Supplementary Information:

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

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Supplementary Text 1: Very low emissions scenario selection for CMIP6 ScenarioMIP

In the framework of the Scenario Model Intercomparison Project[1] (ScenarioMIP) of the Sixth Phase of the Coupled Modelling Intercomparison Project[2] (CMIP6) a total of eight scenarios will be run. Four scenarios are included in Tier 1 of ScenarioMIP and four more in Tier 2. A very low emission scenario with forcing significantly below 2.6 Wm^{-2} is part of Tier 2. Based on the scenario results presented in this paper, a first selection of two candidates has been proposed initially: the marker implementations of SSP1-1.9 and SSP2-1.9, each with their particular characteristics (see Suppl. Material "ScenarioMIP Proposal"). Based on this information, the ScenarioMIP Scientific Steering Committee selected the SSP1-1.9 scenario for inclusion as the very low emission scenario in ScenarioMIP.

Supplementary Text 2: Feasibility of scenarios in models

Under the scenario protocol for this study, modelling frameworks attempted to limit total anthropogenic radiative forcing by 2100 to 1.9 Wm^{-2} (within rounding precision), by globally adjusting a CO_2-equivalent carbon price. In several cases models were not able to provide a scenario under this stringent forcing constraint (see Supplementary Table 1). In such cases, the scenario is referred as an "infeasible" scenario in the model. "Feasibility" or "infeasibility" of scenarios in models is determined in different ways, depending on the modelling framework.

- AIM/CGE: A scenario is infeasible if no solution can be found by the solver.
- GCAM: A scenario is infeasible if no solution can be found by the solver.
- IMAGE: A mitigation scenario is classified as "infeasible" if the climate target could not be reached in the FAIR-SiMCaP model. This IMAGE module uses baseline emissions, CO_2 cost curves (marginal abatement cost curves (MAC), derived from the energy/industry module TIMER) and non-CO_2 cost curves, coupled with MAGICC6 to calculate long-term emission pathways. For each scenario, FAIR-SiMCaP uses 64 runs with different emission profile settings. If none of the runs are able to reach the target, the scenario is considered infeasible.
- MESSAGE-GLOBIOM: A scenario is infeasible if no solution can be found by the optimization solver.
- REMIND-MAgPIE: A scenario is infeasible if no solution can be found by the optimization solver.
- WITCH-GLOBIOM: A scenario is infeasible if no solution can be found by the solver.

For example, in the IMAGE model, the lowest reachable 2100 forcing level under SSP2 assumptions was 2.15 Wm^{-2}. This was the deepest radiative forcing level achievable within the model when a maximum carbon tax trajectory leading up to about 1000 USD/tCO_2 in 2100 is applied. The inability of models to reach the stringent 1.9 Wm^{-2} objective of this study's protocol thus does not imply that scenarios more stringent than 2.6 Wm^{-2} are excluded altogether.

Also assumptions accompanying the SSPs critically influence the feasibility of scenarios in models. Appendix A in ref. 3 provides a detailed overview of the qualitative assumptions in and their variation across SSPs. These assumptions also affect how quickly and pervasively climate policy can be scaled up (see Refs. 3,4). Key barriers and limitations preventing the scenario to meet the modelling protocol specifications are reported in the table below.

Assumed Shared Socioeconomic Pathways (SSP)	Share of models able to produce scenario in line with modelling specifications	Key barriers and limitations preventing the scenario to meet the modelling protocol specifications
SSP1	*6/6*	The SSP1 assumptions include sustainable consumption patterns, low population growth, energy efficiency improving faster than historically, rapid deployment of renewable energy, and global cooperation[3,5]. The latter implies rapid technology diffusion and effective global climate policy from 2020 onwards. As a result, all participating models were able to create scenarios in line with an end-of-century forcing target of 1.9 Wm^{-2}.
SSP2	*4/6*	The SSP2 assumptions represent middle-of-the-road or "dynamics-as-usual" assumptions (meaning that societal changes follow established median experience) two out of six modelling frameworks were not able to create a scenario in line with an end-of-century forcing target of 1.9 Wm^{-2}. A combination of factors led to this outcome in these two modelling frameworks: the fragmentation of climate policy until 2040, inertia in decarbonization of the energy system, medium agricultural intensification and lower levels of natural land protection (compared to SSP1). The latter factors represent barriers to near-term emissions reductions. At the same time, the potential of carbon removal options for SSP2 in these models (BECCS and reforestation) and non-CO_2 reduction measures is insufficient to bring the net radiative forcing to 1.9 Wm^{-2} in 2100. Models that have difficulties to prematurely shut down existing fossil capacities (like IMAGE) and models who are characterized as having a comparably low response to a policy signal because of a relatively limited potential for structural change[6] (like WITCH) show clear difficulties to reach 1.9 Wm^{-2} from these intermediate assumptions.
SSP3	*0/1 (0/4)**	SSP3 assumptions describe a world with high challenges to mitigation including high population growth leading to high food and energy demand, regional rivalry hampering social and technological development (for example, significantly lower non-CO_2 emissions reductions potentials compared to SSP1 or SSP2, or the unavailability in MESSAGE of certain advanced technologies like hydrogen from various sources), lower efficiency in all sectors (and lower than historical improvements in annual energy intensity), low levels of natural land protection allowing for deforestation, a preference for non-renewable energy carriers (leading to high emissions intensity in the reference scenarios, and more residual emissions in, for example, the transport sector) and unsustainable consumption patterns. It is also assumed that climate policies will be fragmented until 2050. The combination of these assumptions leads to no modelling framework being able to create a scenario consistent with limiting radiative forcing to 1.9 Wm^{-2} in 2100.
SSP4	*1/3*	SSP4 assumptions reflect a highly unequal world with disparities in economic and political power leading to increasing inequalities within and across countries over the 21st century. It also assumes that social cohesion degrades and conflict and unrest become increasingly common.[5] Technology development is high in high-tech sectors, and the energy system diversifies. Although SSP4 is designed to represent a world in which challenges to mitigation are low, environmental policies focus on local issues around middle and high income areas.[5] These assumptions lead to weak mitigation targets (e.g. 3.4 Wm^{-2}) being achieved quite easily. However, mitigation becomes disproportionally harder for more stringent mitigation targets. For example, the SSP4 land-use assumptions results in limits to which tropical deforestation can be controlled, which leads to large residual emissions from this sector. For at least one modelling framework, these residual emissions from deforestation render the achievement of a 1.9 Wm^{-2} target unachievable under SSP4 assumptions. Furthermore, large-scale technological solutions are relatively easy to implement given the SSP4 storyline. However, many actors are left behind, and thus mitigation which requires granular solutions at the demand-side are comparatively less successful, and stringent targets which require fundamental demand-side transformations hence become difficult to achieve.
SSP5	*2/4*	The SSP5 world is a high-tech yet fossil-fuel-oriented world in which high energy-intensive lifestyles are adopted.[5] The SSP5 storyline describes a world with a strong believe in technological progress and development of human capital as the path to sustainable development. It is thus a world where measures which are often referred to as 'techno-fixes' feature particularly prominently. The ability to successfully deploy negative emissions technologies and the potential to replace technologies with significant amounts of residual CO_2 emissions appear a key determining factor in making it possible for models to counterbalance the otherwise high energy and resource intensity assumed by the SSP5 narrative. Under these assumptions two out of four modelling frameworks were able to create scenarios consistent with limiting radiative forcing to 1.9 Wm^{-2} in 2100.

** 1 modelling framework attempted to reach 1.9 W m^{-2} in 2100 with SSP3 assumptions, which turned out not to be achievable. Three additional modelling frameworks were already not able to reach 2.6 W m^{-2} in 2100 with SSP3 assumptions.*

Finally, note that scenario feasibility or infeasibility in models differs distinctly from feasibility in the real world (see discussion in main text).

Supplementary Text 3: Literature carbon emissions and budget comparison

Scenarios show a range of 35 to 40 $GtCO_2$ yr^{-1} in global total CO_2 emissions in 2010 (see Figure 1a). This range falls within the 68% uncertainty range of estimated historical global CO_2 emissions in 2010, estimated at 34 to 41 $GtCO_2$ yr^{-1} based on the uncertainties reported in ref. 7.

The IPCC AR5 reported that for limiting global average temperature rise below 1.5°C relative to preindustrial levels in more than 50% or 66% of the assessed simulations[8], cumulative CO_2 emissions from 2011 onward have to be kept below 550 or 400 $GtCO_2$, respectively. We report cumulative emissions budgets for the 1.9 Wm^{-2} scenarios in the range of -175 to 475 $GtCO_2$, with an SSP2 median of 275 $GtCO_2$, over the 2016-2100 period. Over the 2011-2015 period, roughly 200 $GtCO_2$ has been emitted (based on data from ref. 9). The reported IPCC AR5 1.5°C budgets thus translate into about 350 and 200 $GtCO_2$ from 2016 onward, for 50 and 66% of simulations keeping warming to below 1.5°C, respectively. Supplementary Figure 7d, shows that 1.9 Wm^{-2} scenarios reported here reach a 66th percentile warming of about 1.5°C in 2100 in our modelling framework. Although the probabilities reported here and the percentages given in Table 2.2 of ref. 8 are not directly comparable, the budget numbers are broadly consistent particularly taking into account the uncertainties and differences in budget definitions and methods to compute them (see also ref. 10). The Working Group III contribution to the IPCC AR5[11] further mentions that scenarios with a greater than 66% probability of limiting warming to below 1.5°C in 2100 that were at that moment available in the literature were characterized by carbon budgets of 90 to 310 $GtCO_2$ from 2011 to 2100. Adjusted with recent emissions this becomes -110 to 110 $GtCO_2$ from 2016 to 2100, a slightly smaller range than the range found in this new study. An earlier review of 1.5°C-consistent scenarios[12] reported a carbon budget range of 200-415 $GtCO_2$ for the 2011-2100 period, based on scenarios from two modelling frameworks (REMIND and MESSAGE), and without precise RF target. Again adjusting for the roughly 200 $GtCO_2$ emitted between 2011 and 2015, this range becomes 0 to 215 $GtCO_2$. This falls well within the -175 to 475 $GtCO_2$ range identified in this study based on scenarios with six modelling frameworks that aim for limiting end-of-century RF to 1.9 Wm^{-2}.

Supplementary Table 2 reports carbon budgets for alternative time periods.

A recent study[13] (henceforth M17) reported new estimates for cumulative carbon emissions for temperature increments relative to the present decade (2010-2019), based on the distribution of responses in CMIP5 models (for instance, 730 $GtCO_2$ for an additional 0.6°C of warming relative to the 2010-2019 average). The carbon budget estimates presented in the present paper are broadly consistent with the carbon budget estimates reported in the Working Group III Contribution to the Fifth Assessment Report of the IPCC[11], but lower than the M17 study. The latter is due to several methodological differences between the present study and M17, and as a result the different outcomes can be understood.

First, this study assumes about 1°C of total human-induced global mean temperature rise relative to preindustrial levels for the 2010-2019 period, compared to 0.9°C in M17. Recent studies have reported a range of human-induced global warming estimates for the 2010s, depending on the observational data product used[14] (e.g., NOAA/GISS, NOAA/MLOST, or Berkeley Earth, compared to products based on HadCRUT), with the average around 1°C as used here[15]. Second, carbon budgets reported in this study are defined from 2016 to 2100. Until 2100, the SSPx-1.9 scenarios show an additional median warming of about 0.25 to 0.3°C relative to the 2010-2019 period (and slightly more than 0.4°C at the 66th percentile). This is smaller than the 0.6°C in additional warming assumed in M17. The differences described in the two previous points explain a difference in the order of 200-500 $GtCO_2$ between SSPx-1.9 budgets reported here and the budgets reported in M17. Third, because of small lags in the temperature response to CO_2 emissions of up to about a decade[16,17] and the reducing efficiency of atmospheric CO_2 removal with increasing net negative CO_2 emissions[18] cumulative CO_2 emissions for SSPx-1.9 scenarios until 2100 are slightly smaller compared to threshold exceedance budgets[10]. This difference in budget definitions explains about 150-200 $GtCO_2$ of the difference between SSPx-1.9 budgets reported here and the budgets reported in M17. Fourth, the present study uses a probabilistic model setup compared to the frequentist estimates based on the distribution of CMIP5 models by M17. The median temperature response to cumulative emissions of carbon (TCRE) of the present study is consistent with the multi-model mean of the CMIP5 range for the multi-gas forcing of RCP8.5, but the distribution of our probabilistic observationally constrained ensemble differs from the CMIP5 model distribution and spread. This leads to the 66th percentile response of the probabilistic model setup of this study to be roughly comparable to the median CMIP5 response, which results in a correction of about 100 $GtCO_2$ between the SSPx-1.9 and M17 estimates, but in a direction opposite to the corrections mentioned above.

Supplementary Text 4: Land-use evolution

The emissions of land use and land-use change and forestry in our 1.9 Wm^{-2} scenarios show a large spread over the six modelling frameworks assessed here (Suppl. Figure 5). The main variation is driven by the results of the GCAM modelling framework. GCAM allocates land based on expected profitability. It models land-use developments that are technically possible in a model where economic policies can be applied perfectly. As a result, policy-induced profit changes can result in large shifts in land allocation and associated land-use CO_2. For example, afforestation policies, implemented in GCAM through a subsidy to land owners for storing carbon, lead to significant carbon sequestration in the terrestrial system. Increases in the demand for and thus price of bioenergy, however, can lead to significant bioenergy cropland expansion and associated carbon emissions (see refs. 19,20 for more detail). In the 1.9 Wm^{-2} scenarios described in this study this results in decadal emission changes of the order of 10 $GtCO_2$, or about 2 times the estimated global land-use emissions in 2014 (ref. 9). Also when temporarily excluding the GCAM modelling framework from the land-use CO_2 analysis, important differences are found. All but one of the remaining modelling frameworks (REMIND-MAgPIE[21]) show mostly steadily declining land-use CO_2 emissions over time (the IMAGE model also sees emissions occasionally increase during a single decade). In all cases this leads to a net global land-use sink by the second half of the century. In REMIND-MAgPIE land-use CO_2 emissions initially increase and barely reach net zero emissions by the end of the century in SSP2 and SSP5. This difference in model behaviour is due to the inclusion of displacement effects into pasture land caused by high bioenergy production combined with forest protection only[22]. Model uncertainty here dominates the overall socioeconomic uncertainty spanned by the SSPs, although generally lower land-use CO_2 emissions are achieved in SSP1 compared to SSP2.

Supplementary Text 5: Negative emissions in SSPx-1.9 scenarios

SSPx-1.9 scenarios deploy a limited portfolio of conceivable negative emissions technologies (NETs, see refs 23-25). Negative emissions in SSPx-1.9 scenarios are predominantly achieved through the combination of bioenergy with carbon capture and storage (BECCS), with further contributions of CO_2 uptake by the land-use sector and re- and afforestation measures. Although several other NETs are conceivable, like direct air capture and storage (DAC) or enhanced weathering of minerals (see refs 23-25 for an overview), these are not included as mitigation options in these scenarios. The dominance of BECCS options in these scenarios does hence not imply a BECCS requirement. Rather, these scenarios appear to prefer a substantial amount of carbon dioxide removal, and BECCS is the main option currently available in models to achieve that.

In at least half of the IAMs and the here presented SSP1-1.9 and SSP2-1.9 scenarios, the larger BECCS share (>50%) is coming from liquid biofuel production and/or hydrogen production. For these secondary energy carriers downstream energy demand for low-carbon fuels is a key driver while negative emissions are more of a by-product. For example, by 2050 at least 50% of BECCS is coming from non-electric applications in 3 out of 6 models in SSP1, and by 2100 in 4 out of 6 models. If biofuels are produced to displace fossil-based fuels in sectors that cannot be electrified with assumed progress in technologies (e.g., long-distance air travel, some heavy duty vehicles, petrochemicals), utilizing CCS comes only with a small cost increment and energy penalty, because the fuel production processes produce very pure streams of CO_2 that can either be vented or captured, conditioned and stored. This even holds true for first generation biofuel production where CO_2 is produced in fermentation processes for example see ref. 26. The Global Energy Assessment[27] estimates additional capital costs in the range of 2-3% for capture under these circumstances. Under GHG prices consistent with the 1.9 Wm^{-2} target such additional costs are very competitive (Table 12.16 in ref. 27 shows cost estimates for liquid biofuels, Figure 12.24 in the same reference shows breakeven GHG prices to make CCS competitive which are in range of 20-30 $/t$CO_2$-e). The situation for hydrogen production from biomass feedstock is comparable to that for liquid fuels.

BECCS was first presented about 15 years ago[28]. It was subsequently used in several studies[29-31]; the carbon capture and storage (CCS) component was addressed in a dedicated IPCC Special Report[32] in 2005, and BECCS was also discussed by the IPCC Fourth Assessment Report[33] (AR4) in 2007. At the time, the AR4 indicated that "further research is necessary to characterize biomass' long-term mitigation potential, especially in terms of land area and water requirements, constraints, and opportunity costs, infrastructure possibilities, cost estimates (collection, transportation, and processing), conversion and end-use technologies, and ecosystem externalities" in relation to the deployment of BECCS[33]. However, it is only with the publication of the IPCC's Fifth Assessment Report[11] (AR5) that the use of BECCS in scenarios caught wider attention[24,34-36]. This generated both assessments about the water and land resource implications of BECCS and other NETs[23], and commentaries that started a societal debate on what an acceptable or desirable scale of NETs (and BECCS in particular) would be[24,34,37] and how these could be achieved in practice[38]. In addition, other studies also pointed towards limitations in the deployment of measures that are considered sub-components of BECCS: bioenergy production[39,40] and CCS[41,42]. These issues have not been resolved, and since the inception of NETs studies have argued that negative emissions should not be considered as a silver bullet solution, but as a potential contribution in a wider portfolio of mitigation options[11,23,28,33,34,37] which includes energy efficiency measures and deployment of a diverse range of low-carbon technologies.

As illustrated in Supplementary Fig. 20, BECCS contributions vary strongly across the SSPx-1.9 scenarios, with scenarios covering a range of 1 to 16 GtCO_2 of annual CO_2 removal by BECCS in 2050. The same figure also shows clear differences between the various SSP implementations. For example, SSP5-1.9 scenarios, which focus on exploring technological solutions in a strongly developing and energy-intensive world, cover the high end of this range, whereas the green-growth SSP1-1.9 scenarios use markedly less. This variation is a desired outcome of the variations in environmental awareness, the varying rates of social and technological developments and the shift in consumption patterns covered by the narratives of the SSPs.

Dedicated assessments and studies[25,36,43], not all of which are independent of the integrated assessment modelling literature, reported potential annual rates of carbon dioxide removal through BECCS to fall in the range of 2 to 11 GtCO_2 yr^{-1} in 2050 and 15-70 GtCO_2 yr^{-1} in 2100. Also environmental non-governmental organisations have supported this 2050 range, highlighting that a practical figure would be in the lower end of this range according to their assessment[44]. This range covers most SSPx-1.9 scenarios. Exceptions exist at both the higher and the lower end. For example, the two available highly fossil-fuel and technology focussed SSP5 scenarios (developed specifically to allow exploration of trade-offs which would occur in worlds with high energy demand and in which technologies are assumed to provide most of the mitigation solution) use 11 and 16 GtCO_2 yr^{-1} of BECCS in 2050, respectively. At the lower end, two SSP1 (AIM/CGE and GCAM) and one SSP2 (MESSAGE-GLOBIOM) use BECCS in the range of 1-2 $GtCO_2\ yr^{-1}$, and therewith fall below the literature range for year-2050 BECCS deployment. Overall, most SSPx-1.9 scenarios deploy less than 6 $GtCO_2\ yr^{-1}$ of BECCS by 2050.

This variation in BECCS deployment thus provides a clear illustration of how scenarios allow a structured exploration of diverse future worlds. It is clear that not all of these worlds are equally desirable, and the here presented scenario set illustrates how potentially undesirable futures could be identified. Cost-optimal SSP1-1.9 scenarios apply significantly less BECCS than SSP5-1.9 scenarios which have high energy demand and a focus on technological solutions and fossil fuels. While not providing all the answers, our scenarios show that if BECCS use is to be minimized or avoided, a focus on energy efficiency and low energy demand, combined with sustainable consumption patterns that result in less emissions from and pressure on the agricultural sector would be avenues that can be pursued to facilitate this.

Supplementary Text 6: Verifying key characteristics

An earlier study identified key characteristics of 1.5°C scenarios[12]. This study drew upon the information of two modelling frameworks: the REMIND and MESSAGE models. Because some of the 1.9 Wm^{-2} scenarios presented in this paper have been generated by new modelling frameworks, we here verify whether the key characteristics identified in the earlier study still hold, and can spell them out further based on insights from the present multi-model, multi-SSP analysis.

Characteristic 1: CO_2 reductions beyond global net zero emissions
Confirmed: Total global CO_2 emissions reach net zero between 2045 and 2060 (rounded to the nearest 5 years). Net CO_2 emissions in 2100 in our 1.9 Wm^{-2} scenarios are about -5 to -19 $GtCO_2$/yr in SSP1, and -10 to -35 $GtCO_2$/yr in SSP2 (Supplementary Table 2) .

Characteristic 2: Additional GHG reductions mainly from CO_2
Confirmed: As illustrated in Supplementary Figure 21, the incremental mitigation implied by moving from a 2.6 to 1.9 Wm^{-2} scenario is dominated by reductions of CO_2 emissions.

Characteristic 3: Rapid and profound near-term decarbonisation of energy supply
Confirmed: All 1.9 Wm^{-2} scenarios strongly reduce CO_2 emissions from energy supply in the near term (2030 to 2040), with several models achieving net negative emissions from energy supply activities by 2040.

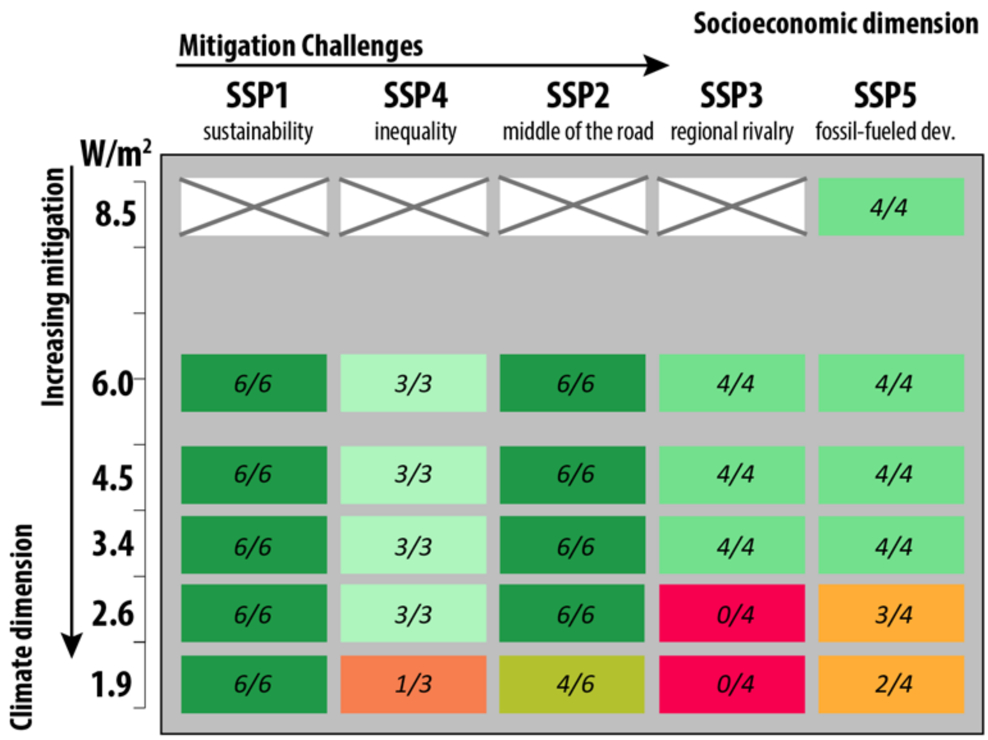
Characteristic 4: Greater mitigation efforts on the demand side
Confirmed: Additional mitigation efforts in the industry, buildings, and transport sectors result in significantly lower emissions over the coming decades and by mid-century (Suppl. Figure 25).

Characteristic 5: Energy efficiency improvements are a crucial enabling factor for 1.5°C
Confirmed: As highlighted in the main body of this manuscript, all 1.9 Wm^{-2} scenarios in line with the Paris Agreement long-term temperature goal limit final energy demand by 2050 to about 10-40% above 2010 levels in SSP2 (rounded to the nearest 5%). Also in the other SSPs, important reductions in final energy demand are projected relative to the baseline. Annual energy intensity improvements between 2020 and 2050 range from -2.4 to -4.1% in SSP1 and from -1.7 to -3.2% in SSP2. For SSP3, a world in which energy intensity improvements are the hardest to achieve, neither 1.9 Wm^{-2} nor 2.6 Wm^{-2} scenarios could be produced, although also strong limitation to the effectiveness of climate policies play an important debilitating role in SSP3.

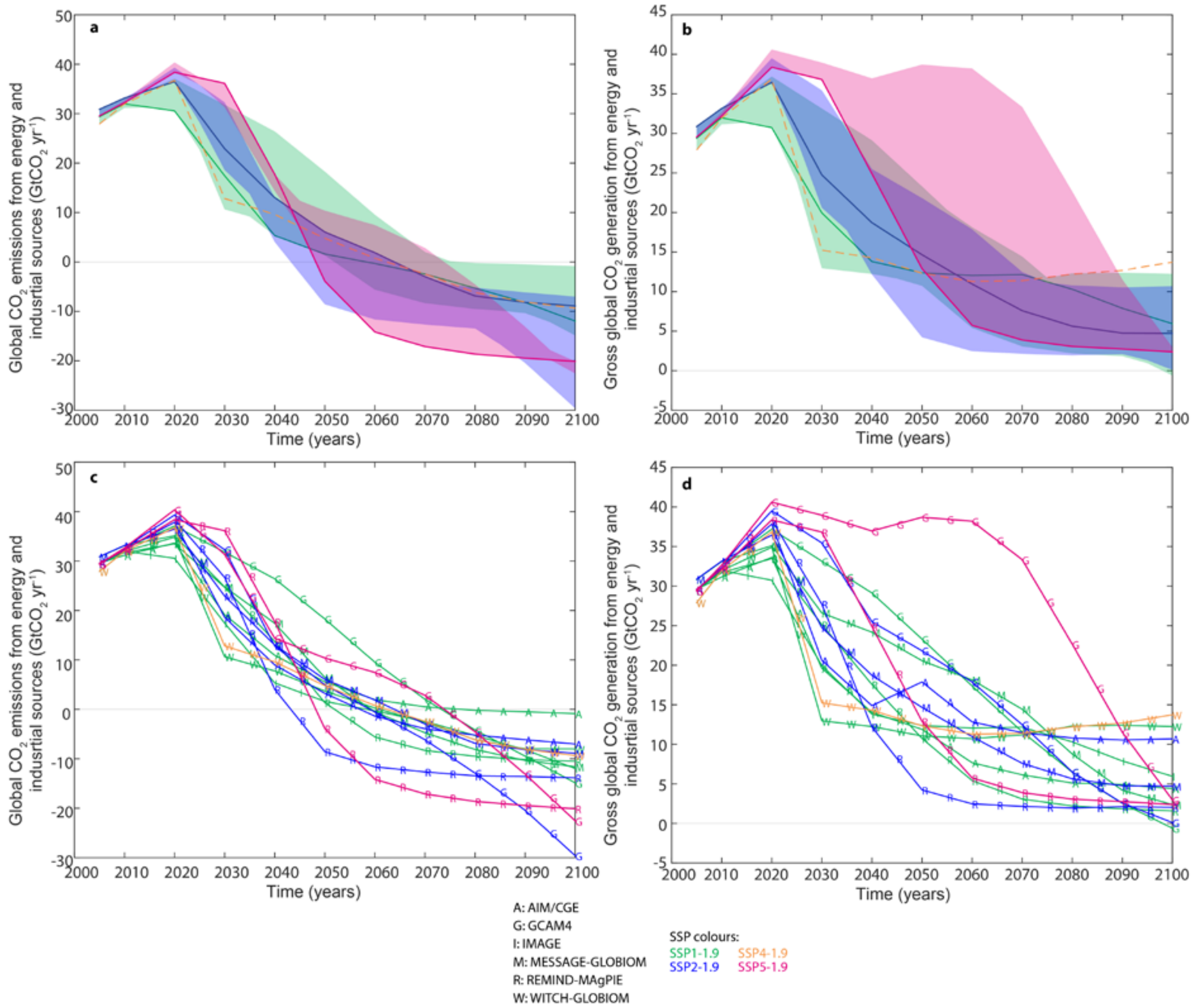
Characteristic 6: higher mitigation costs
Confirmed: Figures 4 and 5 and Supplementary Figures 20-22 show the increase of mitigation costs when moving from a 2.6 to 1.9 Wm^{-2} scenario, particularly in the near term.

Characteristic 7: Comprehensive emission reductions are implemented in the coming decade.
Confirmed: All 1.9 Wm^{-2} scenarios in our study start declining global emissions from 2020 onward. Scenarios thus confirm peaking in 2020. Starting earlier would not be possible due to the modelling protocol constraints specified in the Shared Climate Policy Assumptions[3] (SPAs). Whether later peaking would preclude going to 1.9 Wm^{-2} requires dedicated model experiments.

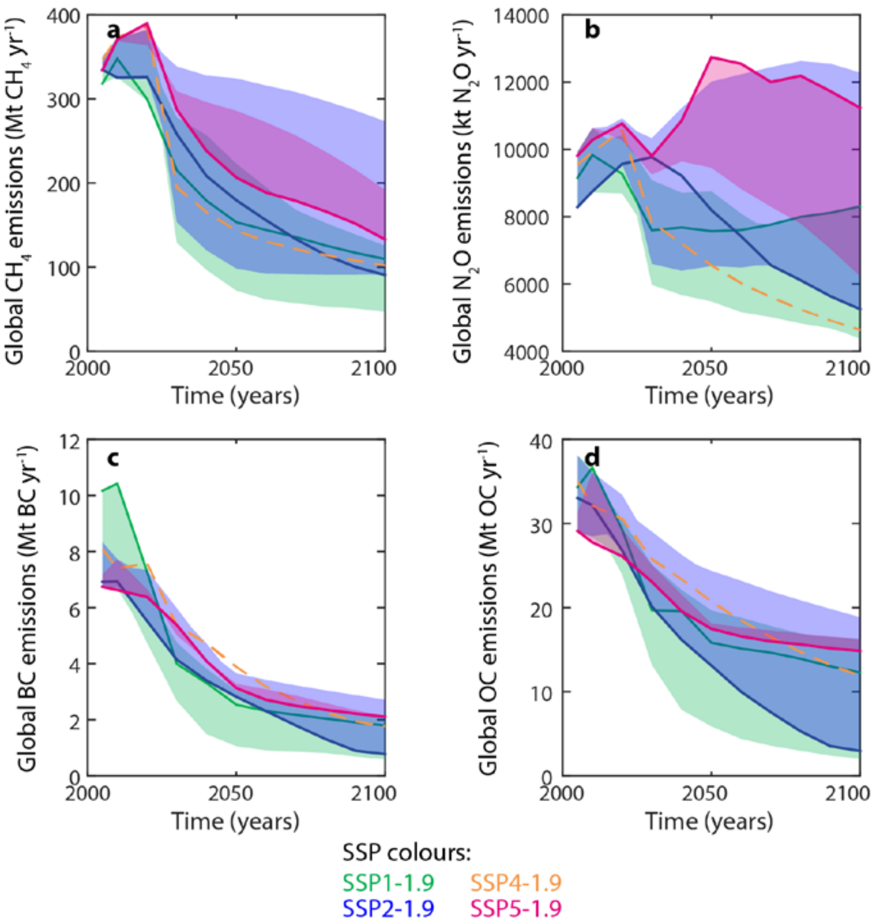
Supplementary Figures



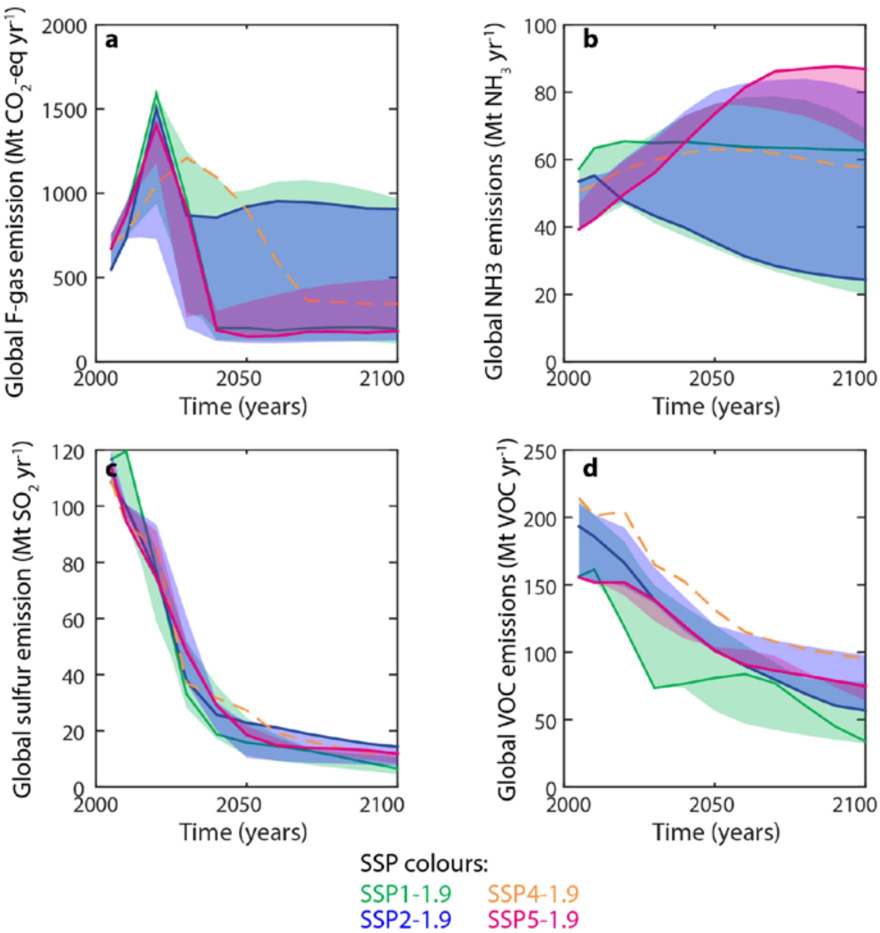
Supplementary Figure 1| Overview of available scenario runs in the SSP-RCP matrix framework. Values in each box represent the number of available scenario runs over the number of participating modelling frameworks.



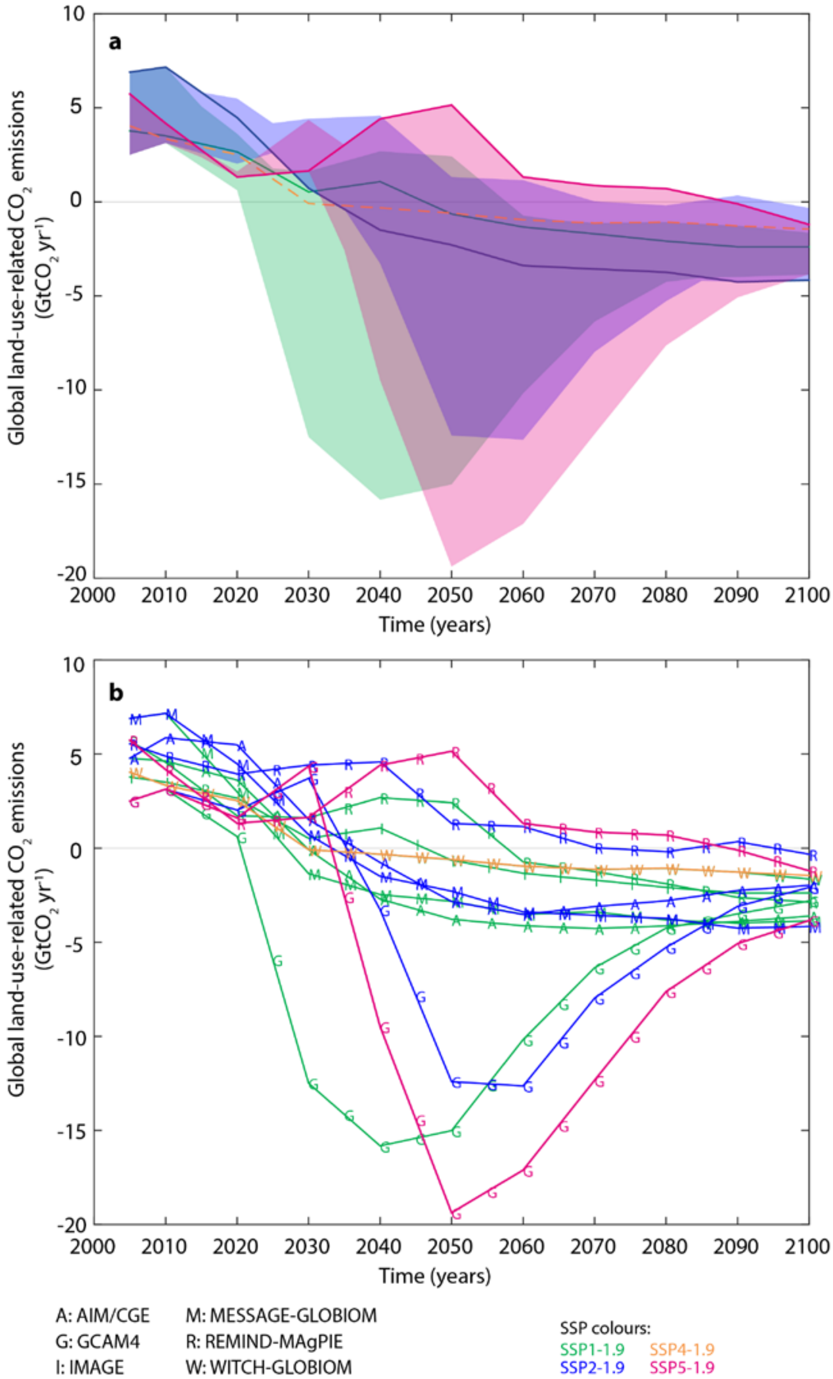
Supplementary Figure 2| Energy and industry related CO_2 emissions and CO_2 generation in 1.9 Wm^{-2} scenarios. **a**, Global CO_2 emissions from energy and industrial sources. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP; **c**, as panel **a**, but with single models highlighted; **b**, Global CO_2 generation (or production) from energy and industrial sources, computed as global total CO_2 emissions from energy and industrial sources plus the global total amount of carbon capture and storage (CCS). Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP; **d**, as panel **b**, but with single models highlighted. Models show important variations in their near-term emission evolution between 2020 and 2030, for example, the very deep emissions reductions modelled by the WITCH model and the less pronounced emission reductions in GCAM. These variations are the result of structural differences between models, requiring models that include a low variation of low-carbon technologies to reduce a lot in the first time step in order to compensate for a relatively limited emission reduction potential in the long term (see Methods and Supplementary Text 2). Beyond model structure, also SSP assumptions on phase-in of climate policies and availability of technologies[3] impact near-term emissions. For example, SSP5 implementations are consistently higher than other available SSP implementations in 2030 in each respective modelling framework reflecting the gradual phase-in of globally coordinated climate policy between 2020 and 2040 and the large potential for CDR in the second half of the century.



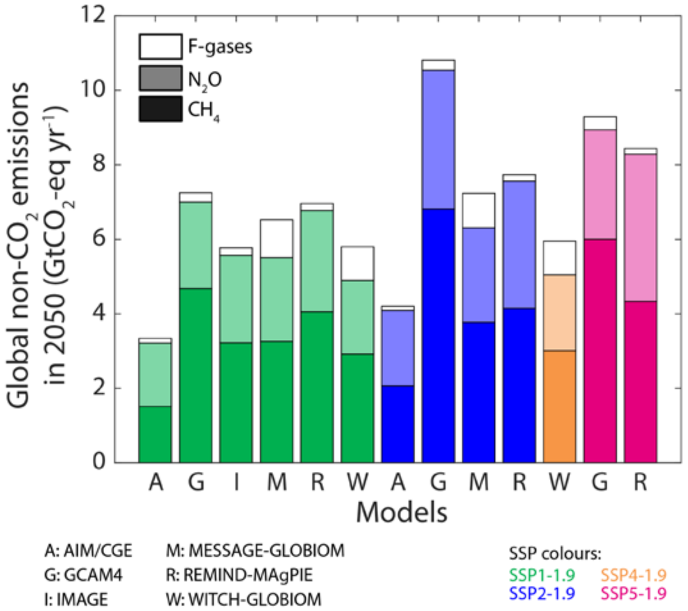
Supplementary Figure 3 | Evolution of anthropogenic emission of greenhouse gases and aerosols in 1.9 Wm^{-2} scenarios. **a**, global total CH_4 emissions; **b**, global total N_2O emissions; **c**, global black carbon (BC) emissions; **d**, global organic carbon (OC) emissions. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP.



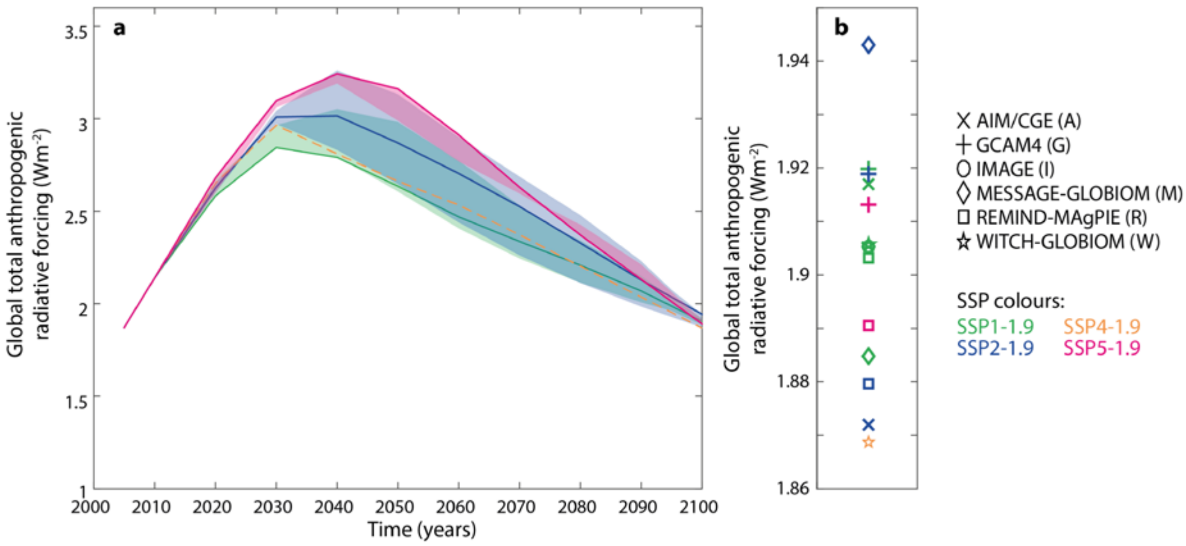
Supplementary Figure 4 | Evolution of anthropogenic emission of greenhouse gases and aerosols in 1.9 Wm^{-2} scenarios. a, global total F-gas emissions; **b**, global total NH_3 emissions; **c**, global total sulphur emissions; **d**, global total non-methane volatile organic compound (VOC) emissions. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP.



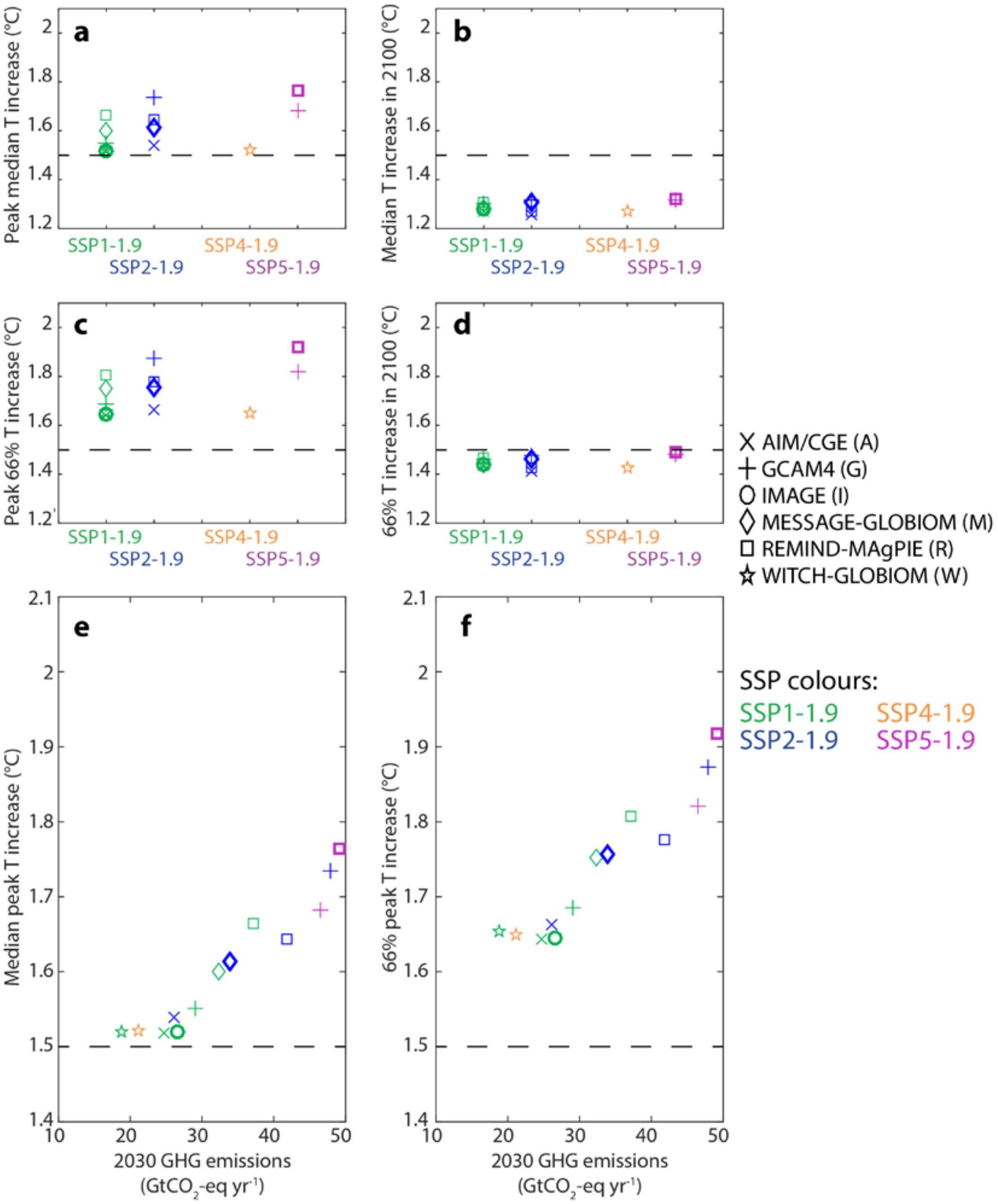
Supplementary Figure 5| Land-use related CO_2 emissions in 1.9 Wm^{-2} scenarios. a, Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP; **b**, as panel **a**, but with single models highlighted.



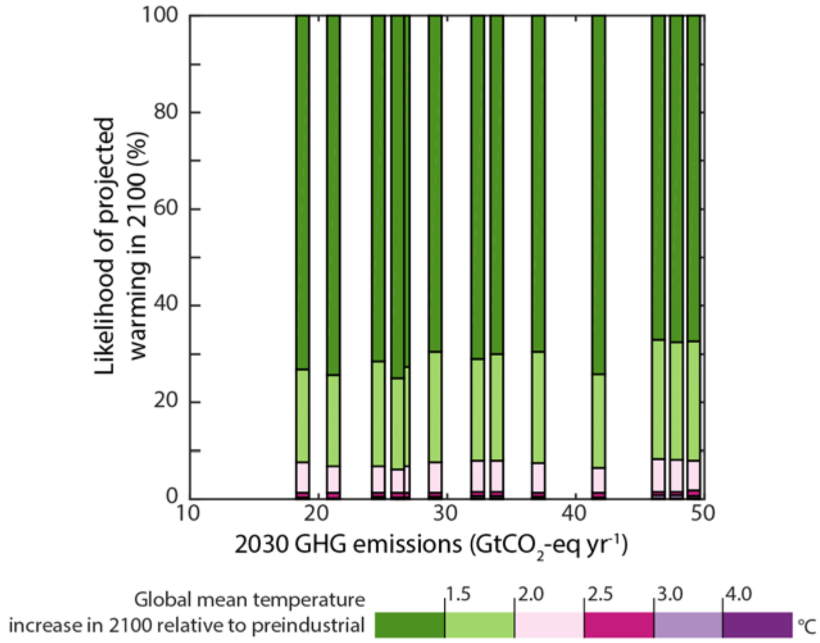
Supplementary Figure 6 | Overview of non-CO_2 GHGs in 2050 in submitted 1.9 Wm^{-2} scenario runs. As Figure 1 panel **c**, in the main manuscript but for 2050 instead of 2100.



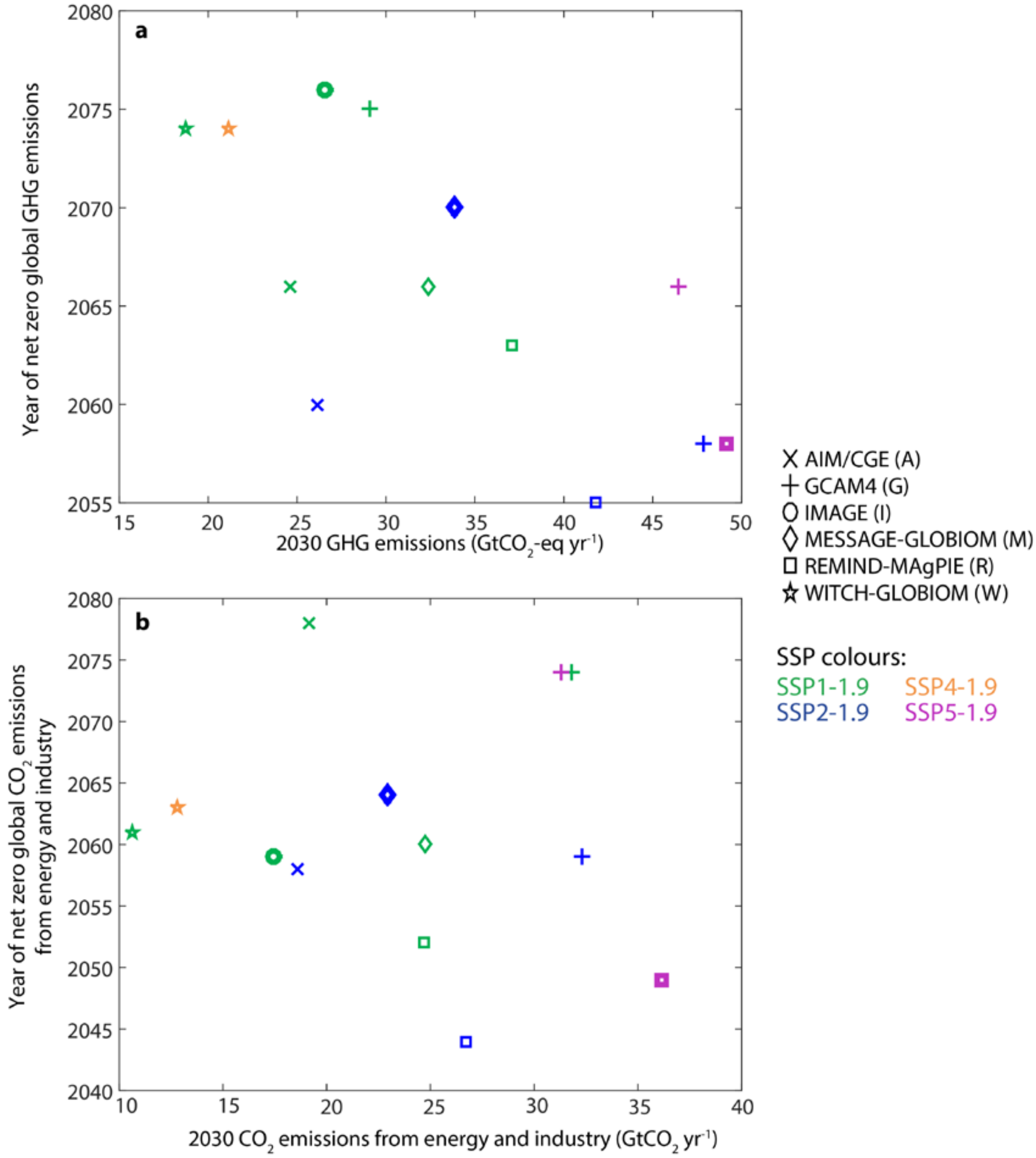
Supplementary Figure 7 | Overview of total anthropogenic radiative forcing in submitted 1.9 Wm^{-2} scenario runs. a, evolution of total anthropogenic forcing over time; **b**, distribution of radiative forcing in 2100. Radiative forcing was computed with the reduced complexity carbon-cycle and climate model MAGICC[45,46]. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP.



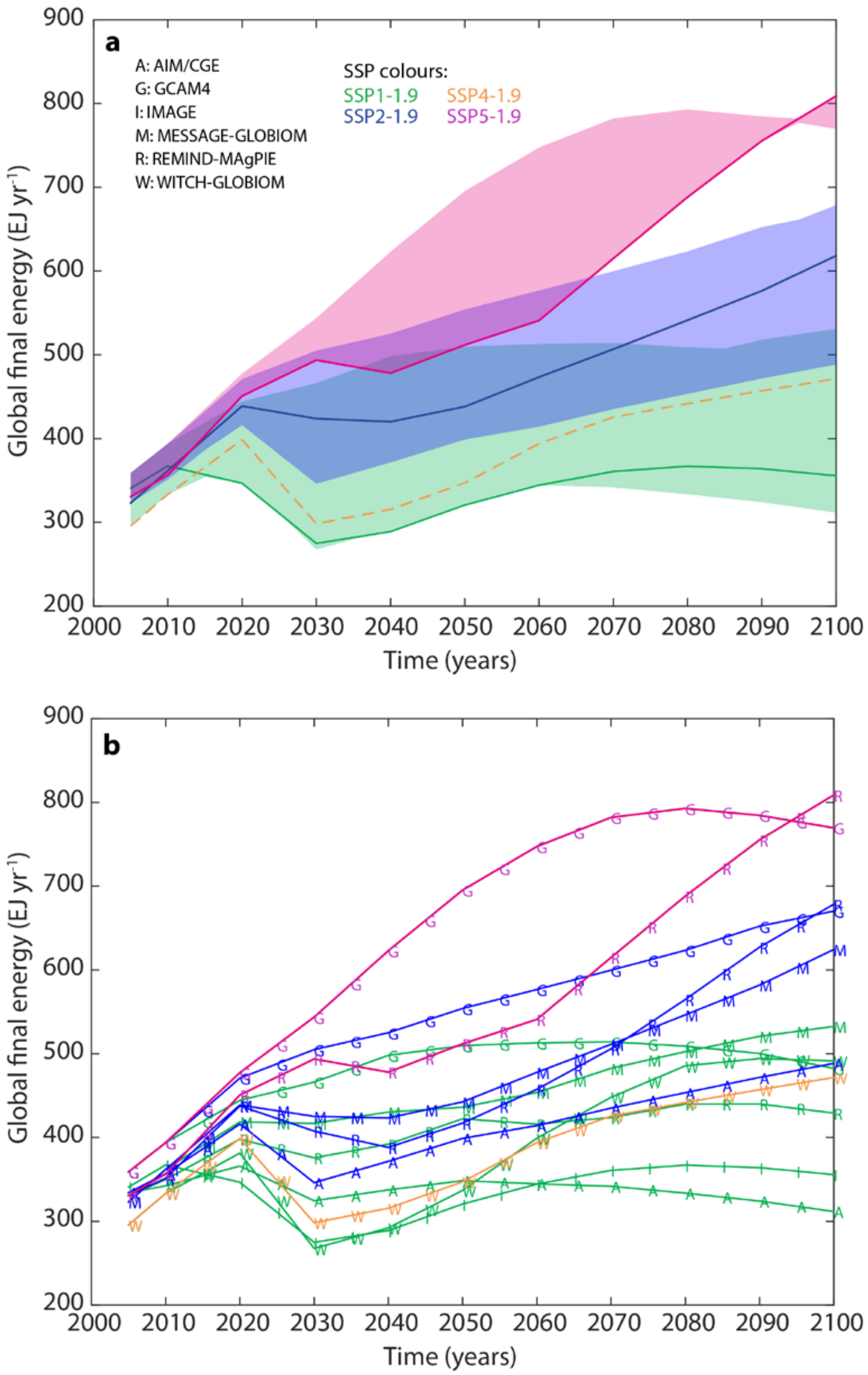
Supplementary Figure 8 | Temperature outcomes of 1.9 Wm^{-2} scenarios. Distribution of median peak (panel **a**) and year-2100 (panel **b**) global mean temperature increase relative to preindustrial levels computed with the reduced complexity carbon-cycle and climate model MAGICC[46] in a probabilistic setup[46,47]; **c**,**d**, as panels **a** and **b** but for 66th percentile warming; **e**,**f**, correlation between 2030 global GHG emissions levels and peak temperature increase. Bold symbols show the marker implementation of each SSP.



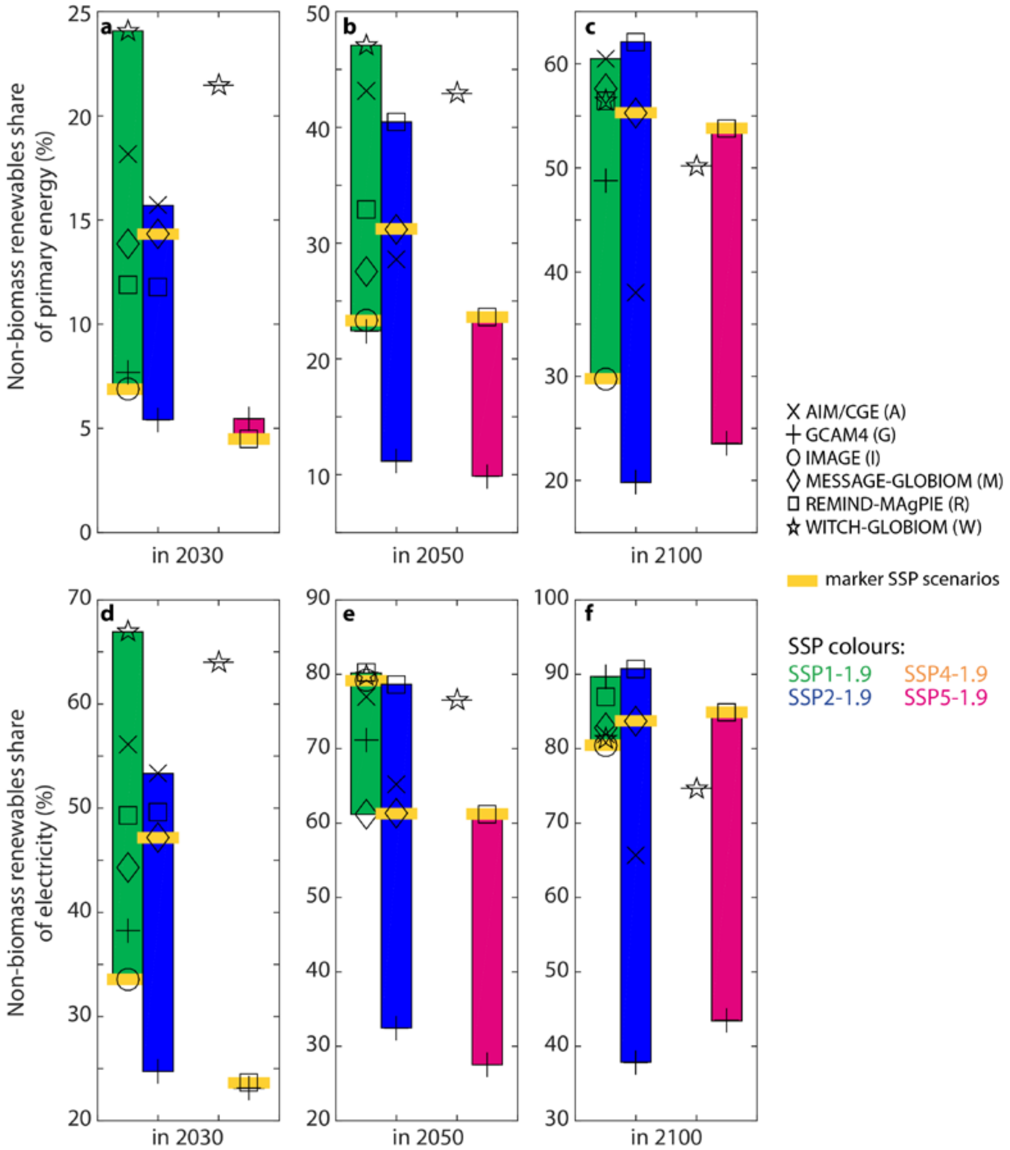
Supplementary Figure 9 | Likelihood of global mean temperature increase relative to preindustrial levels in 2100 across all 1.9 Wm^{-2} scenarios.



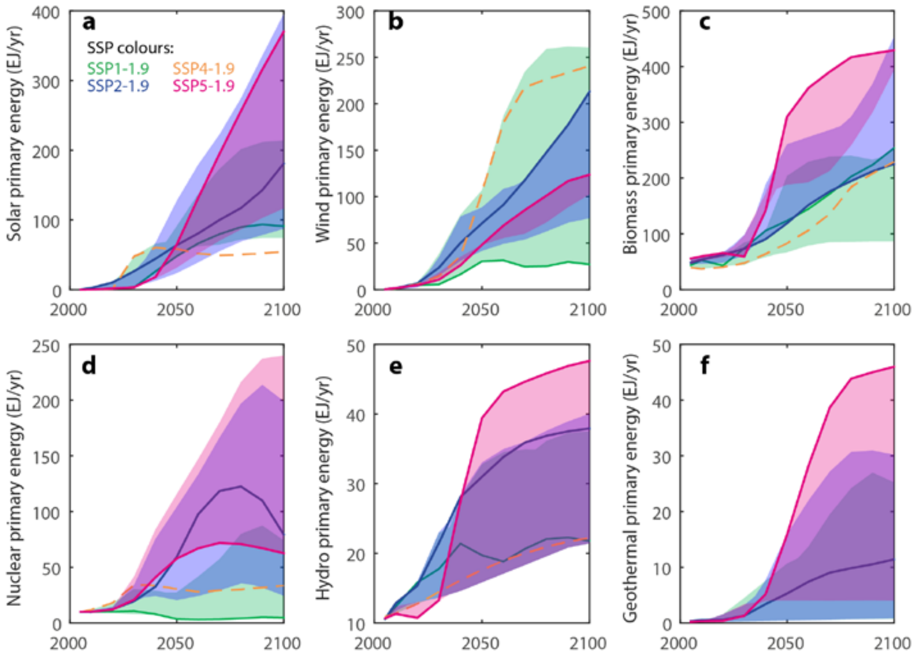
Supplementary Figure 10 | Relationship between 2030 emissions and year of global emissions become net zero. a, Relationship for global Kyoto GHGs; **b**, relationship for global CO_2 emissions from energy and industry. Symbols represent single scenarios. Bold symbols show the marker implementation of each SSP.



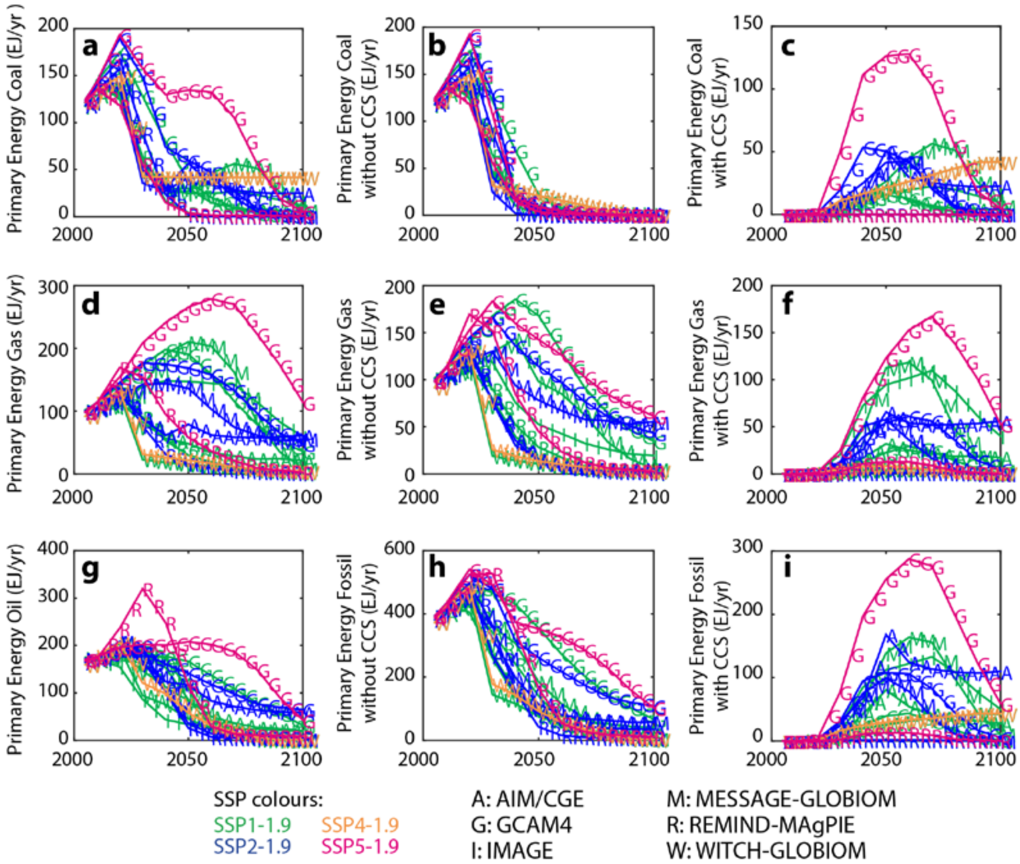
Supplementary Figure 11 | Final energy demand in 1.9 Wm^{-2} scenarios. **a**, Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP; **b**, as panel **a**, but with single models highlighted.



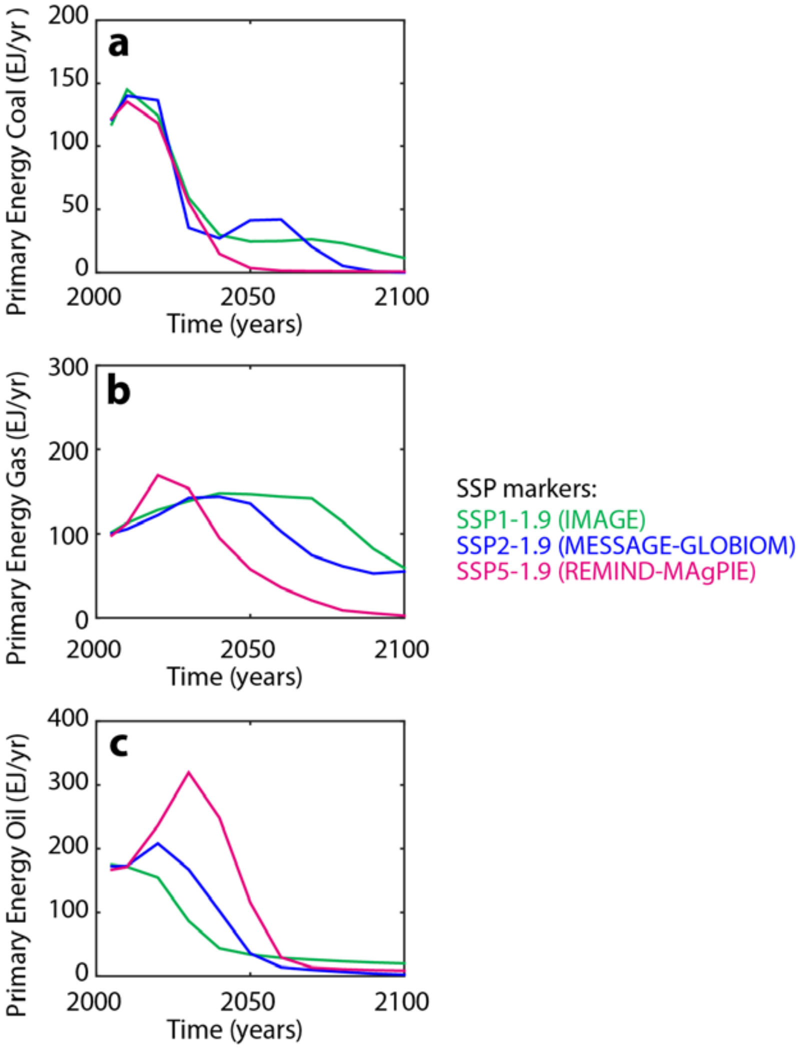
Supplementary Figure 12 | Non-biomass renewable energy share of primary energy and of electricity in 1.9 Wm^{-2} scenarios. Panels **a**, **b**, and **c** show values for 2030, 2050, and 2100, respectively, for primary energy (direct equivalent accounting); Panels **d**, **e**, and **f** show values for 2030, 2050, and 2100, respectively, for the share of non-biomass renewables of electricity (i.e. secondary energy). Non-biomass renewables encompass solar, wind, hydro, and geothermal energy.



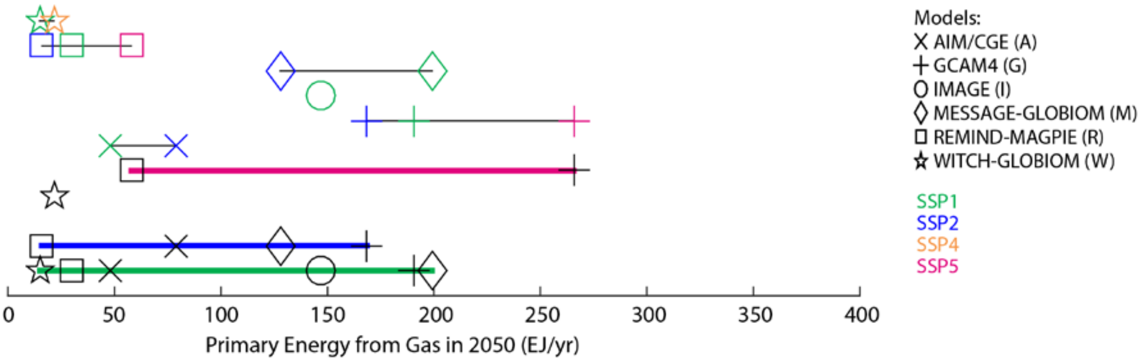
Supplementary Figure 13 | Evolution of primary energy contributions of low or zero-carbon contributions in 1.9 Wm^{-2} scenarios over time. Data is shown for solar (panel **a**), wind (panel **b**), biomass (panel **c**), nuclear (panel **d**), hydro (panel **e**), and geothermal (panel **f**). Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP. Primary energy equivalence is calculated with the direct equivalence accounting.



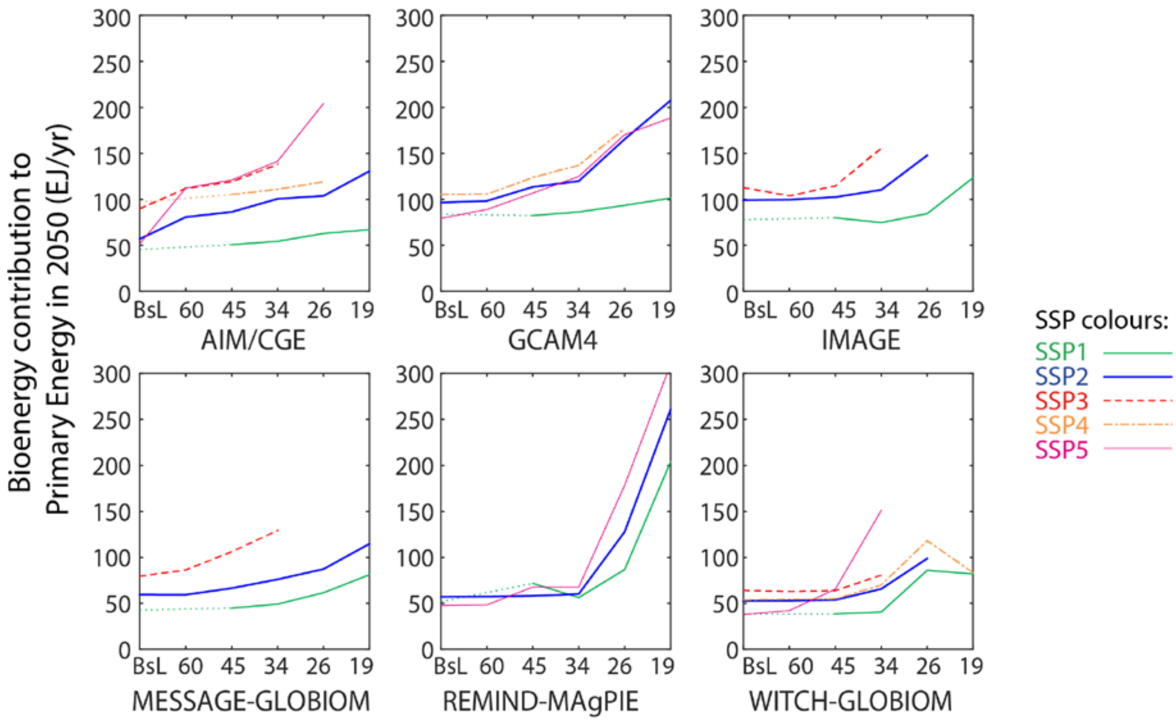
Supplementary Figure 14 | Evolution of primary energy contributions of fossil-fuel energy sources to the primary energy mix in 1.9 Wm^{-2} scenarios over time. Data is shown for coal (panel **a**) without (panel **b**) and with CCS (panel **c**), natural gas (panel **d**) without (panel **e**) and with CCS (panel **f**), oil (panel **g**), and all fossil fuels without (panel **h**) and with CCS (panel **i**). Markers are highlighted in the next figure. The maximum possible coal substitution potential in the industrial sector in WITCH is about 8-12% of final energy demand (see the model documentation on http://doc.witchmodel.org). Therefore, WITCH continues to use a constant level of coal throughout the century, albeit with CCS.



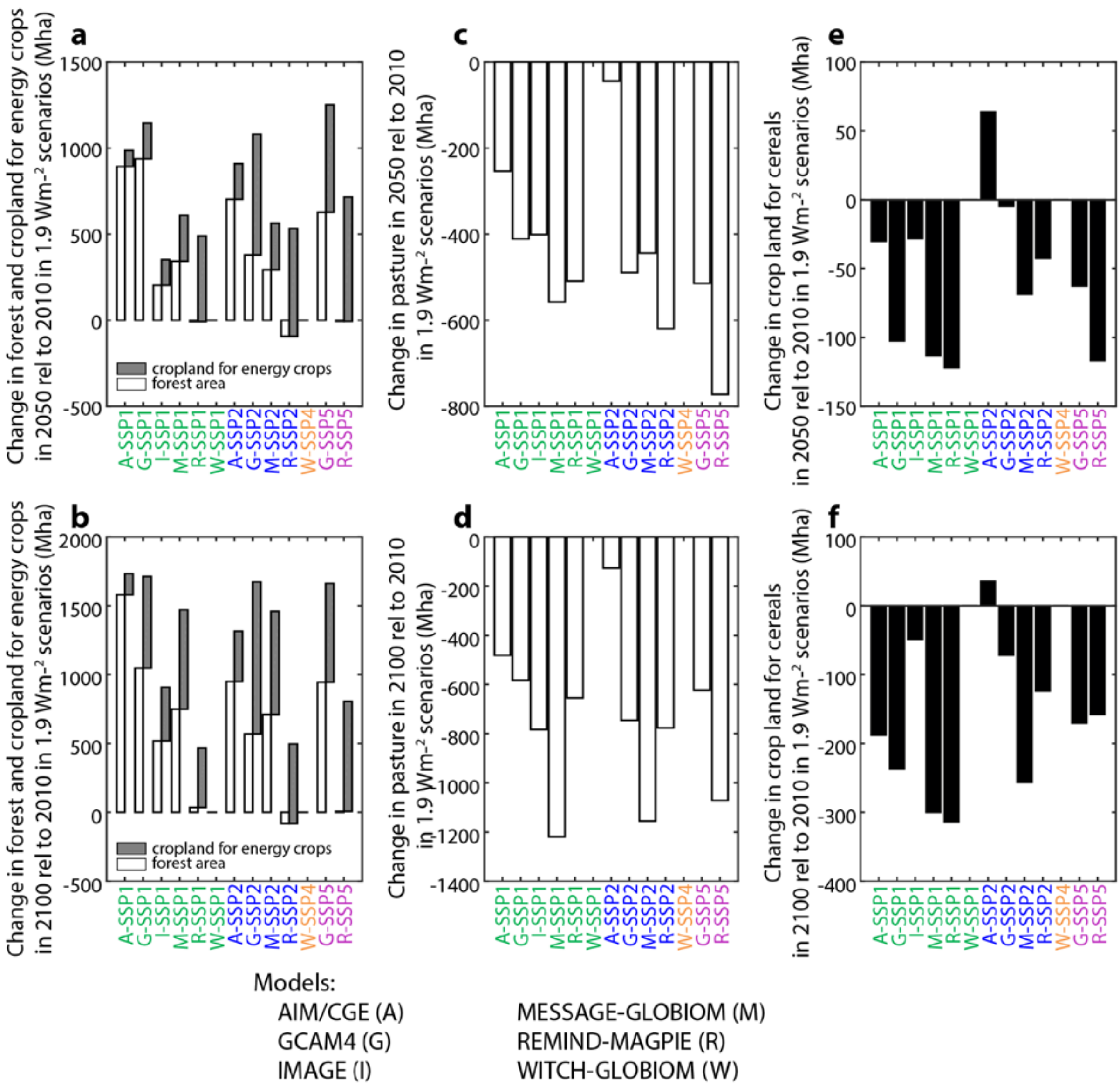
Supplementary Figure 15 | Evolution of primary energy contributions of fossil-fuel energy sources to the primary energy mix in the marker implementation of 1.9 Wm^{-2} scenarios. Data is shown for coal (panel **a**), natural gas (panel **b**), and oil (panel **c**).



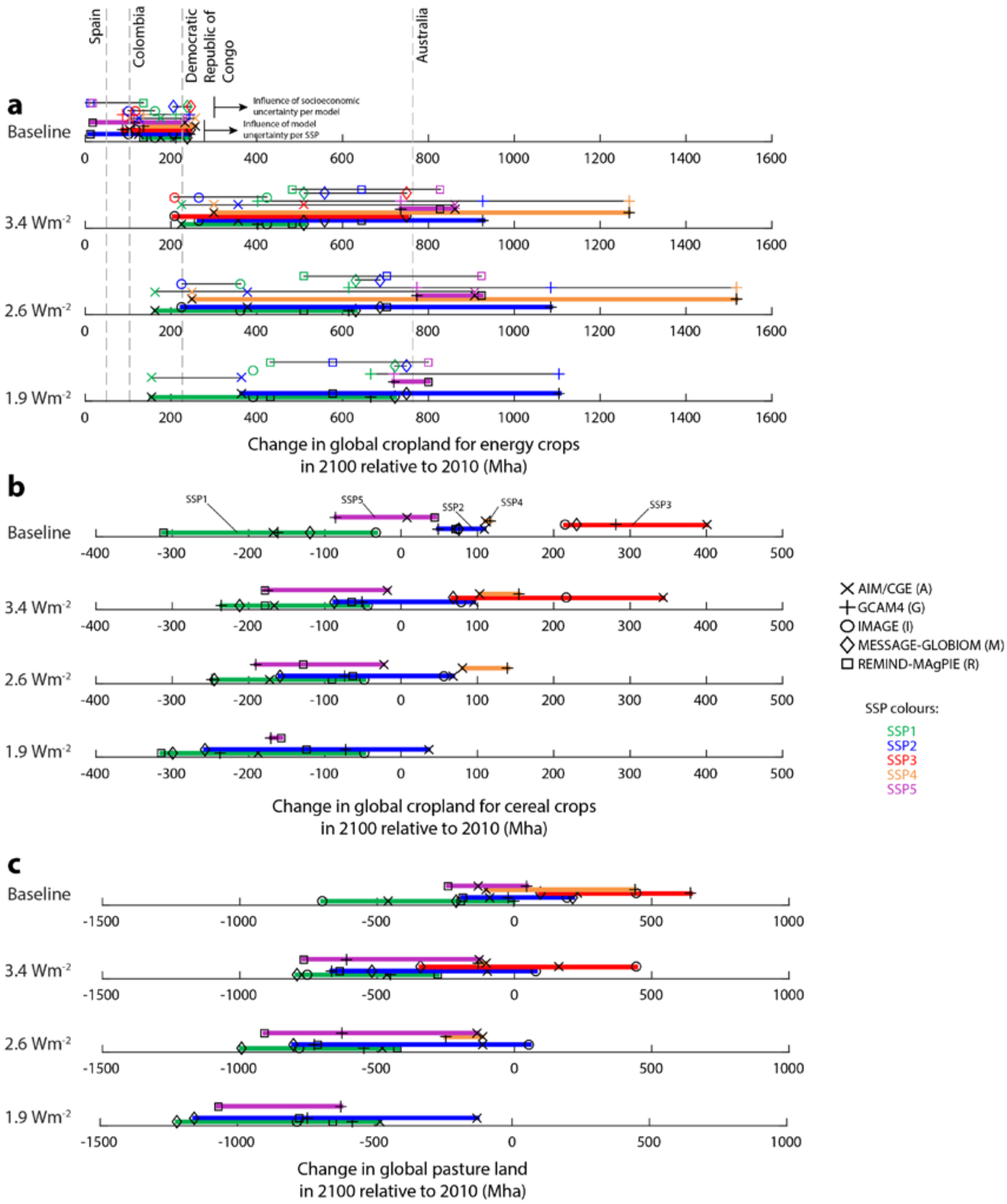
Supplementary Figure 16 | Variation of primary energy contribution of gas in 2050. Both the variations per model across socioeconomic uncertainty dimensions as captured by the SSPs (black lines with coloured symbols) and the variations of model uncertainty per SSPs (coloured lines with black symbols) is shown. Data underlying the ranges with thin black lines and the respective coloured lines are the same, only grouped differently.



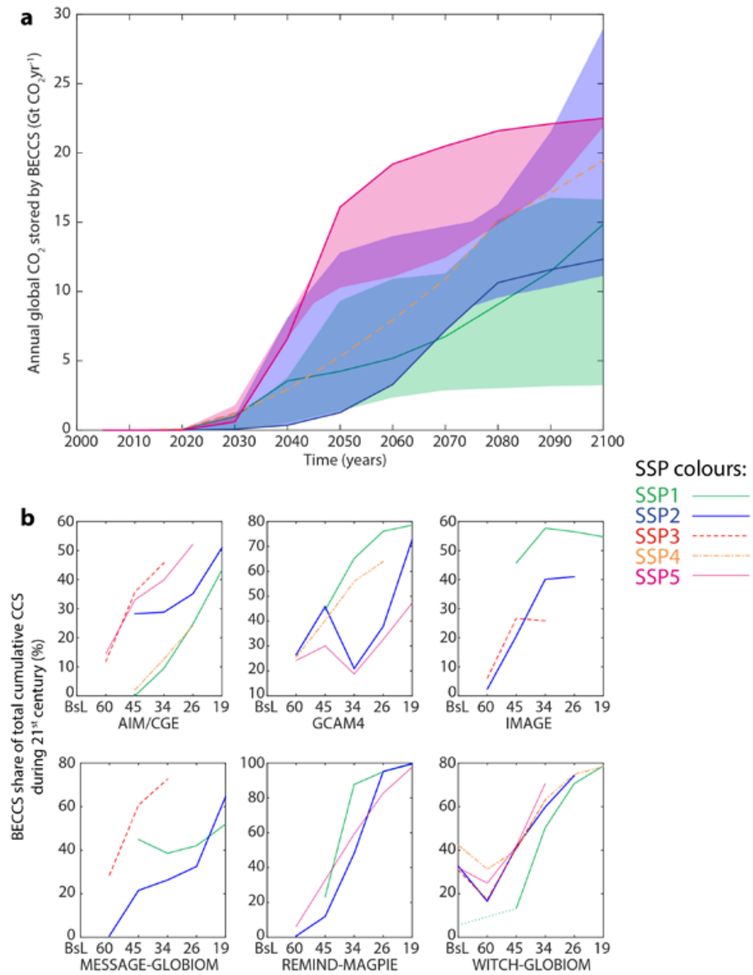
Supplementary Figure 17 | Variation of the bioenergy primary energy in 2050. For each modelling framework and each SSP the absolute amount of bioenergy is illustrated when moving from a world in absence of climate policy (Base) to increasingly more stringent climate targets (6.0, 4.5, 3.4, 2.6, and 1.9 Wm^{-2} in 2100). Note that these values include both the contributions of energy crops and of bioenergy, which have different sustainability implications (Supplementary Table 5)



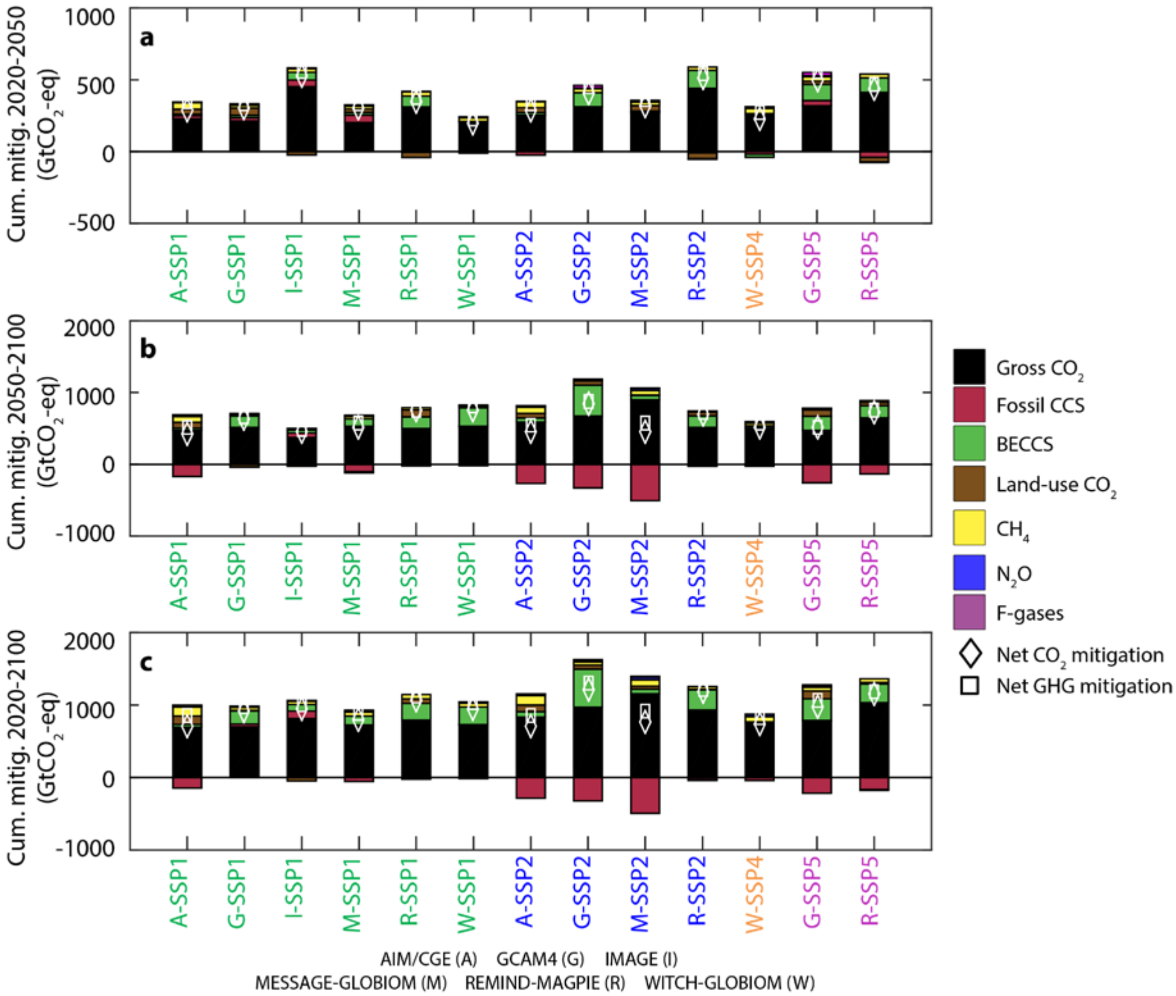
Supplementary Figure 18 | Change of land area in 2050 and 2100 relative to 2010 levels. Global land area change for forest, cropland for energy crops (panels **a** and **b**), land for pasture (panels **c** and **d**), and land for cereals (panels **e** and **f**) is shown.



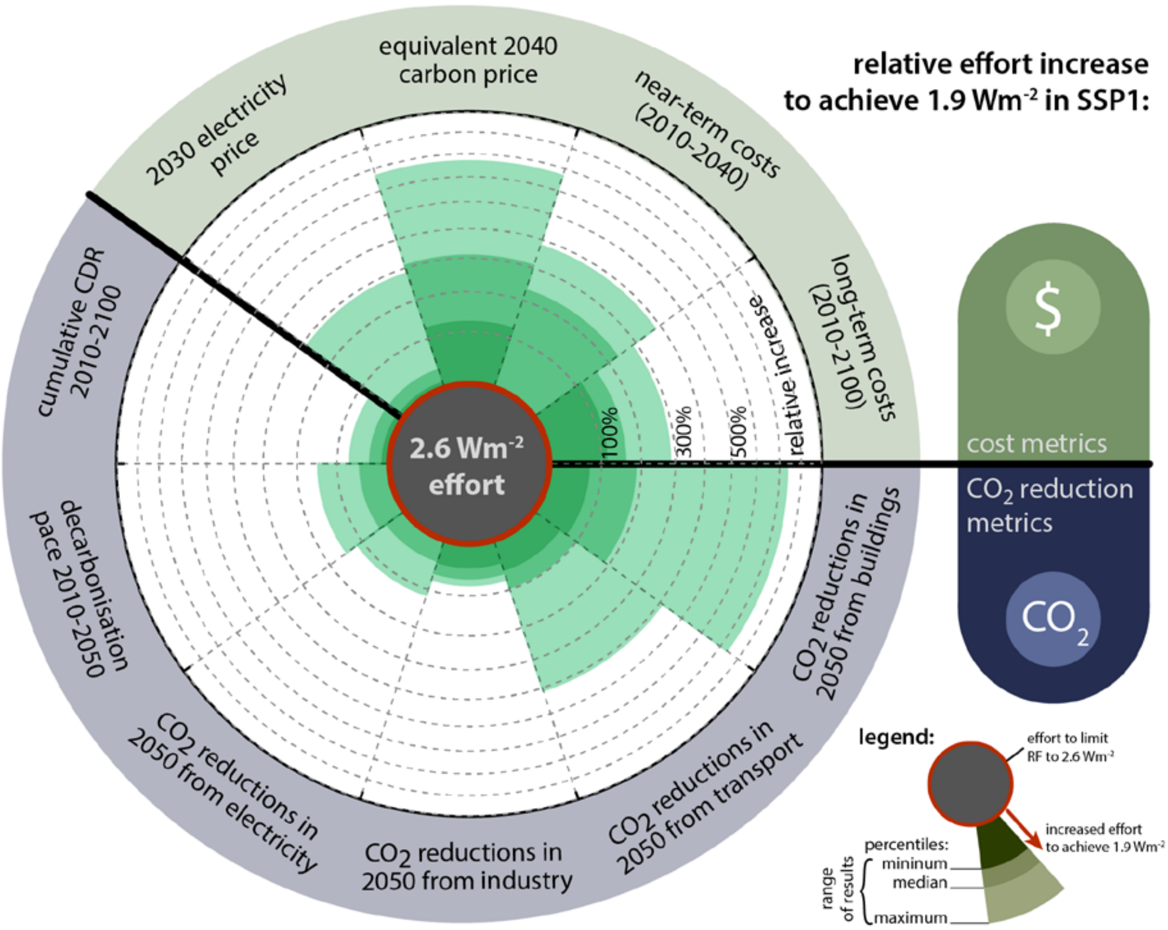
Supplementary Figure 19 | Variation of change of land area dedicated to specific uses in 2100 relative to 2010. For each modelling framework and each SSP the change in global cropland for energy crops (panel **a**), cereal production (panel **b**) and pasture (panel **c**) is illustrated when moving from a world in absence of climate policy (Baseline) to more stringent climate targets (3.4, 2.6, and 1.9 Wm^{-2} in 2100). Both the influence of socioeconomic uncertainty as captured by the SSPs per model (black lines with coloured symbols) and the influence of model uncertainty per SSPs (coloured lines with black symbols) is shown. Data behind thin black lines and thick coloured lines in panel **a** is identical, but grouped differently.



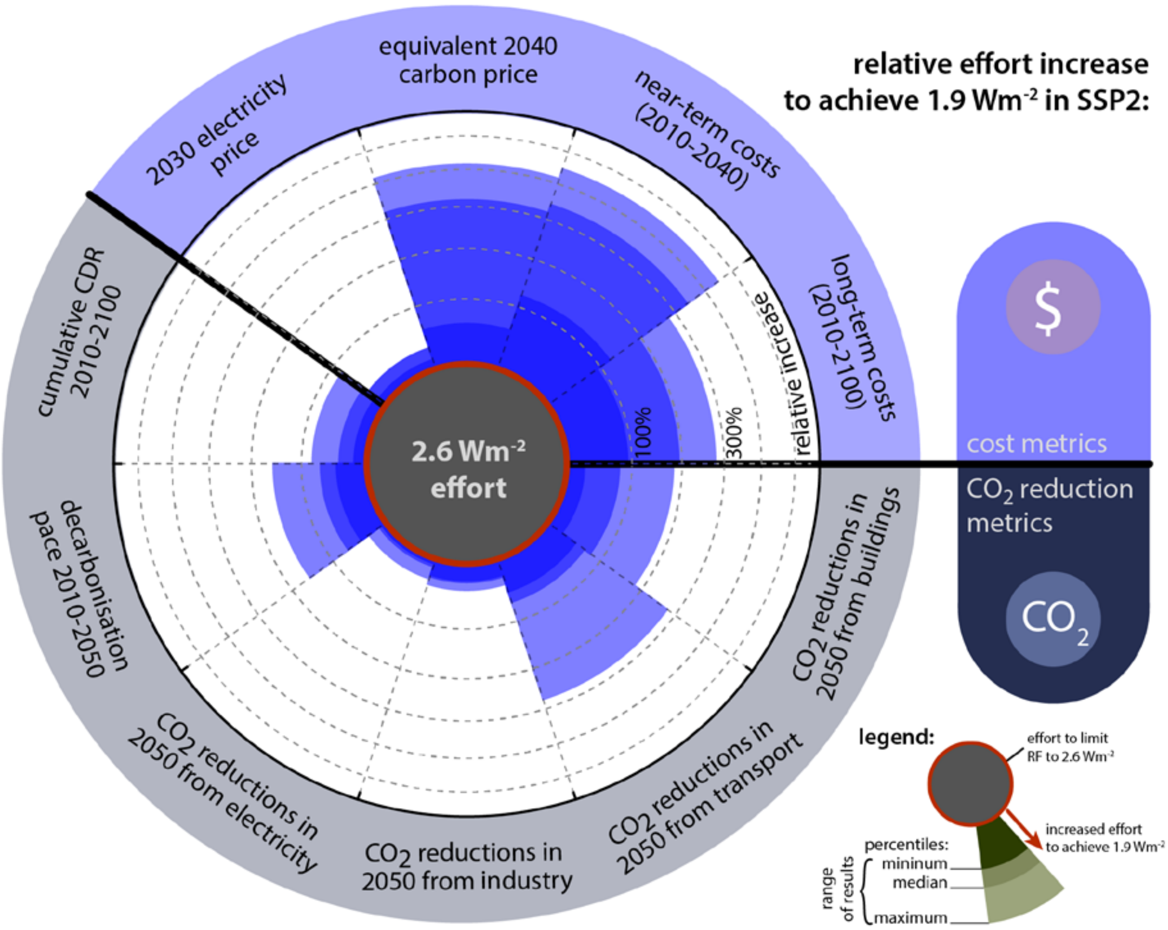
Supplementary Figure 20 | BECCS deployment in 1.9 Wm^{-2} scenarios and in weaker mitigation scenarios. a, Deployment of BECCS over time in 1.9 Wm^{-2} scenarios. Shaded areas show the range per SSP, solid lines the marker scenarios for each SSP, and dashed lines are used in case only one scenario was available for a particular SSP and this scenarios was not the marker implementation of that SSP.; **b**, Variation of the BECCS share of total cumulative CCS over the 21st century. For each modelling framework and each SSP the change in BECCS share is illustrated 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} in 2100). In the Baseline scenario BECCS nor CCS is deployed as it is modelled as a zero carbon price scenario with no incentives to reduce CO_2 emissions.



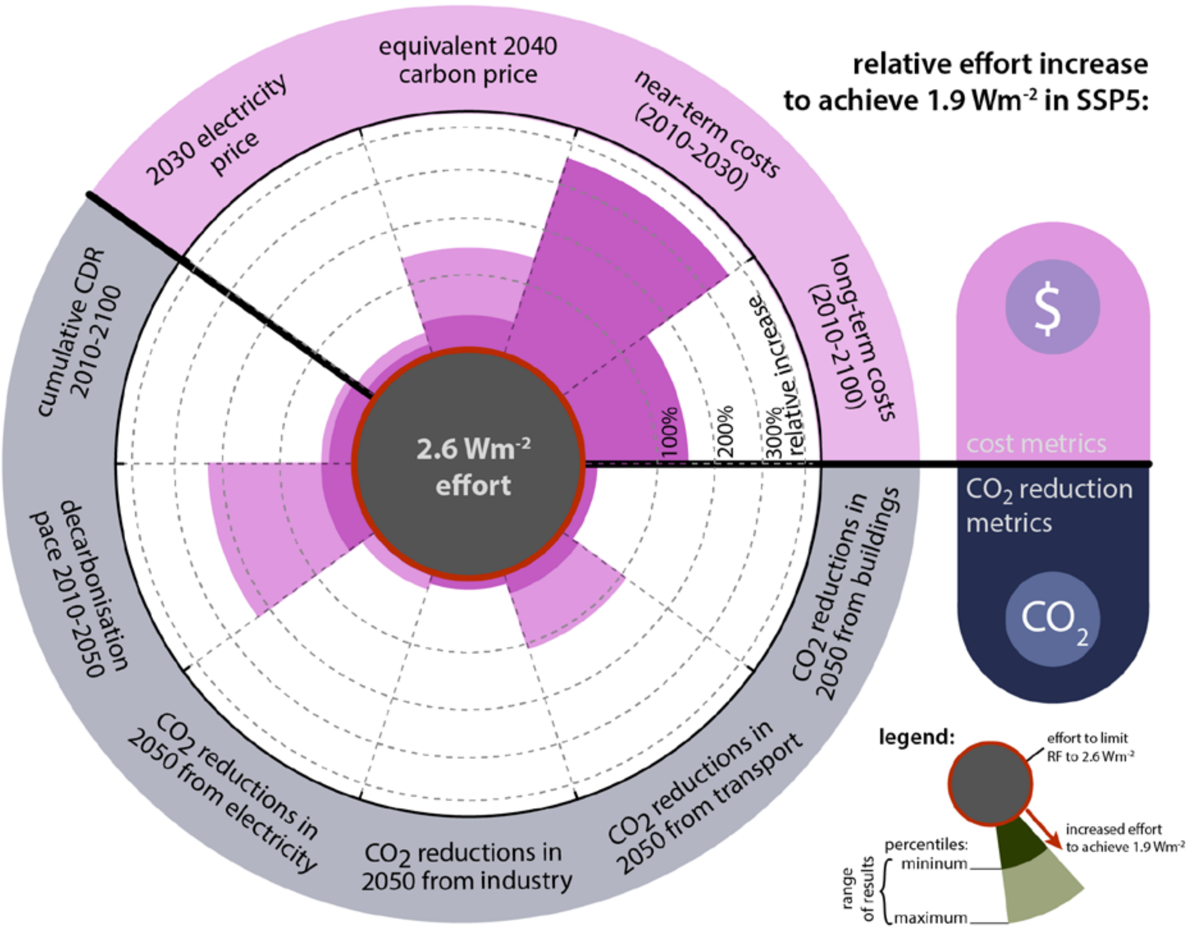
Supplementary Figure 21 | Differential mitigation between 2.6 Wm^{-2} and 1.9 Wm^{-2} scenarios. Cumulative mitigation between 2.6 and 1.9 Wm^{-2} scenarios over the 2020-2050 (panel **a**), 2050-2100 (panel **b**), and 2020-2100 period (panel **c**). The bulk of the differential mitigation is taken up by further reductions of CO_2.



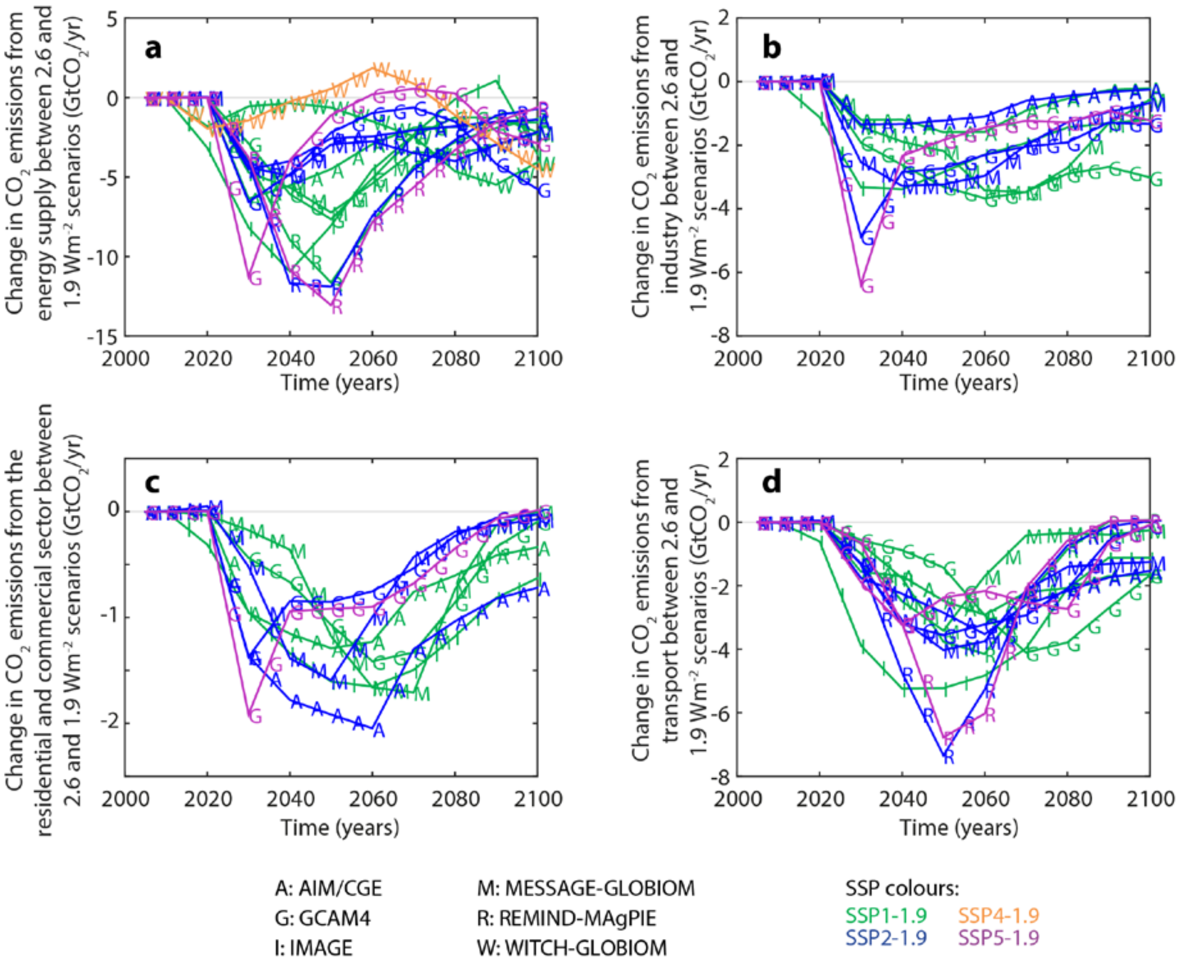
Supplementary Figure 22 | Differential mitigation characteristics when moving from a 2.6 Wm-2 to a 1.9 Wm-2 scenario in SSP1. Updated from ref. 12. Indicators are: long-term mitigation costs (2010–2100 aggregate GDP losses relative to baseline discounted at 5%); short-term mitigation costs (2010–2040 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 uptake by land use and land-use change; decarbonization 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.



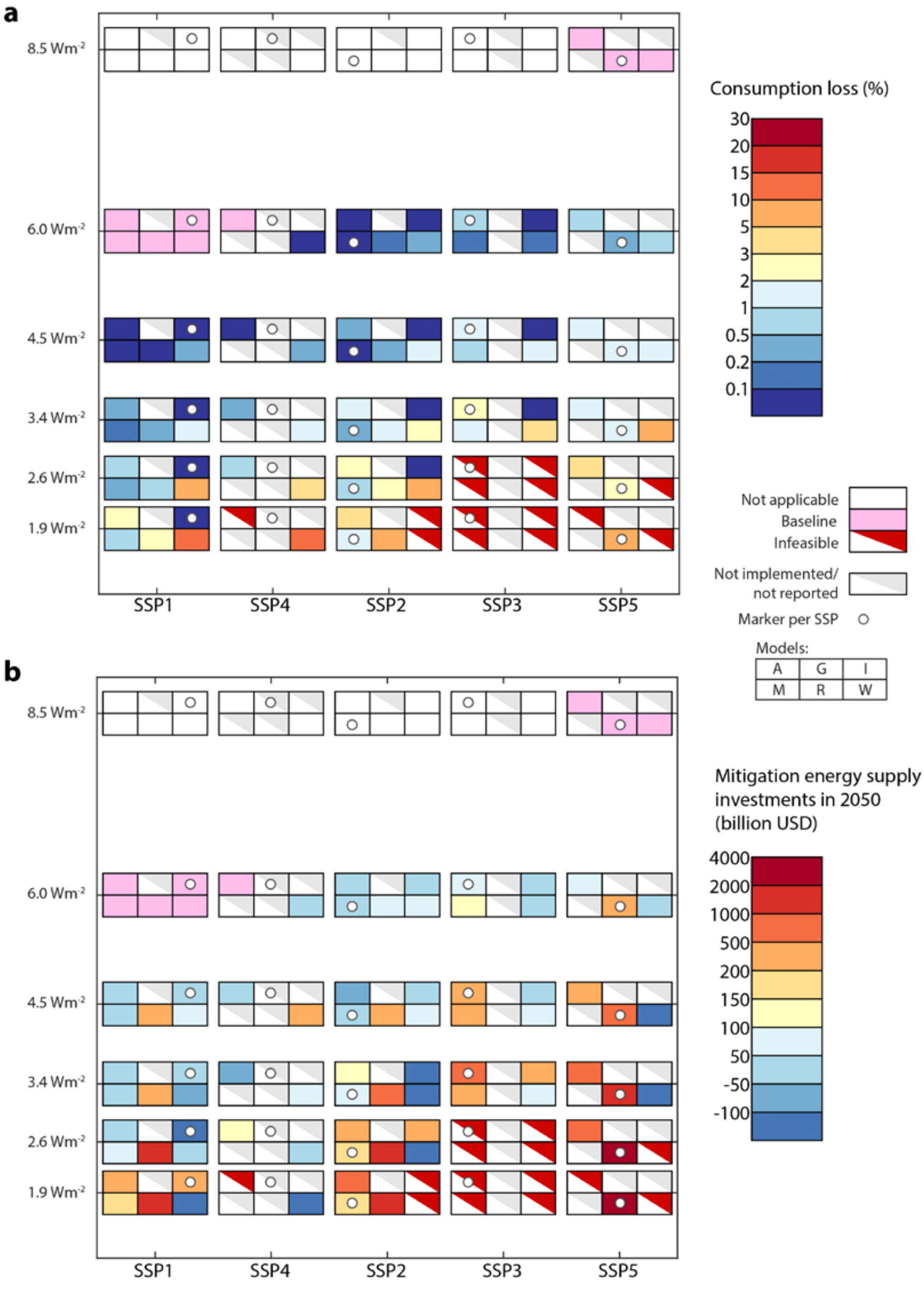
Supplementary Figure 23 | Differential mitigation characteristics when moving from a 2.6 Wm^{-2} to a 1.9 Wm^{-2} scenario in SSP2. Updated from ref. 12. Indicators are: long-term mitigation costs (2010–2100 aggregate GDP losses relative to baseline discounted at 5%); short-term mitigation costs (2010–2040 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 uptake by land use and land-use change; decarbonization 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.



Supplementary Figure 24 | Differential mitigation characteristics when moving from a 2.6 Wm^{-2} to a 1.9 Wm^{-2} scenario in SSP5. Updated from ref. 12. Indicators are: long-term mitigation costs (2010–2100 aggregate GDP 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 uptake by land use and land-use change; decarbonization 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.



Supplementary Figure 25 | Difference in sectorial CO_2 emissions between 2.6 Wm^{-2} and 1.9 Wm^{-2} scenarios. Emissions for the energy supply (panel **a**), the industrial (panel **b**), the residential and commercial (panel **c**), and the transport sector (panel **d**) are shown.



Supplementary Figure 26 | Variation of consumption losses and mitigation investments in energy supply over climate mitigation (in target radiative forcing) and SSP space. a, Consumption losses are computed as the discounted (5% discount rate) global difference between consumption in 1.9 Wm^{-2} scenarios compared to the no-climate-policy baseline over the 2020-2100 period; **b**, Mitigation energy supply investments are the difference between global energy supply investments in 1.9 Wm^{-2} scenarios and the no-climate-policy baseline in 2050. 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. Variation of Figure 5 in the main manuscript.

Supplementary Tables

Supplementary Table 1 | Overview of participating modelling teams and successful scenarios. 1: successful scenario consistent with modelling protocol; 0: unsuccessful scenario; x: not modelled; 0*: not attempted because scenarios for a 2.6 Wm^{-2} target were already found to be unachievable in an earlier study[3]. SSP3-SPA3 for a more stringent 1.9 Wm^{-2} radiative forcing target have thus not been attempted anew by many modelling teams. Marker implementations of each SSP1 are indicated in blue.

Team	Model name	Model label	Model type	Documentation and citation	Reported scenarios				
					SSP1-SPA1	*SSP2-SPA2*	*SSP3-SPA3*	*SSP4-SPA4*	*SSP5-SPA5*
NIES	AIM	A	General equilibrium (GE)	ref. [48]	**1**	**1**	0*	0	0
PNNL	GCAM4	G	Partial equilibrium (PE)	ref. [49]	**1**	**1**	x	0	**1**
PBL	IMAGE	I	Hybrid (systems dynamic model and GE for agriculture)	ref. [50]	**1**	0	0*	x	x
IIASA	MESSAGE-GLOBIOM	M	Hybrid (systems engineering partial equilibrium models linked to aggregated GE)	ref. [51]*	**1**	**1**	0*	x	x
PIK	REMIND-MAgPIE	R	General equilibrium (GE)	ref. [52]	**1**	**1**	x	x	**1**
FEEM	WITCH-GLOBIOM	W	General equilibrium (GE)	ref. [53]	**1**	0	0	**1**	0

Supplementary Table 2 | Annual emissions and CO_2 emissions budgets. Annual CO_2 and GHG emissions, and CO_2 emission budgets in the 1.9 Wm^{-2} scenarios for various time periods. Annual emissions are rounded to the nearest 1 $GtCO_2$ (or $GtCO_2$-eq), emission budgets to the nearest 25 $GtCO_2$, and net zero years to the nearest 5. Minimum, maximum, median, and mean are only provided if sufficient scenarios are available in the respective subset. Values mentioned in the main manuscript are highlighted in blue. Annual CO_2 production from energy and industry represents annual CO_2 emissions from energy and industry increased by the annual amount of carbon capture and storage (CCS).

Scenario subset	Indicator	Minimum	Maximum	Median	Average
SSP1-1.9 Scenarios (# scenarios = 6)					
	Annual GHG emissions ($GtCO_2e\ yr^{-1}$)				
	2010	48	52	49	49
	2020	45	51	50	49
	2030	19	37	28	28
	2040	12	25	17	18
	2050	5	12	10	9
	2100	-13	-2	-9	-8
	Net zero timing (year)	2065	2075	2070	2070
	Annual CO2 emissions from energy and industry ($GtCO_2\ yr^{-1}$)				
	2010	31	33	32	32
	2020	31	37	34	34
	2030	11	32	22	21
	2040	5	26	12	14
	2050	1	18	5	6
	2100	-15	-1	-11	-10
	Net zero timing (year)	2050	2080	2060	2065
	Annual total CO_2 emissions ($GtCO_2\ yr^{-1}$)				
	2010	35	40	36	36
	2020	33	38	37	36
	2030	11	26	19	19
	2040	6	16	9	11
	2050	1	4	3	3
	2100	-18	-4	-14	-12
	Net zero timing (year)	2055	2060	2055	2055
	Annual CO_2 production from energy and industry ($GtCO_2\ yr^{-1}$)				
	2010	31	33	32	32
	2020	31	37	34	34
	2030	13	33	23	23
	2040	12	29	16	18
	2050	11	23	12	15
	2100	-1	12	3	4
	Net zero timing (year)	N/A	N/A	N/A	N/A
	Cumulative CO_2 emissions				
	CO_2 from energy & industry (2016-2050, $GtCO_2$)	525	1025	675	700
	Total CO_2 (2016-2050, $GtCO_2$)	550	775	650	675
	CO_2 from energy & industry (2016-2100, $GtCO_2$)	300	1000	425	525
	Total CO_2 (2016-2100, $GtCO_2$)	250	475	325	325

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Scenario subset	Indicator	Minimum	Maximum	Median	Average
SSP2-1.9 Scenarios (# scenarios = 4)					
	Annual GHG emissions ($GtCO_2e\ yr^{-1}$)				
	2010	49	52	51	51
	2020	53	57	56	55
	2030	26	48	38	37
	2040	13	21	19	18
	2050	2	12	5	6
	2100	-21	-5	-8	-10
	Net zero timing (year)	2055	2070	2060	2060
	Annual CO_2 emissions from energy and industry ($GtCO_2\ yr^{-1}$)				
	2010	32	33	32	33
	2020	36	39	38	38
	2030	19	32	25	25
	2040	4	13	11	10
	2050	-9	6	4	1
	2100	-30	-7	-11	-15
	Net zero timing (year)	2045	2065	2060	2055
	Annual total CO_2 emissions ($GtCO_2\ yr^{-1}$)				
	2010	36	40	38	38
	2020	41	43	42	42
	2030	20	36	27	28
	2040	8	12	9	9
	2050	-7	4	-3	-3
	2100	-32	-9	-14	-17
	Net zero timing (year)	2045	2060	2050	2050
	Annual CO_2 production from energy and industry ($GtCO_2\ yr^{-1}$)				
	2010	32	33	32	33
	2020	36	40	38	38
	2030	21	35	26	27
	2040	12	25	17	18
	2050	4	22	16	15
	2100	0	11	3	4
	Net zero timing (year)	N/A	N/A	N/A	N/A
	Cumulative CO_2 emissions				
	CO_2 from energy & industry (2016-2050, $GtCO_2$)	625	850	700	700
	Total CO_2 (2016-2050, $GtCO_2$)	700	800	750	750
	CO_2 from energy & industry (2016-2100, $GtCO_2$)	0	550	375	325
	Total CO_2 (2016-2100, $GtCO_2$)	-100	400	250	200

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Scenario subset	Indicator	Minimum	Maximum	Median	Average
SSP4-1.9 Scenarios (# scenarios = 1)					
	Annual GHG emissions (GtCO₂e yr⁻¹)				
	2010	-	-	-	48
	2020	-	-	-	53
	2030	-	-	-	21
	2040	-	-	-	17
	2050	-	-	-	11
	2100	-	-	-	-7
	Net zero timing (year)	-	-	-	2075
	Annual CO_2 emissions from energy and industry ($GtCO_2$ yr^{-1})				
	2010	-	-	-	32
	2020	-	-	-	37
	2030	-	-	-	13
	2040	-	-	-	10
	2050	-	-	-	5
	2100	-	-	-	-9
	Net zero timing (year)	-	-	-	2065
	Annual total CO_2 emissions ($GtCO_2$ yr^{-1})				
	2010	-	-	-	35
	2020	-	-	-	39
	2030	-	-	-	13
	2040	-	-	-	9
	2050	-	-	-	4
	2100	-	-	-	-11
	Net zero timing (year)	-	-	-	2060
	Annual CO_2 production from energy and industry ($GtCO_2$ yr^{-1})				
	2010	-	-	-	32
	2020	-	-	-	37
	2030	-	-	-	15
	2040	-	-	-	14
	2050	-	-	-	12
	2100	-	-	-	14
	Net zero timing (year)	-	-	-	N/A
	Cumulative CO_2 emissions				
	CO_2 from energy & industry (2016-2050, $GtCO_2$)	-	-	-	600
	Total CO_2 (2016-2050, $GtCO_2$)	-	-	-	600
	CO_2 from energy & industry (2016-2100, $GtCO_2$)	-	-	-	400
	Total CO_2 (2016-2100, $GtCO_2$)	-	-	-	375

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Scenario subset	Indicator	Minimum	Maximum	Median	Average
SSP5-1.9 Scenarios (# scenarios = 2)					
	Annual GHG emissions ($GtCO_2e\ yr^{-1}$)				
	2010	49	50	-	-
	2020	55	55	-	-
	2030	46	49	-	-
	2040	15	32	-	-
	2050	1	11	-	-
	2100	-19	-14	-	-
	Net zero timing (year)	2060	2065	-	-
	Annual CO_2 emissions from energy and industry ($GtCO_2\ yr^{-1}$)				
	2010	32	33	-	-
	2020	38	40	-	-
	2030	31	36	-	-
	2040	14	18	-	-
	2050	-4	10	-	-
	2100	-23	-20	-	-
	Net zero timing (year)	2050	2075	-	-
	Annual total CO_2 emissions ($GtCO_2\ yr^{-1}$)				
	2010	36	36	-	-
	2020	40	42	-	-
	2030	36	38	-	-
	2040	5	22	-	-
	2050	-9	1	-	-
	2100	-26	-21	-	-
	Net zero timing (year)	2045	2050	-	-
	Annual CO_2 production from energy and industry ($GtCO_2\ yr^{-1}$)				
	2010	32	33	-	-
	2020	38	41	-	-
	2030	37	39	-	-
	2040	25	37	-	-
	2050	13	39	-	-
	2100	2	3	-	-
	Net zero timing (year)	N/A	N/A	-	-
	Cumulative CO_2 emissions				
	CO_2 from energy & industry (2016-2050, $GtCO_2$)	875	900	-	-
	Total CO_2 (2016-2050, $GtCO_2$)	750	975	-	-
	CO_2 from energy & industry (2016-2100, $GtCO_2$)	50	750	-	-
	Total CO_2 (2016-2100, $GtCO_2$)	75	200	-	-

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Scenario subset	Indicator	Minimum	Maximum	Median	Average
All 1.9 Wm^{-2} Scenarios (# scenarios = 13)					
	Annual GHG emissions ($GtCO_2e\ yr^{-1}$)				
	2010	48	52	49	50
	2020	45	57	53	52
	2030	19	49	32	33
	2040	12	32	18	19
	2050	1	12	9	8
	2100	-21	-2	-9	-10
	Net zero timing (year)	2055	2075	2065	2065
	Annual CO_2 emissions from energy and industry ($GtCO_2\ yr^{-1}$)				
	2010	31	33	32	32
	2020	31	40	37	36
	2030	11	36	25	24
	2040	4	26	13	12
	2050	-9	18	5	4
	2100	-30	-1	-12	-13
	Net zero timing (year)	2045	2080	2060	2060
	Annual total CO_2 emissions ($GtCO_2\ yr^{-1}$)				
	2010	35	40	36	37
	2020	33	43	39	39
	2030	11	38	23	24
	2040	5	22	9	11
	2050	-9	4	2	0
	2100	-32	-4	-14	-15
	Net zero timing (year)	2045	2060	2055	2055
	Annual CO_2 production from energy and industry ($GtCO_2\ yr^{-1}$)				
	2010	31	33	32	32
	2020	31	41	37	36
	2030	13	39	25	26
	2040	12	37	18	20
	2050	4	39	13	16
	2100	-1	14	3	5
	Net zero timing (year)	N/A	N/A	N/A	N/A
	Cumulative CO_2 emissions				
	CO_2 from energy & industry (2016-2050, $GtCO_2$)	525	1025	700	725
	Total CO_2 (2016-2050, $GtCO_2$)	550	975	750	725
	CO_2 from energy & industry (2016-2100, $GtCO_2$)	0	1000	400	425
	Total CO_2 (2016-2100, $GtCO_2$)	-100	475	325	275

Supplementary Table 3 | Annual emissions reduction rates. Annual CO_2 and GHG emissions reduction rates over the 2020-2050 period in the 1.9 Wm^{-2} scenarios, rounded to the nearest 0.1% yr^{-1}. Minimum, maximum, median, and mean are only provided if sufficient scenarios are available in the respective subset. Two methods are used: compound annual reduction rates (CAGR) and linear annual reduction rates (LIN). Imaginary rates: "N/A".

Scenario subset	Indicator	Minimum	Maximum	Median	Average
SSP1-1.9 Scenarios (# scenarios = 6)					
	Annual GHG emissions reduction rates				
	CAGR	-7.2%	-4.7%	-5.2%	-5.5%
	LIN	-3.0%	-2.5%	-2.7%	-2.7%
	Annual CO_2 emissions from energy and industry reduction rates				
	CAGR	-10.2%	-2.3%	-6.5%	-6.7%
	LIN	-3.2%	-1.7%	-2.9%	-2.8%
	Annual total CO_2 emissions reduction rates				
	CAGR	-11.1%	-7.2%	-7.9%	-8.5%
	LIN	-3.2%	-3.0%	-3.1%	-3.1%
	Annual CO_2 production from energy and industry				
	CAGR	-3.8%	-1.5%	-3.2%	-2.9%
	LIN	-2.3%	-1.2%	-2.1%	-1.9%
SSP2-1.9 Scenarios (# scenarios = 4)					
	Annual GHG emissions reduction rates				
	CAGR	-11.4%	-5.0%	-7.9%	-8.0%
	LIN	-3.2%	-2.6%	-3.1%	-3.0%
	Annual CO_2 emissions from energy and industry reduction rates				
	CAGR	N/A	N/A	N/A	N/A
	LIN	-4.1%	-2.8%	-3.0%	-3.2%
	Annual total CO_2 emissions reduction rates				
	CAGR	N/A	N/A	N/A	N/A
	LIN	-3.9%	-3.0%	-3.6%	-3.5%
	Annual CO_2 production from energy and industry				
	CAGR	-7.1%	-2.0%	-2.7%	-3.6%
	LIN	-3.0%	-1.5%	-1.9%	-2.1%
SSP4-1.9 Scenarios (# scenarios = 1)					
	Annual GHG emissions reduction rates				
	CAGR	-	-	-	-5.2%
	LIN	-	-	-	-2.7%
	Annual CO_2 emissions from energy and industry reduction rates				
	CAGR	-	-	-	-6.6%
	LIN	-	-	-	-2.9%
	Annual total CO_2 emissions reduction rates	-	-	-	
	CAGR	-	-	-	-7.2%
	LIN	-	-	-	-3.0%
	Annual CO_2 production from energy and industry	-	-	-	
	CAGR	-	-	-	-3.6%
	LIN	-	-	-	-2.2%
SSP5-1.9 Scenarios (# scenarios = 2)					
	Annual GHG emissions reduction rates				
	CAGR	-11.7%	-5.3%	-	-
	LIN	-3.3%	-2.7%	-	-
	Annual CO_2 emissions from energy and industry reduction rates				
	CAGR	N/A	N/A	-	-
	LIN	-3.7%	-2.5%	-	-
	Annual total CO_2 emissions reduction rates			-	-
	CAGR	N/A	N/A	-	-
	LIN	-4.0%	-3.2%	-	-
	Annual CO_2 production from energy and industry			-	-
	CAGR	-3.6%	-0.2%	-	-
	LIN	-2.2%	-0.2%	-	-
All 1.9 Wm^{-2} Scenarios (# scenarios = 13)					
	Annual GHG emissions reduction rates				
	CAGR	-11.7%	-4.7%	-5.5%	-6.7%
	LIN	-3.3%	-2.5%	-2.7%	-2.8%
	Annual CO_2 emissions from energy and industry reduction rates				
	CAGR	N/A	N/A	N/A	N/A
	LIN	-4.1%	-1.7%	-2.9%	-3.0%
	Annual total CO_2 emissions reduction rates				
	CAGR	N/A	N/A	N/A	N/A
	LIN	-4.0%	-3.0%	-3.2%	-3.3%
	Annual CO_2 production from energy and industry				
	CAGR	-7.1%	-0.2%	-3.0%	-3.0%
	LIN	-3.0%	-0.2%	-2.0%	-1.9%

Supplementary Table 4 | Overview inter-model and inter-SSP variations for wind, solar, and natural gas primary energy contributions in 2050. Inter-model variations give the minimum (Min.), maximum (Max.), and maximum difference (Var.) of a specific variable across nominally similar scenarios but generated by different models. Inter-SSP variations give the minimum, maximum, and maximum difference of a specific variable across all available SSPs for a given climate target (for example a 1.9 Wm^{-2} target). The last column provides the number of scenarios on which the other values are based. At times the variation is 0 as only one scenario is available. Primary energy is calculated with the direct equivalence accounting method.

Primary Energy 2050 (EJ yr^{-1})			**Wind**			**Solar**			**Gas**		
		Min.	**Max.**	**Var.**	**Min.**	**Max.**	**Var.**	**Min.**	**Max.**	**Var.**	**# scens**
Ref											
Inter-model variations	SSP1	22	55	**33**	21	59	**39**	122	269	**146**	**6**
	SSP2	6	30	**24**	3	40	**37**	182	260	**78**	**6**
	SSP3	1	21	**19**	1	18	**17**	203	235	**32**	**5**
	SSP4	15	55	**39**	12	26	**14**	132	241	**110**	**3**
	SSP5	1	29	**28**	0	13	**13**	232	379	**147**	**4**
Inter-SSP variations	AIM/CGE	1	46	**45**	1	26	**25**	122	232	**109**	**5**
	GCAM4	10	31	**21**	6	21	**15**	235	379	**144**	**5**
	IMAGE	6	24	**18**	6	29	**23**	232	269	**37**	**3**
	MESSAGE-GLOBIOM	16	30	**13**	18	59	**42**	226	253	**27**	**3**
	REMIND-MAGPIE	9	22	**13**	0	23	**23**	198	379	**181**	**3**
	WITCH-GLOBIOM	21	55	**34**	3	26	**23**	180	318	**138**	**5**
4.5 Wm^{-2}											
Inter-model variations	SSP1	25	96	**71**	23	60	**37**	111	265	**153**	**6**
	SSP2	18	68	**50**	14	44	**30**	137	248	**111**	**6**
	SSP3	11	56	**45**	6	31	**25**	152	231	**79**	**4**
	SSP4	26	99	**73**	17	28	**11**	118	221	**103**	**3**
	SSP5	10	83	**73**	4	27	**23**	182	352	**169**	**4**
Inter-SSP variations	AIM/CGE	10	50	**40**	5	28	**23**	111	182	**71**	**5**
	GCAM4	22	33	**10**	14	23	**8**	221	352	**131**	**4**
	IMAGE	12	25	**13**	12	31	**20**	206	265	**58**	**3**
	MESSAGE-GLOBIOM	32	41	**9**	31	60	**29**	231	247	**16**	**3**
	REMIND-MAGPIE	20	26	**6**	4	34	**30**	180	346	**166**	**3**
	WITCH-GLOBIOM	56	99	**43**	11	27	**17**	152	187	**35**	**5**
2.6 Wm^{-2}											
Inter-model variations	SSP1	24	140	**115**	34	65	**31**	49	245	**196**	**6**
	SSP2	22	110	**88**	18	71	**53**	55	215	**160**	**6**
	SSP3	-	-	**-**	-	-	**-**	-	-	**-**	**0**
	SSP4	36	137	**101**	23	39	**16**	65	169	**104**	**3**
	SSP5	29	44	**15**	17	29	**11**	132	292	**160**	**3**
Inter-SSP variations	AIM/CGE	29	72	**43**	17	40	**22**	75	132	**57**	**4**
	GCAM4	36	48	**12**	21	34	**14**	169	292	**124**	**4**
	IMAGE	22	24	**2**	18	47	**29**	116	193	**76**	**2**
	MESSAGE-GLOBIOM	41	46	**5**	50	65	**15**	215	245	**31**	**2**
	REMIND-MAGPIE	32	40	**9**	23	71	**49**	101	221	**120**	**3**
	WITCH-GLOBIOM	110	140	**29**	33	39	**6**	49	65	**16**	**3**
1.9 Wm^{-2}											
Inter-model variations	SSP1	31	107	**77**	48	91	**43**	15	199	**184**	**6**
	SSP2	42	89	**47**	24	128	**104**	16	169	**153**	**4**
	SSP3	-	-	**-**	-	-	**-**	-	-	**-**	**0**
	SSP4	105	105	**0**	58	58	**0**	22	22	**0**	**1**
	SSP5	48	48	**0**	32	65	**33**	58	266	**208**	**2**
Inter-SSP variations	AIM/CGE	89	107	**19**	54	62	**8**	48	79	**31**	**2**
	GCAM4	42	68	**26**	24	51	**27**	169	266	**97**	**3**
	IMAGE	31	31	**0**	48	48	**0**	147	147	**0**	**1**
	MESSAGE-GLOBIOM	59	71	**13**	64	68	**4**	128	199	**71**	**2**
	REMIND-MAGPIE	48	54	**6**	65	128	**63**	16	58	**42**	**3**
	WITCH-GLOBIOM	105	105	**1**	58	68	**9**	15	22	**7**	**2**

Supplementary Table 5 | Share of energy crops in total bioenergy contributions in 2050 in 1.9 Wm^{-2}. Data is only provided for those models and those scenarios for which this is information was provided.

Model	SSP1	SSP2	SSP3	SSP4	SSP5
Share of energy crops to total bioenergy in 2050					
AIM/CGE					
GCAM4					
IMAGE	38%				
MESSAGE-GLOBIOM					
REMIND-MAgPIE	77%	79%			85%
WITCH-GLOBIOM	0%			0%	
Absolute contribution of energy crops in 2050 (EJ yr^{-1})					
AIM/CGE					
GCAM4					
IMAGE	48				
MESSAGE-GLOBIOM					
REMIND-MAgPIE	157	205			263
WITCH-GLOBIOM	0			0	

Supplementary Table 6 | Change in global forest area in 2050 relative to 2010 levels. Data is only provided for those models and those scenarios for which this is information was provided.

Model	SSP1	SSP2	SSP3	SSP4	SSP5
1.9 Wm^{-2}: Change in global forest area in 2050 relative to 2010 levels					
AIM/CGE	23%	18%			
GCAM4	23%	9%			15%
IMAGE	5%				
MESSAGE-GLOBIOM	9%	8%			
REMIND-MAgPIE	0%	-2%			0%
WITCH-GLOBIOM					
Baseline: Change in global forest area in 2050 relative to 2010 levels					
AIM/CGE	-2%	-5%	-7%	-5%	-4%
GCAM4	3%	-1%	-5%	-2%	1%
IMAGE			-		
	2%	-7%	11%	-6%	-9%
MESSAGE-GLOBIOM	0%	-2%	-4%		
REMIND-MAgPIE	-2%	-3%			-5%
WITCH-GLOBIOM					

Supplementary Table 7 | Definitions for indicators shown in Figure 6. For each SSP, the “baseline scenario” refers to the scenario in which no targeted climate change mitigation action is assumed.

Indicator	**Definition**
Cumulative CO_2 mitigation from baseline in 2020-2100 period in 1.9 Wm^{-2} scenarios ($GtCO_2$)	Difference between cumulative CO_2 emissions in the 2020-2100 period in the baseline scenario and in the 1.9 Wm^{-2} scenario.
Cumulative net land-use CO_2 in 2020-2100 period in 1.9 Wm^{-2} scenarios ($GtCO_2$)	Cumulative net land-use CO_2 emissions and removals over the 2020-2100 period in 1.9 Wm^{-2} scenarios.
Average CO_2 storage from BECCS in 1.9 Wm^{-2} scenarios over 2020-2100 period ($GtCO_2$ yr^{-1})	Average annual amount of CO_2 stored by bioenergy in combination with carbon capture and storage (BECCS) over the 2020-2100 period.
Upscaling of low-carbon primary energy share in 1.9 Wm^{-2} scenarios in 2050 rel. to baseline (-)	Factor by which the year-2050 low-carbon primary energy share has to be scaled up from its levels in the baseline scenario to the levels in 1.9 Wm^{-2} scenarios. Low-carbon primary energy here includes solar, wind, hydro, and geothermal power, as well as nuclear, biomass, and abated fossil fuels (i.e. fossil fuels combined with CCS). The direct equivalent method has been used for primary energy accounting, see e.g. Ref 54.
Reduction in coal primary energy in 1.9 Wm^{-2} scenarios in 2050 rel. to baseline (EJ yr^{-1})	The amount by which the contribution of coal to primary energy supply is reduced between the baseline scenario and the 1.9 Wm^{-2} scenario in 2050.
Reduction in carbon intensity of primary energy in 2050 in 1.9 Wm^{-2} scenarios rel. to baseline (tCO_2 TJ^{-1})	Factor by which year-2050 carbon intensity of primary energy is reduced in the 1.9 Wm^{-2} scenario compared to the baseline scenario. Carbon intensity is computed as global total CO_2 emissions (reported in $MtCO_2$ yr^{-1}) over globally aggregated primary energy (reported in EJ yr^{-1}) in 2050.
Average final energy demand over 2020-2100 period in the 1.9 Wm^{-2} scenario (EJ yr^{-1})	The average over the 2020-2100 period of global final energy demand in the 1.9 Wm^{-2} scenario.
Average annual energy system investment over 2020-2100 period in 1.9 Wm^{-2} scenarios (trillion 2005USD)	The average annual amount of total investments in energy supply over the 2020-2100 period in the 1.9 Wm^{-2} scenario. Note that these investments encompass all investments in energy supply, not just specific climate mitigation investments.
Emission intensity of food production in 1.9 Wm^{-2} scenarios in 2050 (gCO_2-eq $kcal^{-1}$)	Amount of CH_4 and N_2O emitted by agriculture per kcal of global food energy supply in 1.9 Wm^{-2} scenarios in 2050.
Non-CO_2 emissions from agriculture in 1.9 Wm^{-2} scenarios in 2050 ($GtCO_2$-eq yr^{-1})	Amount of CH_4 and N_2O emitted by agriculture in 1.9 Wm^{-2} scenarios in 2050, aggregated with GWP-100 from the IPCC AR4.

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