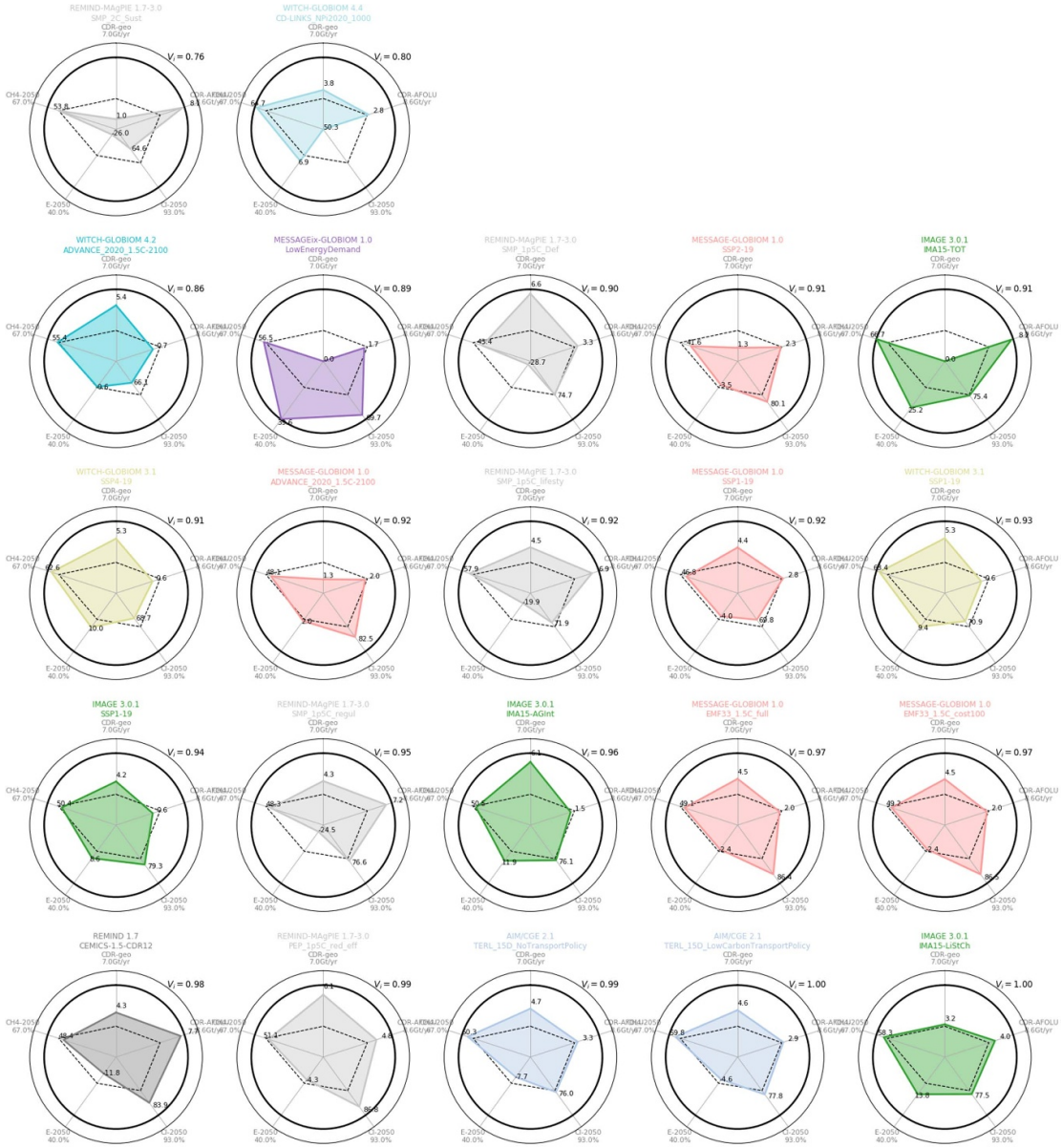

Figure 2. Spider plots for each of the 22 scenarios in the filtered ensemble (the corresponding model and scenario is printed above each plot), in order of increasing coverage, V_i. Note that the AIM/CGE2.1 TERL_15D_LowCarbonTransportPolicy scenario has coverage of V_i=1, despite E_{2050} lying below themedium upper bound due to how the two energy-sector levers are combined to calculate the coverage (see Supplementary material). Each lever has been normalised to the high upper bound (the bold black inner circle on each plot; the absolute value of the upper bound is printed below the lever label). The centre of each spider plot corresponds to the minimum value across the entire ensemble of 50 scenarios for each lever. The medium upper bounds are shown as a dashed polygon. The absolute value of the lever for the given scenario is also printed on the plot. The top row contains the two scenarios singled out in figure 1(c), which exceed the SR1.5 remaining carbon budget for staying below 1.5 °C with a 50% likelihood; these two scenarios also have the lowest coverage of all scenarios in the filtered ensemble. For a similar plot of the complete ensemble of 1.5 °C scenarios with no or low overshoot (50 scenarios), see the supplement.

high upper bound for CDR_{geo} (16.1 $GtCO_2$/yr compared to 7 $GtCO_2$/yr). Furthermore, P4 temporarily overshoots 1.5 °C by more than 0.1 °C due to high near-term CO_2 emissions and consequently high peak cumulative emissions, thus pushing up peak warming.

3.1.3. …and needs all options, not silver bullets

A common critique of ambitious mitigation scenarios is the over-reliance on a single mitigation strategy or technology, i.e. a 'silver bullet', that alone can achieve the 1.5 °C target with low overshoot, without making full use of the available mitigation options. Looking again at figure 2 (especially in comparison to the corresponding figure in the supplement) creates the qualitative impression that 1.5 °C can only be achieved within the high upper bounds if most levers are pulled at challenging levels (i.e. in contrast to reliance on just a few mitigation levers). We confirm this quantitatively by comparing the cumulative histograms of the coverage indicator, V for all scenarios and for the filtered ensemble (figure 3) and find that the filtered scenarios have statistically higher coverage than the entire ensemble, with an average V of 0.93

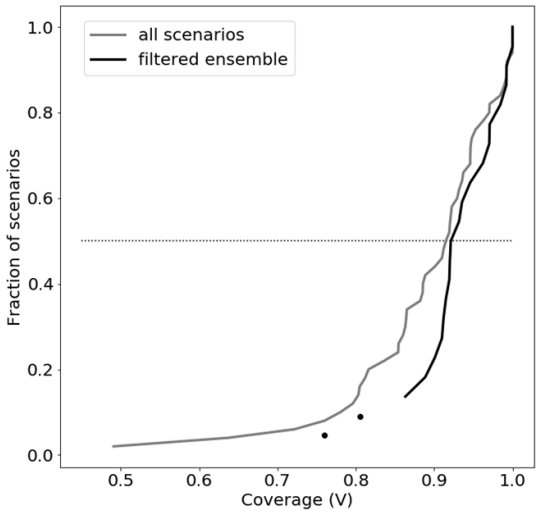

Figure 3. Cumulative histogram of the coverage indicator V for the entire ensemble (grey) and the 22 filtered scenarios (black). The two black points represent the two scenarios in the filtered ensemble with the lowest coverage, which correspond to the two 'outlier' scenarios that exceed the SR1.5 remaining carbon budget for limiting global warming to 1.5 °C with a 50% likelihood. The black curve therefore starts where the fraction of scenarios is 3/22. The horizontal dotted line shows where the fraction of scenarios is 0.5, i.e. it intersects the cumulative histograms at their median values.

compared to 0.89. In fact, the lowest value of V, in the filtered ensemble is 0.76 compared to 0.49 for the entire ensemble. This confirms that most, but not necessarily all, levers need to be pulled at challenging levels to make 1.5 °C attainable. In fact, in most of the filtered ensemble, more than one lever must be pulled at challenging levels.

There is therefore no 'silver bullet' that would allow decarbonisation of the energy system, reduction of energy use, reduction of non-CO_2 emissions, and deploying CDR measures to be dispensed with completely. Even for those scenarios that make substantial use of geologic-CDR (i.e. 3.6–7 $GtCO_2$/yr in 2050), other mitigation levers must still be pulled at challenging levels in order to stay within the carbon budgets.

3.1.4. The SR1.5 includes most relevant mitigation portfolios

We do not find evidence that relevant combinations of mitigation levers, i.e. a broad and extensive use of mitigation portfolios across all levers, are missing from the SR1.5 scenario ensemble. Nine of the 22 scenarios in the filtered ensemble have reasonable coverage of mitigation levers (i.e. $V > 0.95$), two scenarios have full coverage (V=1) and one uses all levers at or beyond the medium upper bounds (note that in the case of the AIM/CGE2.1: TERL_LowCarbonTransportPolicy scenario, V=1 even though E_{2050} is slightly below the medium upper bound, due to how the two energy-sector levers are combined when calculating V - see supplement for more information). We therefore find evidence in support of hypothesis B in table 2, suggesting that achieving the 1.5 °C targets is likely only possible when utilising some mitigation levers at challenging levels. This assessment would only change if there are relevant and significant mitigation levers that are not yet included in the scenarios (e.g. carbon storage in industrial products, ocean CDR and solar reduction management).

However, we do find some room for further investigation of portfolios that favour energy- and land-use-system transformation compared to geologic CDR technologies. Figure 4 offers insight into the 'overuse' or 'underuse' of different mitigation levers within the complete and filtered ensembles (i.e. the mitigation lever is above or below the medium upper bound). In this figure the two energy-sector levers (CI_{2050} and E_{2050}) are combined, as in the calculation of the coverage indicator (for more information see the supplement). We find that the reduction in energy and CH_4 emissions in both the filtered and entire ensembles lie on average close to the medium upper bound, whereas CDR_{geo} tends to lie above it (i.e. it is overused). The spread in CDR_{AFOLU} is large, with a greater tendency to overuse in the filtered ensemble. Given that the reduction in energy-sector emissions contributes over two thirds of the total medium-potential mitigation (see the right-most column of table S2 in the supplement), this suggests there is still some room to increase CO_2 mitigation in the wider SR1.5 scenario ensemble, whilst remaining within the medium upper bounds for all levers. This would potentially reduce overall reliance on speculative CDR technologies and roll-out plans in the scenario ensemble.

3.2. The filtered emissions corridor

We use the upper and lower bounds of the net CO_2 emissions for the filtered ensemble to define a global emissions corridor for our filtered ensemble (composite of light and dark-grey bands in figure 5). The topography of this 1.5 °C corridor covers a narrower option space than the 50 scenarios considered (feint grey lines). The upper bound on this corridor after ~2040 is provided by two 'outlier' scenarios, which we briefly describe.

The outlier scenarios (WITCH-GLOBIOM 4.4: CD_LINKS_Npi2020_1000 and REMIND-MAgPIE 1.7–3.0: SMP_2C_Sust) stand out from the rest of the filtered ensemble in several ways. Firstly, they both have significantly higher cumulative CO_2 emissions until 2100 than the rest of the filtered ensemble and the SR1.5 central estimate of the remaining carbon budget for limiting global warming to 1.5 °C with 50% likelihood (see black dotted curves in figure 1(c)). Secondly, they have the lowest coverage of the mitigation levers compared to the other scenarios in the filtered ensemble ($V = 0.80$ and $V = 0.76$ respectively; see also the top row of figure 2).

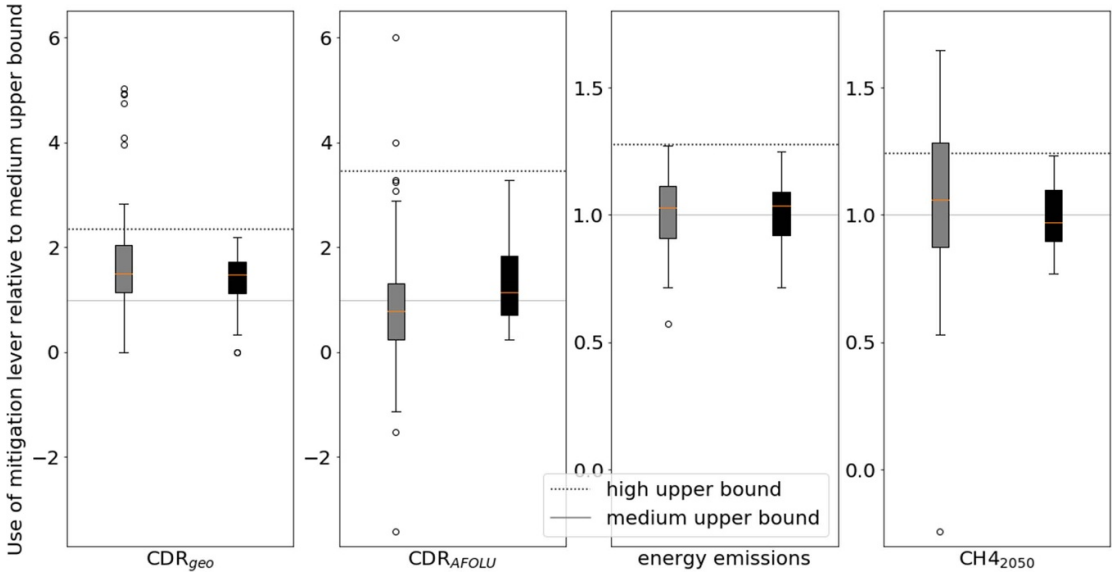

Figure 4. Box and whisker plot of the use of different mitigation levers relative to the respective medium upper bound. The grey box and whisker relate to the entire ensemble, whilst the black box and whisker relate to the filtered ensemble. The position of the high upper bound relative to the medium upper bound is shown as a dotted horizontal line for each mitigation lever, and the position of the medium upper bound is shown with a thin grey horizontal line at a value of 1 in each plot. Note that the two left-hand plots share a coarser vertical scale as the two right-hand plots. The energy emissions lever is a combination of carbon intensity change and energy demand change, as defined in table S2.

The GMT curves resulting from these scenarios nevertheless fall into the '1.5 °C low overshoot' category due to a combination of non-CO_2 dynamics and delayed timing of net zero CO_2 emissions. In the 1.5 °C pathways assessed here, the median non-CO_2 radiative forcing increases until 2030 due to rapid reduction of cooling aerosols and then declines by around two thirds until the end of the century. For the WITCH-GLOBIOM 4.4 scenario, a slow removal of the aerosol cooling and a steep drop in methane leads to significantly lower non-CO_2 forcing in the near-to-medium term, compensating for substantial CO_2 emissions until the time of peak warming around mid century. The reversal of warming in the second half of the century is aided by further declining non-CO_2 forcing and increasing CDR_{geo} that leads to net negative CO_2 emissions after 2070. In the REMIND-MAgPIE scenario, the high use of afforestation peaking around mid-century limits near to medium term accumulation of CO_2 and allows net zero CO_2 to be approached more asymptotically in the 2nd half of the century. At the time net zero CO_2 is obtained (2080), non-CO_2 forcing has dropped to almost half of the median non-CO_2 forcing in 2050 when most 1.5 °C pathways reach their peak warming level. This allows the scenario to reach peak warming later (2060–2070) and with higher levels of cumulative CO_2. When the two outlier scenarios are excluded from the filtered ensemble, the resulting emissions corridor is significantly narrower (dark-grey band in figure 5).

We define three emergent scenario characteristics, which correspond to quantities often referred to within the public debate on climate mitigation: annual emissions in the year 2030 ($CO_{2,2030}$), the year in which net zero emissions is achieved (net-zero), and the year in which net emissions from AFOLU reaches zero (AFOLUzero). In figure 6 the scenario parameters, including the emergent characteristics, for the entire ensemble, as well as the filtered ensemble, are depicted. We see that the filtered scenarios imply approximately halving net annual CO_2 emissions by 2030, achieving carbon neutrality by around 2050, and ensuring that land-use and land-use change practices are a net sink of CO_2 by around 2030. For the filtered ensemble CO_2 emissions in 2030 range from 10 to 24 $GtCO_2$/yr (interquartile range, IQR, 16–22 $GtCO_2$/yr). The year in which net CO_2 emissions reach zero ranges from 2039 to 2082 (IQR 2050–2060). Excluding the outlier scenarios, this range narrows to 2039–2061 (IQR 2049–2057), which is only slightly higher than the interquartile range of net zero emissions for scenarios with no or low overshoot in the SR1.5 (2045–2055).

The right-hand panel of figure 5 shows the filtered 1.5 °C corridor in terms of net emissions from energy and industrial processes only (i.e. including CDR from BECCS), and includes the Shell Sky scenario (Sky scenario | Shell Global n.d.). The Shell Sky scenario clearly lies outside the filtered corridor, with peak cumulative emissions (1440 $GtCO_2$) almost twice as high as the SR1.5 50%-likelihood budget for a low 1.5 °C overshoot, and a slow mitigation pathway only reaching carbon neutrality (for energy and industrial processes) around 2070 (see also the circles in

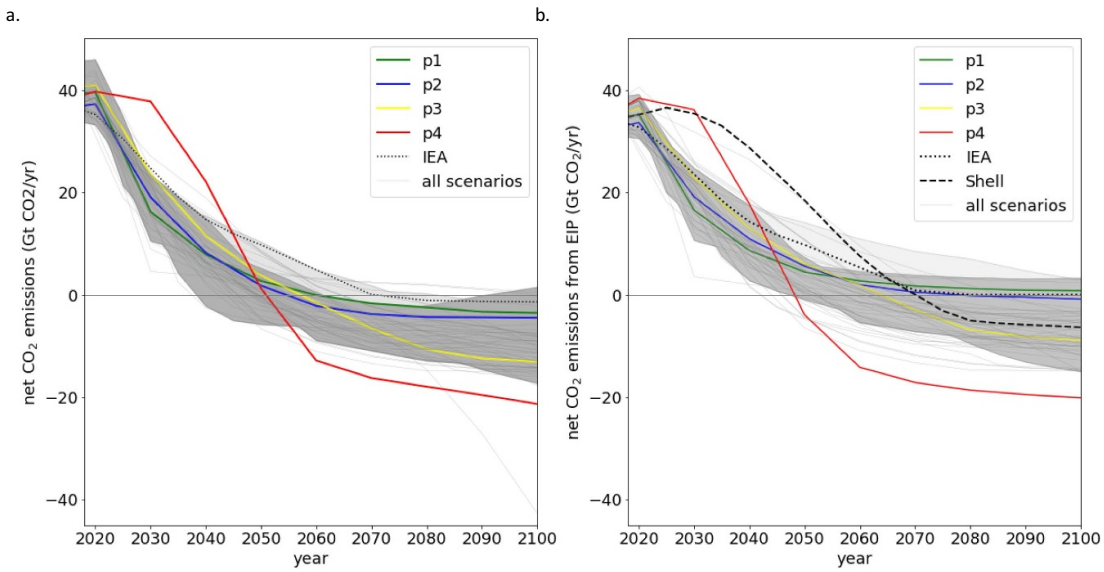

Figure 5. (a) Annual global CO_2 emissions for 2018–2100 for all SR1.5 scenarios categorised as '1.5 °C no overshoot' or '1.5 °C low overshoot' (grey curves). The green, blue, yellow and red curves show the emission paths for the illustrative pathways P1–P4 (respectively) defined in the SR1.5. The combination of the light-grey and dark-grey bands shows the range in CO_2 emissions covered by the filtered ensemble. The dark-grey band alone shows the emissions ranges for the filtered ensemble when the two outlier scenarios, which exceed the SR1.5 remaining carbon budget for limiting global warming to 1.5 °C with a 50% likelihood, are excluded. The dotted curve relates to the International Energy Agency 'Faster Transition Scenario'. (b) As for (a) but only for net CO_2 emissions arising from energy and industrial processes, allowing for the inclusion of the Shell Sky scenario (dashed black curve).

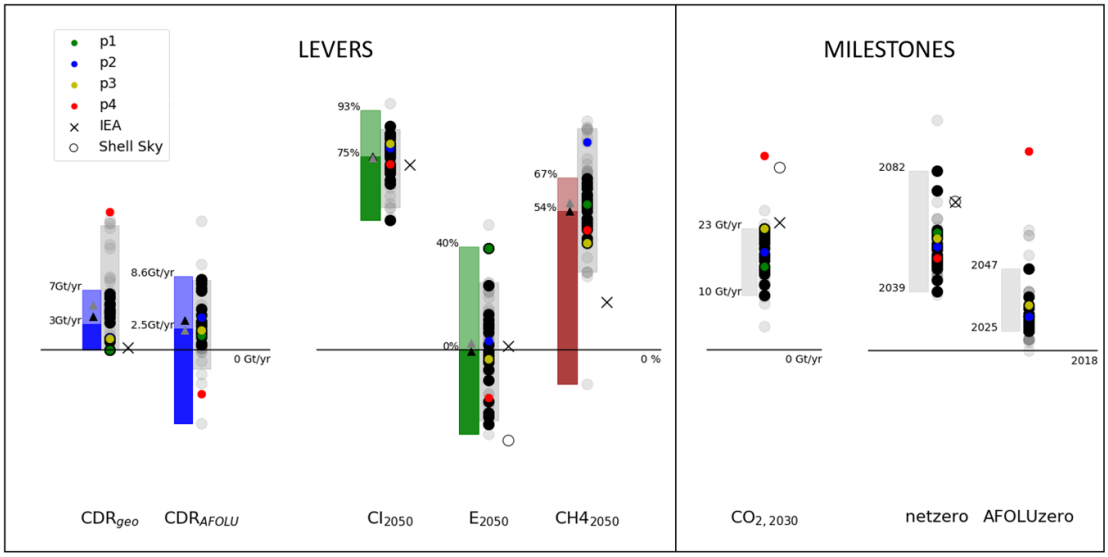

Figure 6. The scenario space covered by the SR15 1.5 °C scenarios. Each point shows the value of the lever given in the column title for a single scenario. The grey vertical blocks underlying the points in the five levers columns show the 5th–95th percentile range for the entire scenario ensemble. The coloured columns show the medium and high upper bounds for the given lever (the values are given as numbers on the plot). Black filled circles represent scenarios that stay within all five high upper bounds (i.e. the filtered ensemble). All other scenarios are depicted with feint filled grey circles. The grey and black triangles give the mean value of the given lever across the whole and the filtered ensemble respectively. The grey vertical blocks in the three milestones columns show the range of the given characteristic within the filtered ensemble. The green, blue, yellow and red points show the lever values for P1–P4 from the SR15, respectively. The crosses correspond to the IEA World Energy Model 2017 'Faster Transition Scenario' and the empty circles correspond to the Shell 'Sky 'scenario. The Shell scenario reports only emissions from energy and industrial processes, and not, for example, emissions from agriculture, so can only be indicatively compared with the other scenarios.

figure 6). This is also evident in the high 2030 emissions compared to the filtered band (the highest 2030 emissions in the filtered scenarios is 26.1 $GtCO_2$/yr; the 2030 emissions for the Shell scenario are 35.4 $GtCO_2$/yr). Interestingly, the most recent Shell 'Sky 1.5' scenario reaches net zero CO_2 emissions significantly earlier (between 2055 and 2060) with an almost identical energy-systems pathway, whilst relying on a

large-scale ramp up of land-based negative emissions (net negative emissions rising from 0 $GtCO_2$/yr in 2040 to 10.5 $GtCO_2$/yr in 2055) (The Energy Transformation Scenarios | Shell Global n.d.).

The IEA scenario (IEA 2018) lies outside the 1.5 °C corridor due to excessive peak and end-of-century cumulative emissions, characterised by late arrival at carbon neutrality (2070) and relatively high 2030 emissions (24.7 $GtCO_2$/yr) (see also crosses in figure 6).

4. Discussion and conclusions

Our analysis contributes to the understanding of how the IPCC 1.5 °C scenario ensemble can be interpreted in the context of the attainability of limiting global warming to 1.5 °C by the end of the century with no or low overshoot. We conclude that none of the SR1.5 1.5 °C scenarios offer a fair chance of staying below 1.5 °C by the end of the century with reasonable use of the potential of mitigation levers (hypothesis A not true in table 2). The chance could be even lower when competition between the levers (e.g. for economic resources) is considered when constructing the upper bounds. Only if mitigation levers are allowed to be used at levels that will be challenging to realise do we identify scenarios within the ensemble that offer a fair chance of achieving the 1.5 °C temperature target with no or low overshoot (hypothesis A* in table 2).

Alternatively, 1.5 °C might be attainable with lower use of mitigation levers than implied in the scenarios if there are substantial mitigation levers that are not employed in the scenarios (hypothesis A* and Not B). This analysis should therefore serve as an incentive to look more closely at the compatibility of mitigation potentials implied by the scenarios and estimates of attainable potentials derived and reported in the scientific literature. Furthermore, the completeness of the suite of mitigation levers employed in the scenarios should be an important consideration in the ongoing development of the Integrated Assessment Models behind the scenarios, as well as the reporting requirements in intercomparison exercises.

In the existing scenario ensemble we find an overreliance on geologic CDR technologies, with some room for more extensive use of energy-sector levers. More specifically, what seems to be missing from the literature is a 1.5 °C scenario with reasonable changes in energy demand (∼0% change until 2050) and use of CDR (∼3 $GtCO_2$/yr and ∼2.5 $GtCO_2$/yr for CDR_{geo} and CDR_{AFOLU}, respectively), but challenging rapid and deep reductions in carbon intensity of energy production (>75% reduction compared to 2018 in 2050). This might facilitate achieving the temperature targets without overly optimistic assumptions on CDR and energy demand. These conclusions complement the myriad recent warnings about the risks and challenges associated with relying too heavily on speculative, large-scale CDR deployment (Field and Mach, 2017, Anderson and Peters 2016, Smith *et al* 2016, Williamson 2016, Minx *et al* 2018). Our analysis is relevant to the discussions of whether we are pushing the climate-change solution onto the shoulders of future generations by focusing on scenarios which shy away from deep decarbonisation and energy-use reduction in the coming decades in favour of betting on the later success of immature technologies.

Not only is the majority of available 1.5 °C scenarios in the SR1.5 questionably optimistic regarding CDR, those that present lower levels (<7 $GtCO_2$/yr and <8.6 $GtCO_2$/yr for CDR_{geo} and CDR_{AFOLU}, respectively), often make very optimistic assumptions on population growth, dietary changes and demand-side changes in the energy system. The scenarios typically do not analyse the broader socio-technical implications (Turnheim *et al* 2015, Geels *et al* 2016, 2017) and the large behavioural and institutional shifts that such transformative changes in energy and land use might entail (van Den Berg *et al* 2019). Rapid innovation of lifestyles, social systems and patterns of global cooperation, in addition to technical innovation, will be critically important for keeping the 1.5 °C target within reach (TWI2050—The World in 2050 2018, Sachs *et al* 2019) and should feature more prominently in discussions of the attainability of 1.5 °C, reflecting the enormity of the 1.5 °C challenge.

Hence we argue that just under half of the 1.5 °C no and low overshoot scenarios in the IPCC SR1.5 offer a realistic chance of stabilising GMT at 1.5 °C by the end of this century, even when mitigation levers are allowed to be used at challenging levels in 2050. This subset does not include the sectoral scenarios from the International Energy Agency and Shell, or the characteristic pathways p2 and p4 defined in the SR1.5. The remaining half of the scenario ensemble tends to overstate the potential of CDR or 'normalise' extremely optimistic assumptions of underlying societal and economic transformations. 1.5 °C cannot be attained with 'silver bullets', all-round portfolios are needed in which most available levers are used at challenging levels by enabling policies, technologies and societal changes beyond what might be deemed feasible today (Jewell and Cherp 2020). This requires nothing less than deep societal and economic transformations that are aligned with the UN Sustainable Development Goals, and adaptation measures to cope with the impacts of even 1.5 °C warming.

Data availability statement

The data analysed in this study are openly available at the following URL/DOI: https://zenodo.org/record/3363345.

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