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ANALYSIS OF COST-EFFECTIVE REDUCTION PATHWAYS FOR MAJOR EMITTING COUNTRIES TO ACHIEVE THE PARIS AGREEMENT CLIMATE GOAL

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Abstract

Achievement of the global climate goal of the Paris Agreement depends on the collective action by individual nations. This is reflected in the nationally determined contributions (NDCs) and long-term strategies (LTS) and/or national climate strategies. NDCs contain national mitigation targets, plans and measures, and were first submitted in the lead-up to the Conference of the Parties (COP) 21 in Paris (2015) (UNFCCC, 2015). To ensure continued progress, the Paris Agreement established a ratcheting process in which the NDCs are evaluated and countries are encouraged to submit more ambitious NDCs. The first facilitative process for this purpose (the Talanoa Dialogue) started in 2018 and subsequent global stocktakes will take place every five years, beginning in 2023. In this context, greenhouse gas reduction targets for the coming years become increasingly important. In the lead-up to COP30 (in 2025), all countries need to submit new NDCs, which should cover intermediate targets for 2040 or 2035. This study uses the least-cost mitigation scenarios for 1.5 °C and 2 °C from Integrated Assessment Models of the latest IPCC's Sixth Assessment Report scenario database. We focused on five major emitting economies (the European Union as a whole (EU-27), China, India, Japan and the United States) and the world. We downscaled the original emission pathways to the regional level for these five major economies and further harmonised the emission data with national inventory data. Our findings are that, in order to keep global warming to 1.5 °C with a limited overshoot, the least-cost greenhouse gas reductions by 2040, for the EU-27, Japan and the United States, are projected between around 70% and 100% relative to 2015 levels (including LULUCF), while for limiting global warming to 2 °C, such projections are between around 40% and 80%. For China, this is 65%–80% and 40%–65%, respectively, and for India 30%–75% and -30%–45%. When comparing the reductions relative to 1990 levels, countries that have experienced a decline in emissions since 1990, such as the EU-27, need to achieve higher reductions (76%–96%, instead of 68%–95%), and countries with a substantial increase in emissions, like China, have lower reductions (-23%–26% compared to 1990 levels). Note that these projections are solely based on least-cost considerations. When it comes to deriving emission levels, an assessment of least-cost considerations should be complemented with an assessment of equity considerations. Equity can be incorporated in international climate policy in various ways, and one way would be for countries to adjust their reduction targets. Based on the existing literature we have analysed the emission reduction targets based on effort-sharing approaches that account for equity principles capability, equality and responsibility. In general, these equity principles lead to higher reductions for the China, the EU-27, Japan, and the United States, and to lower reductions for India. We found for instance EU emission reductions of 97%, 79% and 95% by 2040 compared to 1990 levels (excluding LULUCF) for different equity approaches.

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Executive summary

In order to meet the climate objective of the Paris Agreement through ongoing updated and strengthened NDCs, it is of crucial importance that countries can assess and communicate the relative ambition level of their reduction proposals. This study explores reduction pathways to keep global warming below 1.5 °C or well below 2 °C, as projected in the form of least-cost scenarios of integrated assessment models in the IPCC AR6 scenario database. Such least-cost scenarios form a relevant reference and could possibly result from the use of fairness-based allocations in combination with flexible instruments. Our results show that:

In least-cost scenarios, reductions by 2040 (relative to 2015) to keep global warming to 1.5 °C with a limited overshoot (climate category C1) range between around 70%–100% (10th– 90th percentile range including LULUCF) for the EU-27, Japan and the United States. For a maximum global warming of 2 °C (climate category C3), they range between around 40% and 80%. For China, this is 65%–80% and 40%–65%, respectively, and for India 30%–75% and -30%–35%. Scenarios that have started cost-optimal mitigation in 2020 and achieve the 1.5 °C target with a probability of at least 50% (climate category C1) show median emission reductions by 2040, relative to 2015, of about 70% for China, 80%–85% for the EU-27, Japan and the United States, 40% for India, and about 70% for the world. This corresponds with average annual GHG budgets between 2030 and 2050 of around 30% of 2015 levels for China, 20% for the EU27, 65% for India, 20% for Japan, 20% for the United States and 30% for the world. Scenarios that would achieve the 2 °C targets with a probability of at least 67% (climate category C3) show median emission reductions by 2040 of about 55% for China, 60%–65% for the EU-27 and the United States, 70% for Japan, 50% for the world, and 10% for India. These reductions correspond with average annual GHG budgets between 2030 and 2050 of around 50% of 2015 levels for China, 40% for the EU27, 95% for India, 35% for Japan, 40% for the United States and 55% for the world as a whole. When comparing the reductions relative to 1990 levels, countries that have experienced a decline in emissions since 1990, such as the EU-27, need to achieve higher reductions (76%–96%, instead of 68%–95%), and for countries with a substantial increase in emissions, like China, have lower reductions (-23%–26% compared to 1990 levels).

These median least-cost reductions by 2040 for the EU-27, Japan, the United States and China, are higher than the global median reduction for all climate categories. For India, the reductions are lower. The median estimates show that high-income countries the EU-27, Japan and the United States are projected to achieve higher (about 5–20 percentage points) GHG and CO_2 reductions by 2040, compared to China (upper middle-income country). These high-income countries and China all need to achieve higher reductions by 2040 compared to global reductions, whereas India (lower middle-income country) has lower reductions by 2040. In general, 10th–90th percentile ranges show the same pattern.

Ranges in projected least-cost reductions by 2040 show limited overlap between the climate categories C1 and C3. The 10th–90th percentiles of the GHG reductions by 2040 for C1 and C3 do not overlap for China and the world. The ranges only overlap slightly for the EU-27, India, Japan and the United States. Similarly, CO_2 reductions also show minor overlap. This indicates that, for the selected countries, there is a clear difference in projected reductions corresponding with achieving the 1.5 °C or 2 °C target.

Table S.1
Overview of cost-effective GHG reductions (including land-use net GHG emissions) by 2040, compared to 2015 levels (upper Table) and 1990 levels (lower Table), for the major emitting countries and regions and the world for the different climate categories .

Below 2015 levels:

Category	China	EU27	India	Japan	USA	World
C1	72	81	40	84	85	70
	65–79	68–95	29–77	75–94	71–98	64–85
C1a	70	79	34	83	85	68
	65–78	66–91	26–53	74–92	70–94	62–79
C2	57	69	27	76	67	57
	50–73	49–81	7–50	55–88	48–84	48–72
C3	54	65	11	69	61	48
	39–63	41–78	-28–36	45–81	39–78	37–60

Below 1990 levels:

Category	China	EU27	India	Japan	USA	World
C1	3	86	-33	84	84	
	-23–26	76–96	-55–50	74–93	69–97	
C1a	-4	84	-44	82	84	
	-23–23	74–93	-62– -4	73–91	68–93	
C2	-49	77	-60	74	65	
	-74–6	62–86	-103– -9	53–87	44–83	
C3	-59	74	-96	68	58	
	-109– -29	56–83	-181– -41	43–80	33–76	

National targets are typically based on fairness considerations, in combination with costs. When it comes to deriving emission levels, an assessment of least-cost considerations should be combined with an assessment of equity considerations. Equity can be incorporated in international climate policy in various ways. One way would be for countries to adjust their reduction targets. Based on the existing literature, we analysed the emission reduction targets using effort-sharing approaches that account for equity principles (i.e. capability, equality and responsibility). Equity approaches lead to an increase of 5–40 percentage points for the EU-27, the United States, Japan and China when comparing the 10th and 90th percentiles of least-cost scenarios to minimal and maximal values based on equity principles. For India, this leads to decreases of around 15 to 85 percentage points. Countries can also use other instruments to incorporate equity in international climate policy, such as emission trading, investing in other countries, supporting capacity building or transferring technology (Pachauri et al., 2022; Rogelj, 2019; van Soest, den Elzen, et al., 2021). The results of this study do not indicate how to account for equity considerations, and therefore policymakers should not regard the emission reductions presented in this study as directly indicative of national targets. As van Soest et al. (2012) explain, an assessment of feasible reductions at the national level and considerations of equity, among other things, should supplement the results presented in this study.

The NDCs of the EU-27 and the United States are comparable to the median projected reductions by 2030 for least-cost scenarios that limit global warming to 1.5 °C. For China and India, the NDCs do not align with least-cost scenarios to achieve 1.5 °C or 2 °C. It should be noted that national reduction targets are typically based on fairness considerations. The NDC target of the EU-27 is between and close to the medians of projected reductions for the C2 and C1/C1a categories. The NDC target of the United States aligns with the median of projected reductions for C1a and just below the median of projected reductions for C1. For Japan, the NDC is at the lower end of the projected reduction range by 2030 for C2 and C3, but falls short compared to the median projected reduction for least-cost scenarios limiting global warming to 1.5 °C or 2 °C. The NDCs of China and India are below the 10th–90th percentile range of least-cost emission reduction levels projected for any climate category.

Net-zero targets are often in line with more ambitious least-cost scenarios. The net-zero target years of the EU-27, China, United States and Japan are earlier in time than the median net-zero years for almost all climate categories (the only exception being C1a for the United States, for which the median net-zero year is in line with the net-zero target). For India, it is unclear whether the net-zero target is defined for GHG or CO_2. In case it is for GHG, the target year would be earlier than the median net-zero years for all categories (the median scenario does not reach net-zero before 2100 for most categories). In case it is for CO_2, the target year is 10 years after the median net-zero years for C1, C1a and C2, and before the median year for C3.

The European Scientific Advisory Board on Climate Change finds an EU GHG emission reductions range of 88%–95% by 2040, relative to 1990, and recommends a reduction range of 90%–95%, whereas our study finds 84%–97% with a median of 92% if the selection of scenarios is narrowed down to those that reach climate neutrality by 2050. The European Scientific Advisory Board has published its advice on an EU climate target for 2040 and the associated GHG budget for the 2030–2050 period (European Scientific Advisory Board on Climate Change, 2023). This analysis builds on a selection of scenarios that limit global warming to 1.5 °C with a limited overshoot and are consistent with the European Union's emission reduction objectives for 2030 and 2050. Although the methods applied in the Advisory Board analysis differ from ours, its results can be compared with the results found in our study. For keeping global warming below 1.5 °C with a limited overshoot (climate category C1), the Advisory Board analyses an EU GHG emission reductions range of 88%–95% by 2040, relative to 1990, and recommends reductions of 90%–95%. The GHG budgets for the 2030–2050 period corresponding with the analysed reductions range between 11 and 16 $GtCO_2eq$, and the recommended reductions correspond with a range of 11–14 $GtCO_2eq$. For climate category C1, the current study found EU GHG emission reductions of 76%–96% (10th– 90th percentile range) with a median of 86% by 2040 (relative to 1990 levels) based on least-costs scenarios, which corresponds to a EU's GHG budget for the 2030–2050 period of 7–24 Gt CO_2eq. These ranges are larger than the recommended range by the Advisory Board. Narrowing down the selection of least-cost scenarios to those that achieve the European Union's existing reduction target of climate neutrality by 2050 (which represents only around 40% of all scenarios, see Table 6), the resulting GHG emission reductions and budgets are 84%–97% with a median of 92% and 7–17 Gt CO_2eq with a median of 12 Gt CO_2eq. Based on equity considerations of the three equity principles, i.e. capability, equality and responsibility, we found EU emission reductions of 97%, 79% and 95% by 2040 (excluding LULUCF) for different equity approaches.

1 Introduction

Achievement of the global climate goal of the Paris Agreement depends on the collective action by individual nations. This is reflected in the nationally determined contributions (NDCs) and long-term strategies (LTS) and/or national climate strategies. NDCs contain national mitigation targets, plans and measures, and were first submitted in the lead-up to the Conference of the Parties (COP) 21 in Paris (2015) (UNFCCC, 2015). To ensure continued progress, the Paris Agreement established a ratcheting process in which the NDCs are evaluated and countries are encouraged to submit more ambitious NDCs. The first facilitative process for this purpose (the Talanoa Dialogue) started in 2018 and subsequent global stocktakes will take place every five years, beginning in 2023. Most countries updated their NDCs in 2021 in advance of the COP26 in Glasgow, and several other countries did so in 2022 (Climate Watch, 2023b). Globally, the updated NDCs as of 23 September 2022 are promising an additional annual reduction of 4.8 $GtCO_2$ eq by 2030, relative to the initial NDCs of COP21 in Paris. This, however, means that the aggregated impact remains insufficient to reach the modelled reduction pathways consistent with the climate goal that was set in the Paris Agreement (den Elzen et al., 2022; UNEP, 2022).

The recent IPCC synthesis report also showed that the carbon budgets consistent with the Paris climate goal are rapidly being depleted (IPCC, 2023). In this context, reduction targets for the coming years become increasingly important. In the lead-up to COP30 (in 2025), all countries need to submit new NDCs, which should cover intermediate targets for 2040 or 2035. Countries need to start their preparations for updating their NDCs well before the COP, as this entails an iterative process informed by reviews of the status of contributions (the global stocktake). According to the European Climate Law, for instance, the European Commission should propose an EU climate target for 2040 and a projected indicative EU greenhouse gas budget for the 2030–2050 period within six months of the first global stocktake of 2023, at the latest (European Parliament and the Council of the European Union, 2021). In addition, Article 4 of the agreement sets out that '*all Parties should also strive to formulate and communicate long-term low GHG emission development strategies*' (UNFCCC, 2015). The development of these long-term strategies, including quantifiable national targets, would also provide post-2030 constraints on the national emission pathways. As of 25 July 2023, 66 Parties, responsible for about 70% of global greenhouse gas emissions, have communicated a long-term strategy (Climate Watch, 2023a; UNFCCC, 2023b) and 51 Parties, representing about 60% of global GHG emissions, have communicated a net-zero target (Climate Watch, 2023c).

The emission reduction targets pledged by parties are related to the global emissions target aimed at achieving the Paris climate goal and the contribution that individual countries are willing to make in order to achieve this goal. These targets are strongly influenced by opinions about what these countries consider fair and ambitious, in the light of their national circumstances (UNFCCC, 2015). There is a large body of literature on what could constitute a fair contribution (e.g. see Robiou du Pont et al., 2017; van den Berg et al., 2020). Various equity principles have been proposed and countries are known to have different opinions on their importance (Winkler et al., 2018). In addition to fairness, it also possible to determine regional reduction targets based on cost-optimisation. Part of the literature emphasises the use of flexible instruments (e.g., emission trading) which allows implementing reductions in a cost-optimal way, with the fairness-based targets determining who is financing these reductions. This means that the cost-optimal scenario can always be considered a meaningful reference.

The cost-optimal reductions aligned with the Paris Agreement's temperature goal can be explored with recently developed long-term low GHG emission pathways for meeting the 1.5 °C and 2 °C climate targets as calculated by global Integrated Assessment Models (IAMs) (Riahi et al., 2021; Riahi et al., 2022; van Soest, Aleluia Reis, et al., 2021). These scenarios demonstrate how emission reductions can be distributed over time, across regions, sectors and greenhouse gases, at the lowest costs possible. Furthermore, earlier studies present detailed analyses of the regional GHG emission trajectories of these least-cost scenarios. Roelfsema et al. (2020) use nine different IAMs to compare the impact of national policies with emission pathways consistent with the NDCs and those that lead to maximum temperature increases of well below 2 °C. Additionally, van Soest, den Elzen, et al. (2021) analyse national-level neutrality years based on least-cost 1.5 °C and 2 °C scenarios from six different IAMs. It is critical to realise that these are not necessarily well-alligned with fairness-based allocations. This is further discussed in Section 4.

This study aims to identify and analyse which greenhouse gas emission reduction levels and which 2030–2050 greenhouse gas emission budgets for major emitting economies would be consistent with achieving the climate targets of 1.5 °C and 2 °C at the lowest possible mitigation costs. Our analysis is based on the IPCC's Sixth Assessment Report (AR6) scenario database, which was developed as part of the IPCC AR6 WGIII Report (Byers et al., 2022; Riahi et al., 2022). However, a critical point is that the national inventories use accounting rules that differ from those used by the IPCC. This means that the national emission data and global IPCC data also need to be aligned, as is discussed in this paper(Grassi et al., 2018). We focused on five major emitting economies (the EU-27, China, India, Japan and the United States) and the world as a whole. For the analysis, the original emission pathways were downscaled to the level of model regions for these five major economies (referred to as 'selected countries or regions'). Moreover, emission data and national inventory data were harmonised.

2 Methodology

For this study, we used the least-cost mitigation scenarios from the IPCC's Sixth Assessment Report (AR6) scenario database (Byers et al., 2022) that are compatible with the climate goal of the Paris Agreement. The emission pathways of these scenarios were downscaled to the selected countries and the countries' emission pathways were harmonised with emission inventory data.

2.1 Scenario selection

The IPCC AR6 scenario database is hosted by the International Institute for Applied Systems Analysis (IIASA) and includes results from all IAM scenarios used in the IPCC AR6 report and its chapter on mitigation pathways compatible with long-term goal (IPCC, 2022a; Riahi et al., 2022). The scenarios were developed within various research projects and afterwards collected to be included in the database. GHG emission scenarios reported in the AR6 database are weighted by 100-year global warming potentials from the AR6 report. These scenarios contain domestic emission data only on a regional level and for major emitting countries, and international shipping and aviation are reported in another category. From the scenario database, we selected all available scenarios in climate categories C1 (limit 1.5 °C with at least 50% probability, with limited or no overshoot), C2 (limit 1.5 °C with at least 50% probability, with high overshoot) and C3 (limit 2 °C with at least 67% probability). These scenarios can be considered to be consistent with the climate goal of the Paris Agreement, i.e., *'holding the increase in average global temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels'* (UNFCCC, 2015).

In addition to these categories, we also included scenarios in category C1a, which is a subcategory of C1 that contains scenarios reaching global net-zero greenhouse emissions in the second half of this century. This is consistent with Article 4 of the Paris Agreement, i.e. *'reach global peaking of greenhouse gas emissions as soon as possible […] and […] to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.'*

Table 1 shows the compatibility of scenarios in all selected climate categories with the climate goal and net-zero greenhouse gas target of the Paris Agreement, i.e. achieving net-zero greenhouse gas emissions before the end of the century. It shows that only C1a scenarios are compatible with keeping temperature increase below 2 °C with a very high probability, and also with keeping the overshoot in temperature increase of 1.5 °C limited (0.1 °C) and achieving the global net-zero target in the second half of the 21st century. C1 is also compatible with the 1.5 °C and 2 °C goal, but does not achieve the net-zero target. C2 has a higher overshoot before reaching 1.5 °C and a lower likelihood for of meeting 2 °C, but achieves the net-zero target in the second half of the 21st century in most (87%) cases. C3 achieves only the 2 °C target (67% probability) and achieves a global net-zero target in 30% of cases.

Table 1
Compatibility of climate categories with the climate goal and greenhouse gas neutrality target of the Paris Agreement. Source: adjusted from Table SPM.2 in IPCC (2022b).

Characteristics of scenarios	C1	C1a	C2	C3
Temperature increase (50% probability) at peak / in 2100	1.6 °C / 1.3 °C	1.6 °C / 1.2 °C	1.7 °C / 1.4 °C	1.7 °C / 1.6 °C
Likelihood of staying below 2 °C throughout the century	90% (86%–98%)	90% (85%–98%)	82% (71%–95%)	76% (68%–91%)
Median timing of achieving global net-zero GHGs (% net-zero pathways)	2095–2100 (52%)	2070–2075 (100%)	2070–2075 (87%)	Not reached (30%)
Median timing of achieving global net-zero CO_2*	2050–2055	2050–2055	2055–2060	2070–2075

** Although achieving net-zero CO_2 is not mentioned the Paris Agreement, it was added for the sake of completeness.*

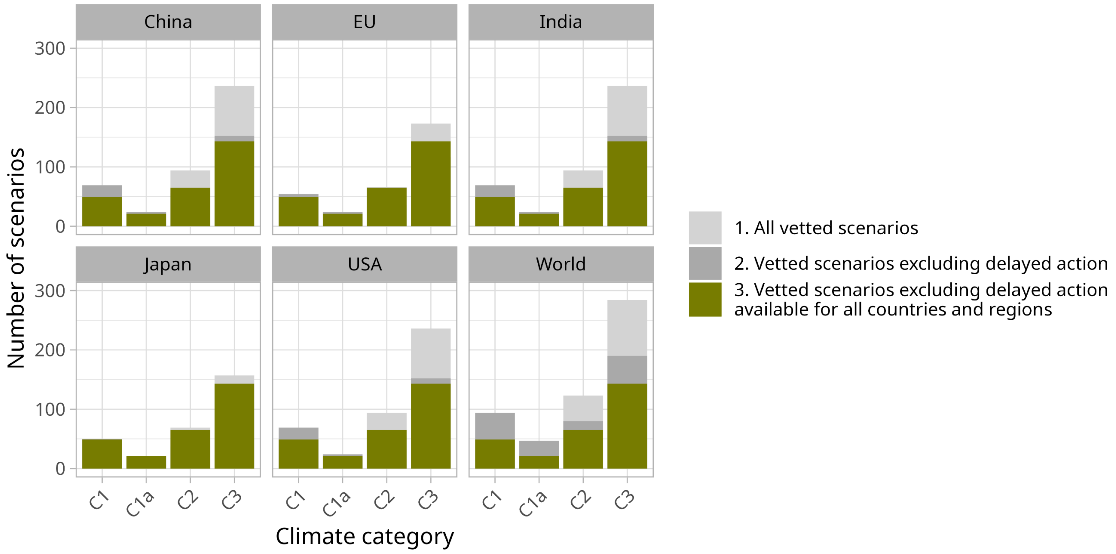
The selection of scenarios based on climate categories was narrowed further by three restrictions. Firstly, only 'historically vetted' scenarios are selected. This means that such scenarios only show a small deviation from the historical trend. Secondly, we focused on long-term least-cost pathways starting from 2020 and consistent with keeping the warming below a certain temperature limit (1.5 °C or 2 °C). Therefore, scenarios that represent delayed action and assume non-least-cost pathways until 2030 were excluded from our selection[1]. This resulted in different numbers of scenarios per country. To allow comparison between countries and regions, the final selection only included scenarios that were available on all countries and regions. Figure 1 shows the effect of the restrictions on the number of selected scenarios. The effect is minor for the European Union and Japan, and larger for China, the United States, India and especially the world. In general, excluding the scenarios that represent delayed action had the most effect. For the world, selecting only the scenarios available on all regions had a large effect as well, because a relatively large number of scenarios was available only on the world as a whole.

2.2 Regional downscaling

The models in the final selection involve various definitions of regions. For some models, the modelled regions containing China or EU-27 include other countries as well. For example, in three selected models, the region 'Europe' covers the EU-27 plus the United Kingdom and several other countries, while in another model this region covers the EU-27 plus the United Kingdom but without Croatia. To estimate the emission pathway of the selected country or region using the emission pathway of a similar region modelled by the IAM, we used two scaling methods: simple linear scaling using a fraction based on countries' national inventory data, and a more advanced method based on van Vuuren et al. (2007), which is based on CO_2 emission intensities. The latter method is used when the GHG emission levels of the selected country or region are lower than 95% of GHG emissions of the modelled region. Appendix A contains a more detailed description of the downscaling methods.

[1] Scenarios with delayed action were excluded (labelled with policy category P3: 'globally coordinate climate policies with delayed action' (i.e., from 2030 onwards or after 2030).

Figure 1
Numbers of scenarios per climate category and per selected country or region and the world after each selection step: 1) all historically vetted scenarios; 2) additionally selected scenarios representing only immediate global action; and 3) additionally selected common scenarios that are available only on all countries and regions.



2.3 Harmonisation to emission inventory data

Historical emissions officially reported by countries to the UNFCCC (UNFCCC, 2023a) generally differ from those used by IAMs (Rogelj et al., 2016). Especially substantial are differences in land-use emissions, because of conceptual differences in how global models and national greenhouse gas inventory data (NGHGIs) define 'anthropogenic' CO_2 fluxes from land use, simplified and/or incomplete representation of forest management in global models and inaccurate and/or incomplete estimation of LULUCF fluxes in NGHGIs (Grassi et al., 2018). For the harmonisation of LULUCF CO_2 emissions, we used an offset method based on Grassi et al. (2021) and converging to 2100 to harmonise the emission pathways of countries and regions to the latest NGHGI data. For the other GHG emissions, we used the offset method based on convergence as proposed by Rogelj et al. (2011). More specifically, we harmonised model emissions with the inventory emissions in a country or region from 2015 onwards, and converged the absolute difference (for LULUCF CO_2) or relative difference (for other GHG emissions) between the two in 2015 linearly to 0 by 2100. For the harmonisation of global emission pathways, we used data from Grassi et al. (2022); (Gütschow et al., 2021) on LULUCF CO_2, data from EDGAR (Olivier & Peters, 2020) on emissions from international aviation and shipping, and data from PRIMAP (Gütschow et al., 2021) on other GHG emissions. For other countries or regions, we used emissions reported to the UNFCCC (UNFCCC, 2023a). As a large part of the difference between the UNFCCC and other emission inventories is caused by the definition of LUC emissions, it is in principle possible to convert between these definitions if it is done consistently, i.e. changing both the anthropogenic and natural flows. Hence, the harmonisation does not lead to a change in temperature.

3 Results

This section presents the greenhouse gas emission reduction levels and greenhouse gas emission budgets over the 2030–2050 period that are consistent with the Paris Agreement's climate goal, for five major emitting countries or regions (China, the EU-27, India, Japan and the United States) and the world as a whole. The IAMs covered are AIM, GCAM, GEM-E3, IMAGE, POLES, and REMIND. Appendix B contains an overview of the number of selected scenarios per model and various characteristics of each selection.

Section 3 presents the emission pathways and the resulting indicators (i.e. emission reductions, greenhouse gas and CO_2 emission budgets and net-zero target years) based on default settings, including LULUCF emissions. Section 4 focuses on the robustness of the results by exploring the impact of including LULUCF emissions and the impact of equity principles.

3.1 Impact of modification on pathways and reductions

We applied two modifications to the regional emission pathways from the various models, i.e.: (i) regional downscaling, which combines linear and advanced downscaling, and (ii) harmonisation of emissions using national inventory data. Figure 2 shows the impact of these two modifications on the regional emission pathways for the selected countries for category C1. For the EU-27, both regional downscaling and harmonisation are shown to result in lower projected emission levels and a reduction in the range of emission corridors. We found a similar impact for the other countries, although regional downscaling had a lower effect: quite a few models cover India, China, the United States and Japan as their model regions. Harmonisation resulted in lower emissions as well, mainly due to differences between model data and inventory data for LULUCF emissions (Grassi et al., 2017; Grassi et al., 2018). The effect of harmonisation proved particularly significant for India, given the large range of emissions across models in 2015. The effects of modifications on emission pathways for climate categories C1a, C2 and C3 were similar to the effects of modifications on scenarios of category C1 (Appendix C, Figures C.1–C.3).

Figure 3 illustrates the impact of regional downscaling and harmonisation on the projected reductions by 2040, relative to 2015 levels, for climate category C1. The reductions were calculated by dividing the difference between 2040 GHG emissions and 2015 GHG emissions by 2015 GHG emissions. The figure shows that regional downscaling has a limited effect on the projected reduction levels. The impact of harmonisation on 2040 reduction targets differs across individual countries or regions. For the EU-27, Japan, the United States and the world it results in an (in some cases very minor) increase in the median reduction estimate and 10th–90th percentiles. For China, harmonisation causes a minor decrease in the median reduction estimate, while the 10th and 90th percentiles stay approximately the same. For India, it results in a decrease in the median and 10th percentile, and an increase in the 90th percentile. Figure C.4 in Appendix C shows the projected reduction by 2040 for the other climate categories. Most figures show similar effects of the modification steps on projected reduction levels.

Figure 2
Cost-effective GHG emission pathways for the selected major emitting countries and regions, as well as the world, resulting from each modification step for category C1: (0) No modified pathways for various model-dependent regions, (1) regional downscaling of the pathways from the model regions to the selected countries, and (2) harmonisation of pathways of the countries and the world with national inventory emission data. The black dashed line represents the median of the scenarios.

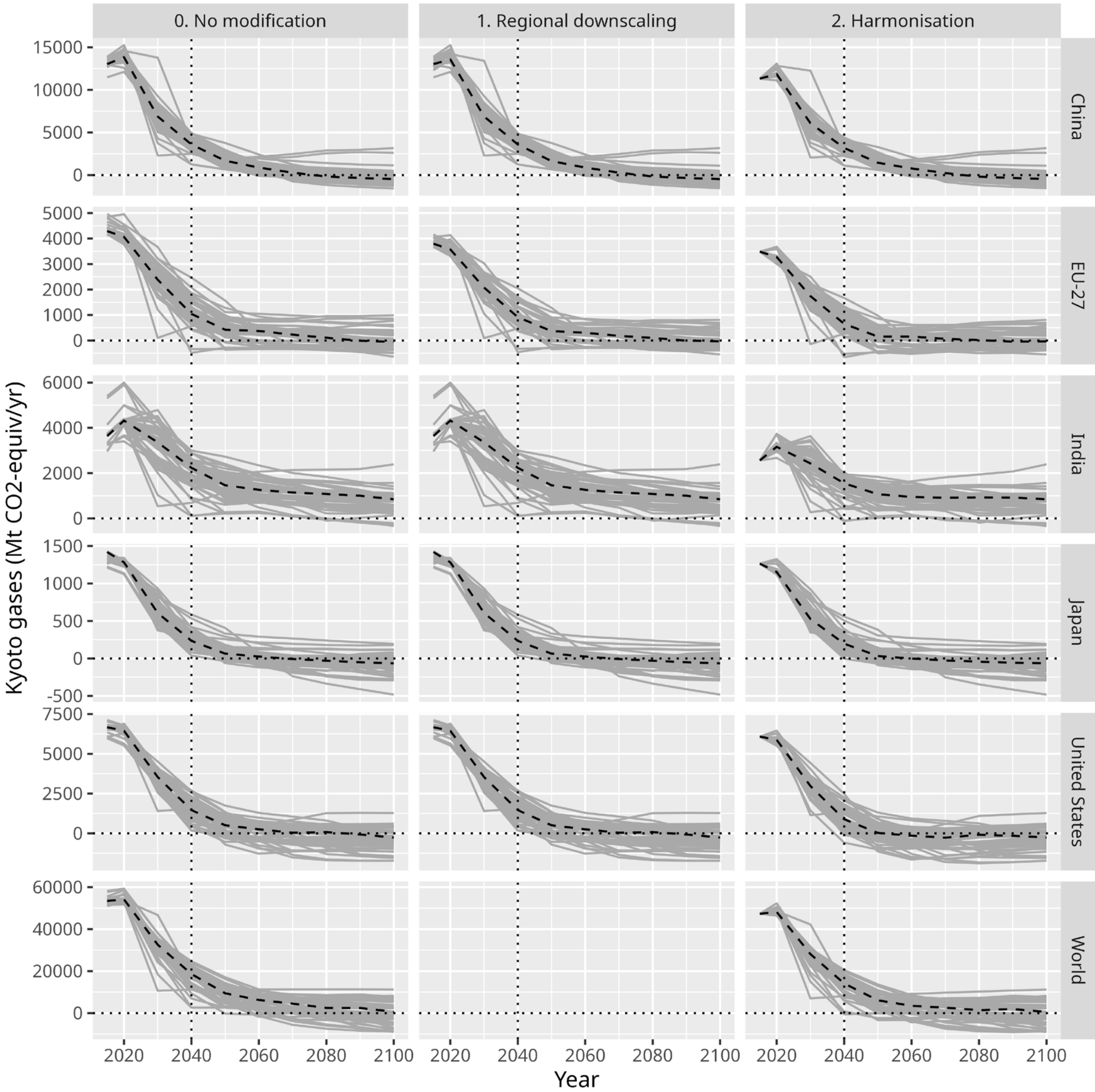
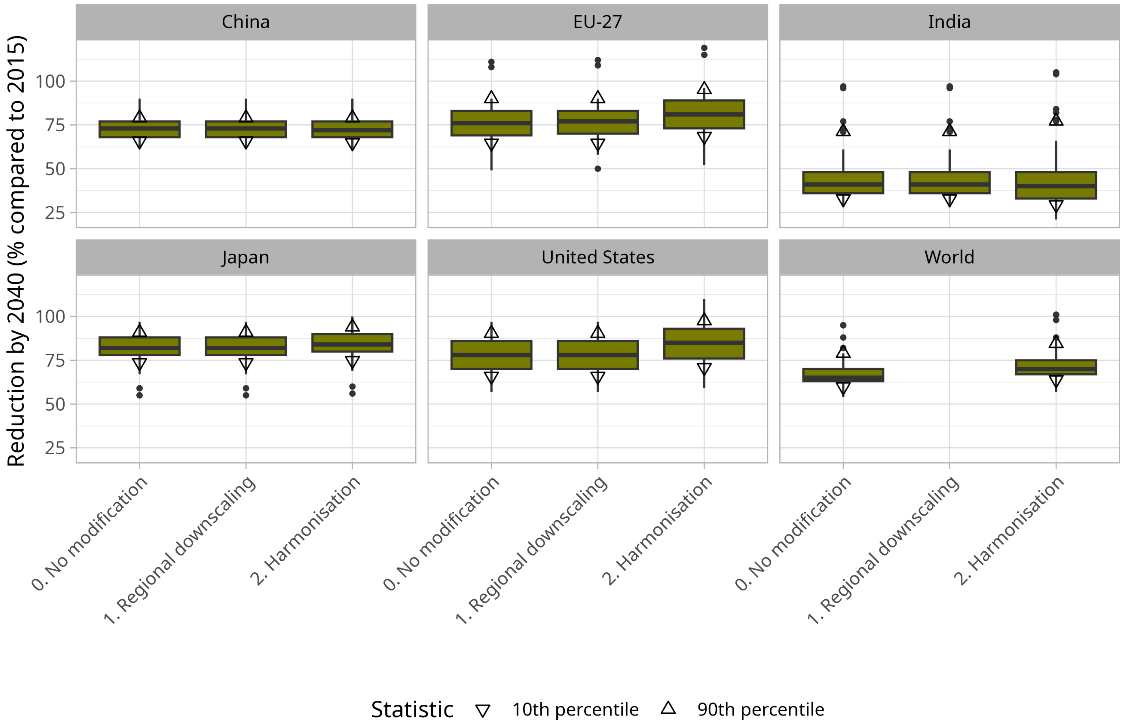


Figure 3
Projected cost-effective reductions by 2040 compared to 2015 levels for China, the EU-27, India, Japan and the United States, and the world, per modification step for category C1. The boxes of the boxplots show the median estimate, the 25th to 75th percentiles ranges. The whiskers of the boxplots represent values until 1.5 times the inter-quartile range. The black dots represent outliers outside of this range. The triangles represent the 10th and 90th percentiles. The modification steps shown are (1) No modification pathways for various model-dependent regions, (2) regional linear and advanced downscaling of the pathways, (3) the harmonisation of the pathways with the national inventory GHG emission data.



3.2 Reductions by 2040

Figure 4 and Table 2 show the resulting reductions by 2040, relative to 2015 levels, per country or region and per climate category. To keep global warming to 1.5 °C with a limited overshoot (climate category C1 of the IPCC AR6), the median projected reductions by 2040 for the EU-27, Japan and the United States should be 81%–85%, relative to 2015 levels, for China this should be 72%, for the world as a whole 70%, and for India 40%. To keep it at or below 2 °C (C3), the median projected reductions by 2040 would need to be 61%–69%, relative to 2015 levels, for the EU-27, Japan and the United States, 54% for China, 48% for the world, and 11% for India.

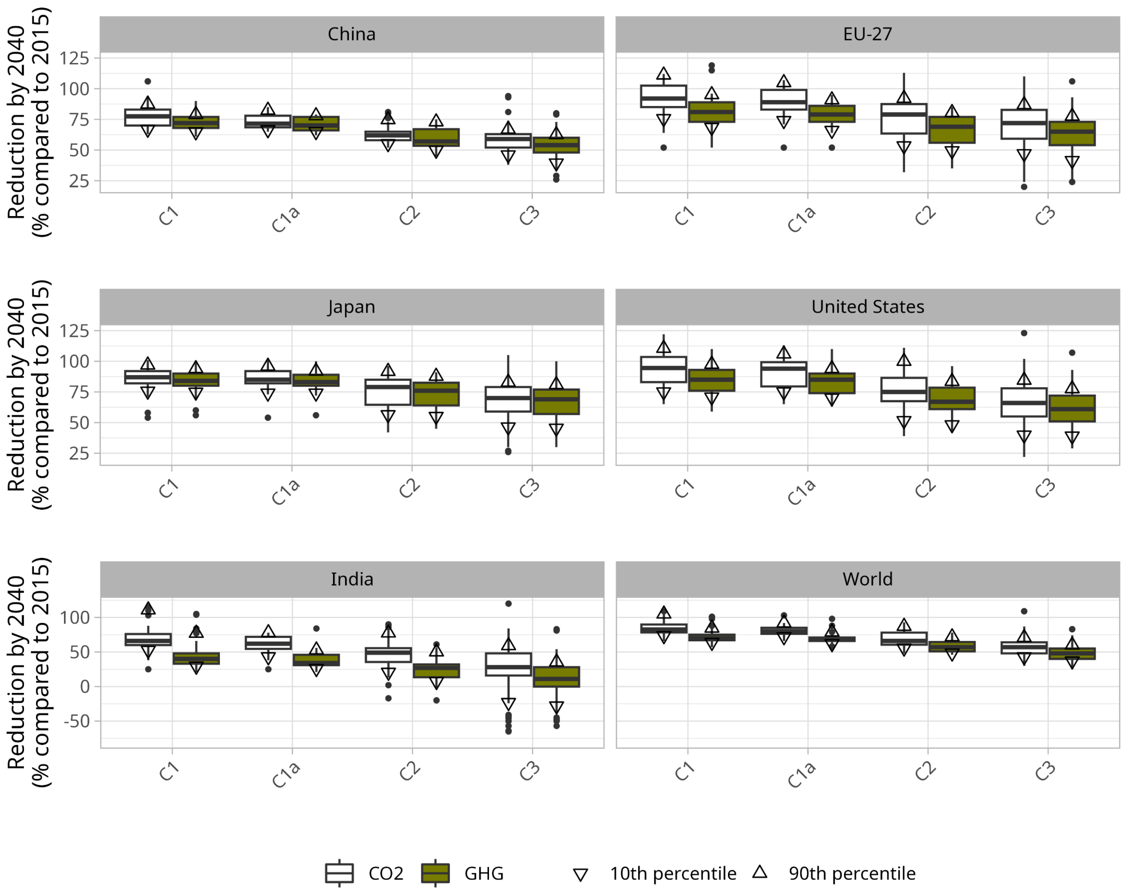
High-income countries (as defined by The World Bank (2023)) Japan, the EU-27, and the United States would achieve slightly higher reductions by 2040 compared to China (upper middle-income country). These high-income countries and China all have higher reduction levels by 2040 compared to India (lower middle-income country). The results also indicate that the median of projected reductions for the EU-27, Japan, the United States and China, is higher than the global median reduction estimate across all climate categories. However, the median of projected reductions for India are lower compared to the global median. Differences in projected reductions are mostly due to reduction potentials and projected emission growth, as a result of population and income growth. For India, the growth in both population and income is high compared to other regions, leading to lower reductions.

Figure 4 and Table 2 also indicate that there is an increase of about 15 to 30 percentage points in the mean reductions for all countries when moving from the C3 to the C1 category. For instance, China's mean reduction in 2040 increases from 54% to 72% (relative to 2015 levels).

When comparing the reductions relative to 2015 with those relative to 1990, countries/regions that have experienced a decline in emissions since 1990, such as the EU, show an increase in reductions (median of 86% for C1). Countries with a substantial increase in emissions, such as China, show lower reductions (median of 3% for C1).

Finally, note that the ranges of projected reductions are large, i.e., that the level of uncertainty in mitigation requirements is high. The largest 10th to 90th percentile range is 64 percentage point for India under category C3. The smallest is 13 percentage point for China under C1a.

Figure 4
Projected cost-effective reductions by 2040 compared to 2015 levels for China, the EU-27, India, Japan, the United States and the world per category, based on regionally scaled and harmonised emission pathways (including net GHG emissions from land use). The boxes of the boxplots show the median, the 25th to 75th percentile ranges. The whiskers of the boxplots represent values until 1.5 times the inter-quartile range. The black dots represent outliers outside of this range*. The triangles represent the 10th and 90th percentiles. Note that the figures for India and the world have a different scaling on the y-axis.



*For readability purposes, a single outlier for India in C3 around value -150 was removed from this visualisation

Table 2
GHG reductions in %, by 2040, compared to 2015 levels (upper table) and 1990 levels (lower table), for the major emitting countries and regions and the world as a whole for the various climate categories. Values represent the median estimates and the 10th to 90th percentile ranges. Table D.1 contains reductions by 2030, 2040 and 2050 compared to 2015, 2005 and 1990 levels.

Below 2015 levels:

Category	GHG/CO_2	Statistic	China	EU27	India	Japan	USA	World
C1	GHG	Median	72	81	40	84	85	70
		(range)	65–79	68–95	29–77	75–94	71–98	64–85
	CO_2	Median	78	93	68	87	95	83
		(range)	67–88	76–111	52–111	76–97	75–111	74–105
C1a	GHG	Median	70	79	34	83	85	68
		(range)	65–78	66–91	26–53	74–92	70–94	62–79
	CO_2	Median	72	89	62	85	95	80
		(range)	66–82	74–105	43–78	74–96	75–106	72–92
C2	GHG	Median	57	69	27	76	67	57
		(range)	50–73	49–81	7–50	55–88	48–84	48–72
	CO_2	Median	62	79	49	79	75	66
		(range)	55–75	53–92	21–78	56–92	52–100	56–87
C3	GHG	Median	54	65	11	69	61	48
		(range)	39–63	41–78	-28–36	45–81	39–78	37–60
	CO_2	Median	59	72	28	70	66	57
		(range)	46–67	47–87	-23–59	46–83	40–85	43–71

Below 1990 levels:

Category	GHG/CO_2	Statistic	China	EU27	India	Japan	USA
C1	GHG	Median	3	86	-33	84	84
		(range)	-23–26	76–96	-55–50	74–93	69–97
	CO_2	Median	3	95	5	86	94
		(range)	-41–46	82–109	-41–131	74–97	73–112
C1a	GHG	Median	-4	84	-44	82	84
		(range)	-23–23	74–93	-62– -4	73–91	68–93
	CO_2	Median	-22	92	-12	84	94
		(range)	-43–26	80–104	-68–34	72–96	72–107
C2	GHG	Median	-49	77	-60	74	65
		(range)	-74–6	62–86	-103– -9	53–87	44–83
	CO_2	Median	-63	84	-50	78	72
		(range)	-93– -9	65–94	-134–33	53–91	46–100
C3	GHG	Median	-59	74	-96	68	58
		(range)	-109– -29	56–83	-181– -41	43–80	33–76
	CO_2	Median	-77	79	-112	68	62
		(range)	-133–-43	60–90	-264– -21	43–82	34–83

3.3 Reduction pathways

We compared projected 2030 GHG emission reductions according to the selected cost-optimal scenarios to NDC reduction targets for that year, based on the results presented in Table 3. These results show that the NDC reduction targets of the EU-27 and United States are most in line with median reductions of cost-optimal pathways to achieving the 1.5 °C climate target.

The updated NDC of China is aimed at reducing CO_2 intensity levels (emissions per unit of GDP) by 65% from 2005 levels, by 2030, non-fossil share (around 25%) by 2030 and a peaking of CO_2 emissions before 2030 (den Elzen et al., 2022; Nascimento et al., 2022). Based on multiple national and global studies, the UNEP Emissions Gap Report (2022) finds projected emissions for the NDC target of -100% (-120– -70%) below 2005 levels. This is below the 10th–90th percentile range of cost-optimal emission reduction levels by 2030 for any climate category (Table 3). By 2035, the medians of projected cost-optimal CO_2 emission reductions for China are around 25–35 percentage points higher compared to projections by 2030. This increases to 40–60 percentage points by 2040, and 70–90 percentage points by 2050. In general, medians of projected least-cost GHG emission trajectories relative to 2015 are slightly more stringent for China than for the world. Especially for C1 and C3, the medians of levels for China show stronger reductions than the medians of global levels (Figure 5).

The EU-27 NDC reduction target of 55% below 1990 emission levels by 2030 is in between median emission reduction levels projected for C1/C1a and C2. The NDC target is at the lower side of the 10th–90th percentile range of emission reduction levels projected for category C1 and C1a and above the medians of cost-optimal emission reduction levels projected for category C2 and C3. Compared to projections by 2030, the medians of projected cost-optimal GHG emission reductions for the EU-27 are around 10–15 percentage points higher by 2035, around 25 percentage points higher by 2040 and 35–40 percentage points higher by 2050. Medians of projected least-cost GHG emission trajectories relative to 2015 for the EU-27 are more stringent than those for the world. The medians of GHG emission trajectories relative to 2015 for the EU-27 reduce more than the medians of global trajectories, especially before 2050 (Figure 5).

India submitted an updated NDC in August 2022, aiming to decrease GHG emissions intensity by 45% below 2005 levels and increase the share of non-fossil energy capacity in the power sector to 50%, both by 2030. This NDC corresponds to a greenhouse gas emission level of about 80% by 2030 above 2015 emission levels (based on Nascimento et al., 2022, which takes the updated NDC target into account). This is below the 10th–90th percentile range of cost-optimal emission reduction levels projected for any climate category. Medians of projected cost-optimal GHG emission reductions by 2035 are about 25–40 percentage points higher compared to medians of projected reductions by 2030. By 2040 and 2050, they are about 45–60 percentage points and 80–90 percentage points higher. Compared to medians of projected least-cost GHG emission trajectories relative to 2015 for the world, GHG emission trajectories for India are higher. This is mainly caused by a rise in emission levels before 2030.

In its NDC, Japan pledges a 46% reduction by 2030, from 2013 levels, including LULUCF credits, which amount to 47.7 $MtCO_2$ eq/year. Japan uses a gross-net approach, which means the target excludes LULUCF in its base year while it is included in the target year. This results in a maximum emission level of 807 Mt CO_2 eq/year including LULUCF by 2030, which implies a reduction of 36% compared to its 2015 emission level. This falls just below the 10th–90th percentile range of emission reduction levels projected for C1, and is on the slightly lower side of the 10th–90th percentile range of cost-optimal emission reduction levels projected for C2 and C3. Compared to the projected medians for 2030, the cost-optimal CO_2 reductions for Japan will be around 15–20 percentage points higher by 2035, 25–35 percentage points higher by 2040 and 40–50 percentage points higher by 2050. Projected medians of least-cost GHG emission trajectories relative to 2015 are slightly lower for Japan than for the world, mainly due to stronger reductions before 2040.

The US NDC reduction target of 50%–52%, below 2005 levels, by 2030 is close to the median of emission reduction levels for C1a, but is above those projected for categories C2 and C3, and just below those for category C1. The projected medians of cost-optimal GHG emission reductions by 2035 are about 10–20 percentage points higher compared to those by 2030. By 2040 and 2050, respectively, they are about 25–35 percentage points and 40–45 percentage points higher. Compared to projected medians of least-cost GHG emission trajectories relative to 2015 for the world, those for the United States are slightly lower.

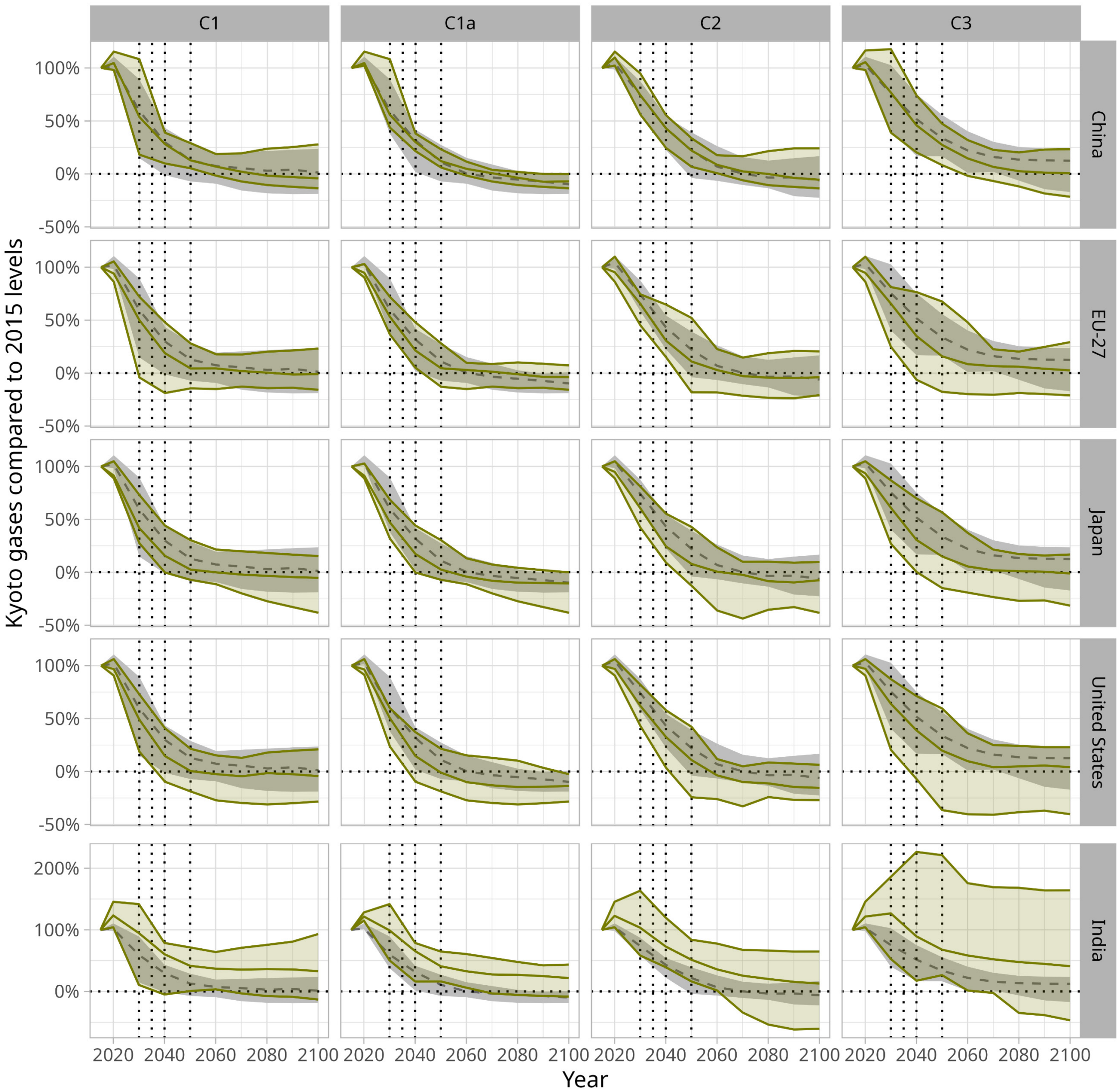
The results from this study align with those by den Elzen et al. (2022), who conclude that only the NDCs submitted by the EU-27 and United Kingdom, and the United States and Canada are in line with a cost-optimal pathway to achieving the 1.5 °C climate target. Their analysis is based on cost-optimal 2 °C and 1.5 °C scenarios developed with six integrated assessment models, based on van Soest, den Elzen, et al. (2021).

Note that the analysis of the regional distribution of reductions is based on the lowest possible costs, globally. When it comes to deriving reduction targets, as has been done for setting the reduction target of the NDC, such a perspective 'should be complemented with an assessment of feasible reductions at the national level, considerations of equity and national model results, among other things' (van Soest, den Elzen, et al., 2021). Section 4 contains a comparison of reductions based on least-cost scenarios and those based on equity principles.

Table 3
NDC reduction targets and least-cost emission reductions by 2030 in % for the major emitting countries and regions for different climate categories. Values represent the median estimates and the 10th to 90th percentile ranges. Table D.1 contains results including and excluding scenarios that are available for all countries or regions and reductions by 2030, 2035, 2040 and 2050 compared to 2015, 2005 and 1990 levels.

Country	NDC target 2030	GHG/ CO_2	Base year	Statistics	C1	C1a	C2	C3
China	-100	CO_2	2005	Median	18	12	-18	-25
				Range	0-41	2-24	-29--2	-47-4
EU-27	55	GHG	1990	Median	63	60	51	51
				Range	53-71	53-67	47-62	47-62
India	-80	GHG	2015	Median	5	1	-3	-27
				Range	-21-42	-24-23	-42-17	-48-25
Japan	36	GHG	2015	Median	58	53	40	39
				Range	39-68	45-67	25-53	20-55
United States	50–52	GHG	2005	Median	56	54	44	42
				Range	47-67	50-63	32-55	27-55

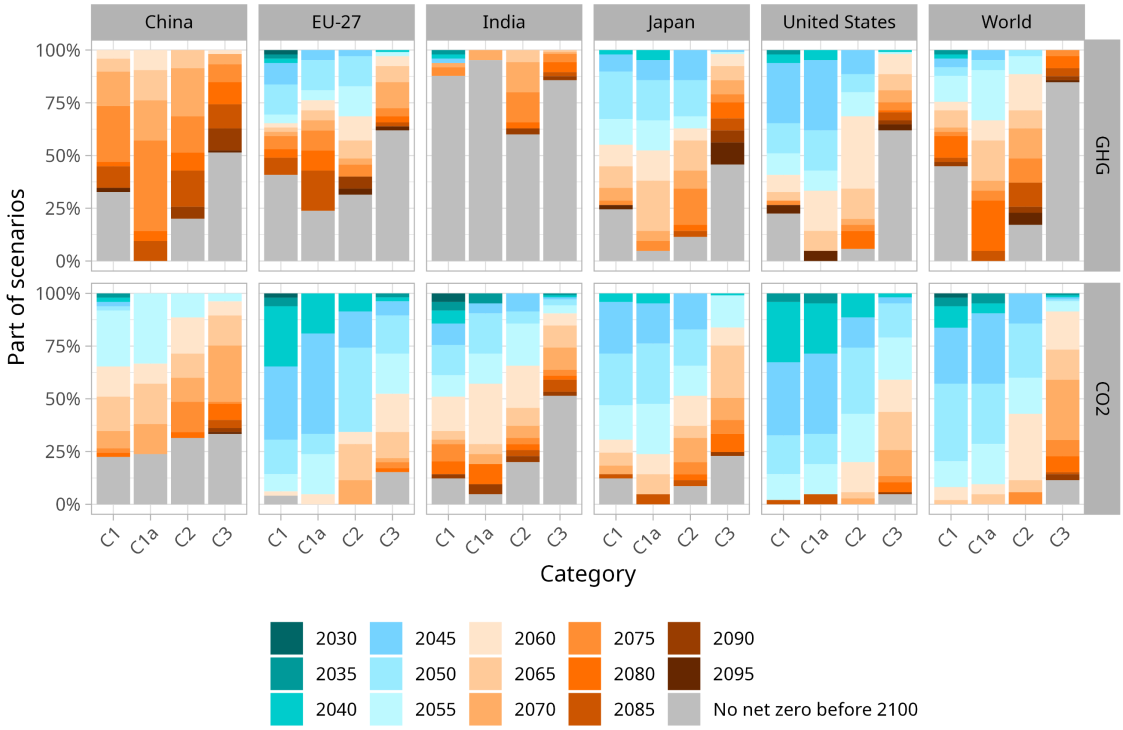
Figure 5
Ranges of cost-effective GHG emission pathways for the selected major emitting countries and regions, compared to the world (in grey). The line in the middle represents the median of the scenarios. Note that the figures for India have a different scaling on the y-axis.



3.4 Net-zero dates

Net-zero years are defined, in 5-year steps, as the first year that GHG emissions reach below net zero. Many scenarios do not reach net zero for a country or region before 2100. Within category C1a, the scenarios with the smallest and largest percentages of achieving net-zero GHG before 2100, are: 5% of scenarios for India and 100% of scenarios for China (Figure 6).

Figure 6
Cost-effective net-zero years for GHG and CO_2 for China, the EU-27, India, Japan, the United States and the world, per category.



Across all categories, the United States is projected to reach net-zero GHG emissions the earliest, with the year 2055 for C1 (based on the median pathways, see Figure 2 or Figure 5 for a visualisation of this median). India is projected to do so the latest, not reaching net-zero before 2100 for any category. The influence of moving from category C1 to category C3, on a net-zero year, differs per country or region. For the EU-27, this is at least 15 years, for China at least 25 years and for the United States at least 45 years (for C3, the median pathway for these countries or regions does not reach net zero before 2100). For Japan, the difference between the median GHG net-zero year for C1 and for C3 is 35 years. For India and the world, both C1 and C3 do not show median net-zero years before 2100. The difference between GHG and CO_2 median pathways for net-zero years differs per region and category, as well. When both reach net zero before 2100, net-zero CO_2 is reached 5–40 years earlier than net-zero GHG.

All countries or regions in our selection have net-zero targets. The EU, Japan and the United States aim to reach net-zero GHG emissions by 2050 (Climate Analytics & NewClimate Institute, 2023), which is before or in line with the projected median net-zero dates for all categories. The Chinese target of CO_2 neutrality before 2060 is also before or in line with projected median net-zero years for all categories. For India, it is not certain whether the net-zero target of 2070 is for GHG or CO_2. If it refers to GHG emissions, it is in line with scenarios that project neutrality relatively early, as most scenarios do not project GHG neutrality before 2100 for India. If the target is for CO_2, the target year is 10 years after the median net-zero years for C1, C1a and C2, and before the median year for C3.

Table 4
Cost-effective net-zero years for the median of GHG and CO_2 emission pathways for China, the EU-27, India, Japan, the United States and the world per category. An empty cell indicates that net zero will not be reached before 2100.

Category	GHG/CO_2	China	EU-27	India	Japan	United States	World
C1	GHG	2075	2085		2060	2055	
C1a	GHG	2075	2080		2060	2050	2065
C2	GHG	2080	2065		2065	2060	2075
C3	GHG				2095		
C1	CO_2	2060	2045	2060	2050	2045	2050
C1a	CO_2	2060	2045	2060	2050	2045	2050
C2	CO_2	2065	2050	2060	2060	2050	2055
C3	CO_2	2070	2060		2070	2060	2070
Difference CO_2-GHG							
C1		-15	-40		-10	-10	
C1a		-15	-35		-10	-5	-15
C2		-15	-15		-5	-10	-20
C3					-25		

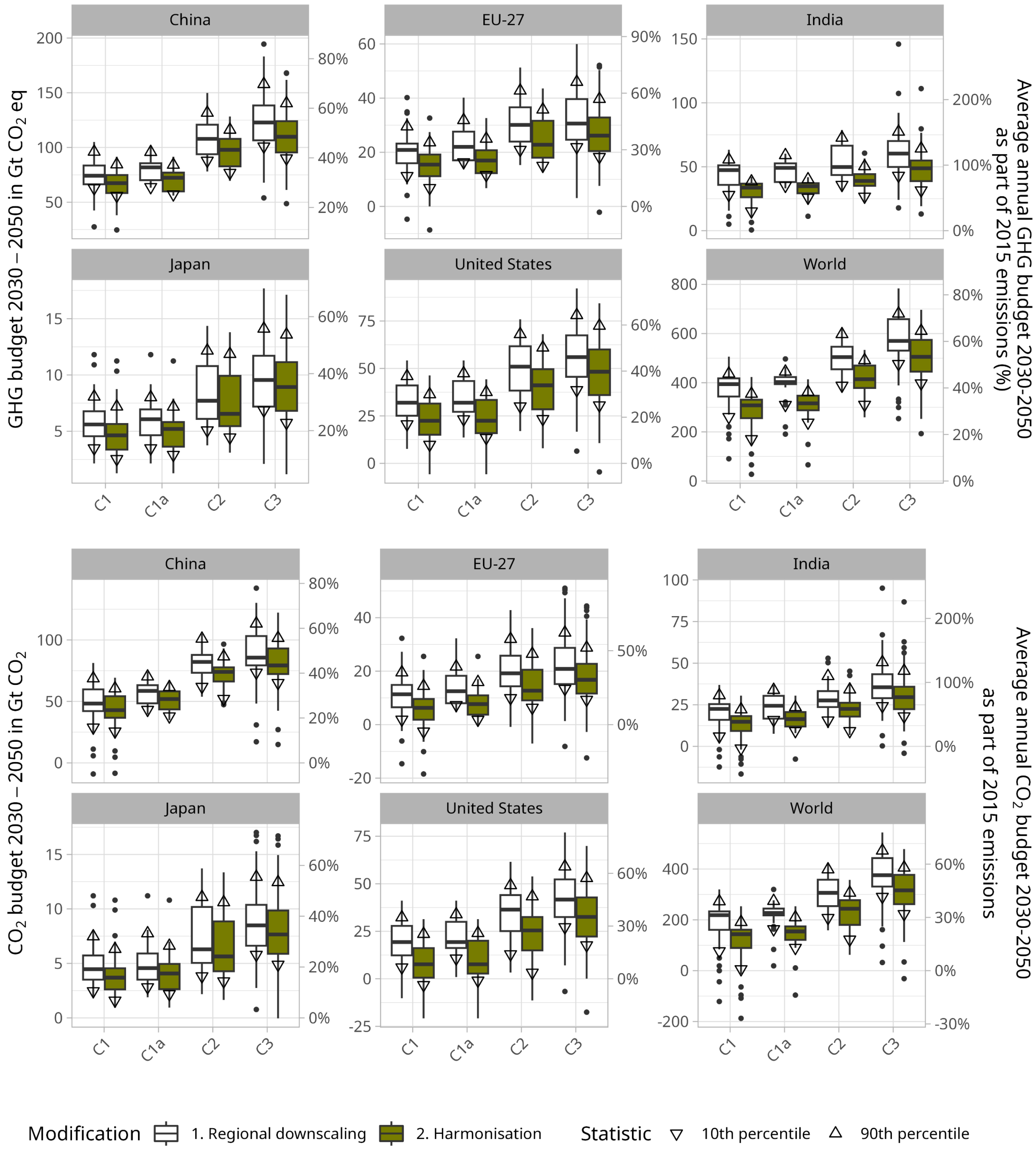
3.5 GHG and CO_2 budgets

Figure 7 shows the GHG budgets for the 2030–2050 period (i.e. including the year 2030 and excluding 2050 itself) per country or region and per climate category. To give an example, for the EU-27, the total harmonised GHG budget for the 2030–2050 period for category C1 is about 15 $GtCO_2$ eq (10th–90th percentiles of 7–24), which is about 4.4 (2.0–6.8) times the 2015 levels. This implies that there is an average annual budget of 22% (10%–34%) of 2015 levels, which is close to the reduction estimates presented in section 3.2. The average annual GHG budgets based on median budgets for the other countries and regions also align with the reduction estimates in Section 3.2 (Table D.3).

Note that the figure also presents budgets based on scenarios that are only regionally scaled and not harmonised. For instance, for the EU-27, medians based on unharmonised budgets are about 15% to 35% higher compared to those based on harmonised budgets. We present both budgets based on harmonised and non-harmonised scenarios, because harmonised pathways can be compared with scenarios based on national inventory data (which are used for national communication), while budgets based on non-harmonised pathways are used for climate calculations.

The CO_2 budgets for the 2030–2050 period (i.e. including the year 2030 and excluding 2050 itself) per country or region and per climate category show a trend that is similar to that of the GHG budgets (Figure 7). For instance, for the EU-27, the median value of CO_2 budgets is 41% (C1) to 64% (C3) of the median value of GHG budgets. Regional median harmonised CO_2 budgets range from 34% (C1a for the United States) to 86% (C2 for Japan) of the median harmonised GHG budget. Within CO_2 budgets, median values based on harmonised budgets for the EU-27 are 55% (C1) to 80% (C3) of median values based on unharmonised budgets. Tables D.2 and D.3 present all budgets and average annual budgets based on harmonised and non-harmonised pathways for GHG and CO_2.

Figure 7
GHG and CO_2 budgets for the 2030–2050 period for China, the EU-27, India, Japan and the United States, as well as the world, for the various climate categories, based on regionally scaled emission pathways and regionally scaled and harmonised emission pathways. On the left y-axis, the budget is shown in Gt CO_2 equivalent. The right y-axis shows the average annual budget relative to 2015 emission levels in %, which is calculated by dividing the GHG budget by the 2015 emission level of the country or region and dividing that by 20 years. The boxes of the boxplots show the median, the 25th to 75th percentile range. The whiskers of the boxplots represent values up to 1.5 times the inter-quartile range. The black dots represent outliers. The triangles represent the 10th and 90th percentiles.

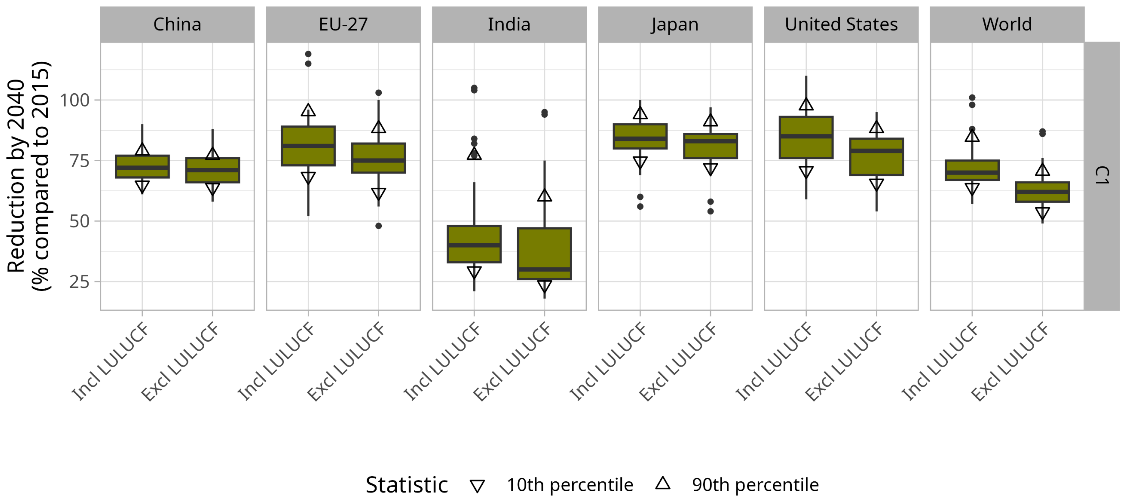


4 Discussion: robustness of results

4.1 Impact of including or excluding LULUCF emissions

By default, LULUCF emissions are included in the results of this study. There are large uncertainties in LULUCF emissions for reasons that are explained in section 2.3. Due to this, LULUCF emissions are sometimes excluded from studies (Robiou du Pont et al., 2017). Including or excluding LULUCF emissions can have a noteworthy effect on GHG reductions by 2040. For all selected countries or regions, reductions are lower when excluding LULUCF (Figure 8 for C1, Appendix E.1 shows similar results for the other categories). For most countries and regions, differences in median values range between 3 and 11 percentage points (EU-27, India, United States, the world). These differences are smaller for China and Japan (1-3 percentage points).

Figure 8
Projected GHG reductions by 2040 from 2015 for China, the EU27, India, Japan, the United States and world per category, based on pathways that are regionally scaled and harmonised including LULUCF (default) and excluding LULUCF for climate category C1. The boxes of the boxplots show the median, the 25th percentiles and the 75th percentiles. The whiskers of the boxplots represent values until 1.5 times the inter-quartile range. The black dots represent outliers outside of this range. The triangles represent the 10th and 90th percentiles. Table E.1 shows results for the other categories.



4.2 Emission reductions based on equity considerations

The IPCC AR6 scenario database contains least-cost scenarios only. This means that achieving climate targets and the regional distribution of mitigation actions are based on the lowest possible costs, globally. However, the United Nations Framework Convention on Climate Change (UNFCCC) also refers to other important considerations, including equity principles, which can be important in the regional distribution of reduction efforts: under the UNFCCC all countries agreed to ‘common but differentiated responsibilities and respective capabilities' in mitigating climate change (UNFCCC, 1992). Different ways to operationalise this aspect in global climate policy have been proposed, such as adjustment of reduction targets, international emission trading instruments, international climate finance or support to capacity building or to technology transfer (Pachauri et al., 2022; Rajamani et al., 2021; Rogelj, 2019; van Soest, den Elzen et al., 2021).

There is no commonly agreed methodology to define equity considerations, which is a topic of research (e.g. Robiou du Pont et al., 2017; van den Berg et al., 2020). Several studies have analysed future greenhouse gas emission allowances and reduction targets for different regions based on a wide range of effort-sharing approaches that account for equity principles (for an overview, see Höhne et al., 2014). The IPCC AR5 report (Clarke et al., 2015) groups the existing effort-sharing approaches into six categories, using specific definitions of equity principles and distributive justice, including responsibility, capability, equality, responsibility-capability-need, equal cumulative per capita emissions and staged approaches, based on Höhne et al. (2014). Some approaches may lead to extreme outcomes, which might be impossible to achieve through domestic emission reductions. This can be overcome by allowing emission trading between countries.

The sections above present regional emission pathways that were all based on this cost-effective approach of allocating the reductions across countries. The main focus of this section is to present initial allocations of emission reduction targets from a wide range of effort-sharing approaches based on the IPCC AR5 effort-sharing categories, for achieving the climate targets of 2 °C and 1.5 °C of the Paris Agreement, without an assessment of the feasibility and costs of these approaches. Höhne et al. (2014) assess more than 40 studies and conclude that the reduction targets resulting from the effort-sharing approaches are often largely determined by the way the equity principle is implemented. They further find that the distribution of emission reduction targets can differ significantly between such approaches, depending on the effort-sharing approach used, the concentration stabilisation level and shape of the global emission pathway. The study by Robiou du Pont et al. (2017) is one of the few studies that present countries' reduction targets for 2030, 2040 and 2050, for a wide range of effort-sharing approaches to achieving the 2 °C and 1.5 °C objectives. It also presents the timing of net-zero greenhouse gas emission allowances. More specifically, Robiou du Pont et al. (2017) identify global cost-optimal mitigation scenarios consistent with the Paris Agreement goal and allocate their emissions dynamically to countries according to five equity approaches, each representing one of the IPCC AR5 equity categories, i.e.: capability to pay, equality with the dynamic Equal Per Capita (EPC) approach, responsibility-capability-need with the Greenhouse Development Rights (GDR), historical responsibility with the Equal Cumulative Per Capita and national circumstances regarding current emission levels with the grandfathering approach (also named Constant Emissions Ratio).

We excluded the grandfathered and GDR results from this study, and focused only on the effort-sharing approaches based on the three key equity principles, i.e. capability, equality and responsibility. We justified this exclusion on the basis of the following arguments of Robiou du Pont and Meinshausen (2018), who argue that a grandfathering approach, a status-quo approach that allocates equal emission mitigation rates to all countries, is considered unfair (Peters et al., 2015), which is also further supported by the literature (e.g., Dooley et al., 2021). The grandfathering approach is supported only implicitly by some countries through their pledges. The GDR approach was developed to distribute mitigation efforts among global citizens whose income exceeds a specific threshold (Baer et al., 2008). Although the GDR method is very complex and incorporates more indicators compared to other existing approaches in the literature, its dependence on hypothetical business-as-usual emissions and Gini projections, which lack widespread consensus, gives rise to a significant sensitivity that cannot be easily solved. Furthermore, the equity principles of responsibility and capacity, which form the basis of the GDR approach, are represented by the equal cumulative per capita (CPC) and capability (CAP) approaches, respectively.

Equity approaches lead to an increase of around 10 percentage points for the EU-27, 10-20 percentage points for the United States and around 15 percentage points for China when comparing the 10th and 90th percentiles of least-cost scenarios for C1 to minimal and maximal values based on equity principles. For India, this leads to decreases of around 15 to 85 percentage points. Note that Robiou du Pont et al. use global least-cost pathways based on cost-optimal reductions starting from 2010, and report for EU-28 instead of EU-27. The influence of scaling towards EU-27 and cost-optimal reductions starting from 2015 would be minor.

Table 5
GHG Reduction by 2040, compared to 2015 levels, for the major emitting countries and regions and the world, for the various climate categories for the effort-sharing calculations based on the three equity principles (capability to pay (CAP), equality (Equal Per Capita or EPC) and responsibility (Equal Cumulative Per Capita or CPC). Based on Robiou du Pont et al. (2017), equity calculations exclude LULUCF emissions. For comparison, the results from the least-cost approaches are also presented. Appendix F contains the reductions based on equity principles relative to 1990 levels.

Equity outcomes (excl. LULUCF emissions):

Temperature increase 2100	Principle	China	EU-28	India	Japan	United States	World
1.5 °C	CAP	94	96	44	95	98	60
	EPC	78	74	-4	80	87	60
	CPC	92	93	-49	96	97	60
2 °C	CAP	90	91	2	92	97	29
	EPC	61	54	-83	66	78	29
	CPC	75	70	-108	74	74	29

Least-cost outcomes (excl. LULUCF emissions):

Category	Statistics	China	EU-27	India	Japan	United States	World
C1 (1.5 °C)	Median (range)	71 (64–77)	75 (62–88)	30 (24–60)	83 (72–91)	79 (66–88)	62 (54–71)
C1a (1.5 °C)	Median (range)	69 (64–76)	73 (61–82)	28 (21–49)	80 (72–89)	79 (66–86)	59 (53–69)
C2 (1.5 °C)	Median (range)	55 (46–71)	62 (46–72)	22 (2–45)	74 (55–83)	61 (44–74)	46 (38–59)
C3 (2 °C)	Median (range)	52 (37–61)	60 (38–72)	8 (-24–32)	66 (45–79)	57 (36–70)	41 (28–53)

4.3 Comparing projected EU 2040 reductions and GHG budgets of the European Scientific Advisory Board on Climate Change and this study

The European Scientific Advisory Board on Climate Change (Advisory Board) provided an advice on a 2040 emission reduction target and an EU greenhouse gas emission budget for the 2030–2050 period (European Scientific Advisory Board on Climate Change, 2023). They conducted a comprehensive assessment on pathways compatible with a maximum temperature increase of 1.5°C with limited overshoot. Their findings highlight the urgent need for ambitious actions to address climate change. Their report also outlines possible pathways and related overarching policy choices to achieve the necessary emission reductions. Our report also provides a 2040 emissions reduction target and an EU GHG emissions budget for the same period, based on the IPCC AR6 scenario database.

Table 6 contains a comparison of the two studies, which shows multiple differences. First of all, our study only uses scenarios available in the AR6 scenario database, while the Advisory Board also included other scenarios. The two studies subsequently apply different selection criteria to these scenarios, and although the ways in which the scenarios are processed in the studies are similar, there are differences in the realisation of the processing steps. The resulting emission reductions and budgets in our study have a larger spread than the Advisory Board results, but the Advisory Board results are within this spread.

Another important difference in scenario selection between the studies, is the consistency with the EU's emission reduction objectives for 2030 and 2050. Table 7 shows the emission reductions and budgets that would result if such a criterium had been applied in our study, as well. The table shows that selecting only the scenarios that would reach net-zero by 2050 (representing 39% to 63% of all scenarios for C1, depending on the definition of net-zero) would result in a more narrow range of emission reductions and budgets which is also close to the Advisory Board results.

Table 6
Comparison between the study by the European Scientific Advisory Board on Climate Change and **our** current study

	European Scientific Advisory Board on Climate Change	This study
Scenarios	Over 1,000 EU emission pathways were analysed, including scenarios from the AR6 scenario database and additional scenarios. From those, **36 scenarios** were selected that: passed quality control and vetting were consistent with limiting global warming to 1.5 °C with no or only limited overshoot; 1. were consistent with the EU's emission reduction objectives for 2030 and 2050; 2. did not display characteristics exceeding one or more thresholds that would raise geophysical or sociocultural feasibility concerns, such as geological storage capacity or the rate of decline in final energy demand 3. Within this selection, **7 scenarios** were found within environmental risk levels, and **5 scenarios** were found within environmental risk levels and technological deployment challenge levels.	Over 1,000 EU emission pathways were analysed from the AR6 scenario database, and identified. Form those, **54 scenarios** were selected that: 1. passed quality control and vetting 2. assumed direct action 3. were consistent with limiting global warming to 1.5 °C with no or only limited overshoot (climate category C1) 4. were available for all selected countries and regions
Processing	Scaling towards EU-27 by using a rescaling algorithm based on a range of criteria including historical data, planned capacities, and nationally-available resources. Harmonisation up to 2019: • CO_2 emissions from energy: offset converging to 2050 • LULUCF emissions: constant offset • Total non-CO_2 emissions: offset converging up to 2050	Scaling to the EU-27 by using both a linear method and an advanced method based on emission intensity. Harmonisation up to 2015: • GHG emissions: relative offset converging up to 2100 • LULUCF emissions: absolute offset converging up to 2100
The EU 2040 climate target	The Advisory Board found net emission reductions of 88%–92% by 2040, relative to 1990 levels, based on the final 5 scenarios, and concluded that reductions of up to 95% would be possible if technological challenges could be overcome. Based on this, the Board recommends net emissions reductions of **90%–95%** by 2040, relative to 1990 levels.	*Full set of IPCC scenarios:* We found projected net emission reductions of **86% [76%–96%]** by 2040, relative to 1990 levels, for climate category C1 based on least-costs considerations. *Focus on IPCC scenarios that reach net-zero:* When we selected scenario that reach net-zero, we found projected net emission reductions of **92% [84%–97%]** by 2040, relative to 1990 levels, for climate category C1 based on least-costs considerations.

		Equity: Based on calculations by Robiou du Pont et al. (2017) regarding equity considerations, we found that net emission reduction for the interpretations of three key equity principles, i.e. capability, equality and responsibility are: **97%**, **79%** and **95%** by 2040, relative to 1990 levels (excluding LULUCF). We exclude LULUCF emissions given the uncertainty and different approaches towards LULUCF (Robiou du Pont et al., 2017).
EU's GHG budget for the 2030–2050 period	The net emission reductions of 88%–92% correspond to a budget of 14–16 Gt CO_2 eq. 95% corresponds with 11 Gt CO_2 eq. The Board recommends a budget of **11–14 Gt CO_2 eq**.	*Full set of IPCC scenarios:* **15 [7–24] Gt CO_2 eq** for climate category C1 based on least-costs considerations. *Focus on IPCC scenarios that reach net-zero:* **12 [7–17] Gt CO_2 eq** for climate category C1, based on least-costs considerations.

Table 7
Impact of EU27 C1 results based on all selected scenarios and on those reaching net-zero in 2050. Two different definitions of net-zero were applied: GHG emissions below or equal to 300 Mt CO_2eq by 2050 and GHG emissions below or equal to 150 Mt CO_2eq by 2050.

Net-zero	**No. of scenarios**	**Result type**	**Median**	**Range**
No net zero	54	Emission reduction (%) Budget 2030-2050 (Mt CO_2eq)	86 15	76–96 7–24
Net zero defined as <= 300 Mt CO_2eq	34	Emission reduction (%) Budget 2030-2050 (Mt CO_2eq)	90 12	82–97 7–18
Net zero defined as <= 150 Mt CO_2eq	21	Emission reduction (%) Budget 2030-2050 (Mt CO_2eq)	92 12	84–97 7–17

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Appendices

Appendix A: Method for the selection of regional pathways

This Appendix contains an overview of the definitions of regions per model, the selected countries or regions for this study and which method is used to estimate the emission pathway of the selected country or region from the modelled region. It also contains a detailed description of the applied downscaling methods.

Table A.1 shows per model the model region and the modifications we did to scale to the selected region. Information about AIM/CGE, GCAM, GEM-E3, IMAGE, POLES, and REMIND was retrieved from respectively National Institute for Environmental Studies and Kyoto University (2020), Joint Global Change Research Institute (2022), Institute of Communication And Computer Systems (2016), PBL Netherlands Environmental Assessment Agency (PBL) (2020), Joint Research Centre - European Commission (2016), and Luderer et al. (2015).

Table A.1
Selected models, their regional coverage and modifications to estimate the emission pathway of the selected country or region.

Model	Selected country or region in this analysis	Coverage of model region	Modifications to downscale model region to selected country or region
AIM/CGE	EU-27	Europe: EU-28, Norway, Switzerland, Iceland, Bosnia Herzegovina, Servia, Montenegro, North Macedonia, Albania	Simple scaling to estimate the emission pathway of EU-28, advanced downscaling method to estimate emission pathway of EU-27
GCAM	EU-27	EU-28 without Croatia	Simple scaling to estimate the emission pathway of EU-28, advanced downscaling method to estimate emission pathway of EU-27
GEM-E3	EU-27	EU-28	Advanced downscaling method to estimate emission pathway of EU-27
IMAGE	EU-27	Europe: EU-28, Norway, Switzerland, Iceland, Bosnia Herzegovina, Servia, Montenegro, North Macedonia, Albania	Simple scaling to estimate the emission pathway of EU-28, advanced downscaling method to estimate emission pathway of EU-27
POLES	EU-27	EU-28	Advanced downscaling method to estimate emission pathway of EU-27
REMIND	EU-27	EU-28	Advanced downscaling method to estimate emission pathway of EU-27
AIM	China	China	

GCAM	China	China	
GEM-E3	China	China	
IMAGE	China	China, Mongolia	Simple scaling to estimate the emission pathway of China
POLES	China	China	
REMIND	China	China	
AIM	India	India	
GCAM	India	India	
GEM-E3	India	India	
IMAGE	India	India	
POLES	India	India	
REMIND	India	India	
AIM	Japan	Japan	
GCAM	Japan	Japan	
GEM-E3	Japan	Japan	
IMAGE	Japan	Japan	
POLES	Japan	Japan	
REMIND	Japan	Japan	
AIM	United States	United States	
GCAM	United States	United States	
GEM-E3	United States	United States	
IMAGE	United States	United States	
POLES	United States	United States	
REMIND	United States	United States	

Linear scaling was applied if the emissions of the selected country or region were strongly dominant in the modelled region. The method is described, for example, by van Vuuren et al. (2007) and assumes that the relative difference in emissions between the modelled region and the selected country or region will stay the same. In other words, that growth rates for these regions will be similar. Data on emissions in 2015 were used to determine the relative difference, as this is the most recent year for which emission data are available on all regions. National inventory data retrieved from UNFCCC (2023a) were used where possible. If the data were unavailable from UNFCCC, data from EDGAR (Olivier & Peters, 2020) and FAOSTAT (FAOSTAT, 2020) were used. The 2015 fraction was multiplied with model-region emissions for all future years.

If the GHG emissions of the selected country or region would be less than 95% of the GHG emissions of the modelled region, we used a more advanced downscaling method based on van Vuuren et al. (2007). The method of the advanced downscaling is applied on CO_2 emissions excluding LULUCF (land use, land-use change and forestry), and is for instance used to estimate EU-27 emission pathways from EU-28 emission pathways. For some models, these EU-28 emission pathways are a result of linear downscaling from regions slightly different from EU-28, as explained in the previous section. The idea of the method is that, while CO_2 emission intensities may differ between countries within the modelled region for historical years, the CO_2 emission intensity for those countries within the region are assumed to converge to the same level in 2100. In detail, the method entails the following: First, CO_2 emission intensity pathways are determined for the selected country or region and other countries within the available region (in the example, these are EU-27 and the United Kingdom). For each country or region, a constant annual linear growth rate ($CO_2I_{c;lgr}$) is determined starting from 2015 CO_2 emission intensity levels (national inventory data retrieved from UNFCCC (2023a) when possible, or else from EDGAR (Olivier & Peters, 2020) and FAOSTAT (2020)) ($CO_2I_{c;h;2015}$, $MtCO_2$ eq GDP^{-1}) and ending at the 2100 levels projected for the available region (e.g. EU-28) ($CO_2I_{m;2100}$).

$$CO_2I_{c;lgr} = \frac{CO_2I_{c;h;2015} - CO_2I_{m;2100}}{2100 - 2015}$$

For each year (y), the CO_2 emission intensity level is determined by multiplying the linear growth rate with the number of years between y and 2015, and adding this to 2015 levels.

$$CO_2I_{c;y} = CO_2I_{c;h;2015} + (y - 2015) * CO_2I_{c;lgr}$$

In order to determine CO_2 emission levels for the country ($CO_{2_{c;y}}$), the resulting CO_2 emission intensity values for the country or region are multiplied with its GDP projections derived from SSPs (Gidden et al., 2019).

$$CO_{2_{c;y}} = CO_2I_{c;y} * GDP_{SSP;y}$$

Finally, the CO_2 emission levels of each country or region are multiplied with a common scaling factor to ensure consistency between the summed CO_2 emission levels of the downscaled regions and the CO_2 emission level projected by the model for the whole region.

$$CO_{2_{c;y;consistent}} = \left(\frac{\sum CO_{2_{c;y}}}{CO_{2_{m;y}}}\right) * \ CO_{2_{c;y}}$$

For LULUCF CO_2 emissions and non-CO_2 emissions, we assume that they follow the original regional emission growth trend and apply a linear scaling factor.

Appendix B: Characteristics of scenario selection

The IAMs covered in the final selection of scenarios are AIM, GCAM, GEM-E3, IMAGE, POLES, and REMIND. Some characteristics are unequally represented: scenarios of specific models (e.g. REMIND) and specific research projects (e.g. ENGAGE) appear more often in the IPCC AR6 scenario database and in our selection than others, and almost all scenarios are based on socioeconomic pathway SSP2.The figures below contain an overview of the number of selected scenarios per model, research project, climate category (C1, C2, C3), assumed SSP and policy category.

Figure B.1
Number of scenarios in our selection per model (including version). The figure shows the final selection of scenarios: it includes all climate categories, and does not contain scenarios involving delayed action or scenarios that are not available for all countries and regions.

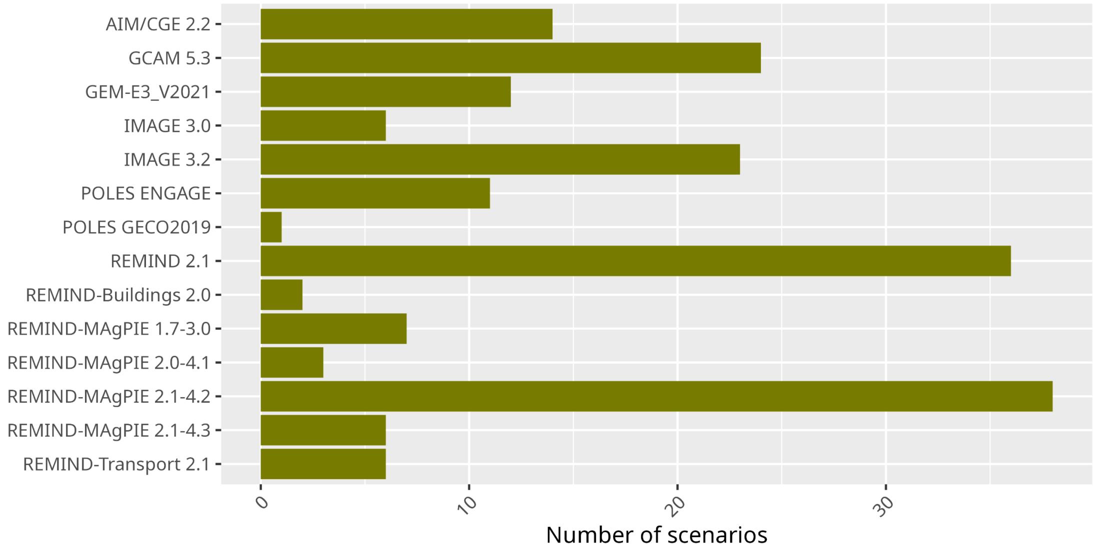


Figure B.2
Number of scenarios in our selection per climate category. The figure shows the final selection of scenarios. Therefore it does not contain scenarios involving delayed action or scenarios that are not available for all countries and regions.

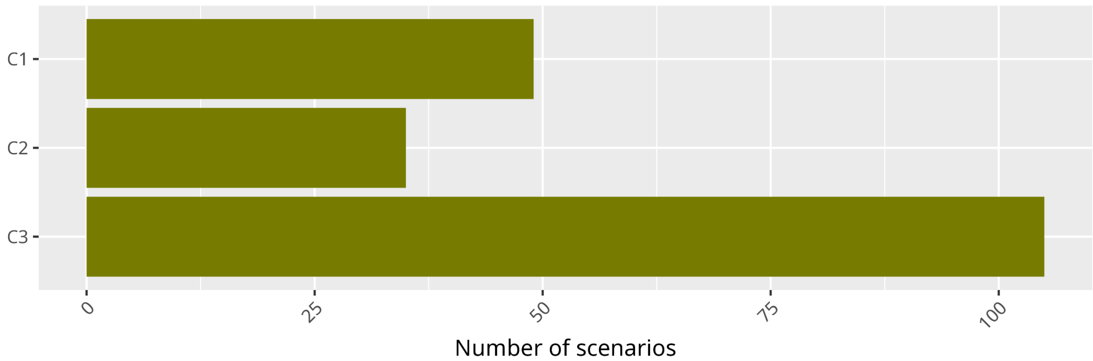


Figure B.3
Number of scenarios in our selection per study. The figure shows the final selection of scenarios: it includes all climate categories, and does not contain scenarios involving delayed action or scenarios that are not available for all countries and regions.

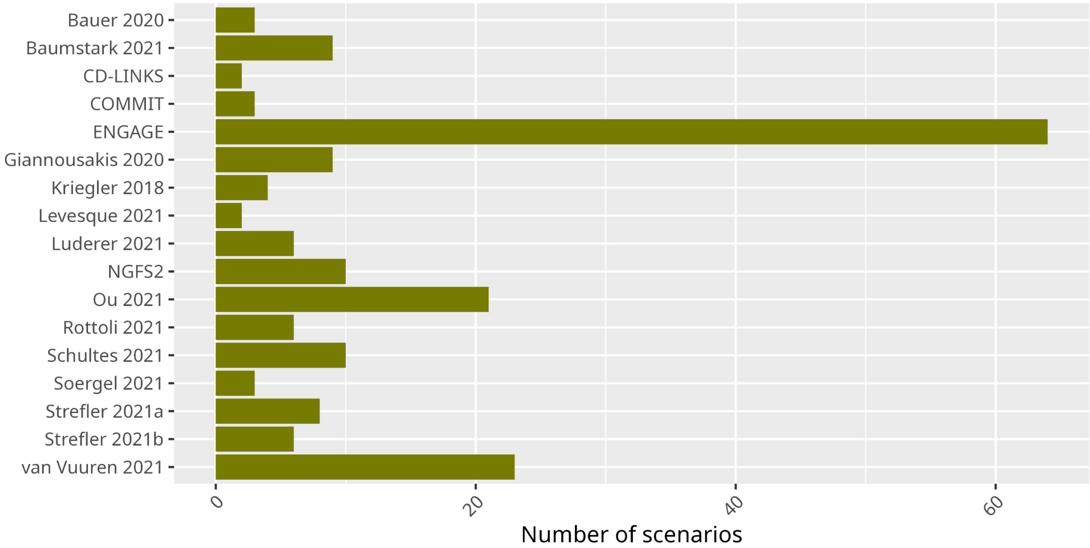


Figure B.4
Number of scenarios in our selection per SSP. The figure shows the final selection of scenarios: it includes all climate categories, and does not contain scenarios involving delayed action or scenarios that are not available for all countries and regions.

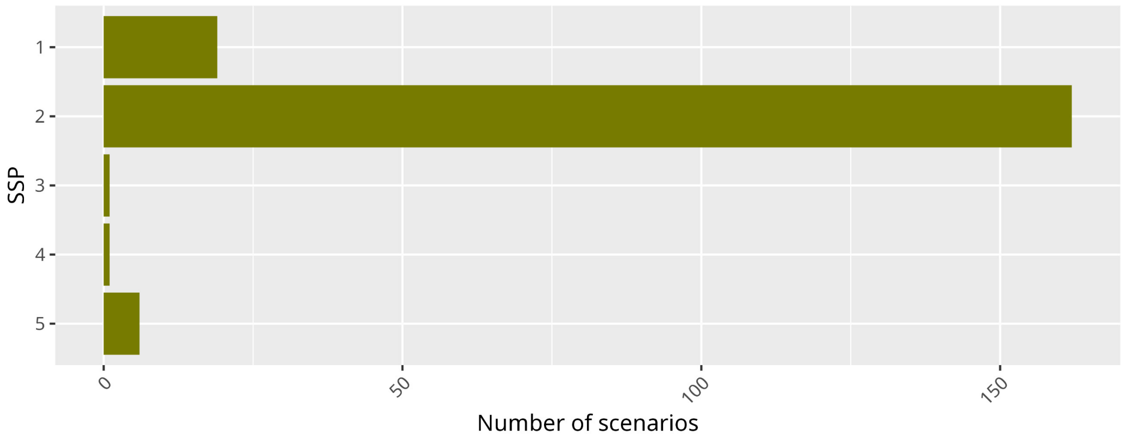
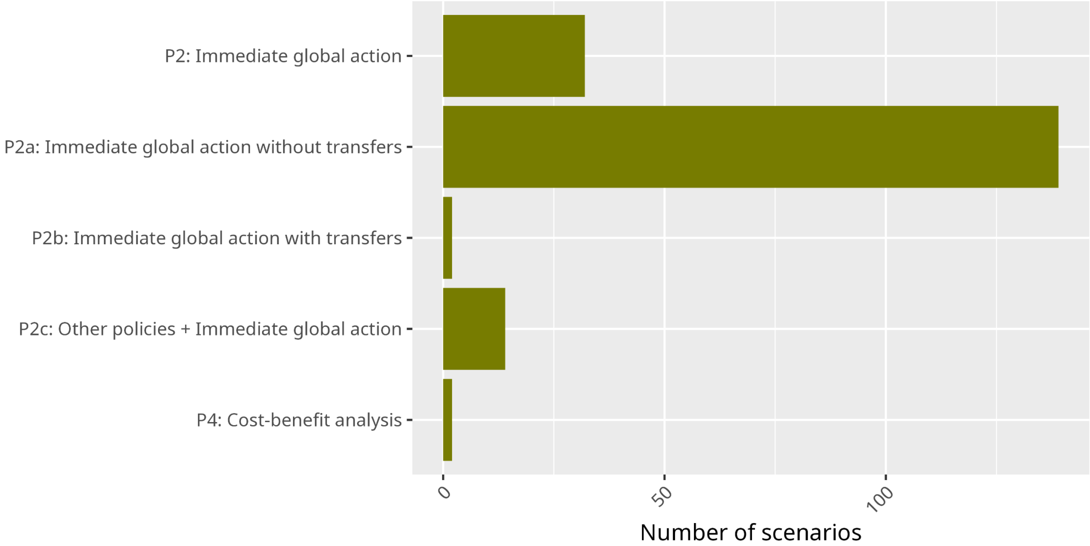


Figure B.5
Number of scenarios in our selection per policy category. The figure shows the final selection of scenarios: it includes all climate categories, and does not contain scenarios involving delayed action or scenarios that are not available for all countries and regions.



Appendix C: Effects of modification steps

Figure C.1
GHG emission pathways for the selected major regions emitting countries and regions, as well as the world, resulting from each modification step for category C1a. (0) No modified pathways for various model-dependent regions, (1) regional down-scaling of the pathways from the model regions to selected countries (e.g. EU-27), (2) harmonisation of the pathways of the countries and the world with national inventory emission data. The black dashed line represents the median of the scenarios.

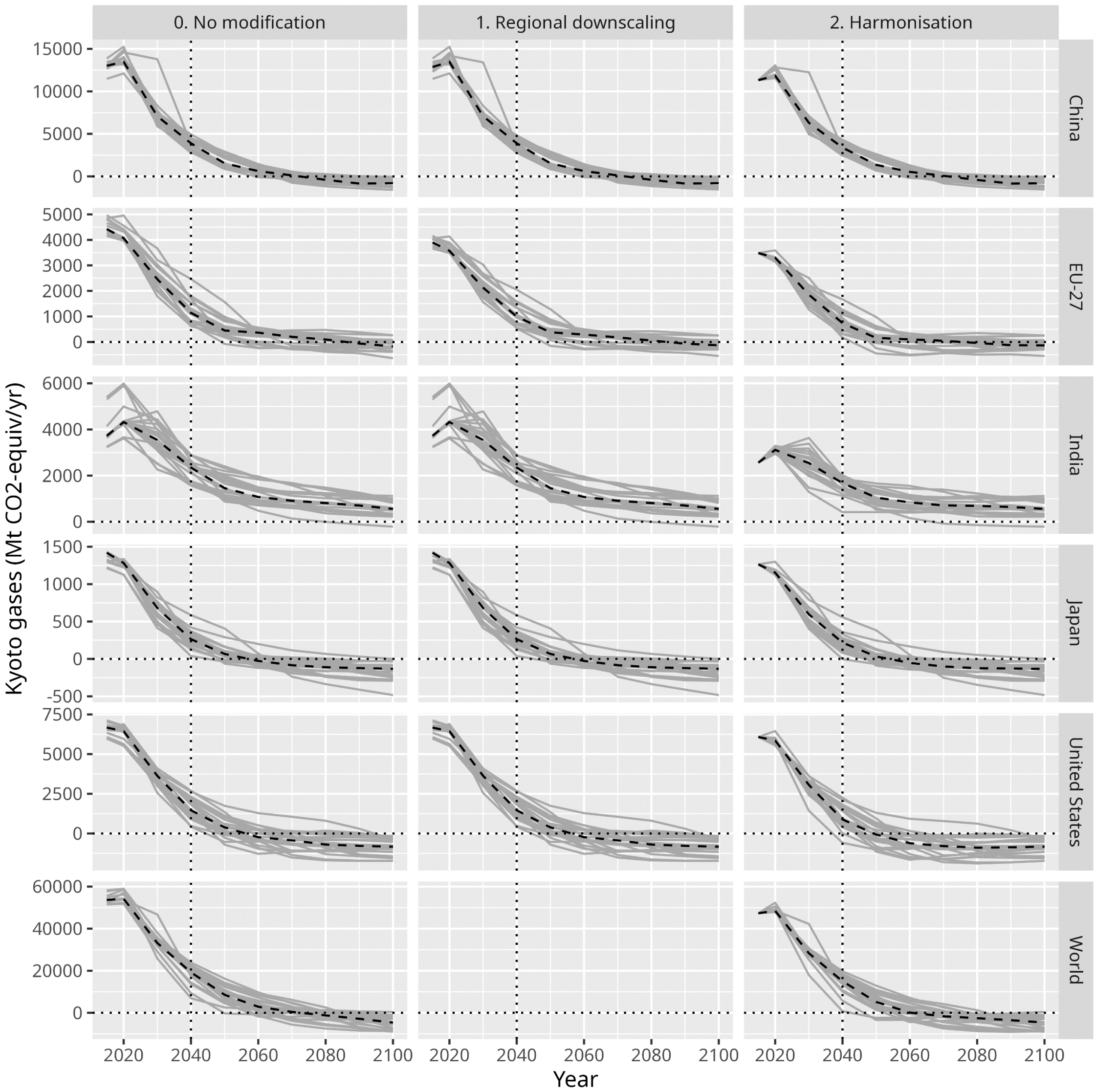


Figure C.2

GHG emission pathways for the selected major regions emitting countries and regions, as well as the world, resulting from each modification step for category C2. (0) No modified pathways for various model-dependent regions, (1) regional down-scaling of the pathways from the model regions to selected countries (e.g. EU-27), (2) harmonisation of the pathways of the countries and the world with national inventory emission data. The black dashed line represents the median of the scenarios.

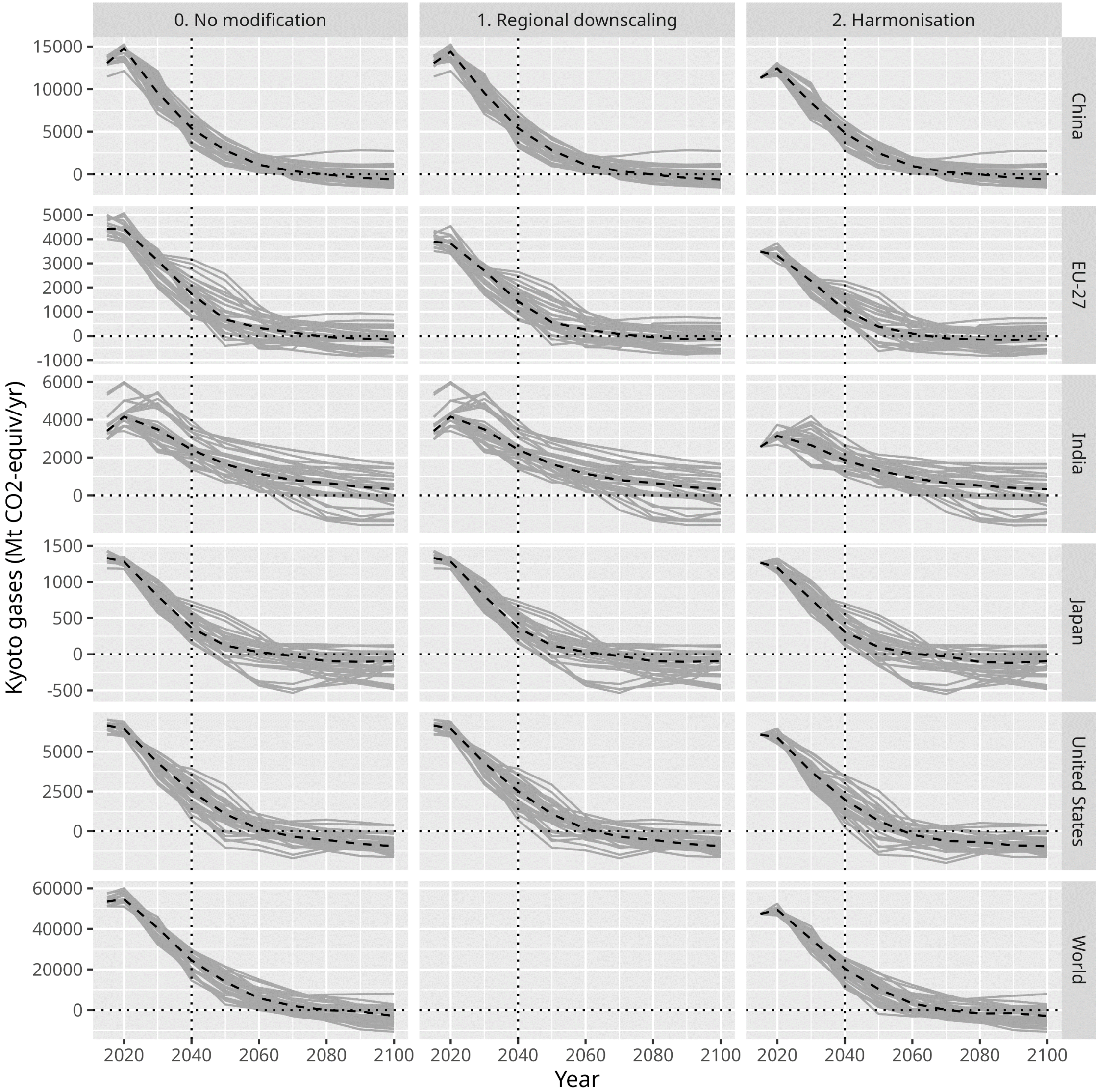


Figure C.3

GHG emission pathways for the selected major regions emitting countries and regions, as well as the world, resulting from each modification step for category C3. (0) No modified pathways for various model-dependent regions, (1) regional down-scaling of the pathways from the model regions to selected countries (e.g. EU-27), (2) harmonisation of the pathways of the countries and the world with national inventory emission data. The black dashed line represents the median of the scenarios.

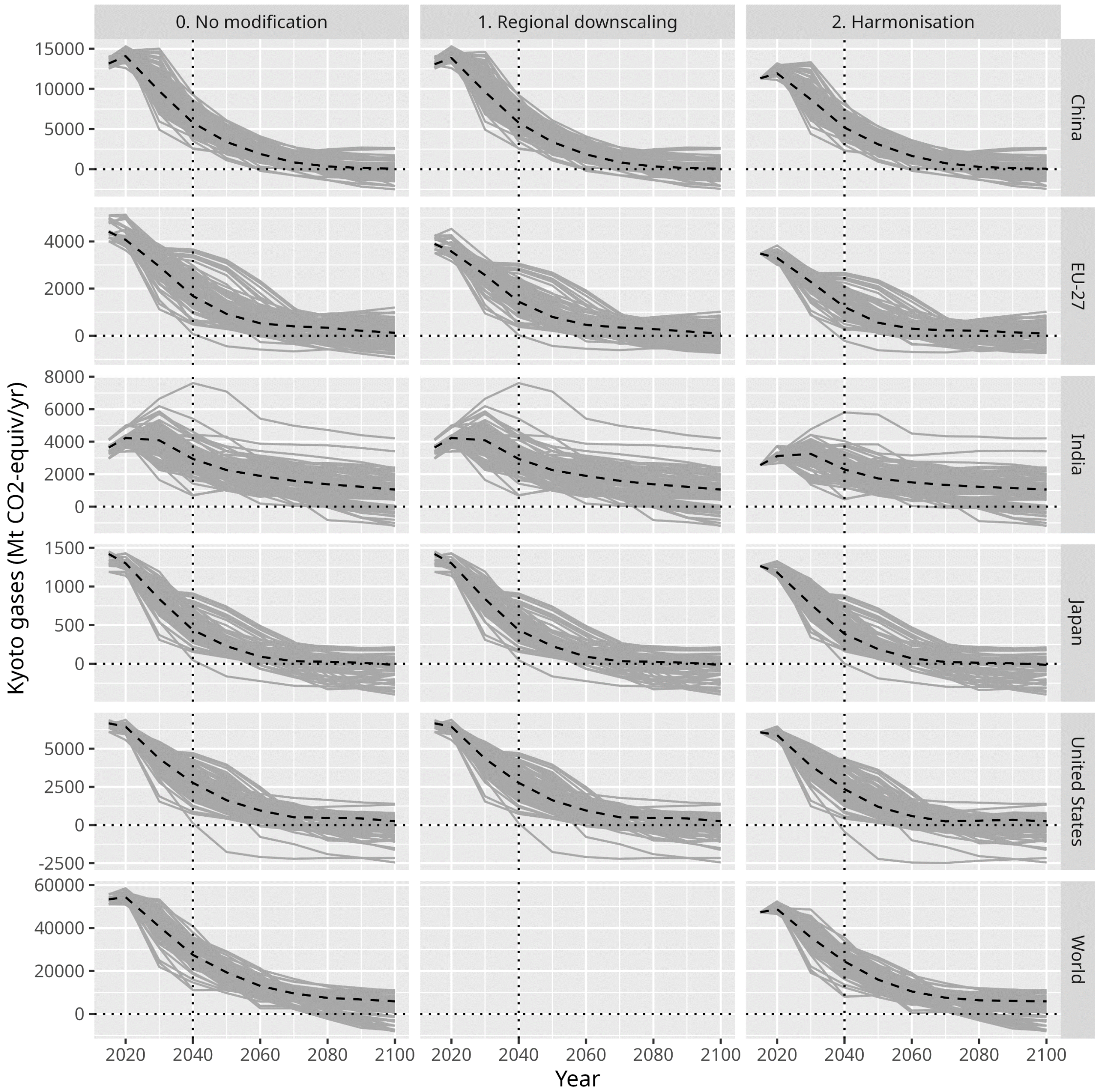
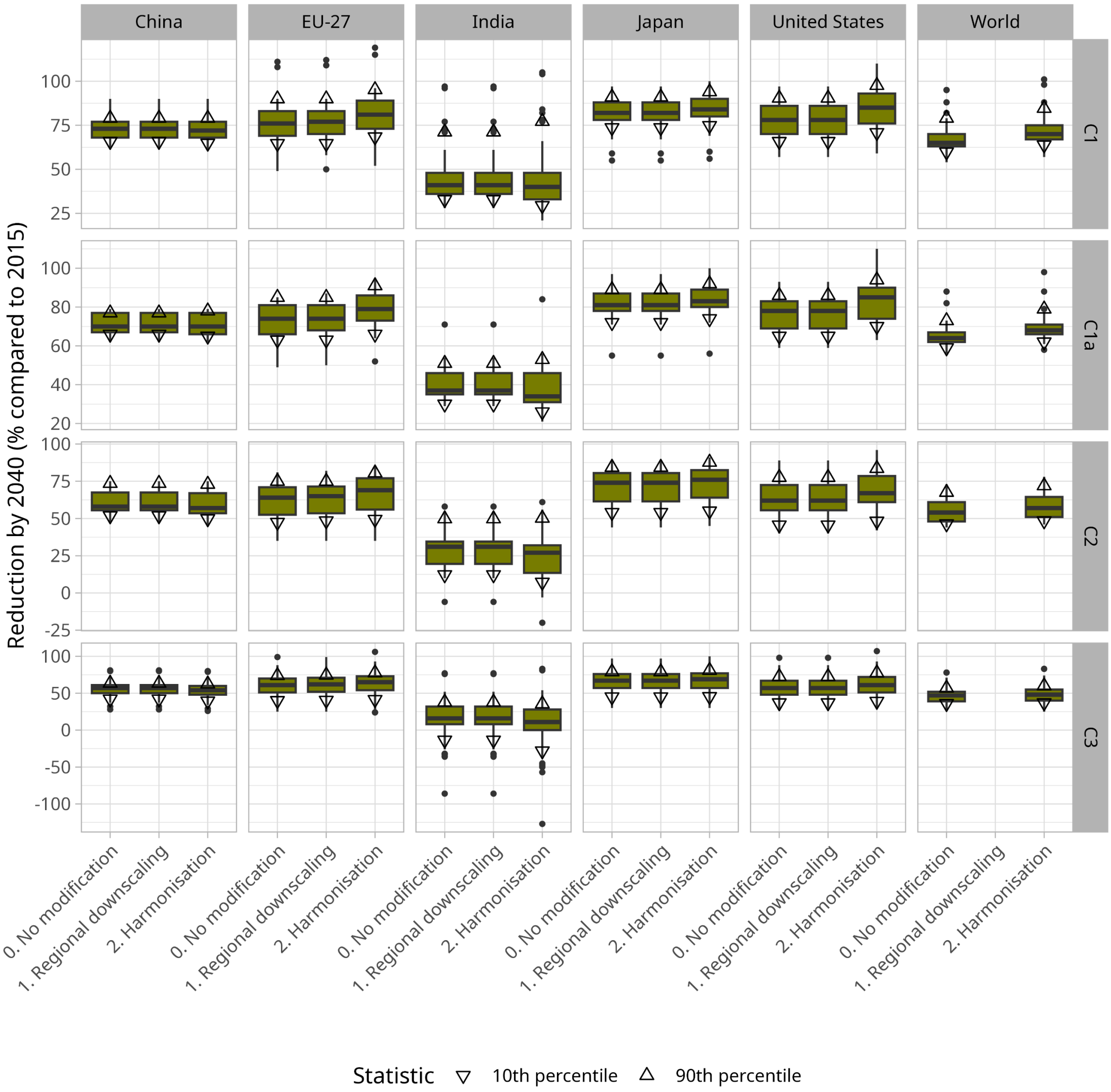


Figure C.4
Projected reductions by 2040 compared to 2015 levels for China, the EU-27, India, Japan and the United States, and the world, per modification step for all categories: (0) No modified pathways for various model-dependent regions, (1) regional downscaling of the pathways from the model regions to the selected countries, and (2) harmonisation of pathways of the countries and the world with national inventory emission data. The black dashed line represents the median of the scenarios.



Appendix D: Reductions, budgets and net-zero years

Table D.1
GHG reduction statistics in percentages, per category and per country or region for projected reductions in 2030, 2040 and 2050, calculated from 2015, 2005 and 1990. Numbers are based on harmonised scenarios.

Category	Year	Year compared to	Group	Statistic	China	EU-27	India	Japan	United States	World
C1	2030	2015	GHG	Median	46	50	5	58	51	41
			GHG	Range	36–59	37–61	-21–42	39–68	42–64	35–52
			CO_2	Median	50	55	12	60	56	46
			CO_2	Range	39–64	40–69	-30–55	40–68	44–68	40–62
		2005	GHG	Median	16	59	-46	59	56	30
			GHG	Range	0–37	47–68	-86–11	40–68	47–67	24–44
			CO_2	Median	18	63	-55	61	62	36
			CO_2	Range	0–41	51–75	-130–20	42–69	51–72	28–54
		1990	GHG	Median	-86	63	-108	56	47	
			GHG	Range	-123–-40	53–71	-164–-26	36–66	37–61	
			CO_2	Median	-118	66	-160	57	51	
			CO_2	Range	-166–-55	54–77	-286–-34	36–66	38–65	
	2035	2015	GHG	Median	63	67	29	73	71	56
			GHG	Range	55–69	54–79	8–58	62–82	57–82	52–73
			CO_2	Median	66	75	52	75	78	65
			CO_2	Range	59–76	58–91	17–81	63–85	61–93	59–85
		2005	GHG	Median	43	73	-10	74	73	49
			GHG	Range	30–52	62–82	-42–34	63–82	61–84	44–68
			CO_2	Median	46	80	16	76	80	58
			CO_2	Range	32–61	66–93	-47–67	64–85	66–93	51–82
		1990	GHG	Median	-27	76	-57	72	68	
			GHG	Range	-56–-8	65–84	-101–7	60–81	54–81	
			CO_2	Median	-44	81	-41	73	75	
			CO_2	Range	-80–-4	68–93	-147–44	60–84	56–92	
	2040	2015	GHG	Median	72	81	40	84	85	70
			GHG	Range	65–79	68–95	29–77	75–94	71–98	64–85
			CO_2	Median	78	93	68	87	95	83
			CO_2	Range	67–88	76–111	52–111	76–97	75–111	74–105
		2005	GHG	Median	56	84	7	85	87	65
			GHG	Range	45–66	74–96	-9–65	75–94	74–98	57–83
			CO_2	Median	64	94	43	87	95	80

			CO_2	Range	47–80	80–109	16–119	77–97	78–109	68–106
		1990	GHG	Median	3	86	-33	84	84	
			GHG	Range	-23–26	76–96	-55–50	74–93	69–97	
			CO_2	Median	3	95	5	86	94	
			CO_2	Range	-41–46	82–109	-41–131	74–97	73–112	
	2050	2015	GHG	Median	87	96	58	97	100	87
			GHG	Range	79–94	84–109	41–86	89–104	89–112	79–100
			CO_2	Median	94	109	91	101	112	107
			CO_2	Range	84–101	95–124	76–121	91–107	99–129	95–127
		2005	GHG	Median	80	96	36	97	100	85
			GHG	Range	68–90	87–107	8–78	90–103	90–111	76–100
			CO_2	Median	91	107	85	101	110	108
			CO_2	Range	74–101	96–120	57–138	92–107	99–125	95–132
		1990	GHG	Median	56	97	9	97	100	
			GHG	Range	28–78	88–107	-30–69	89–104	88–113	
			CO_2	Median	76	107	74	101	113	
			CO_2	Range	29–103	96–118	28–163	91–108	99–132	
C1a	2030	2015	GHG	Median	44	47	1	53	50	40
			GHG	Range	38–51	37–56	−24–23	45–67	45–59	35–43
			CO_2	Median	47	52	9	53	54	44
			CO_2	Range	40–54	38–63	−33–35	45–68	45–62	39–49
		2005	GHG	Median	13	56	−53	54	54	30
			GHG	Range	4–24	47–64	-92–-19	46–67	50–63	24–33
			CO_2	Median	12	60	−60	55	60	33
			CO_2	Range	2–24	49–70	-134–-14	46–69	52–66	28–39
		1990	GHG	Median	−93	60	−117	51	45	
			GHG	Range	-113–-69	53–67	-172–-69	43–65	41–55	
			CO_2	Median	-130	63	-168	50	49	
			CO_2	Range	-160–-100	53–72	-292–-92	41–66	39–58	
	2035	2015	GHG	Median	61	63	25	70	69	55
			GHG	Range	55–66	52–77	5–42	62–79	57–77	51–62
			CO_2	Median	62	71	48	72	76	64
			CO_2	Range	58–71	58–84	9–68	63–81	62–84	57–72
		2005	GHG	Median	39	70	-15	71	72	47
			GHG	Range	30–47	60–81	-47–10	63–80	61–79	42–56
			CO_2	Median	39	77	9	73	79	57
			CO_2	Range	30–52	65–87	-59–43	64–81	67–86	49–66
		1990	GHG	Median	-36	73	−63	69	67	
			GHG	Range	-56–-17	64–83	-109–-27	60–78	54–75	
			CO_2	Median	-62	78	−53	70	73	
			CO_2	Range	-84–-26	68–88	-168–5	61–79	58–82	
	2040	2015	GHG	Median	70	79	34	83	85	68
			GHG	Range	65–78	66–91	26–53	74–92	70–94	62–79
			CO_2	Median	72	89	62	85	95	80
			CO_2	Range	66–82	74–105	43–78	74–96	75–106	72–92
		2005	GHG	Median	53	82	-1	83	87	63

			GHG	Range	45–65	72–92	-14–27	74–92	73–94	55–75
			CO_2	Median	54	91	33	85	95	77
			CO_2	Range	46–72	78–104	0–60	75–96	78–105	66–90
		1990	GHG	Median	-4	84	-44	82	84	
			GHG	Range	-23–23	74–93	-62–-4	73–91	68–93	
			CO_2	Median	-22	92	-12	84	94	
			CO_2	Range	-43–26	80–104	-68–34	72–96	72–107	
	2050	2015	GHG	Median	88	95	59	97	101	89
			GHG	Range	79–94	83–101	41–77	90–104	89–117	79–97
			CO_2	Median	88	108	89	101	111	106
			CO_2	Range	83–98	94–117	74–109	90–107	99–135	93–116
		2005	GHG	Median	81	96	37	97	101	87
			GHG	Range	67–90	86–101	8–64	90–104	90–115	76–97
			CO_2	Median	81	107	81	101	110	108
			CO_2	Range	72–96	95–114	55–115	90–107	99–131	92–120
		1990	GHG	Median	58	97	10	97	101	
			GHG	Range	28–78	88–101	-30–49	89–104	88–118	
			CO_2	Median	50	106	68	101	113	
			CO_2	Range	26–91	95–113	24–126	89–108	98–139	
C2	2030	2015	GHG	Median	26	35	-3	40	38	26
			GHG	Range	10–38	29–49	-42–17	25–53	25–51	20–37
			CO_2	Median	28	39	-1	43	42	32
			CO_2	Range	21–38	30–54	-52–35	26–56	26–53	21–40
		2005	GHG	Median	-16	46	-60	41	44	13
			GHG	Range	-41–3	41–58	-119–-28	27–54	32–55	7–27
			CO_2	Median	-18	50	-78	45	49	19
			CO_2	Range	-29–-2	43–62	-167–-14	28–57	35–59	6–28
		1990	GHG	Median	-157	51	-127	37	33	
			GHG	Range	-213–-114	47–62	-212–-82	22–50	18–47	
			CO_2	Median	-210	54	-199	39	36	
			CO_2	Range	-241–-170	47–65	-348–-91	21–53	18–48	
	2035	2015	GHG	Median	47	53	12	61	55	43
			GHG	Range	35–58	40–65	-22–38	41–70	38–70	35–53
			CO_2	Median	50	60	27	64	61	53
			CO_2	Range	39–62	43–76	-21–61	42–72	39–80	43–64
		2005	GHG	Median	17	61	-35	61	60	33
			GHG	Range	-1–34	50–71	-89–5	42–71	44–73	24–45
			CO_2	Median	18	67	-29	65	65	44
			CO_2	Range	0–37	53–81	-113–30	43–73	47–83	32–57
		1990	GHG	Median	-84	65	-92	59	52	
			GHG	Range	-125–-47	55–74	-168–-35	38–69	33–68	
			CO_2	Median	-117	69	-116	62	56	
			CO_2	Range	-165–-66	56–82	-256–-18	38–70	33–79	
	2040	2015	GHG	Median	57	69	27	76	67	57
			GHG	Range	50–73	49–81	7–50	55–88	48–84	48–72
			CO_2	Median	62	79	49	79	75	66

			CO_2	Range	55–75	53–92	21–78	56–92	52–100	56–87
		2005	GHG	Median	33	75	-13	76	70	49
			GHG	Range	22–58	58–84	-43–23	56–88	53–85	40–67
			CO_2	Median	38	83	11	80	78	60
			CO_2	Range	27–59	62–93	-40–60	57–92	58–100	47–85
		1990	GHG	Median	-49	77	-60	74	65	
			GHG	Range	-74–6	62–86	-103–-9	53–87	44–83	
			CO_2	Median	-63	84	-50	78	72	
			CO_2	Range	-93–-9	65–94	-134–33	53–91	46–100	
	2050	2015	GHG	Median	78	89	49	92	89	78
			GHG	Range	71–91	64–108	24–70	76–111	74–112	69–95
			CO_2	Median	84	104	74	95	102	95
			CO_2	Range	75–94	70–123	52–111	77–115	83–130	78–114
		2005	GHG	Median	66	91	20	92	90	74
			GHG	Range	54–87	70–107	-17–53	77–110	76–111	63–94
			CO_2	Median	74	103	54	95	102	94
			CO_2	Range	59–90	76–119	17–119	78–114	85–126	74–117
		1990	GHG	Median	24	92	-13	92	88	
			GHG	Range	-1–70	73–106	-67–33	75–111	72–114	
			CO_2	Median	33	103	22	95	102	
			CO_2	Range	-7–74	77–118	-39–132	75–116	81–133	
C3	2030	2015	GHG	Median	23	34	-27	39	36	25
			GHG	Range	4–41	24–48	-48–25	20–55	20–50	8–35
			CO_2	Median	23	37	-30	39	36	25
			CO_2	Range	10–41	25–52	-60–33	21–55	20–51	9–38
		2005	GHG	Median	-20	46	-96	40	42	12
			GHG	Range	-50–8	37–57	-129–-16	22–55	27–55	–8–24
			CO_2	Median	-25	48	-129	40	44	11
			CO_2	Range	-47–4	39–61	-182–-18	23–56	30–57	-8–26
		1990	GHG	Median	-166	51	-178	36	31	
			GHG	Range	-233–-105	43–61	-225–-65	16–52	13–46	
			CO_2	Median	-231	52	-284	35	29	
			CO_2	Range	-289–-154	43–64	-373–-99	15–52	11-46	
	2035	2015	GHG	Median	39	50	-6	54	49	36
			GHG	Range	23–55	32–64	-46–28	34–69	30–65	25–50
			CO_2	Median	46	54	5	54	51	42
			CO_2	Range	28–59	35–70	-49–41	33–71	29–69	27–57
		2005	GHG	Median	5	59	-64	54	54	25
			GHG	Range	-19–29	44–70	-125–-12	36–70	36–69	12–41
			CO_2	Median	12	63	-68	55	57	30
			CO_2	Range	-18–34	47–75	-163–-3	35–72	38–73	13–49
		1990	GHG	Median	-110	63	-133	51	45	
			GHG	Range	-164–-57	49–73	-220–-58	31–68	24–63	
			CO_2	Median	-133	65	-182	51	46	
					-210–-76	51–77	-341–-73	28–69	22–66	
	2040	2015	GHG	Median	54	65	11	69	61	48

		GHG	Range	39–63	41–78	-28–36	45–81	39–78	37–60
		CO_2	Median	59	72	28	70	66	57
		CO_2	Range	46–67	47–87	-23–59	46–83	40–85	43–71
	2005	GHG	Median	28	71	-38	70	65	39
		GHG	Range	5–42	51–81	-98–1	46–81	44–80	26–54
		CO_2	Median	33	77	-26	71	70	49
		CO_2	Range	12–46	57–89	-117–28	48–83	47–87	32–66
	1990	GHG	Median	-59	74	-96	68	58	
		GHG	Range	-109--29	56–83	-181--41	43–80	33–76	
		CO_2	Median	-77	79	-112	68	62	
		CO_2	Range	-133--43	60–90	-264--21	43–82	34–83	
2050	2015	GHG	Median	73	84	32	85	80	66
		GHG	Range	62–80	61–93	-1–58	69–94	60–92	55–77
		CO_2	Median	77	95	58	87	88	78
		CO_2	Range	69–85	70–107	21–84	71–97	67–103	66–92
	2005	GHG	Median	57	87	-5	85	82	61
		GHG	Range	40–69	67–94	-56–35	70–94	64–93	48–73
		CO_2	Median	63	96	26	87	89	73
		CO_2	Range	50–76	76–105	-40–72	72–97	71–103	60–90
	1990	GHG	Median	5	88	-49	84	79	
		GHG	Range	-32–31	71–95	-121–8	68–93	57–92	
		CO_2	Median	1	96	-24	86	87	
		CO_2	Range	-33–36	77–105	-136–54	69–97	63–104	

Table D.2
Statistics on GHG and CO_2 budgets for 2030–2050 in Gt CO2 eq per category and per country or region. Numbers are based on harmonised scenarios. Modification '1' means regional downscaling, and modification '2' harmonisation.

Category	GHG/CO2	Modification	Statistic	China	EU-27	India	Japan	United States	World
C1	GHG	1	Median	74.2	20.9	47.4	5.61	32	394
		1	Range	62.8–96.1	11.2–29.5	28–55.7	3.49–8.08	20.6–45.9	261–437
		2	Median	67.4	15.4	33.7	4.64	22.4	308
		2	Range	55.9–84.6	6.81–23.6	15.1–38.5	2.54–7.2	9.83–36.4	171–355
	CO2	1	Median	48.3	11.4	22.5	4.47	19.3	218
		1	Range	28.8–68.8	1.89–19.5	6.01–30.6	2.45–7.48	6.02–32.3	76.8–273
		2	Median	42.9	6.29	14.8	3.69	7.65	144
		2	Range	25.6–60.6	−2.57–14.5	−1.2–22.2	1.59–6.32	−3.25–23.6	6.03–191
C1a	GHG	1	Median	81.9	22	49.1	6.07	32	402
		1	Range	63.9–95.9	16.3–31.9	35.2–59	3.5–8.02	23.2–47.4	310–445

		2	Median	72.3	16.9	34.8	5.21	22.5	316
		2	Range	57.3–84.2	11.6–25	25.8–40.2	2.91–7.19	13.4–37.5	238–363
	CO2	1	Median	58.6	12.5	24.4	4.57	19.3	227
		1	Range	43.2–70.2	7.34–21.7	15.9–33.9	2.81–7.76	10.7–33.9	163–274
		2	Median	51.9	7.68	16.4	4.07	7.65	154
		2	Range	37.9–61.6	1.85–15.9	9.26–23.5	2.18–6.61	−0.915–24.1	89.9–210
C2	GHG	1	Median	108	30.1	49.8	7.71	51	504
		1	Range	88–132	20.9–42.8	35.9–72.7	5.08–12.2	30.1–68.1	388–597
		2	Median	97.9	22.8	38.9	6.55	41.1	414
		2	Range	76.9–116	15–35.8	26.7–50.4	4.46–11.9	23.4–61	311–492
	CO2	1	Median	82.1	19.2	27.6	6.29	36.4	306
		1	Range	61.9–101	9.94–32	15.6–42.2	3.82–11.1	12.9–49.2	208–398
		2	Median	74	12.7	22.5	5.64	25.5	244
		2	Range	52.1–86.6	6.34–26.5	9.23–34.2	3.36–10.6	3.26–43.4	122–306
C3	GHG	1	Median	123	30.6	60.3	9.55	56	570
		1	Range	101–158	21.9–46	43–77.4	6.86–14.1	38.6–78.1	476–681
		2	Median	110	26.2	48.8	8.93	48.3	505
		2	Range	90.1–140	18.3–39.7	31.6–64.2	5.75–13.6	30.6–72.5	398–611
	CO2	1	Median	85.6	20.8	35.5	8.49	41.7	375
		1	Range	73.5–113	13.4–34.4	24.2–50.6	5.8–12.9	27.2–59.1	291–472
		2	Median	79.3	16.8	29.6	7.66	32.6	316
		2	Range	65.1–102	9.32-28.8	18.1–45.4	4.89–12.5	17.7-53	223–405

Table D.3
Statistics on yearly average GHG and CO_2 budgets for 2030–2050 in Gt CO2 eq as compared to 2015 emissions per category and per country or region, in percentages. Numbers are based on harmonised scenarios. Modification '1' means regional downscaling, and modification '2' harmonisation.

Category	GHG/CO2	Modification	Statistic	China	EU-27	India	Japan	United States	World
C1	GHG	1	Median	32.8	29.9	92.4	22.2	26.3	41.7
		1	Range	27.8–42.4	16.1–42.4	54.7–108.6	13.8–31.9	17–37.8	27.5–46.2
		2	Median	29.8	22.2	65.7	18.3	18.5	32.5
		2	Range	24.7–37.4	9.8–33.9	29.5–75.1	10–28.5	8.1–29.9	18–37.5
	CO2	1	Median	26.4	20.5	58.6	19.2	20.9	31.3

		1	Range	15.8–37.7	3.4–35.3	15.6–79.7	10.5–32.1	6.5–34.9	11–39.1
		2	Median	23.5	11.4	38.5	15.8	8.3	20.6
		2	Range	14–33.2	−4.6–26.2	−3.1–57.8	6.8–27.1	−3.5–25.5	0.9–27.4
C1a	GHG	1	Median	36.2	31.6	95.8	24	26.3	42.5
		1	Range	28.2–42.4	23.4–45.7	68.6–115.2	13.8–31.7	19.1–39	32.7–47
		2	Median	31.9	24.3	67.9	20.6	18.5	33.4
		2	Range	25.3–37.2	16.6–35.8	50.4–78.4	11.5–28.4	11–30.9	25.1–38.3
	CO2	1	Median	32.1	22.6	63.5	19.6	20.9	32.5
		1	Range	23.7–38.5	13.3–39.2	41.5–88.3	12.1–33.3	11.6–36.7	23.4–39.3
		2	Median	28.4	13.9	42.7	17.5	8.3	22.1
		2	Range	20.7–33.8	3.3–28.8	24.1–61.2	9.4–28.3	−27	12.9–30.1
C2	GHG	1	Median	47.6	43.2	97.2	30.5	41.9	53.3
		1	Range	38.9–58.2	30–61.3	70–141.8	20.1–48.1	24.7–56	41–63.1
		2	Median	43.2	32.7	75.9	25.9	33.8	43.8
		2	Range	34–51.3	21.6–51.3	52.1–98.3	17.6–46.9	19.2–50.2	32.8–51.9
	CO2	1	Median	45	34.7	71.8	27	39.4	43.9
		1	Range	33.9–55.3	18–57.9	40.6–109.8	16.4–47.5	14–53.2	29.7–57
		2	Median	40.6	23	58.6	24.2	27.5	34.9
		2	Range	28.6–47.4	11.5–47.8	24–88.9	14.4–45.5	3.5–46.9	17.5–43.9
C3	GHG	1	Median	54.3	43.9	117.7	37.8	46.1	60.2
		1	Range	44.6–69.7	31.4–66	83.9–151	27.1–55.8	31.8–64.2	50.3–71.9
		2	Median	48.5	37.5	95.2	35.3	39.7	53.4
		2	Range	39.8–62	26.2–56.9	61.6–125.3	22.7–53.7	25.2–59.6	42–64.5
	CO2	1	Median	46.9	37.7	92.4	36.4	45.1	53.8
		1	Range	40.3–62.1	24.2–62.2	63–131.6	24.8–55.5	29.4–63.9	41.6–67.6
		2	Median	43.5	30.3	76.9	32.8	35.2	45.2
		2	Range	35.7–55.7	16.9–52	47–118.1	20.9–53.4	19.1–57.3	31.9–58.1

Table D.4
Statistics on GHG and CO2 net–zero years per category and per country or region. Numbers are based on harmonised scenarios that reach net–zero before 2100.

Category	GHG/CO_2	Statistic	China	EU-27	India	Japan	United States	World
C1	GHG	Median	2075	2050	2058	2055	2050	2060
		Range	2065-2085	2044-2085	2038-2075	2045-2070	2045-2065	2045-2080
	CO_2	Median	2060	2045	2055	2050	2045	2050
		Range	2054-2070	2040-2052	2040-2075	2045-2065	2040-2055	2040-2055
C1a	GHG	Median	2075	2072	2070	2058	2050	2065
		Range	2065-2080	2050-2085	2070-2070	2045-2066	2045-2065	2055-2080
	CO_2	Median	2060	2045	2060	2050	2045	2050
		Range	2055-2070	2040-2055	2050-2080	2045-2065	2040-2055	2045-2055
C2	GHG	Median	2075	2060	2072	2065	2060	2070
		Range	2068-2085	2050-2086	2066-2078	2045-2075	2046-2074	2055-2086
	CO_2	Median	2065	2050	2060	2055	2050	2055
		Range	2055-2075	2045-2068	2048-2076	2045-2074	2042-2060	2045-2063
C3	GHG	Median	2080	2070	2080	2080	2068	2080
		Range	2070-2090	2060-2080	2072-2088	2060-2095	2060-2090	2075-2090
	CO_2	Median	2070	2055	2065	2065	2060	2070
		Range	2060-2080	2045-2065	2050-2085	2055-2080	2050-2070	2060-2080

Appendix E: Reductions by 2040 compared to 2015 including and excluding LULUCF emissions

Table E.1
GHG reduction statistics in percentages, per category and per country or region for projected reductions in 2040, calculated from 2015, including and excluding LULUCF emissions. Numbers are based on harmonised scenarios.

Category	LULUCF	Statistic	China	EU	India	Japan	United States	World
C1	Incl	Median	72	81	40	84	85	70
		range	65–79	68–95	29–77	75–94	71–98	64–85
	Excl	Median	71	75	30	83	79	62
		range	64–77	62–88	24–60	72–91	66–88	54–71
C1a	Incl	Median	70	79	34	83	85	68
		range	65–78	66–91	26–53	74–92	70–94	62–79
	Excl	Median	69	73	28	80	79	59
		range	64–76	61–82	21–49	72–89	66–86	53–69
C2	Incl	Median	57	69	27	76	67	57
		range	50–73	49–81	7–50	55–88	48–84	48–72
	Excl	Median	55	62	22	74	61	46
		range	46–71	46–72	2–45	55–83	44–74	38–59
C3	Incl	Median	54	65	11	69	61	48
		range	39–63	41–78	-28–36	45–81	39–78	37–60
	Excl	Median	52	60	8	66	57	41
		range	37–61	38–72	-24–32	45–79	36–70	28–53

Appendix F: Reductions by 2040 based on equity principles

Table F.1
GHG Reduction by 2040, compared to 1990 levels, for the major emitting countries and regions and the world, for the various climate categories for the effort-sharing calculations based on the three equity principles (capability to pay (CAP), equality (Equal Per Capita or EPC) and responsibility (Equal Cumulative Per Capita or CPC). Based on Robiou du Pont et al. (2017), equity calculations exclude LULUCF emissions.

Equity outcomes (excl. LULUCF emissions):

Temperature increase 2100	Principle	China	EU-28	India	Japan	United States	World
1.5 °C	CAP	79	97	-42	95	98	41
	EPC	24	79	-161	80	87	41
	CPC	73	95	-275	80	97	41
2 °C	CAP	64	93	-148	92	97	-5
	EPC	-36	64	-360	64	77	-5
	CPC	12	77	-423	73	73	-5