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SUPPLEMENTARY INFORMATION
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Energy system transformations for limiting end-of-century warming to below 1.5 °C

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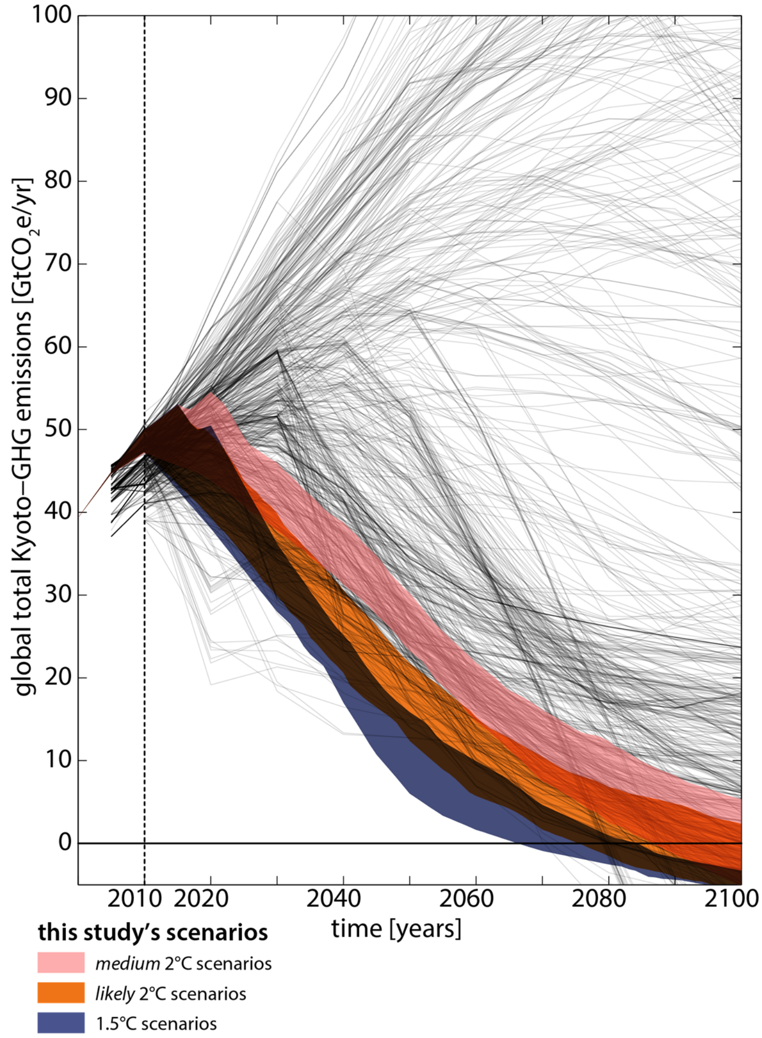
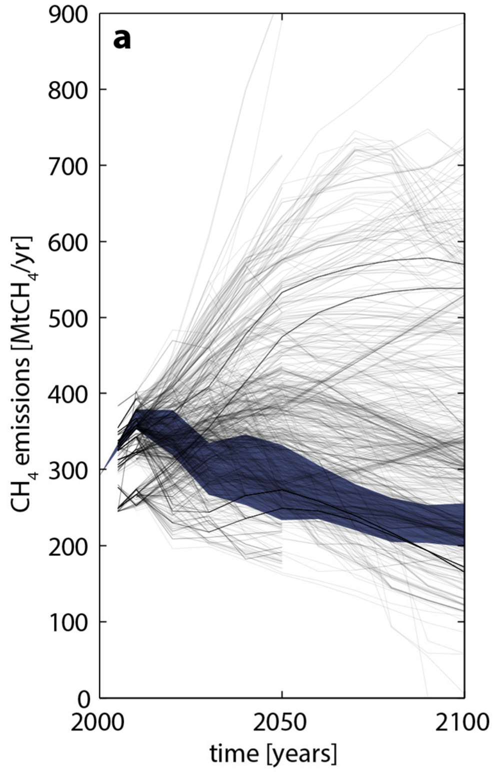
TABLE OF CONTENTS

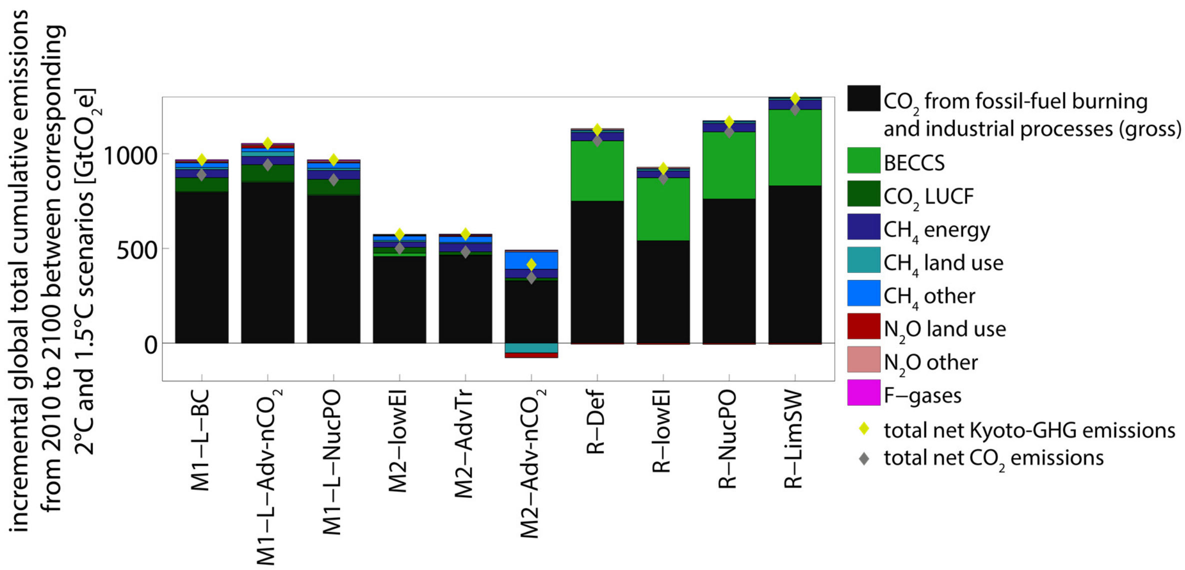
SUPPLEMENTARY FIGURES



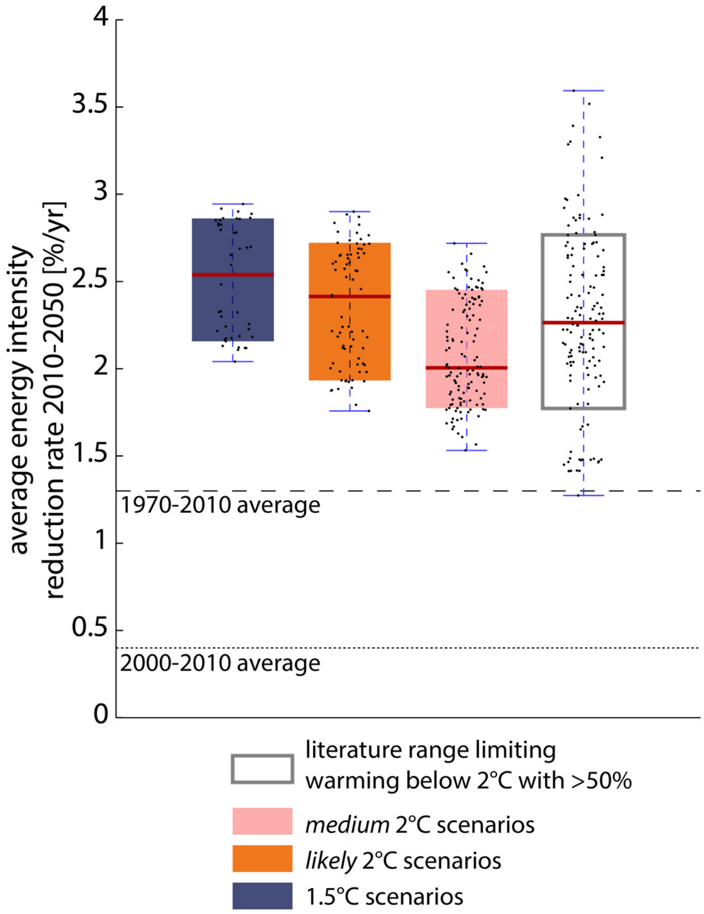
Supplementary Figure 1 | Emission profiles of *1.5°C-consistent scenarios*. Total global annual Kyoto-basket emissions over time (GWP-100 weighted). Ranges represent the 15th-85th percentile of scenarios in our set that limit warming during the 21st century below 2°C with 50-66% (*medium 2°C scenarios*, pink) and >66% chance (*likely 2°C scenarios*, orange), and in 2100 below 1.5°C with >50% chance (*1.5°C scenarios*, blue). Thin black lines are scenarios included in the IPCC AR5 scenario database.



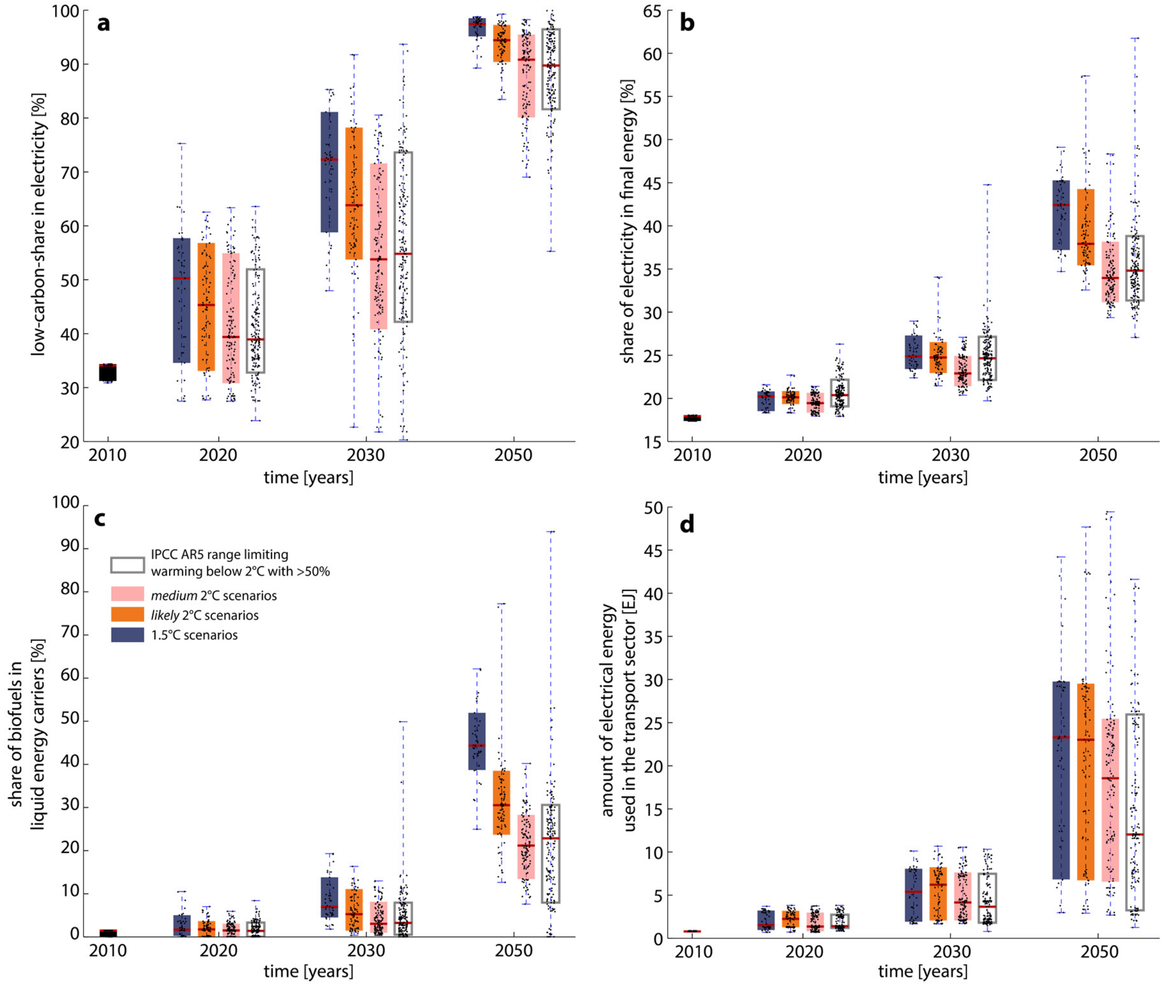
Supplementary Figure 2 | Non-*CO_2* emission profiles of *1.5°C-consistent emission* pathways.
Emission ranges (min-max) of methane (*CH_4*, left) and nitrous-oxide (*N_2O*, right) emissions from scenarios that limit warming to below 1.5°C by 2100 with at least 50% chance (dark blue range) on a backdrop of all emission trajectories available in the IPCC AR5 scenario database (thin black lines).



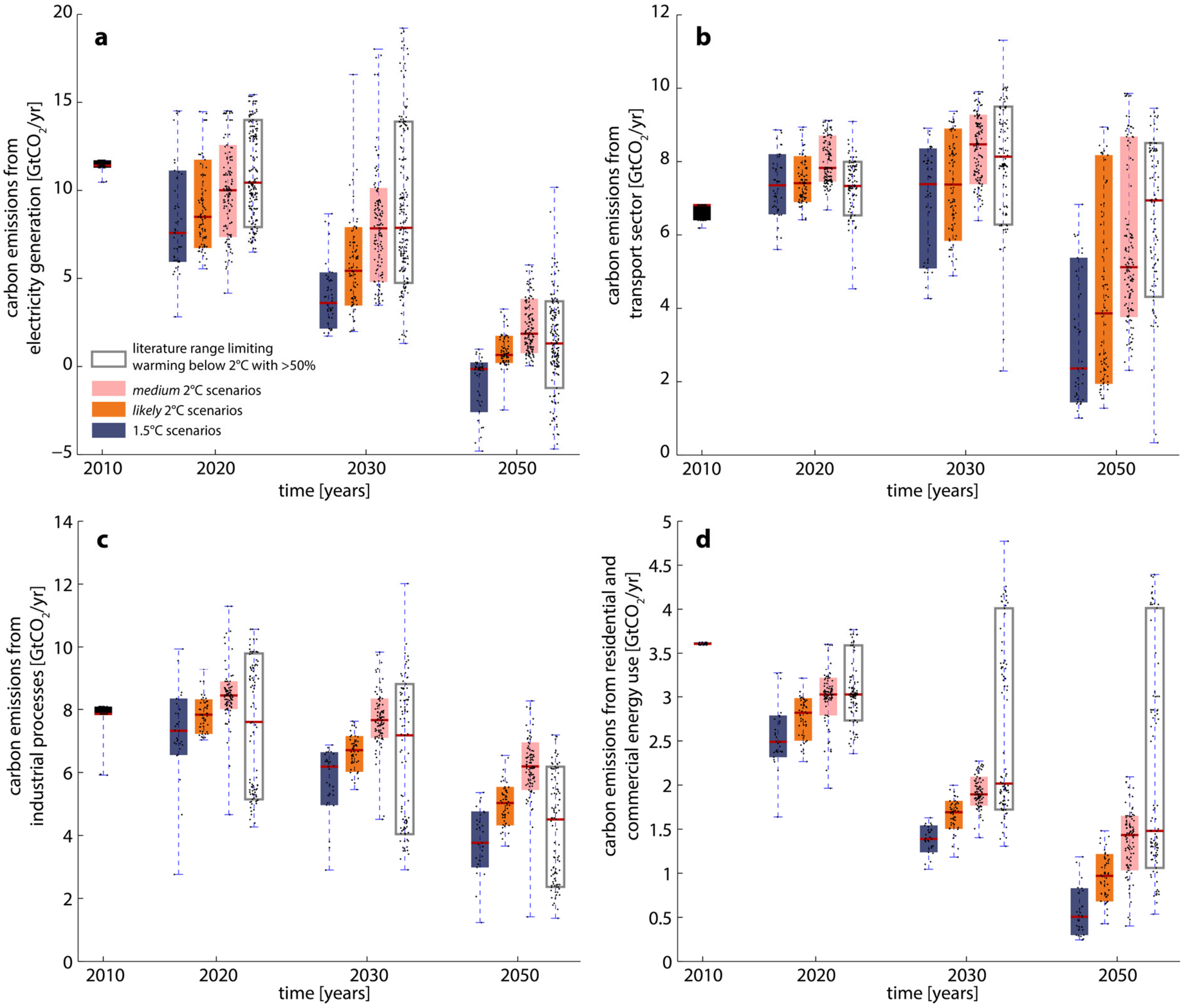
Supplementary Figure 3 | Sectorial breakdown of greenhouse gas emissions. Incremental emissions reductions in *1.5°C scenarios* beyond those performed in corresponding *2°C-consistent scenarios*. Detailed explanations of the scenarios labels are provided in Supplementary Table 4. Non-CO_2 gases account for more than half of the cumulative GWP-100-weighted CO_2-equivalent emissions between 2010 and 2100 in *1.5°C-consistent scenarios*. This is because emissions from certain non-CO_2 sources are particularly hard to mitigate (for example CH_4 emissions from land use). Incremental emission reductions between corresponding *2°C* and *1.5°C scenarios* are dominated by reductions in CO_2 emissions through reduced fossil-fuel use, higher deployment of BECCS and increased land-use sinks, which combined account for more than 90% of incremental emissions reductions. CO_2-equivalence is defined by means of the AR4 GWP-100 metric.



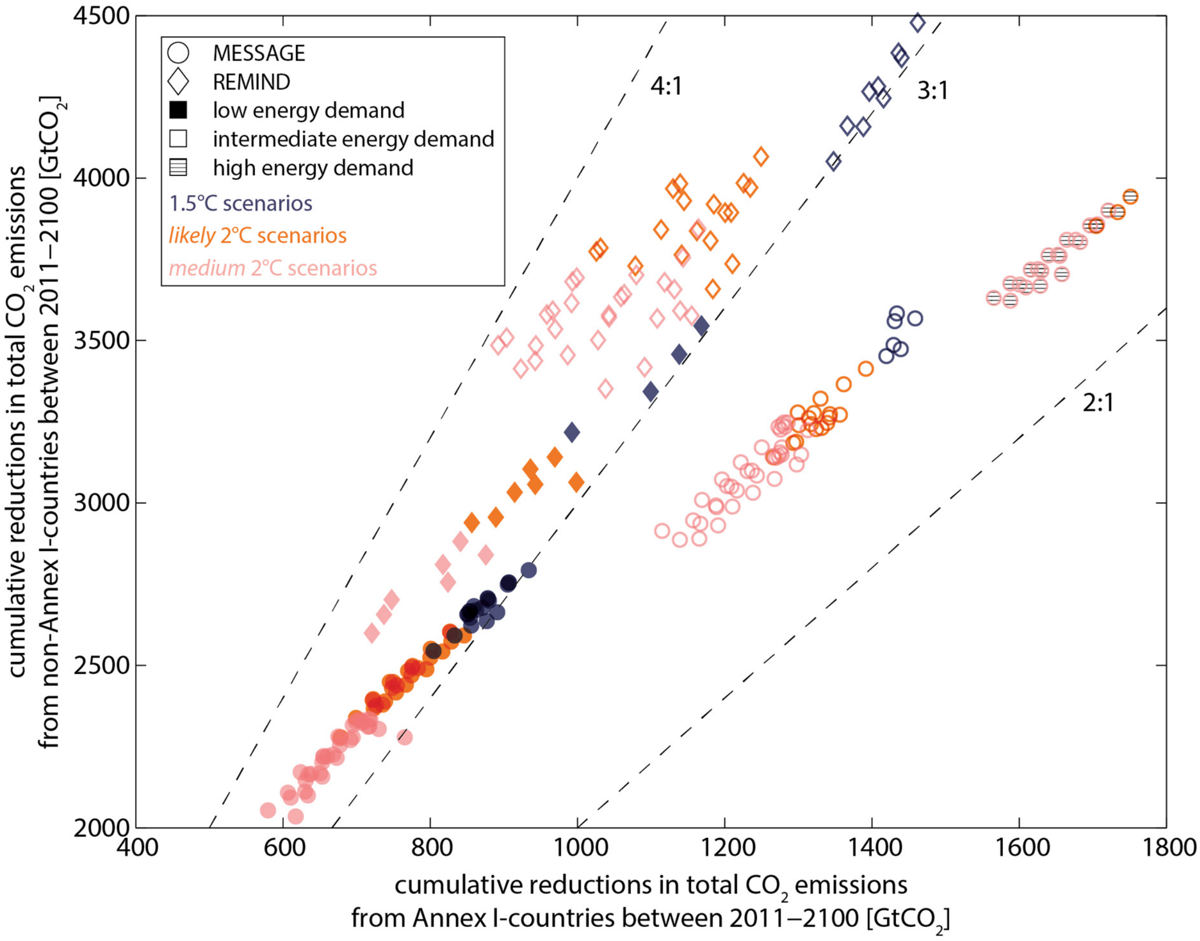
Supplementary Figure 4 | Energy intensity improvements. Average global final energy intensity improvements from 2010 to 2050. Box plots show the median (red line), the 15th to 85th percentile range (box), and the minimum-maximum range (whiskers). Dots represent single scenarios. Dashed and dotted horizontal lines indicate 1970-2010 and 2000-2010 average values based on data from the International Energy Agency (IEA) and the World Bank.



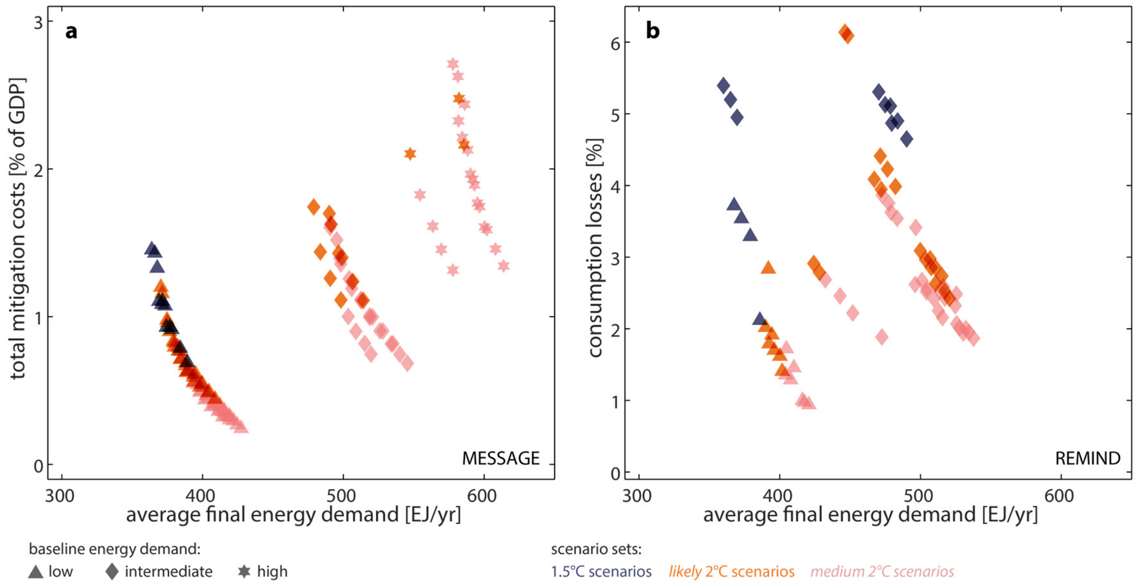
Supplementary Figure 5 | Decarbonisation indicators for 1.*5°C-consistent scenarios.* (**a**) Share of low-carbon energy in global electricity generation. "low-carbon" is here defined as renewable, nuclear and CCS; (**b**) share of electricity in final global energy; (**c**) share of biofuels in global final energy; (**d**) total amount of electrical energy used in the global transport sector. Box plots show the median (red line), the 15th to 85th percentile range (box), and the minimum-maximum range (whiskers). Dots represent single scenarios.



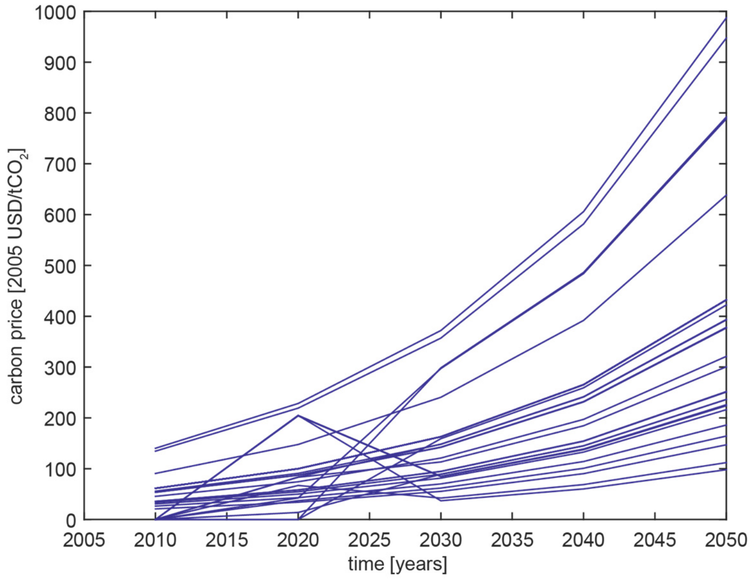
Supplementary Figure 6 | Sectorial breakdown of energy-related *CO_2* emissions. (**a**) Carbon emissions resulting from global electricity generation; (**b**) direct carbon emissions generated by the global transport sector; (**c**) global direct carbon emissions resulting from industrial processes (like cement production); (**d**) direct carbon emissions from global residential and commercial energy use. Box plots show the median (red line), the 15th to 85th percentile range (box), and the minimum-maximum range (whiskers). Dots represent single scenarios. Note that indirect emissions, i.e. emissions from the energy supply sector for (electrical) energy consumed by end-use sectors, are not included here in the sector emissions.



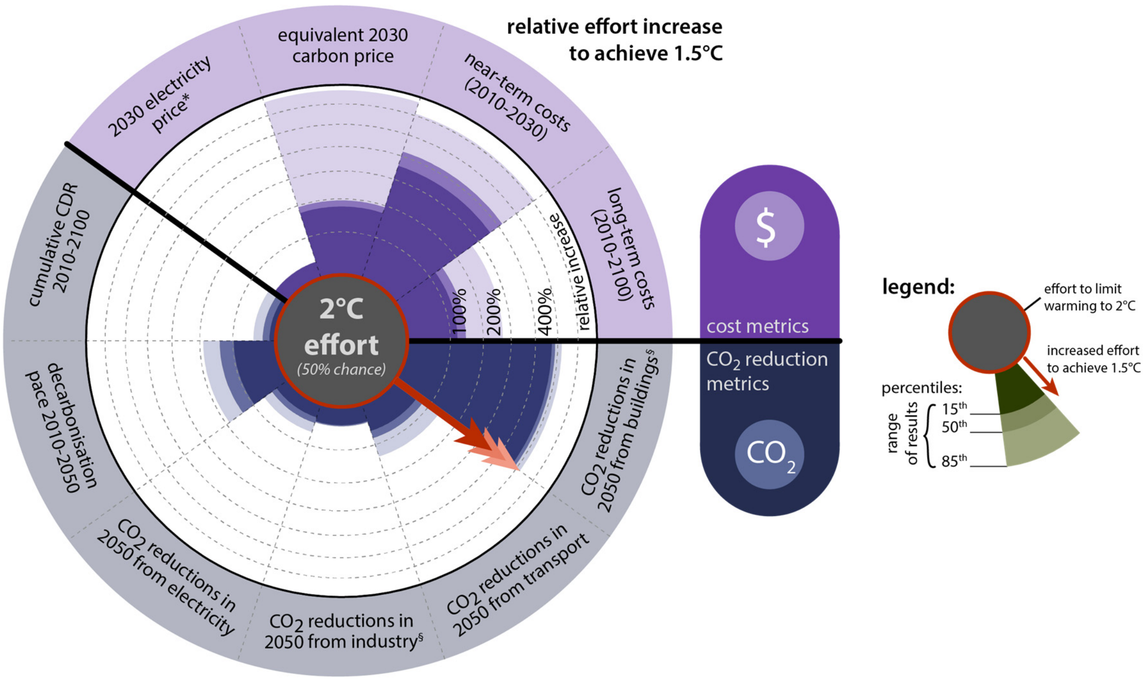
Supplementary Figure 7 | Comparison of cumulative CO_2 reductions in Annex I and non-Annex I countries. Regional (Annex I vs. non-Annex I) cumulative CO_2 emission reductions are calculated as difference between baseline emissions (in the virtual absence of future climate policies) and emissions in the *1.5°C* and *2°C scenarios* cumulated over the period 2011-2100. Mitigation measures which countries would have implemented before 2011 are accounted for in the baseline emissions of these countries.



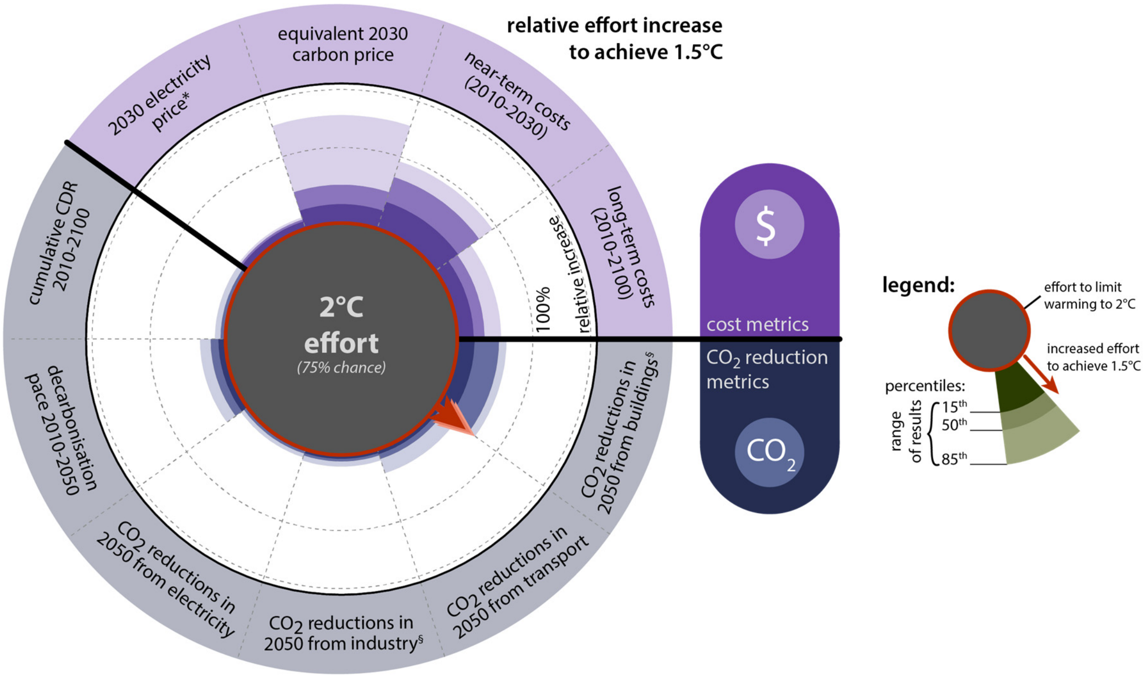
Supplementary Figure 8 | Mitigation costs for *1.5* and *2°C scenarios*. Aggregated, discounted mitigation costs from 2010-2100 (discount rate 5%) as a function of the average final energy demand from 2010 to 2100. Scenarios are coded in function of the underlying baseline energy demand evolution (low, intermediate and high represented by triangles, diamonds, and stars, respectively), their probability of limiting warming to particular temperature levels (pink, orange and blue). Panel **a** provides total mitigation costs from the MESSAGE model scenarios, and panel **b** provides consumption losses for the scenarios from the REMIND model. The mitigation costs methodology is described in the Methods section.



Supplementary Figure 9 | Carbon price time series for *1.5°C consistent scenarios.* Equivalent carbon prices are provided in *2005 USD/tCO$_2$*. Most *1.5°C scenarios* in our set initiated mitigation in 2010, with carbon prices ramping up during until 2050. Only few scenarios are available that still have a zero carbon price by 2020. The temporary peak in carbon prices around 2020 is present in scenarios that impose emission reductions in the near term (by 2020), which are more stringent than what a least-cost approach would require. Therefore carbon prices decline again afterward.



Supplementary Figure 10 | Overview of the relative change in mitigation contributions or characteristics for *1.5°C-consistent scenarios* relative to corresponding *2°C-consistent scenarios* (50% chance). Indicators are: long-term mitigation costs (2010-2100 aggregate discounted at 5%), short-term mitigation costs (2010-2030 aggregate discounted at 5%), 2030 equivalent carbon price level, electricity price in 2030, the total level of CO_2 removal between 2010-2100 (CDR), the 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 emission 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. For indicators marked with * only REMIND provides data. For indicators marked with § only MESSAGE provides data. All changes are provided relative to the reference case of limiting warming to below 2°C with 50% chance.



Supplementary Figure 11 | Overview of the relative change in mitigation contributions or characteristics for *1.5°C-consistent scenarios* relative to corresponding *2°C-consistent scenarios* (75% chance). Indicators are: long-term mitigation costs (2010-2100 aggregate discounted at 5%), short-term mitigation costs (2010-2030 aggregate discounted at 5%), 2030 equivalent carbon price level, electricity price in 2030, the total level of CO_2 removal between 2010-2100 (CDR), the 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 emission 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. For indicators marked with * only REMIND provides data. For indicators marked with § only MESSAGE provides data. All changes are provided relative to the reference case of limiting warming to below 2°C with 75% chance.

SUPPLEMENTARY TABLES

Supplementary Table 1 | Emission characteristics of *1.5°C scenarios* in our set. Emissions scenarios that follow the 15th percentile path until 2050 are supposed to follow the 85th percentile path from 2050 until 2100 in order to remain consistent with 1.5°C.

1.5°C scenarios						
Number of available scenarios: **37**						
Year of annual net global CO_2 (including LULUCF) emissions becoming zero*: **2050 (2045-2060)**						
Year of annual net global Kyoto greenhouse gas emissions becoming zero*: **2075 (2065-2085)**						
Global carbon budgets ** **(global total CO_2 emissions) [GtCO$_2$]**						
Time window	*2016-2025*	*2026-2050*	*2051-2075*	*2076-2100*	*2011-2050*	*2011-2100*
15th percentile	257	235	-242	-356	679	199
median	**288**	**309**	**-138**	**-341**	**797**	**350**
85th percentile	352	377	-64	-289	895	415
Annual emissions of all Kyoto greenhouse gases ** **(Kyoto-GHG – GWP-100 weighted) [GtCO$_2$e/yr]**						
Year	*2020*	*2025*	*2030*	*2050*	*2100*	
minimum	31	31	26	4	-10	
15th percentile	38	33	28	6	-6	
median	**41**	**37**	**33**	**13**	**-5**	
85th percentile	50	43	36	16	-3	
maximum	56	49	40	19	-2	

* Rounded to nearest 5 years. Format: median (15th percentile – 85th percentile)
** Rounded to nearest *GtCO$_2$* or *GtCO$_2$e/yr*

Supplementary Table 2 | Emission characteristics of *likely 2°C scenarios* in our set. Emissions scenarios that follow the 15th percentile path until 2050 are supposed to follow the 85th percentile path from 2050 until 2100 in order to remain consistent with a *likely* (>66%) chance of limiting warming the below 2°C. Note that the set of *likely 2°C scenarios* is explicitly excluding scenarios that would be stringent enough as to fall in the *1.5°C scenario* subset.

Likely 2°C scenarios						
Number of available scenarios: **72** Year of annual net global CO_2 (including LULUCF) emissions becoming zero*: **2065 (2060-2070)** Year of annual net global Kyoto greenhouse gas emissions becoming zero*: **2090 (2085-after 2100)**						
Global carbon budgets** **(global total CO_2 emissions) [GtCO$_2$]**						
Time window	*2016-2025*	*2026-2050*	*2051-2075*	*2076-2100*	*2011-2050*	*2011-2100*
15th percentile	283	362	-32	-306	739	322
median	**306**	**454**	**16**	**-255**	**895**	**634**
85th percentile	363	538	80	-115	1029	855
Annual emissions of all Kyoto greenhouse gases** **(Kyoto-GHG – GWP-100 weighted) [GtCO$_2$e/yr]**						
Year	*2020*	*2025*	*2030*	*2050*	*2100*	
minimum	36	31	26	9	-10	
15th percentile	40	36	32	18	-6	
median	**44**	**40**	**37**	**20**	**-3**	
85th percentile	49	45	40	23	4	
maximum	56	58	60	26	12	

* Rounded to nearest 5 years. Format: median (15th percentile – 85th percentile)
** Rounded to nearest *GtCO$_2$* or *GtCO$_2$e/yr*

Supplementary Table 3 | Emission characteristics of *medium 2°C scenarios* in our set. Emissions scenarios that follow the 15th percentile path until 2050 are supposed to follow the 85th percentile path from 2050 until 2100 in order to remain consistent with a *medium* (50-66%) chance of limiting warming the below 2°C.

Medium 2°C scenarios						
Number of available scenarios: **124** Year of annual net global CO_2 (including LULUCF) emissions becoming zero*: **2070 (2065-2075)** Year of annual net global Kyoto greenhouse gas emissions becoming zero*: **2095 (2085-after 2100)**						
Global carbon budgets** **(global total CO_2 emissions) [GtCO$_2$]**						
Time window	*2016-2025*	*2026-2050*	*2051-2075*	*2076-2100*	*2011-2050*	*2011-2100*
15th percentile	311	505	35	-287	990	862
median	**336**	**589**	**136**	**-213**	**1107**	**1026**
85th percentile	395	674	200	-61	1226	1283
Annual emissions of all Kyoto greenhouse gases** **(Kyoto-GHG – GWP-100 weighted) [GtCO$_2$e/yr]**						
Year	*2020*	*2025*	*2030*	*2050*	*2100*	
minimum	35	35	35	17	-9	
15th percentile	44	41	38	23	-5	
median	**47**	**44**	**42**	**26**	**-2**	
85th percentile	55	49	46	30	5	
maximum	57	60	63	34	16	

* Rounded to nearest 5 years. Format: median (15th percentile – 85th percentile)
** Rounded to nearest *GtCO$_2$* or *GtCO$_2$e/yr*

Supplementary Table 4 | Overview scenario names. Definition of scenario labels shown in Supplementary Figure 3. More detail can be found in the original publications referenced below. Scenarios marked with * highlight scenario setups included for the computation of the ranges in Figure 5. Scenarios marked with § are exclusively used for Supplementary Figure 5 and not in Supplementary Figure 3.

Scenario label	Description
M1-L-BC*	Scenario created with the MESSAGE model and originally published and described in Ref. 1. Assumes a full portfolio of mitigation technologies (BC: base case) and a high energy-efficient future resulting in a low energy demand (L).
M1-L-Adv-nCO_2*	Scenario created with the MESSAGE model and originally published and described in Ref. 1. Assumes a full portfolio of mitigation technologies and a high energy-efficient future resulting in a low energy demand (L). This scenario additionally assumes continued improvements over the course of the century in the mitigation potential of non-CO_2 greenhouse gases (Adv-nCO_2).
M1-L-NucPO*	Scenario created with the MESSAGE model and originally published and described in Ref. 1. Assumes a high energy-efficient future resulting in a low energy demand (L), and a phase-out of nuclear power generation over the coming decades (NucPO).
M1-L-LimBio§	Scenario created with the MESSAGE model and originally published and described in Ref. 1. Assumes a high energy-efficient future resulting in a low energy demand (L), and a limited availability of bioenergy due to sustainability concerns (LimBio).
M2-lowEI	Scenario created with the MESSAGE model and originally published and described in Ref. 2. Assumes a full portfolio of mitigation technologies and a high energy-efficient future resulting in a low energy demand (lowEI).
M2-AdvTr	Scenario created with the MESSAGE model and originally published and described in Ref. 2. Assumes a full portfolio of mitigation technologies, an intermediate future energy demand, and an advanced electrification of the transport sector (AdvTr).
M2-Adv-nCO_2	Scenario created with the MESSAGE model and originally published and described in Ref. 2. Assumes a full portfolio of mitigation technologies, an intermediate future energy demand, and continued improvements over the course of the century in the mitigation potential of non-CO_2 greenhouse gases (Adv-nCO_2).
R-Def*	Scenario created with the REMIND model and originally published and described in Ref. 3. Assumes a full portfolio of mitigation technologies and an intermediate future energy demand (Def: default).
R-lowEI*	Scenario created with the REMIND model and originally published and described in Ref. 3. Assumes a full portfolio of mitigation technologies and a high energy-efficient future resulting in a low energy demand (lowEI).
R-NucPO*	Scenario created with the REMIND model and originally published and described in Ref. 3. Assumes a high energy-efficient future resulting in a low energy demand, and a phase-out of nuclear power generation over the coming decades (NucPO).
R-LimSW*	Scenario created with the REMIND model and originally published and described in Ref. 3. Assumes the renewable energy potential of wind and solar power to be limited (LimSW), and an intermediate future energy demand.

SUPPLEMENTARY TEXT 1

RELATIONSHIP TO IPCC AR5 1.5°C ASSESSMENT

The Working Group III Contribution to the Fifth Assessment Report[4] (AR5 WGIII) of the Intergovernmental Panel on Climate Change (IPCC) only includes a limited assessment of scenarios that return warming to below 1.5°C. The report[5] provides a brief qualitative discussion and very limited quantitative information of the characteristics of 1.5°C scenarios based on an assessment of studies available in the literature[1-3]. However, the 1.5°C scenarios from these studies were not contributed to the IPCC AR5 WGIII scenario database on which the IPCC AR5 WGIII's quantitative assessment of mitigation pathways relied[*]. There are several reasons for this. First, the database was populated on a voluntary basis. Second, the AR5 database received major contributions from large-scale integrated assessment modelling intercomparison (IAM) experiments (for example, from Refs. 6-18), and modelling teams often refrained from contributing additional scenarios from single-model studies that were carried out (like those reported in Refs. 1-3). Since the IAM intercomparison exercises did not attempt to produce scenarios towards limiting warming below 1.5°C, almost none were reported to the AR5 database. Third, from some additional studies[19,20] which also looked at the question of 1.5°C with other modelling frameworks, no scenarios were contributed into the AR5 database.

Scenarios in the IPCC AR5 WGIII assessment were grouped based on their concentration rather than their temperature outcome. This eases comparability with the results for the representative concentration pathways[21-23] (RCP) across IPCC working groups. However, at the same time it complicates the interpretation of AR5 WGIII results in terms of keeping warming below specific temperature limits, in particular 1.5°C, for which no specific corresponding concentration category (or RCP) is available. The lowest scenario category of the IPCC AR5 WGIII report corresponds to a *likely* chance[24] (>66%) of limiting warming to below 2°C, and is not explicit about options for limiting warming to below 1.5°C with a compelling probability.

Comparison of *1.5°C scenario* results from IPCC AR5 and from this study	**IPCC AR5**	**This study**
Methodology	10th to 90th percentile ranges of scenarios limiting warming to below 1.5°C by 2100 with at least 60%, separately received from earlier published studies[1-3].	15th to 85th percentile ranges of scenarios limiting warming to below 1.5°C by 2100 with at least 50%, in our scenario set.
Cumulative CO_2 2011-2050	655–815 $GtCO_2$	680-895 $GtCO_2$
Cumulative CO_2 2011-2100	90–350 $GtCO_2$	200-415 $GtCO_2$
Global CO_2e emission reductions from 2010 levels in 2050	70-95%	66-88%
Global CO_2e emission reductions from 2010 levels in 2100	110-120%	107-113%

[*] Hosted at the International Institute for Applied Systems Analysis – IIASA, and available at: https://secure.iiasa.ac.at/web-apps/ene/AR5DB

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