Authors:

Joeri Rogelj[a,b,*], Alexander Popp[c] , Katherine V. Calvin[d], Gunnar Luderer[c], Johannes Emmerling[e,f], David Gernaat[h,i], Shinichiro Fujimori[a,g], Jessica Strefler[c], Tomoko Hasegawa[a,g], Giacomo Marangoni[e,f], Volker Krey[a], Elmar Kriegler[c], Keywan Riahi[a], Detlef P. van Vuuren[h,i], Jonathan Doelman[h], Laurent Drouet[e,f], Jae Edmonds[d], Oliver Fricko[a], Mathijs Harmsen[h,i], Petr Havlík[a], Florian Humpenöder[c], Elke Stehfest[h], Massimo Tavoni[e,f,j]

Affiliations:

a Energy Program, International Institute for Applied Systems Analysis (IIASA), 2361 Laxenburg, Austria
b Institute for Atmospheric and Climate Science, ETH Zurich, Universitätstrasse 16, 8006 Zurich, Switzerland
c Potsdam Institute for Climate Impact Research (PIK), Telegraphenberg A31, 14473 Potsdam, Germany
d Joint Global Change Research Institute, Pacific Northwest National Laboratory, 5825 University Research Court Suite 3500, College Park, MD 20740, USA
e Fondazione Eni Enrico Mattei, Corso Magenta 63, 20123 Milan, Italy
f Centro Euro-Mediterraneo sui Cambiamenti Climatici, Corso Magenta 63, 20123 Milan, Italy
g National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Japan
h PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands
i Copernicus Institute for Sustainable Development, Utrecht University, The Netherlands
j Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy

* To whom correspondence should be addressed: rogelj@iiasa.ac.at

Title:

Scenarios towards limiting global-mean temperature increase below 1.5°C

Introductory paragraph:

The 2015 Paris Agreement calls for countries to pursue efforts to limit global-mean temperature rise to 1.5°C. The transition pathways that can meet such a target have not, however, been extensively explored. Here we describe scenarios that limit end-of-century radiative forcing to 1.9 Wm^{-2}, and consequently restrict median year-2100 warming to below 1.5°C using six integrated assessment models and a simple climate model, under different socio-economic, technological and resource assumptions from five Shared Socioeconomic Pathways (SSPs). The 1.9 Wm^{-2} scenarios are characterized by a rapid shift away from traditional fossil-fuel use towards large scale low-carbon energy supplies, reduced energy use, and carbon-dioxide removal. However, 1.9 Wm^{-2} scenarios could not be achieved in several models under SSPs with strong inequalities, high baseline fossil-fuel use, or scattered short-term climate policy. Further work can help understanding the real-world implications of these scenarios.

Main Text:

Scenarios of the energy-economy-land system can facilitate the integrated assessment of climate change impacts and mitigation. For the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), four Representative Concentration Pathways[1] (RCPs) provided climate research with a set of consistent climate forcings[2-4]. More recently, the Shared Socioeconomic Pathways (SSPs) have been developed[5,6]. SSPs provide a socioeconomic dimension to the integrative work started by the RCPs[7]. This framework provides a basis of internally consistent socioeconomic assumptions that represent development along five distinct storylines[8]: development under a green-growth paradigm[9] (SSP1); a middle-of-the-road development along historical patterns[10] (SSP2); a regionally heterogeneous development[11] (SSP3); a development which breeds both geographical and social inequalities[12] (SSP4); and a development path that is dominated by high energy demand supplied by extensive fossil-fuel use[13] (SSP5).

Prior to 2015, international climate policy under the United Nations Framework Convention on Climate Change (UNFCCC) focused on the goal of keeping global-mean temperature increase below 2°C relative to pre-industrial levels[14]. The Paris Agreement reset this long-term goal to holding the increase well below 2°C and pursuing efforts to limit it to 1.5°C[15]. In this study, we present a new set of stringent climate change mitigation scenarios consistent with 1.5°C in 2100. Six integrated assessment models participated in this exercise (AIM[11], GCAM4[12], IMAGE[9], MESSAGE-GLOBIOM[10], REMIND-MAgPIE[13], and WITCH-GLOBIOM[16]), each of which attempted to model scenarios that limit end-of-century radiative forcing (RF) to 1.9 Wm^{-2} under various SSPs (henceforth also called 'SSPx-1.9' scenarios, Methods). This scenario set allows the structured exploration of climate change at a level consistent with limiting global-mean temperature increase in 2100 to 1.5°C with approximately 66% probability (see Fig. 1 and specifics below). Overall, all teams were able to produce 1.9 Wm^{-2} scenarios in SSP1, and 4 were successful in SSP2. Of the 3 and 4 modelling frameworks that attempted to model 1.9 Wm^{-2} scenarios in SSP4 and SSP5, 1 and 2 were successful, respectively (see Methods, Suppl. Table 1, Suppl. Fig. 1, Suppl. Text 2). From this set of 1.9 Wm^{-2} scenarios, a further, stringent climate mitigation scenario has been selected for inclusion in the Scenario Model Intercomparison Project[17] (ScenarioMIP) of the Sixth Phase of the Coupled Model Intercomparison Project[18] (CMIP6), as well as other CMIP6 MIPs (e.g. refs 19,20, Suppl. Text 1, Figure 1a, Methods).

Emission and climate-related outcomes

CO_2 and other greenhouse gas (GHG) emissions peak before 2030 and decline rapidly over the next two to three decades in SSPx-1.9 scenarios (Fig. 1, and Suppl. Figures 2-6 for other emissions). By 2050, annual CO_2 and GHG emissions are in the range of -9 to 6 and 1 to 13 billion tons of CO_2-equivalent emissions ($GtCO_2$-eq/yr, Methods), respectively, across all available scenarios. Underlying these reductions is a phase-out of industry and energy-related CO_2 production at a rate of 0.2-7.1%yr^{-1} (median: 3.0%yr^{-1}, see Suppl. Tables 2 and 3 for a complete overview), combined with rapid upscaling of carbon capture and storage (CCS) and carbon dioxide removal (CDR, see further below). Near-term emissions vary across the SSPs because, in contrast to SSP1, the effectiveness of near-term climate policies is assumed to be limited in other SSPs (defined by so-called Shared Policy Assumptions[5,21]). In that case, global mitigation is regionally scattered and accelerates slower over the next few decades, and needs to accelerate faster later on.

All scenarios presented here lead to 1.9 Wm^{-2} RF in 2100 within rounding precision (Suppl. Fig. 7), but they differ in their likelihood of limiting warming below specific temperature levels. All scenarios keep warming to below 2°C with more than 66% probability (Fig. 1d), and maximum (peak) median temperature estimates vary from 1.5°C to 1.8°C. Near-term mitigation plays a determining role here: higher 2030 emissions come with a temperature penalty (Suppl. Fig. 8). The probability of limiting peak warming to below 1.5°C relative to preindustrial levels is roughly halved and peak temperature about 0.2°C higher if emissions are at the high (>45 $GtCO_2$-eq/yr) instead of the low (<30 $GtCO_2$-eq/yr) end of the available range in 2030 (Fig. 1e). By 2100, this variation disappears and all scenarios limit warming below 1.5°C with about 66% probability (Suppl. Figs 8-9). Whether these pathways provide an acceptable interpretation of the Paris Agreement long-term temperature goal is not a scientific but a political question[22,23], which we do not address.

Across all 13 available scenarios, net zero GHG emissions are reached around 2055-2075 (rounded to the nearest 5 year). Net zero CO_2 emissions are reached earlier (Suppl. Table 2). The year of reaching net zero GHG emissions is inversely correlated with emissions in 2030. For example, scenarios with 2030 GHG emissions higher than 40 $GtCO_2$-eq/yr reach global net zero GHG emissions before 2060 (Suppl. Fig. 10). Cumulative CO_2 emissions over the 2016-2100 period range from -175 to 475 $GtCO_2$ (SSP2 median: 250 $GtCO_2$, rounded to the nearest 25 $GtCO_2$). End-of-century non-CO_2 RF strongly influences the variation across this range[24] (Fig. 1f). These values are consistent with earlier published estimates (Suppl. Text 3) and lead to 2100 atmospheric CO_2 concentrations in the 350-390 ppm range. Potential feedbacks which are currently not included, like CO_2 and CH_4 release from permafrost thawing or changes in other natural sources, can reduce carbon budgets further[25,26] and hence alter the presented climate outcomes.

Even in these very stringent mitigation pathways, sizeable remaining CH_4 and N_2O emissions are projected by all models (Fig. 1c, Suppl. Fig. 6), and in 2100 respectively 53-85% and 59-95% of these emissions originate from agriculture. The uncertainty in CH_4 and N_2O emissions is large with inter-model variations dominating inter-SSP variations. High and low estimates for 2100 differ by a factor 2 to 3, mainly due to uncertainties of how emissions from agriculture are treated and can be mitigated in different models[27,28]. Significant uncertainties also remain in the CO_2 mitigation contribution of the land-use sector[28] (Suppl. Fig. 5). Here, emissions decline over the long term, but whether and to what degree the land-use sector becomes a global sink is very model dependent (Suppl. Text 4).

System transformations

Achieving drastic emission reductions requires a transformation of the global economy. Earlier studies have discussed the implications of such a global transformation for the energy and land-use system[29], highlighting the importance of limiting future energy demand[29] in keeping warming to below 1.5°C and of changing consumption patterns[30] combined with sustainable intensification of agriculture[31]. We here focus on confirming these characteristics and exploring the extent to which they vary across SSPs.

All 1.9 Wm^{-2} scenarios in this study strongly limit energy demand growth (Fig. 2d, Suppl. Fig. 11), energy intensity reduction rates of 2-4%yr^{-1} from 2020 to 2050 (Fig. 2d). In SSP2, final energy demand in 2050 is limited to 10-40% above 2010 levels (rounded to the nearest 5%). This compares to 10% below to 30% above, and 45-75% above 2010 levels in SSP1 and SSP5, respectively. Energy conservation is thus a common strategy in stringent mitigation scenarios, but also has its limits.

Also energy supply has to be transformed to achieve deep emissions reductions. This includes upscaling of bioenergy and renewable energy technologies, shifting away from freely emitting fossil fuel use, and the deployment of CDR such as Bioenergy with Carbon Capture and Sequestration (BECCS) or large-scale afforestation (see Supplementary Text 5 for a discussion of CDR in SSPx-1.9 scenarios). Non-biomass renewables (solar, wind, hydro, and geothermal) scale up rapidly over the 21st century (Fig. 2a), reaching mid-century electricity shares of 60-80% and 32-79% in SSP1 and SSP2, respectively (Suppl. Fig. 12). In the marker SSP scenarios, these shares are 79%, 60%, and 61% in SSP1, SSP2, and SSP5, respectively. Both solar and wind are projected to scale up consistently across the different SSPs (Suppl. Fig. 13). Particularly for wind, inter-model variations dominate over differences induced by different SSPs, a feature also present in less stringent mitigation pathways[32] (Suppl. Table 4). SSP2 and SSP5 1.9 Wm^{-2} scenarios see a strong upscaling of nuclear power, while in SSP1, and particularly its marker implementation, the contribution of nuclear decreases from today's levels (Suppl. Fig. 13).

Under all SSPs, 1.9 Wm^{-2} scenarios show a clear shift away from unabated fossil fuels (i.e., without CCS, Fig. 2c), and a phase-out of all fossil fuels. The marker implementations exhibit rapidly declining contributions of coal until 2040 (less than about 20% of its 2010 contribution in 2040), followed by a phase out of oil until 2060 (Suppl. Fig. 14-15). The potential contribution of natural gas to the primary energy mix is most uncertain, with mid-century contributions ranging from 22 to 267 $EJyr^{-1}$ across all scenarios compared to about 100-110 $EJyr^{-1}$ in 2010. Differences in preferences for gas supply across models here dominate the variation in costs and availability assumptions due to alternative socioeconomic pathways (Suppl. Table 4, Suppl. Fig. 16).

Bioenergy is deployed in large amounts in all 1.9 Wm^{-2} scenarios, and this can raise concerns for food security or biodiversity[33-35]. These concerns depend both on how and how much bioenergy is produced. Bioenergy demand can be met through dedicated energy crops or through residues. The latter come with fewer trade-offs than dedicated bioenergy crops[35]. Models, however, project very different shares for the use of residues (Suppl. Table 5), and further research clarifying its potential would be essential. For 2050, global technical bioenergy potentials (including energy crops and residues) were identified ranging from <50 to >500 $EJyr^{-1}$. High, medium and low agreement was attributed to potentials of 100, 300 and >300 $EJyr^{-1}$, respectively[33]. Bioenergy use is increased by 1-5% per year between 2020 and 2050 in 1.9 Wm^{-2} scenarios. Total bioenergy use in 2050 is kept below about 300 $EJyr^{-1}$, and in most cases below 150 $EJyr^{-1}$ (Suppl. Fig. 17). In a green-growth SSP1 world, markedly lower bioenergy contributions are projected compared to an SSP2 world which continues the historical experience (34-112 $EJyr^{-1}$ lower in 2050). Putting this into context, scenarios project approximately 100 $EJyr^{-1}$ of bioenergy use (full range: 38-112, with important variations across SSPs) in baseline scenarios without any climate policy (Suppl. Fig. 17).

In 1.9 Wm^{-2} scenarios, land for energy crops and forest area is generally projected to expand over the 21st century, with large variations across models, and this can impact land for agriculture and water availability[36,37] (Fig. 2f, Suppl. Fig. 18). However, in SSP1 the decrease in agricultural land in 1.9 Wm^{-2} scenarios is quite similar to what is projected in a no-climate-policy baseline merely due to low demand for agricultural commodities and high agricultural intensification. Pasture is one of the activities most impacted by expanding other land uses and declines robustly across models and SSPs (Suppl. Fig 19). In the middle-of-the-road SSP2 world, pastures decreases by 1-20% in 2050 compared to 2010 levels, and also in SSP1 this is 8-16%. In a fossil-fuel intensive SSP5 scenario it declines by 15-25%. It is important to note that SSP1 baseline scenarios already project a pasture-land decrease of 1-11% due to shifts towards less meat-intensive diets, limited food waste and a return of world population to 7 billion people by 2100.[5,9,28] This reaffirms the important role that changes in food consumption in combination with sustainable intensification of agriculture play for stringent mitigation[28,31,38].

Large-scale afforestation and reforestation can make an important contribution to the overall CDR effort. In the sustainable SSP1 world, pressure on land is relatively low, and forest area in 2050 can thus expand by 0-24% relative to 2010. However, in the middle-of-the-road SSP2 scenarios, results are mixed, with some models projecting forest area to decrease by 2% and others report an increase of up to 18%. SSP5 sees a change of 0-16% (Suppl. Table 6). Not all models explicitly include afforestation as a mitigation option and ranges thus span results which are not fully comparable across models. However, in all 1.9 Wm^{-2} scenarios climate policy leads to a net forest expansion compared to no-climate-policy baselines (Fig. 2e). Integrated policy packages are required that ensure food security is achieved together with climate change mitigation[39].

BECCS contributes the largest part of CDR in 1.9 Wm^{-2} scenarios (Suppl. Fig. 20). Between 150-1200 $GtCO_2$ (rounded to nearest 25), equivalent to about 4-30 years of current annual emissions, is removed from the atmosphere via BECCS over the 21st century, with significant variation between models and across SSPs (Fig. 3a,d). SSP1 shows the lowest BECCS deployment over the 21st century (150-700 $GtCO_2$) due to its lower final energy demand and baseline emissions, compared to SSP2 (400-975 $GtCO_2$) and SSP5 (950-1200 $GtCO_2$). None of the SSPx-1.9 scenarios explicitly attempted to limit the contribution from BECCS. The here reported numbers hence represent projections of estimated cost-effective BECCS deployment in 1.9 Wm^{-2} scenarios, but do not represent minimum BECCS requirements in a strict sense.

Abated fossil fuels – i.e. fossil fuels combined with CCS (Fossil-CCS) – are often utilized by models as a bridging solution. However, Fossil-CCS still results in residual CH_4 emissions from coal mining or gas handling, and CO_2 emissions due to imperfect capture and leakage. These emissions can become too significant for very stringent mitigation transitions. Indeed, almost all 1.9 Wm^{-2} scenarios deploy less cumulative Fossil-CCS than weaker mitigation scenarios (Fig. 3c). Optimal 1.9 Wm^{-2} strategies are thus not merely 'more of the same'. Overall, the BECCS share of total CCS increases (Suppl. Fig. 20). CDR is thus preferred over Fossil-CCS in very stringent mitigation scenarios.

Differential mitigation

An earlier study[40] identified characteristics of 1.5°C pathways in comparison to 2°C pathways. These characteristics were (i) greater mitigation efforts on the demand side; (ii) energy efficiency improvements; (iii) CO_2 reductions beyond global net zero; (iv) additional GHG reductions mainly from CO_2; (v) rapid and profound near-term decarbonisation of energy supply; (vi) higher mitigation costs; and (vii) comprehensive emission reductions implemented in the coming decade. Using our 1.9 Wm^{-2} and 2.6 Wm^{-2} scenarios as proxies for 1.5°C and 2°C pathways, these characteristics still hold when assessed with four additional models and varying socioeconomic assumptions (Fig. 4, Suppl. Text 6, and results above). None of the 1.9 Wm^{-2} scenarios peak emissions after 2020, and 82-98% of additional cumulative mitigation over the 2020-2100 period is achieved through CO_2 reductions (Suppl. Fig. 21). Figure 4 further illustrates the relatively stronger demand-side mitigation efforts in 1.9 Wm^{-2} scenarios, particularly in the transport and building sectors (see also Suppl. Figs 22-24).

Mitigation costs increase substantially between 1.9 and 2.6 Wm^{-2} scenarios reflecting higher marginal abatement costs (Figs 4-5). The *relative* carbon price increase is largest in SSP2 (Fig. 4) and also SSP1 sees large *relative* increases across all models (Suppl. Figs 22-24). However, in *absolute* terms, carbon prices (Fig. 5), consumption losses, and energy supply mitigation investments (Suppl. Fig. 26) are highest when assuming the less favourable socioeconomic conditions of SSP2, SSP4, and SSP5. For instance, the average discounted carbon prices (discounted to 2010 over the 2020-2100 period, Fig. 5) are estimated to be about 50-165 USD $tCO_2\text{-eq}^{-1}$ in SSP2 (rounded to the nearest 5). They are roughly 35-65% lower in SSP1, and for the two reported SSP5 scenarios the change is -30% and +5%, respectively. The large range of carbon prices is mainly driven by model uncertainties, which were already identified for 2.6 Wm^{-2} scenarios[5], but is here more pronounced due to the more stringent target.

Enabling and disabling factors

Our results show that some socioeconomic developments and assumptions about policy effectiveness preclude achieving stringent mitigation futures (Fig. 5). Such failures were anticipated for SSP3, where a very heterogeneous regional development and debilitating policy assumptions already rendered limiting end-of-century RF to 2.6 Wm^{-2} unachievable in the models[5] (Suppl. Text 2). However, in SSP4 and SSP5 limiting RF to 1.9 Wm^{-2} proved difficult too. In SSP4, a world that breeds both geographical and social inequalities, only one-out-of-three models attempting a 1.9 Wm^{-2} scenario was successful. Weak mitigation is achieved rather easily in SSP4.[5,12] However, the lack of control over land-related emissions in developing countries and lower acceptability of CCS in developed countries in SSP4 make very low emissions pathways unachievable[12]. Also in SSP5, a world dominated by high economic growth and fossil-fuel development, challenges to mitigation are high[13]. Finally, under a middle-of-the-road development (SSP2) and under a green-growth paradigm (SSP1) four and six models, respectively, were able to produce a 1.9 Wm^{-2} scenario (Suppl. Table 1).

Mitigation challenges for achieving a 1.9 Wm^{-2} target thus differ strongly across the SSPs, as illustrated by the various panels in Fig. 6. For example, the amount of CO_2 emission that has to be avoided varies by a factor of two between SSP1 and SSP5 worlds in 1.9 Wm^{-2} scenarios (Fig. 6a). The projected use of BECCS varies by a factor 2 to almost 3 between SSP1, and SSP2 and SSP5, respectively (Fig. 6c), and also land-use CO_2 mitigation contributions vary massively yet less distinctly (Fig. 6b). Furthermore, the shift away from baseline development implied by the energy system transformation is also markedly smaller in SSP1 than in SSP2 or SSP5 (Fig. 6d-f), and hence comes with potentially lower overall societal hurdles. Even when overcoming these differences in starting points, the difficulty or facility of achieving deep mitigation remains very diverse across SSPs. In particular, the lower level of final energy demand that can be achieved in SSP1 implies a smaller energy supply system[5,32] (Fig. 6g) and thus also a smaller amount of investment needs to decarbonize it (Fig. 6h). Finally, also residual emissions from agriculture and the emission intensity of food production differ strongly between SSPs (Fig. 6i-j) highlighting that challenges have to be overcome in all sectors. Each of these dimensions identifies avenues for potential policy intervention.

Interpretation and feasibility

What can SSPx-1.9 scenarios teach us about the feasibility of limiting warming to 1.5°C? Typically, feasibility refers to a multi-dimensional concept that considers aspects of geophysics, technology, economics, societal acceptance, institutions, and politics, amongst other. In this context, integrated scenarios provide insights about the technological and economic assumptions under which a global climate goal could or could not be achieved. However, because models are stylized, imperfect representations of the world, feasible dynamics in a model might be infeasible in the real world, while vice versa infeasibility in a model might not mean that an outcome is infeasible in reality.

For example, modelled energy transition pathways assume broad social acceptance, convergence towards global cooperation, and limited political inertia or institutional barriers – conditions which are different in reality. At the same time, reality can also move faster than assumed in models.[41] Advanced and pervasive information technologies which dominate our lives today would not have been considered feasible half a century ago, and also recent real-world cost reductions for renewable energy technologies exceeded expectations even of the more optimistic scenarios from 20 years ago.

Earlier studies have highlighted the importance of deriving insights from scenarios that are able to reach the intended target, and scenarios that indicate under which conditions a target cannot be met[42]. This led to the development of more sophisticated interpretations of structured scenario ensembles which suggest that the proportion of successful scenario results can be used as an indicator of infeasibility risk[43]. In this context, our scenarios can illustrate that multiple technologically salient options are available for limiting warming increase to 1.5°C, but that the risk of failure increases markedly in the high growth, unequal, and/or energy intensive worlds of SSP3, SSP4, and SSP5. Any interpretation of models unable to reach a certain target comes with caveats because models, including IAMs, are coarse approximations of reality. Real-world feasibility of a particular scenario also depends on factors not covered by current IAMs (like social support) or enabling factors (like rapid technology development). These might shift assessments of feasibility in either a more positive or negative direction.

The policy scenarios reported here thus inform certain aspects, but should not be considered as an absolute statement on feasibility[29]. Policy analysts and advisors still need to translate the insights of this and other related studies[36,40,44-48] into a more complete assessment of feasibility, which accounts for the broader context of societal preferences, politics, and recent real-world trends.

Going forward

This study set out to develop a new set of stringent integrated community scenarios that can facilitate the assessment of climate impacts, mitigation, and adaptation challenges in the context of the Paris Agreement. However, continued research is needed. A stronger involvement of the social sciences that study *how* societies change and transform can provide valuable additional complementary insights. To facilitate such further analysis, data presented here are made available to the wider community. Finally, the SSP1-1.9 marker implementation will be included as a very low climate change scenario in CMIP6 ScenarioMIP (Suppl. Text 1), and detailed climate data for these scenarios will become available in the 2018-2020 timeframe[17,18].

Figure captions

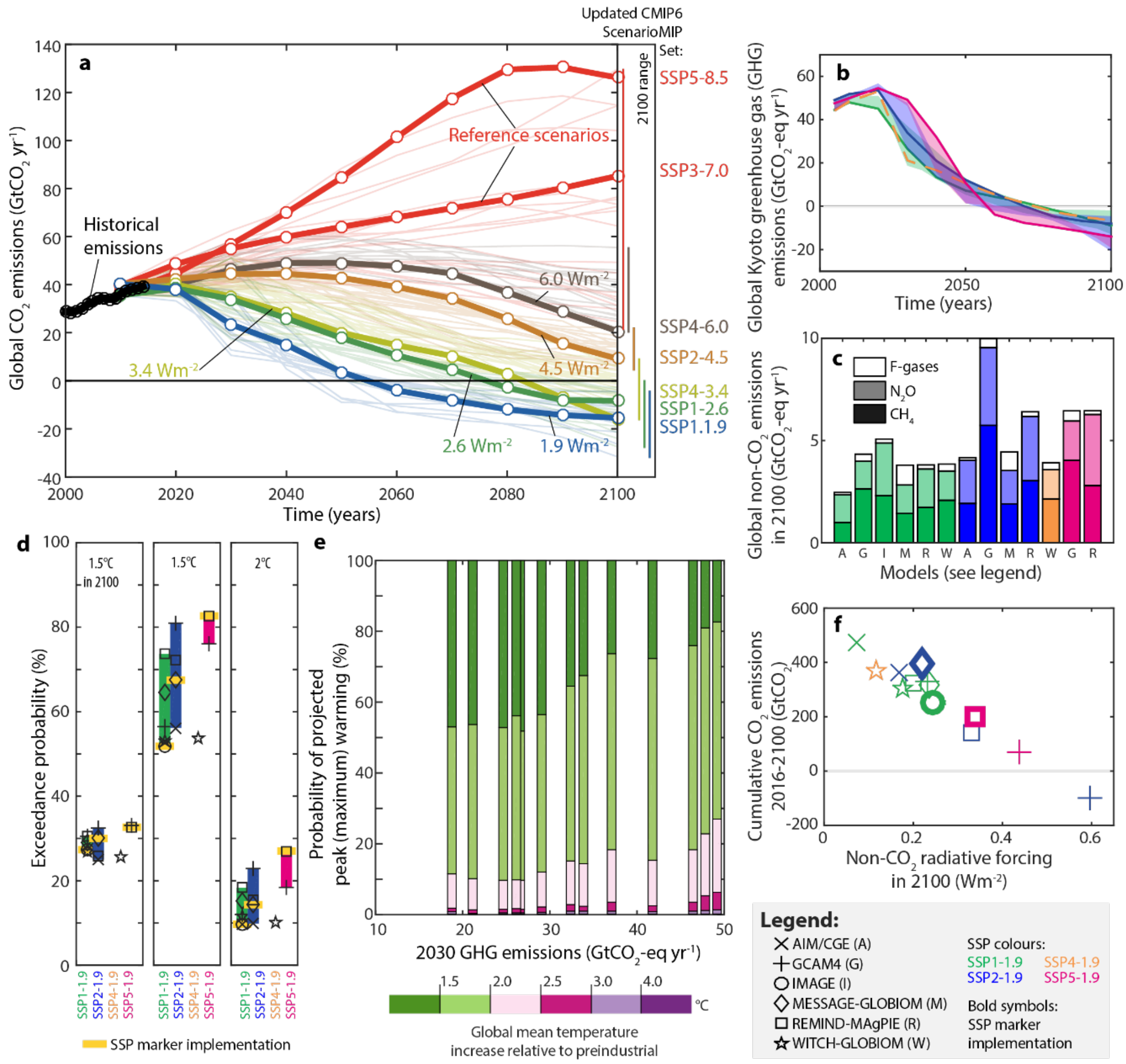

***Figure 1 | Emission and temperature characteristics of 1.9 Wm^{-2} scenarios under varying SSPs. a**, Global CO_2 emissions of SSP scenarios with the selected CMIP6 ScenarioMIP subset highlighted. Historical emission from ref. 49. All other panels show 1.9 Wm^{-2} scenario data only; **b**, Global Kyoto GHG emissions. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines single scenarios that are not markers. Single model detail is provided in Supplementary Figure 2; **c**, Non-CO_2 GHGs per scenario in 2100; **d**, Exceedance probability of various temperature limits for 1.9 Wm^{-2} scenarios with bars showing the full range over all available scenarios per SSP. Except for the first sub-panel all other panels give the exceedance probability over the entire 21st century; **e**, Probability of peak warming versus 2030 GHG emissions in 1.9 Wm^{-2} scenarios; **f**, Dependence of cumulative CO_2 emissions on non-CO_2 RF in 2100.*

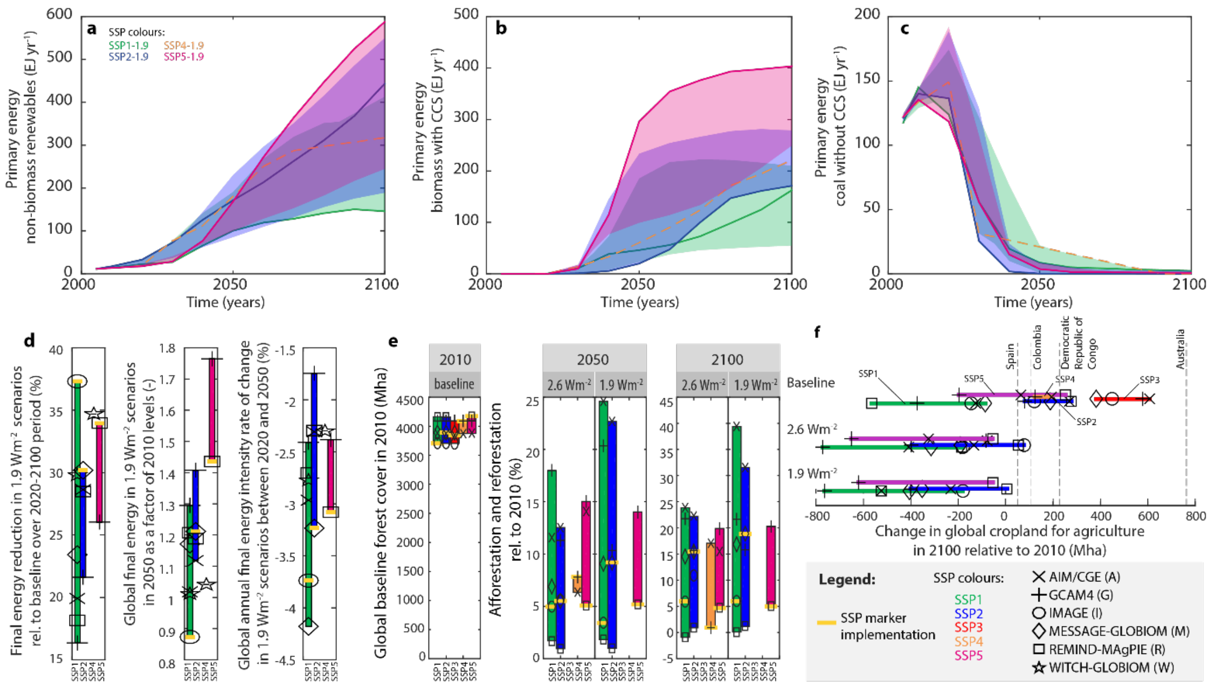

Figure 2 | Overview of key decarbonisation characteristics in 1.9 Wm⁻² scenarios. ***a****, Primary energy from non-biomass renewables (wind, solar, hydro, and geothermal energy);* ***b****, Primary energy from biomass with CCS (BECCS);* ***c****, Primary energy from coal without CCS. Shaded areas in panels* ***a-c*** *show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines single scenarios that are not markers;* ***d****, Illustration of global final energy demand in 1.9 Wm⁻² scenarios showing the average reduction from baseline over the 2020-2100 period, the change in 2050 compared to 2010 levels, and the annual rate of final energy intensity change, respectively;* ***e****, Global forest cover, and change relative to 2010 due to afforestation and reforestation in 2.6 and 1.9 Wm⁻² scenarios;* ***f****, Change in global cropland for agriculture in 2100 relative to 2010 in 'Baseline' scenarios in absence of climate change mitigation, as well as in 2.6 and 1.9 Wm⁻² scenarios. Results are grouped per SSP (coloured lines with black symbols).*

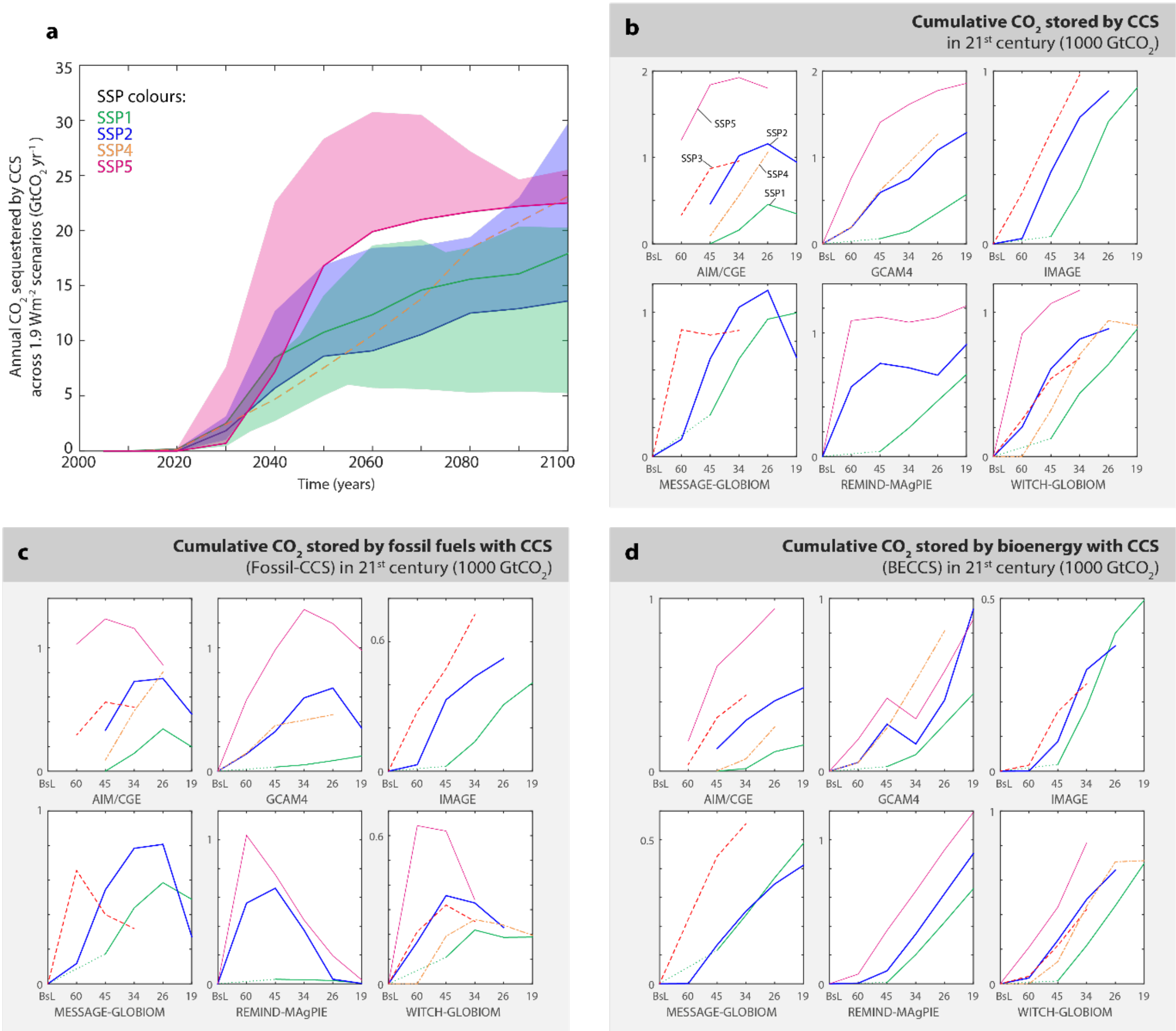

***Figure 3 | BECCS, Fossil-CCS and CCS across SSPs and across climate targets. a**, Annual amount of CO_2 stored by CCS in 1.9 Wm^{-2} scenarios. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines single scenarios that are not markers; **b**, Variation per modelling framework and per SSP of cumulative CO_2 stored by CCS during the 21st century when moving from a world in absence of climate policy (baseline, BsL) to increasingly more stringent climate targets (6.0, 4.5, 3.4, 2.6, and 1.9 Wm^{-2}); **c**,**d**, As panel **b** but for Fossil-CCS and BECCS, respectively. Note that axis limits vary across models.*

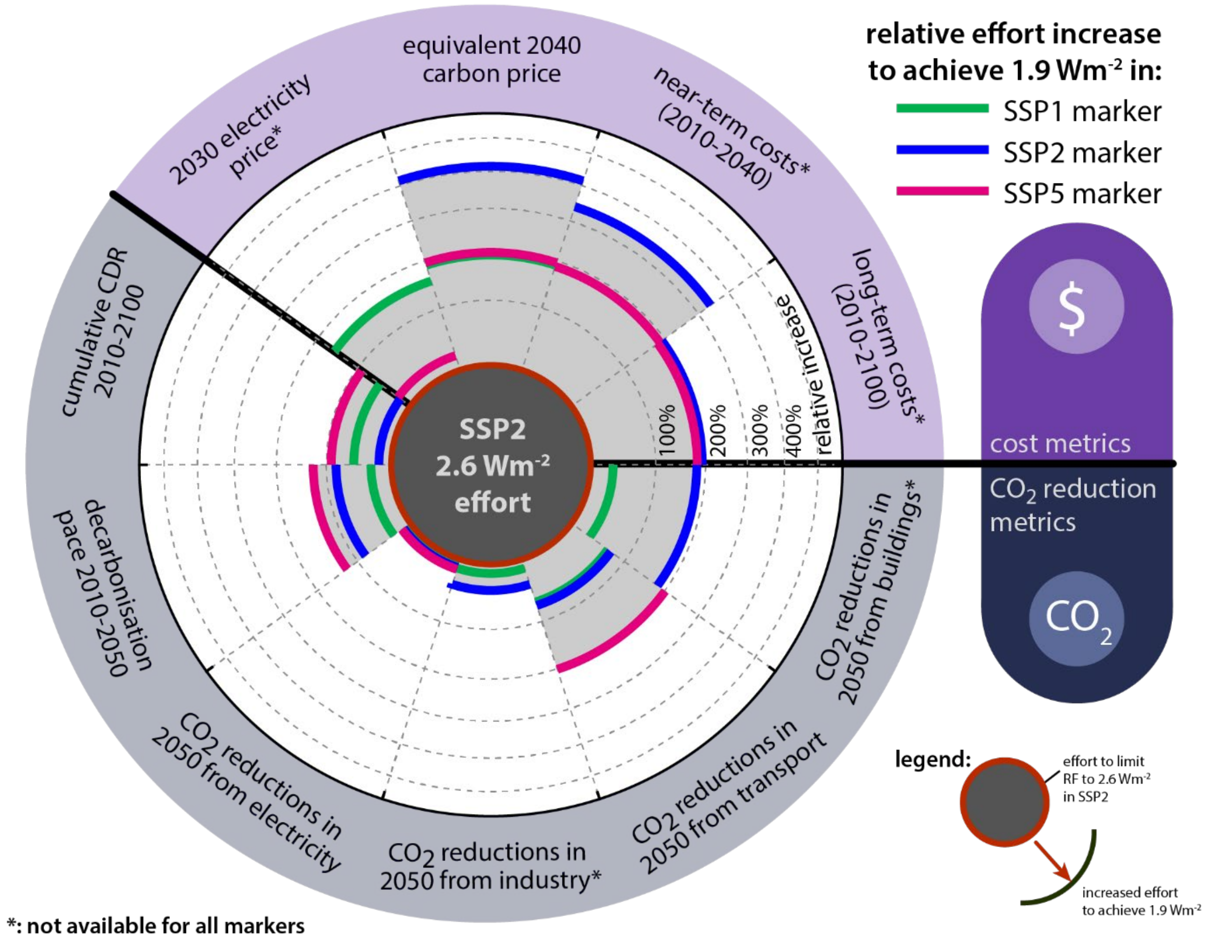

Figure 4 | Differential mitigation characteristics when moving from a 2.6 Wm^{-2} SSP2 scenario to a 1.9 Wm^{-2} scenario under three SSP assumptions (SSP1, SSP2, SSP5). *Updated from ref. 40. Indicators are: long-term mitigation costs (2010–2100 aggregate consumption losses relative to baseline discounted at 5%); short-term mitigation costs (2010–2040 aggregate discounted at 5%); 2040 global emission-weighted equivalent carbon price level; electricity price in 2030; cumulative CDR between 2010 and 2100 including BECCS and CO_2 removal by land use and land-use change; decarbonisation pace (average linear 2010–2050 rate of reductions in energy-related CO_2 emissions); reductions in CO_2 emissions from electricity from baseline in 2050; reductions in CO_2 emissions from industry from baseline in 2050; reductions in CO_2 emission from transport from baseline in 2050; and reductions in CO_2 emissions from buildings from baseline in 2050. Data is shown for the marker implementations of SSP1, SSP2, and SSP5. Ranges per SSP are provided in Suppl. Figs 22-24.*

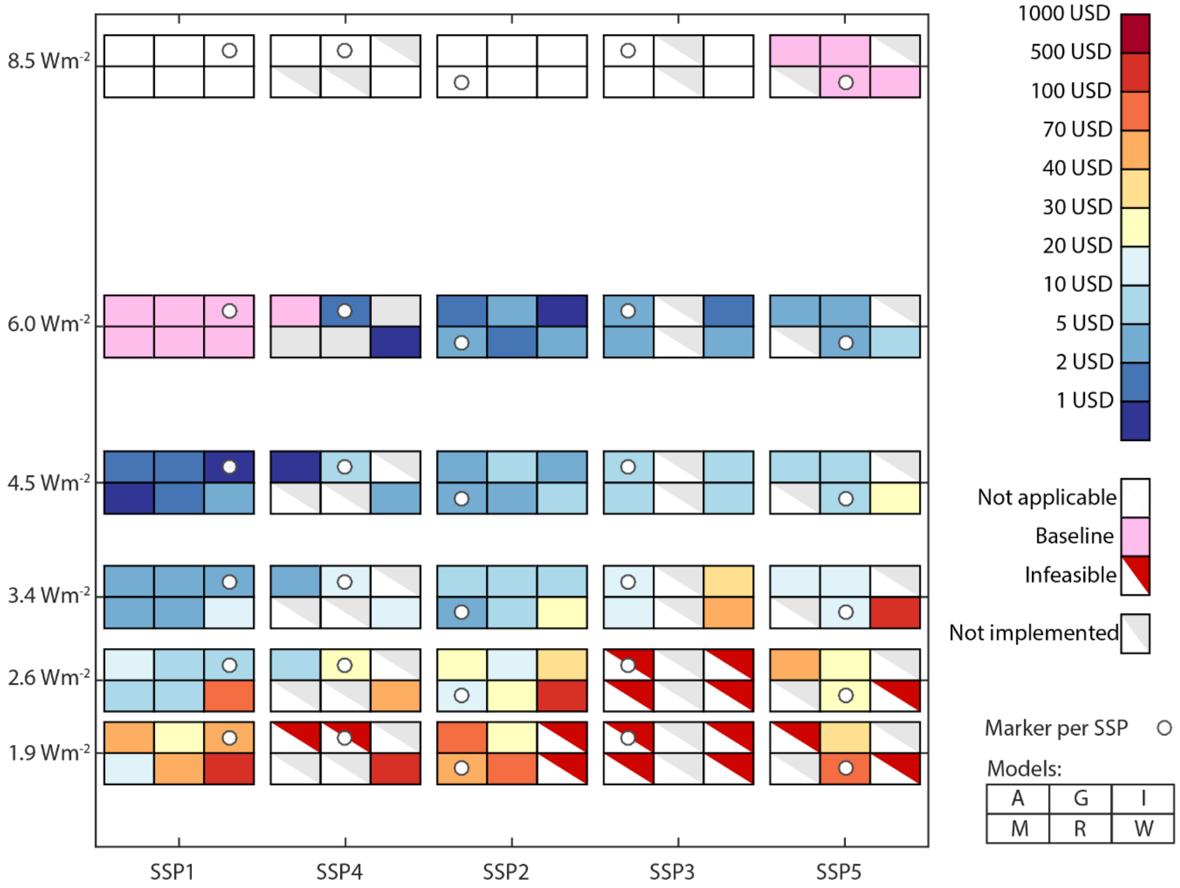

Figure 5 | Variation of carbon prices over SSP and radiative forcing target space. *Shown values are average global average carbon prices over the 2020-2100 period discounted to 2010 with a 5% discount rate. Mitigation challenges are assumed to increase from left to right across the SSPs (i.e., SSP1, SSP4, SSP2, SSP3, SSP5). Each box represents one model-SSP-RF target combination. A: AIM/CGE, G: GCAM4, I: IMAGE, M: MESSAGE-GLOBIOM, R: REMIND-MAgPIE, W: WITCH-GLOBIOM. All scenarios with a carbon price greater than 0 (i.e. all but the baselines) have been designed to reach one of the RF targets on the vertical axis. Models for which no baseline data is indicated have baselines which result in an end-of-century RF between 6.0 and 8.5 Wm^{-2}.*

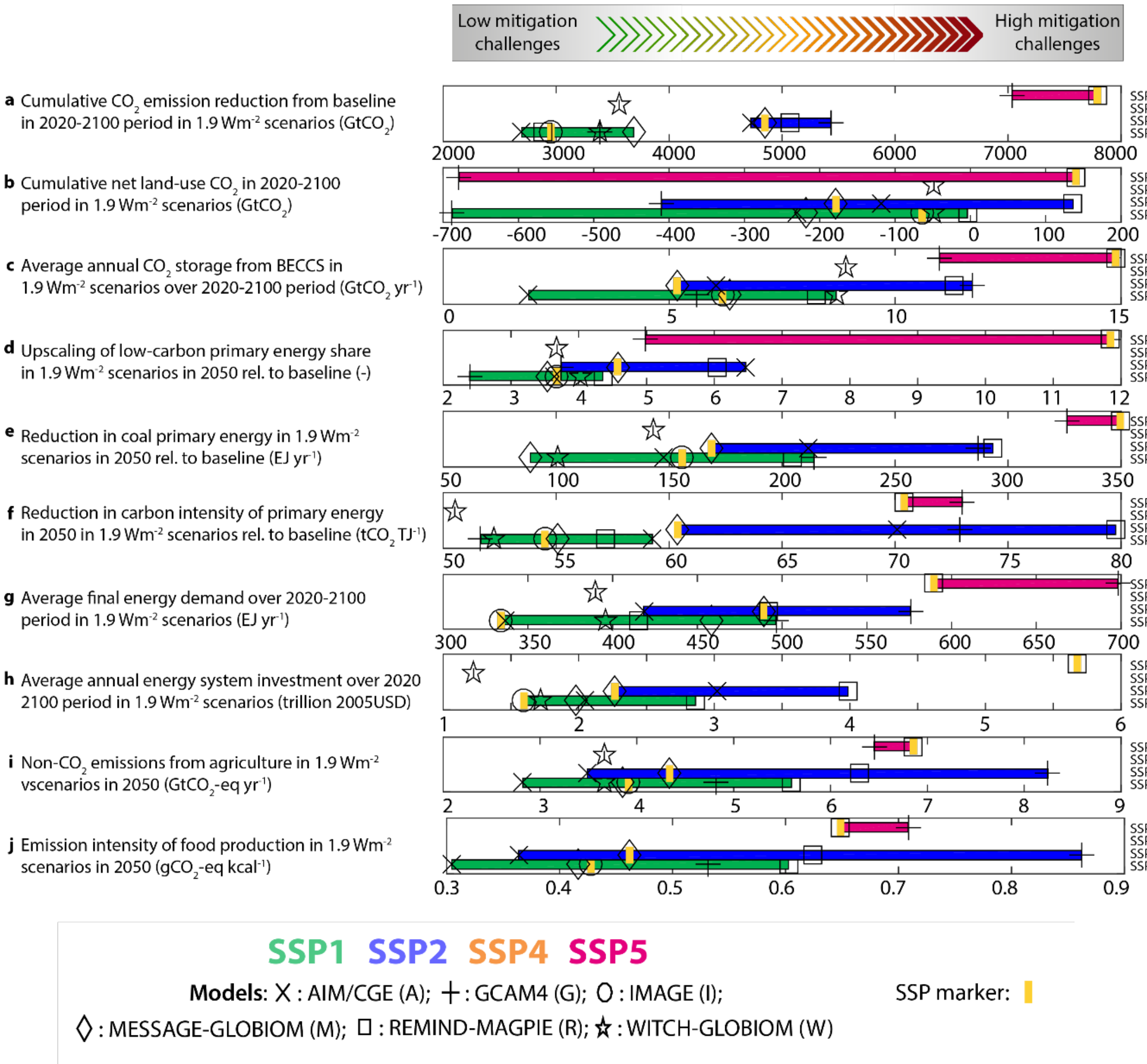

***Figure 6 | Variation in mitigation challenges for limiting end-of-century RF to 1.9 Wm^{-2} across the SSPs. a-j**, Panels show various dimensions of climate change mitigation challenges. A description of the ten indicators shown here is provided in Suppl. Table 7. Ranges show the minimum-maximum range across models per SSP. Symbols show single models. The yellow stripe indicates the marker implementation for each respective SSP. As not all modelling frameworks provide all necessary indicators, some panels show less models. No model was able to produce a 1.9 Wm^{-2} scenario for SSP3.*

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Methods

Methodological context The IPCC AR5 assessed pathways that limited RF in 2100 to 2.6 Wm^{-2}, allowing a higher level during the century[29]. This level was deemed *likely* (>66% probability) to limit global-mean temperature rise to below 2°C relative to preindustrial levels by 2100[50]. There are various motivations to explore even more stringent scenarios. For example, in several regions and particular subsystems, like tropical coral reefs, the impacts for a global average temperature rise of 2°C can already be considerably large[51,52]. Recent research also reported discernible differences in impacts between a 1.5°C and a 2°C warmer world[53], and these future impacts depend on the evolution of both the climate and the socioeconomic system. Our new scenarios provide a quantification of these dimensions for 1.5°C worlds, and can serve as a starting point for further research by other communities like, for example, the adaptation, water, or sustainable development communities. The scenarios presented here are an extension of efforts to provide scenarios for the integrated assessment of climate-change-related challenges[5,6,54]: the SSP scenario matrix framework[7]. Studies already use these narratives to explore the actions required to limit RF in 2100 to levels varying from 8.5 Wm^{-2} down to 2.6 Wm^{-2} (ref. 5,9-13,16,28,32,44), and their detailed emissions and land-use developments[5] serve as inputs for CMIP6 ScenarioMIP[17], as well as other MIPs[19,20].

Modelling protocol Participating modelling teams were asked to provide scenarios that comply with specific modelling characteristics and that are derived with the same models, model versions and assumptions as used for the SSPs[5] (see also below). The modelling protocol consisted of a set of simulations in which total anthropogenic RF in 2100 is limited to 1.9 Wm^{-2}. The limit of 1.9 Wm^{-2} is evaluated with the simple carbon-cycle and climate model MAGICC[55] in a setup comparable to the initial setup used for the RCPs[4]. The 1.9 Wm^{-2} limit was selected to result in at least 0.3°C of global mean temperature increase difference with corresponding 2.6 Wm^{-2} scenarios, which would be consistent with at least 50% of the global land surface experiencing statistically significant changes in temperatures[56]. The 1.9 Wm^{-2} limit is achieved in the IAMs by adjusting the CO_2-equivalent carbon price. This means that the RF target is achieved through reductions in GHG emissions and related co-emissions, but not through intentional increases in aerosol emissions or solar radiation management. Scenarios are run for all SSPs available in each respective modelling framework, and with their corresponding Shared Climate Policy Assumptions or SPAs[21], which influence the regional and sectorial application of CO_2-equivalent carbon prices (see annexes in ref. 5). Scenarios are labelled with the forcing target identifier "1.9" in combination with the respective SSP identifier, for example, SSP1-1.9 for a 1.9 Wm^{-2} scenario with SSP1 assumptions. For each SSP, a marker implementation has been identified which represents the characteristics of that SSP particularly well[5]. If appropriate, insights are drawn from a comparison of marker scenarios only. As was the case with RCP and SSP construction, no account of climate feedbacks to human activities and associated emissions is taken in the scenarios reported here.

Model participation Six modelling frameworks participated in this study: AIM/CGE[11], GCAM4[12], IMAGE[9], MESSAGE-GLOBIOM[10], REMIND-MAgPIE[13], and WITCH-GLOBIOM[16]. To ensure consistency and comparability, the study was carried out with the same model versions and setup as used for the other SSP-RCP work[5]. Detailed descriptions of the SSP implementations in all participating frameworks are available as part of a special issue on the quantification of the SSPs[9-13,16], with overview papers showing a comparison of results[5] as well as a synthesis of key insights related to the energy system[32] and land use[28]. An overview of model documentation, including the native regional resolution of the models and extensive references, is available in Appendix D of ref. 5. Supplementary Table 1 provides a succinct overview of the modelling frameworks and key references.

Two modelling framework have slightly updated their model setups since their earlier SSP-RCP work published in ref. 5: (I) GCAM: The implementation of near-term policy restrictions as dictated by the

Shared Policy Assumptions[5,21] (SPA) has been modified for "F2" (see ref. 5) by ensuring that a linear carbon price trajectory is followed between 2020 and 2040. GCAM's agricultural assumptions in 2020 have been adjusted to better align emissions with observations. In particular, agricultural productivity estimates from 2011 to 2020 have been reduced; (II) WITCH: A recalibration in the supply cost curves of Storage and Transportation of CO_2 has been carried out. Based on the regional storage costs curves of ref. 57, availability curves per region have been fitted to provide better cost estimates as the amount of stored CO_2 increases significantly, and to ensure the estimated storage potential is in line with more recent publications.

Not all modelling teams attempted to model all SSPs, and many only implemented a subset, either because their model was not appropriate to represent the particularities of a specific SSP or because of time and resource constraints. No SSP3-1.9 scenarios have been reported as already reaching a 2.6 Wm^{-2} target under these assumptions was not possible[5] (Suppl. Table 1, Suppl. Fig. 1, Suppl. Text 2). Marker implementations are available for 1.9 Wm^{-2} scenarios for SSP1, SSP2, and SSP5.

The set of modelling frameworks participating in this study represents an ensemble of opportunity. However, it nevertheless represents a wide variety of modelling approaches and model behaviour. Several different model types are represented, including Computable General Equilibrium (CGE) models, partial equilibrium models, and hybrid models which combine a systems dynamics or a systems engineering model with a CGE (see Supplementary Table 1). Three frameworks are intertemporal optimization frameworks, and the other three are recursive dynamic frameworks (see Table 1 in Ref. 5). The set of modelling frameworks spans the whole spectrum of model response classes as identified in ref. 58, i.e. from low (WITCH) to high response (e.g. REMIND, GCAM, MESSAGE). Considering these various dimensions, the ensemble of opportunity of modelling frameworks participating in this study spans a wide diversity of models available.

The scenarios presented here do not consider all potential CDR options (for example, they do not include direct air capture, enhanced weathering, biochar, soil organic carbon, or ocean fertilization), and exclude solar radiation management. In these scenarios, CDR is thus mainly achieved with BECCS or afforestation.

Emission and temperature assessment GHG emissions here always refer to the gases of the Kyoto basket (i.e. CO_2, CH_4, N_2O, HFCs, PFC and SF_6 but excluding the recently added gas NF_3)[59], aggregated with 100-year Global Warming Potentials from the IPCC Fourth Assessment Report[60]. Global-mean temperature change is reported relative to the 1850-1900 base period, here referred to as preindustrial. Exceedance probabilities are computed with a probabilistic setup of the MAGICC model[61,62] similar to the setup used in the IPCC AR5 Working Group III contribution[29]. The distribution of equilibrium climate sensitivity assumed in this setup is derived from the climate sensitivity assessment of the IPCC Fourth Assessment Report and hence fully consistent therewith[62]. Our setup shows similar results when updated to the values of the IPCC's most recent assessment (see ref. 63). The implied transient climate response distribution has a median of 1.7°C with a 5 to 95 percent range of 1.2 to 2.4°C. The performance of this model setup is compared to the response of complex general circulation models in Figure 6.12 of ref. 29.

Data availability Scenario data for all SSPx-1.9 scenarios will be made accessible online via the SSP Database portal: https://tntcat.iiasa.ac.at/SspDb/

Additional References for Methods

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Author Contributions
JR coordinated the conception and writing of the paper, performed the scenario analysis, and created the figures; JR, KVC, AP, GL, JE, SF, EK, KR, and DvV designed the scenarios, which were developed and contributed by all modelling teams, with significant contributions from SF (AIM/CGE), KVC (GCAM), DG, ES, JD, MH, DvV (IMAGE), OF, PH, VK, JR, KR (MESSAGE-GLOBIOM), JS, FH, AP, GL, EK (REMIND-MAgPIE), and JE, GM, LD, MT (WITCH-GLOBIOM); all authors provided feedback and contributed to writing the paper.

Conflict of interest
The authors declare no conflict of interest.