Supplementary information to

Decoupling the cost estimations and equity implications of decarbonisation from carbon pricing

Shiya ZHAO[1,2], Shinichiro FUJIMORI [1,2,3,*], Ken OSHIRO [4], Tomoko HASEGAWA [5,1,3]

1 * Department of Environmental Engineering, Kyoto University, C1-3 361, Kyotodaigaku Katsura, Nishikyoku, Kyoto 6158540, Japan.

2 International Institute for Applied System Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

3 Center for Social and Environmental Systems Research, National Institute for Environmental Studies (NIES), 162 Onogawa, Tsukuba, Ibaraki 3058506, Japan

4 Faculty of Environmental Earth Science, Hokkaido University, N10W5, Kita-ku, Sapporo 0600810, Japan

5 Research Organization of Science and Technology, Ritsumeikan University, Kitaku, Kyoto 603-8577, Japan.

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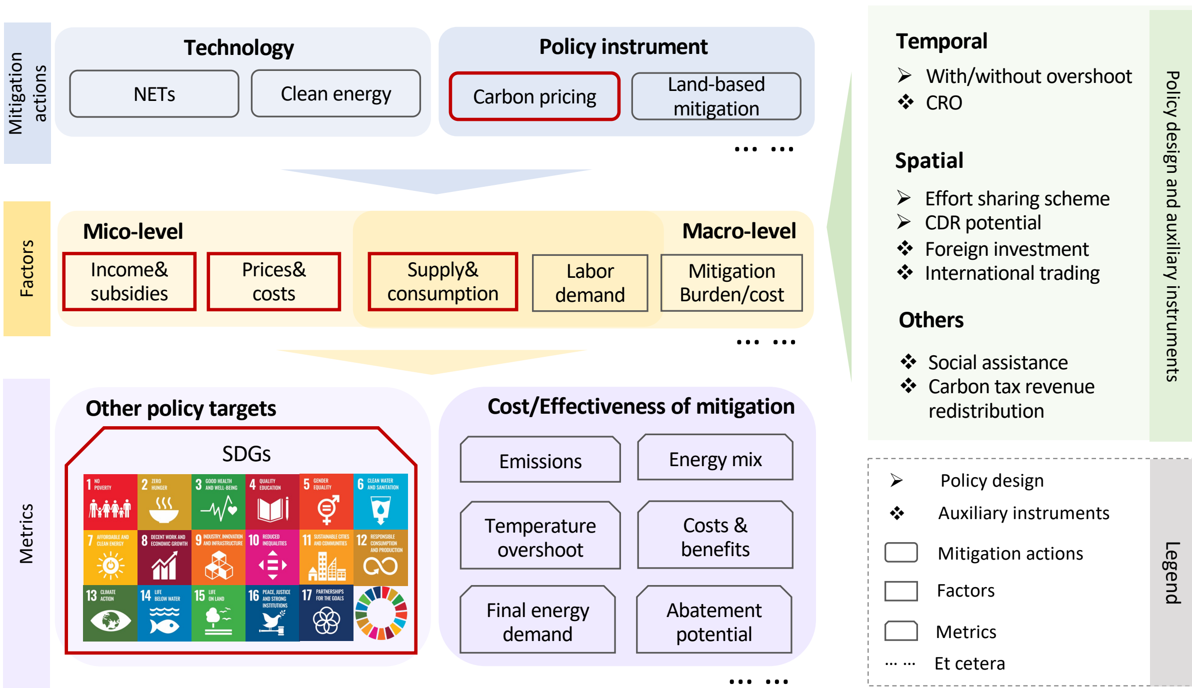
SI. 1 Position of the study and modeling framework

SI. 1.1 Position of the study

Positioning our study in the justice framework proposed by Zimm and colleagues [1], our study is focused on mitigation and climate policies (area of justice) at the global and regional scales (scale of justice), detailing equity issues (form of justice) through assessment of welfare and nutrition-related indicators (metrics of justice) based on an egalitarian viewpoint (pattern of justice).

Common aspects of equity considerations, which are divided into four layers, are illustrated in SI. Fig. **1** based on the literature listed in SI. Table ***1***. The four layers are “Mitigation actions”, “Policy design and auxiliary instruments”, “Factors” and “Metrics”. “Mitigation actions” represent policies, technological developments and transitions directly aimed at reducing emissions. “Policy design and auxiliary instruments” includes the design and implementation of mitigation policies and other policy instruments that aid the mitigation actions, whether by improving the effectiveness of mitigation actions, reducing adverse policy impacts, or facilitating other policy targets such as Sustainable Development Goals (SDGs). “Factors” refers to the drivers of changes in the “Metrics” used to evaluate policy impacts.

Our study is focused on the policy instrument of carbon pricing and we argue that there is a potential to reduce the impacts on poverty, income inequality and food insecurity of decarbonisation to a negligible level by moving beyond explicit carbon pricing. We reveal the mechanism underlying the effects of carbon pricing policies by decomposing the relevant factors, as illustrated in SI. Fig. **1**. In contrast to previous studies that introduce new auxiliary policy instruments along with carbon pricing to achieve multiple policy targets, our study originated from the question of what would happen if decarbonisation occurs without carbon pricing, which is currently the case in most low-income countries. Our analysis demonstrates that distributional impacts and consequences for poverty and hunger risk observed in most climate policy studies are induced by the imposition of carbon pricing.



SI. Fig. 1 Summary of economic assessment studies of climate policies and positioning of our study (marked with red lines). Labour demand, as a factor directly underlying unemployment, is driven by supply and consumption. We separate these factors in the figure because labour demand is an explicit driver of unemployment, while supply and consumption have indirect effects on unemployment. Energy access, energy poverty, and some health impacts are included as components of poverty, which is multidimensional in nature but is narrowed to a definition based on expenditure thresholds. Health impacts from emissions and heat stress are also important metrics for consideration of equity. However, we focus on distributional justice measured in terms of SDG1 (No Poverty), SDG2 (Zero Hunger) and SDG11 (Reduced Inequalities). Health impacts thus are beyond the scope of our assessment.

SI. Table 1 Equity studies in the climate policy literature, with a special focus on the economic aspects.

Mitigation action	Metrics	Policy design and anxiliary instrument	Factor	Scale	Type	Paper
Carbon pricing	Emissions& costs	CRO*	Burden of mitigation	Global	IAM	Bednar et al, 2021[2]
	Inequality	-	Income&subsidies, Prices&costs, Supply&consumption	Regional	IAM	Fragkos et al, 2021[2]
		Carbon tax revenue redistribution	Income&subsidies, Prices&costs	National		Zhao et al, 2022[3]
		International cooperation		Global, National		Gazzotti et al, 2021[4]
		-	Prices&costs	Regional	MRIO	Steckel et al, 2021[5]
	Poverty	Carbon tax revenue redistribution	Income&subsidies, Prices&costs	Global	IAM	Fujimori et al, 2023[6]
		Carbon tax revenue redistribution	Prices&costs	Global, Regional		Soergel et al, 2021[7]
	Poverty, Inequality	-	Income&subsidies, Prices&costs	Global	Empirical analysis	Dorband et al, 2019[8]
		-		National	IAM	Zhao et al, 2022[9]
		Carbon tax revenue redistribution	Prices&costs	Global, National		Budolfson et al, 2021[10]

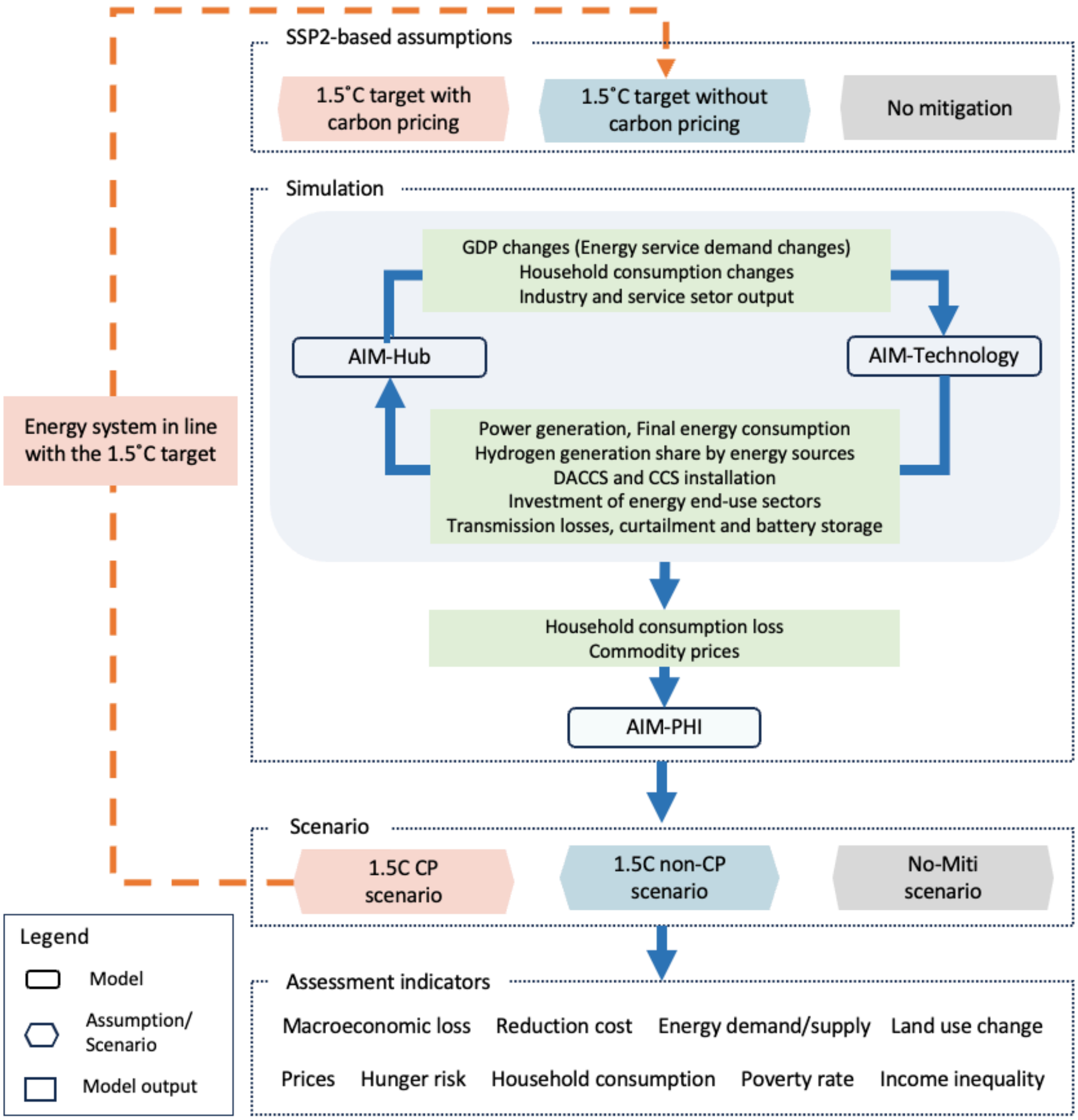
	Poverty, Inequality	Social assistance	Income&subsidies, Prices&costs	Global, Regional	MRIO	Malerba et al, 2022[11]
				National		Malerba et al, 2021[12]
	Unemployment, Poverty	-	Labor demand	Global, National	MRIO	Malerba and Wiebe, 2021[13]
Carbon pricing, NETs**	Emissions	Institutional capability, Effort sharing	Burden of mitigation, Prices&costs	Global	IAM	Gidden et al, 2023[14]
	Inequality	CDR*** potentials	Income&subsidies, Prices&costs			Andreoni et al, 2024[15]
Clean energy	Unemployment	-	Labor demand	National, Subnational	Sectoral models	Xie et al, 2023[16]
	Unemployment Poverty		Income&Subsidies, Prices&Costs, Supply&Consumption, Labor demand	Global	Review	Carley and Knisky, 2020[17]
Land-based mitigation	Food insecurity	-	Prices&costs, Supply&consumption	Global	IAM	Fujimori et al, 2022[18]
			Prices&costs, Burden of mitigation	Global, Regional	Scenario data	Jaiswal et al, 2024[19]

* CRO: carbon removal obligations

** NETs: Negative emission technologies

*** CDR: Carbon dioxide removal

SI. 1.2 Modeling framework



SI. Fig. 2 Model overview

SI. 1.3 Scenarios

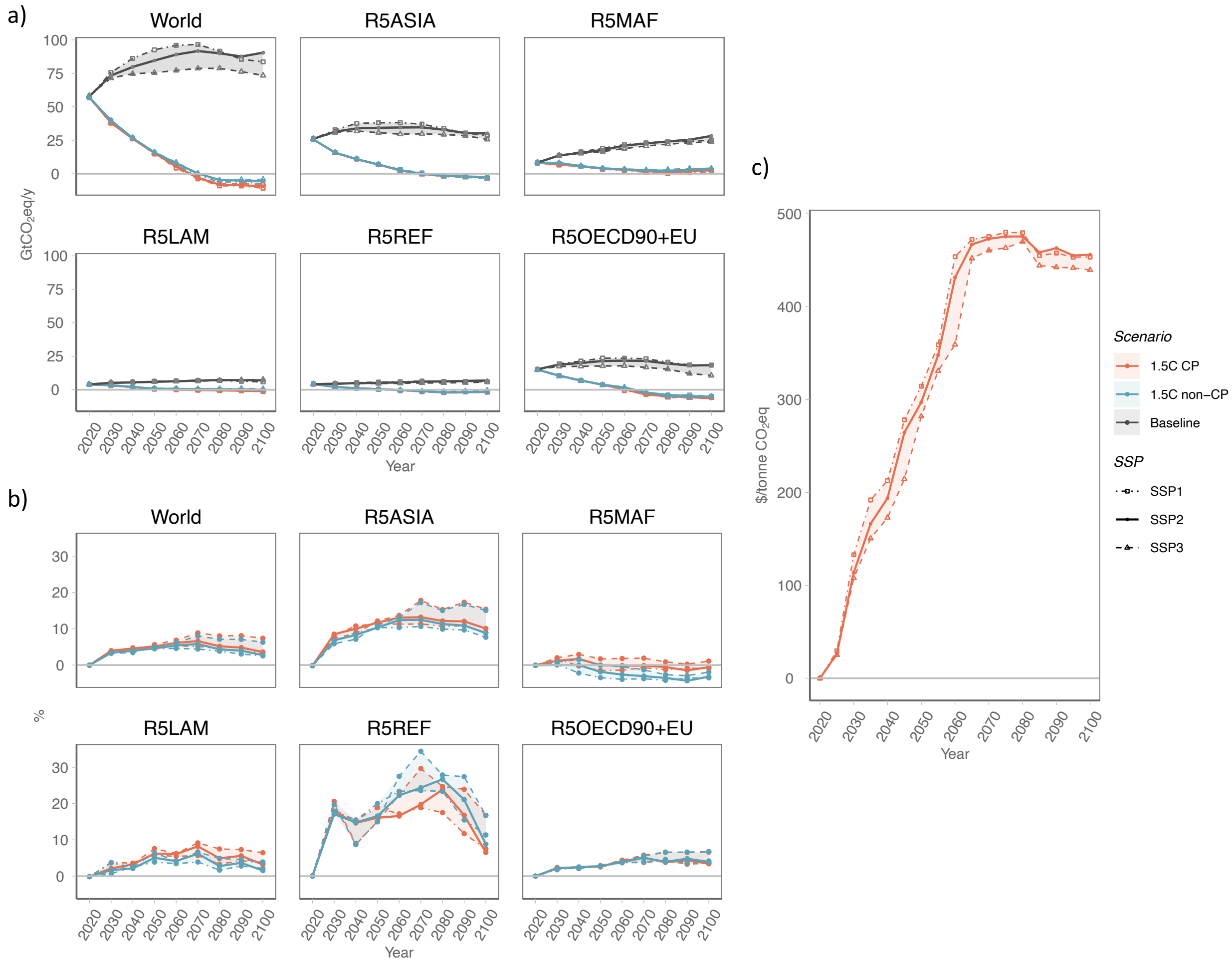
SI. Table 2 Scenario list

Scenario category	Scenario code (AIMPHI)	Scenario name	Assumptions					
			AgProd	GDP&Pop	Inequality assumptions	Direct carbon tax exemption	Climate policy	Target
Main	Base	Baseline	None	SSP2	SSP2	No	-	-
	1p5C	1.5C CP	None	SSP2	SSP2	No	Carbon pricing	1.5˚C
	1p5C_woc	1.5C non-CP	None	SSP2	SSP2	No	Without explicit carbon pricing	1.5˚C
Sensitivity-AgProd	SSP2_Base_HighAgTech	-	High	SSP2	SSP2	No	-	-
	SSP2_1p5C_HighAgTech	-	High	SSP2	SSP2	No	Carbon pricing	1.5˚C
	SSP2_1p5C_HighAgTech_woc	-	High	SSP2	SSP2	No	Without explicit carbon pricing	1.5˚C
	SSP2_Base_LowAgTech	-	Low	SSP2	SSP2	No	-	-
	SSP2_1p5C_LowAgTech	-	Low	SSP2	SSP2	No	Carbon pricing	1.5˚C
	SSP2_1p5C_LowAgTech_woc	-	Low	SSP2	SSP2	No	Without explicit carbon pricing	1.5˚C
Sensitivity-GDP&Pop	SSP1_Base	-	None	SSP1	SSP1	No	-	-
	SSP1_1p5C	-	None	SSP1	SSP1	No	Carbon pricing	1.5˚C
	SSP1_1p5C_woc	-	None	SSP1	SSP1	No	Without explicit carbon pricing	1.5˚C
	SSP3_Base	-	None	SSP3	SSP3	No	-	-
	SSP3_1p5C	-	None	SSP3	SSP3	No	Carbon pricing	1.5˚C
	SSP3_1p5C_woc	-	None	SSP3	SSP3	No	Without explicit carbon pricing	1.5˚C

Sensitivity-Inequality	Base_Gini1	-	None	SSP2	SSP1	No	-	-
	1p5C_Gini1	-	None	SSP2	SSP1	No	Carbon pricing	1.5˚C
	1p5C_Gini1_woc	-	None	SSP2	SSP1	No	Without explicit carbon pricing	1.5˚C
	Base_Gini3	-	None	SSP2	SSP3	No	-	-
	1p5C_Gini3	-	None	SSP2	SSP3	No	Carbon pricing	1.5˚C
	1p5C_Gini3_woc	-	None	SSP2	SSP3	No	Without explicit carbon pricing	1.5˚C
Sensitivity-Target	2C	-	None	SSP2	SSP2	No	Carbon pricing	2˚C
	2C_woc	-	None	SSP2	SSP2	No	Without explicit carbon pricing	2˚C
Decomposition	1p5C_expt	-	None	SSP2	SSP2	Yes	Carbon pricing	1.5˚C
	SSP2_1p5C_HighAgTech_expt	-	High	SSP2	SSP2	Yes	Carbon pricing	1.5˚C
	SSP2_1p5C_LowAgTech_expt	-	Low	SSP2	SSP2	Yes	Carbon pricing	1.5˚C
	SSP1_1p5C_expt	-	None	SSP1	SSP1	Yes	Carbon pricing	1.5˚C
	SSP3_1p5C_expt	-	None	SSP3	SSP3	Yes	Carbon pricing	1.5˚C

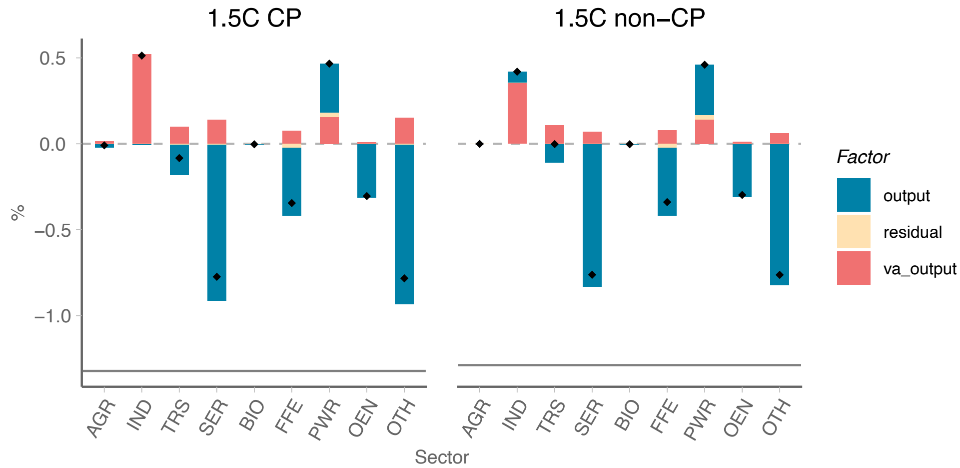
SI 2. Macroeconomic impacts

SI 2.1 Emission pathways and carbon prices in the 1.5° C pathways



SI. Fig. 3 Mitigation pathways of the scenarios. a) GHG emissions trajectories. b) Consumption losses compared to the baseline for all modelling scenarios. c) Carbon price trajectories in the carbon pricing scenarios. The shades indicate the range of SSP variations.

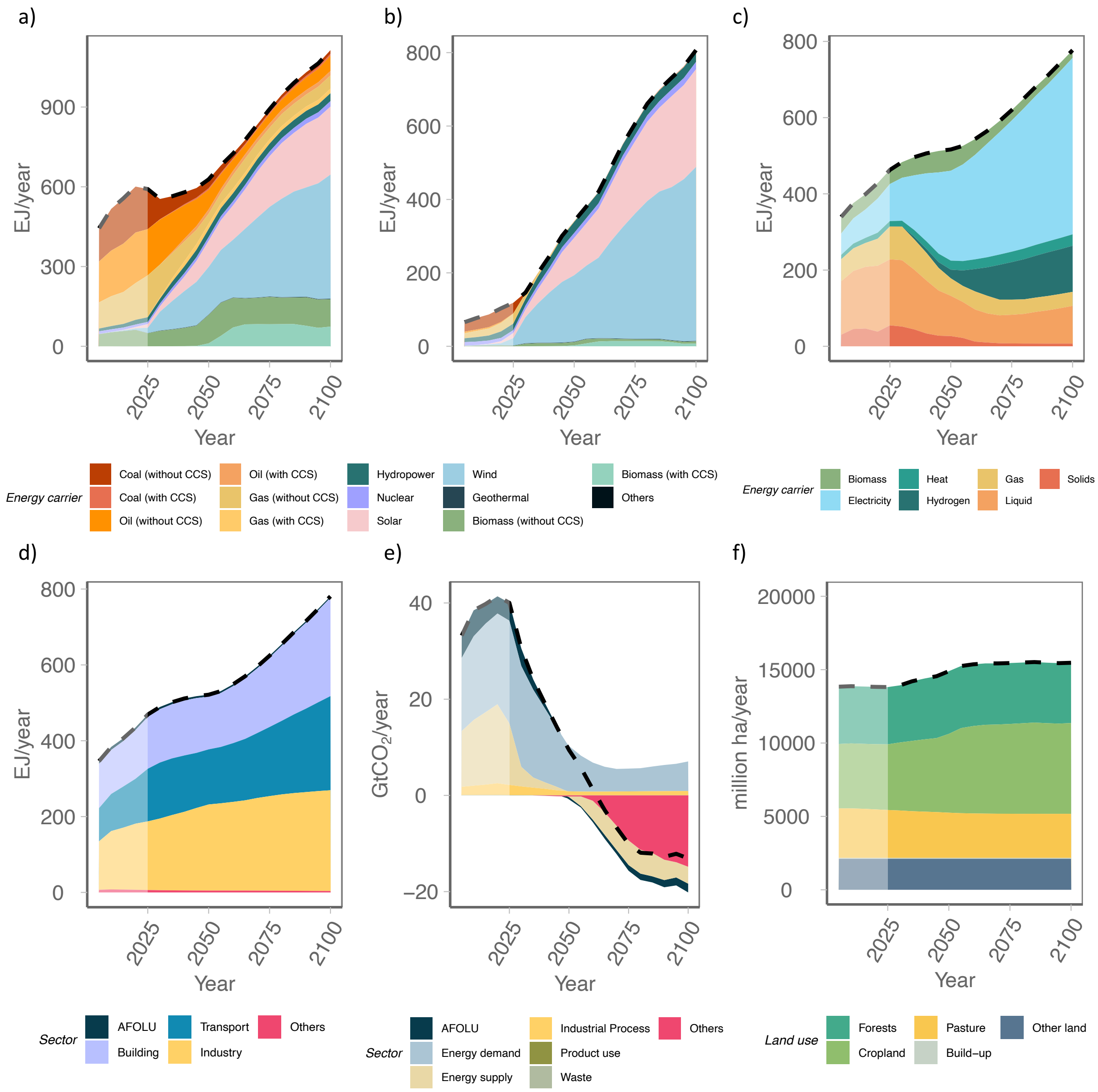
SI 2.2 Decomposition analysis of macroeconomic losses



SI. Fig. 4 Sectoral and factoral contributions to GDP losses associated with climate policies, presented as percentage changes in GDP, with (1.5C CP) and without (1.5C non-CP) explicit carbon pricing. In this figure, output denotes the percentage change in GDP due to the change in sectoral output and va_output denotes the percentage changes in GDP due to changes in sector value-added efficiency and residual effects. AGR is the agricultural sector, IND denotes the industrial sector, TRS is the transport sector, and SER represents the service sector. BIO is bioenergy production, FFE denotes the fossil fuel energy supply, PWR is the power generation sector, OEN represents other energy supply, and OTH denotes other sectors. In addition to the sectors shown here, carbon capture and sequestration contributes to around 0.05% gains in total GDP under both the 1.5C CP and 1.5C non-CP scenarios, but is not included in this decomposition analysis because it is absent from the baseline scenario.

To determine sectoral contributions to GDP losses, the value added by each sector is decomposed into three factors of output changes, value-added efficiency (value-added per output) and residuals, and compared between scenarios with and without carbon pricing. The main reason for the GDP loss is decreased output due to climate actions. Decarbonisation without an explicit carbon price reduces the loss of sectoral outputs from all sectors. Increases in value-added efficiency lead to significant gains in value added by the industrial sector, while other sectors, represented by the service sector, show marked losses in output. Gains of value-added efficiency in the industrial sector compensate for the output loss. The pattern of impacts among sectors does not change greatly with explicit carbon pricing, but the magnitude of changes is smaller in the absence of carbon pricing.

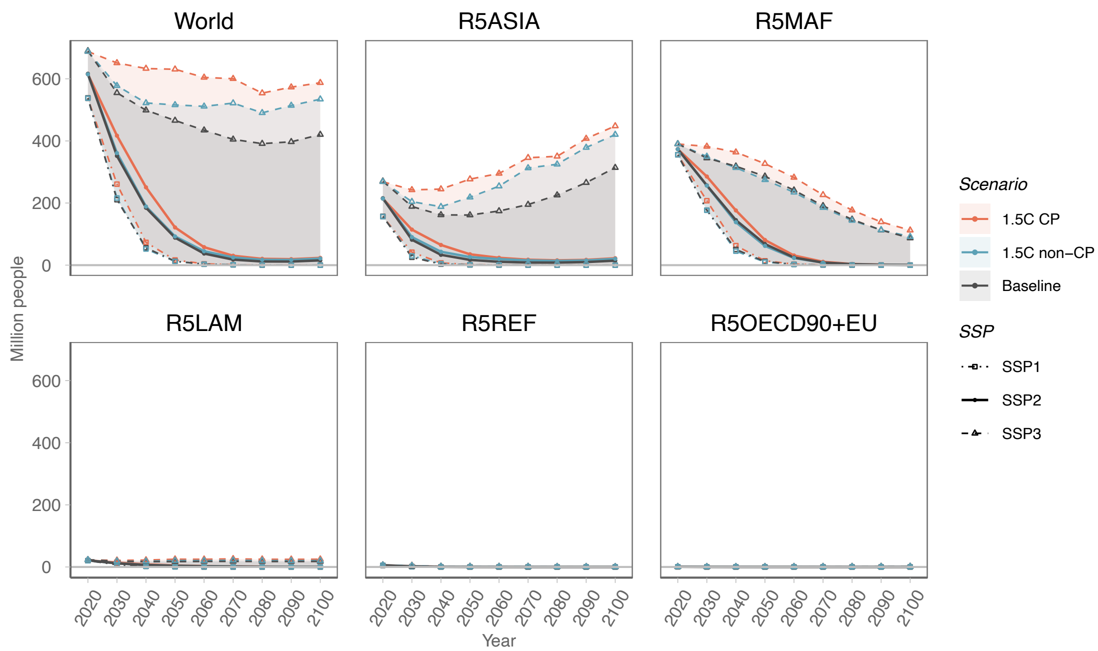
SI 2.3 Energy system and land use pattern



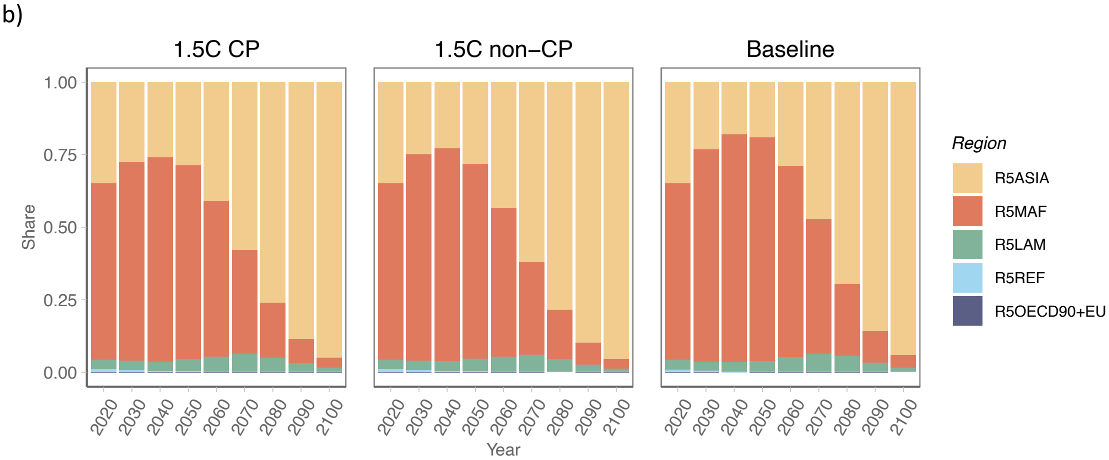
SI. Fig. 5 Energy system and land use in the 1.5C non-CP scenario: a) primary energy supply and its breakdown, b) power generation mix, c) final energy consumption by energy carrier and d) by sector, e) CO_2 emissions and f) land-use pattern.

SI 3. Poverty and hunger risk

a)

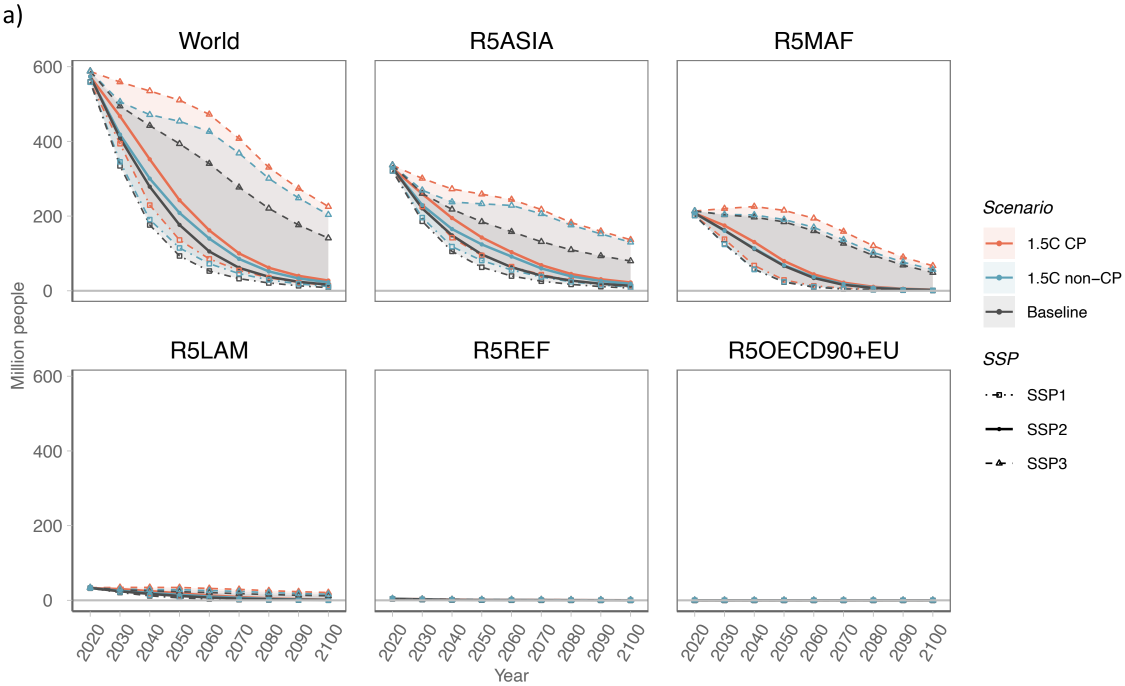


b)

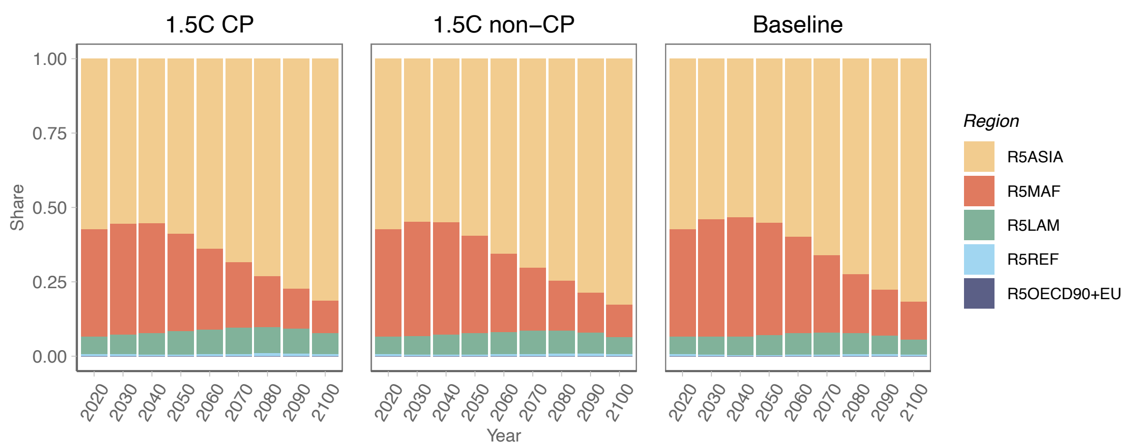


SI. Fig. 6 Regional poverty projections. a) Poverty headcount ($1.9 per capita per day) and b) regional composition of the poverty headcount projection are in the SSP2-based scenario. In a), shades indicate the range of SSP variations. Poverty headcount is greatest in Asia, where the population is large, and Africa, where the poverty rate is high. The former region is subject to more climate policy impacts in the long term, while the latter region experiences more impacts in the short to medium term. In b), we see that the Middle East and Africa contribute over 70% of the poverty headcount in the baseline scenario, but the proportion contributed by Asia grows under mitigation scenarios, especially CP scenarios, mainly due to its large population.

a)



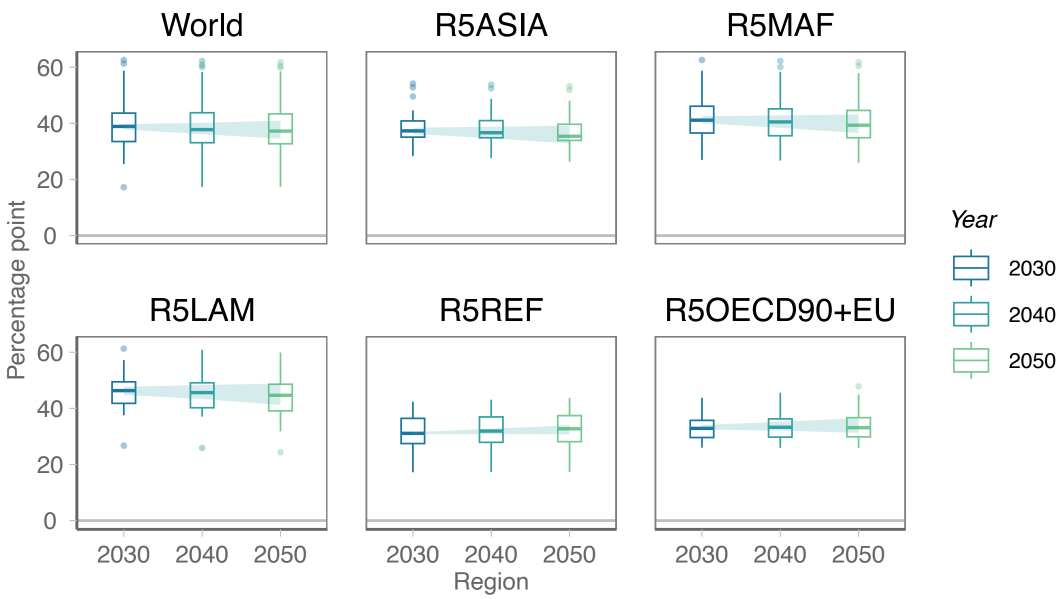
b)



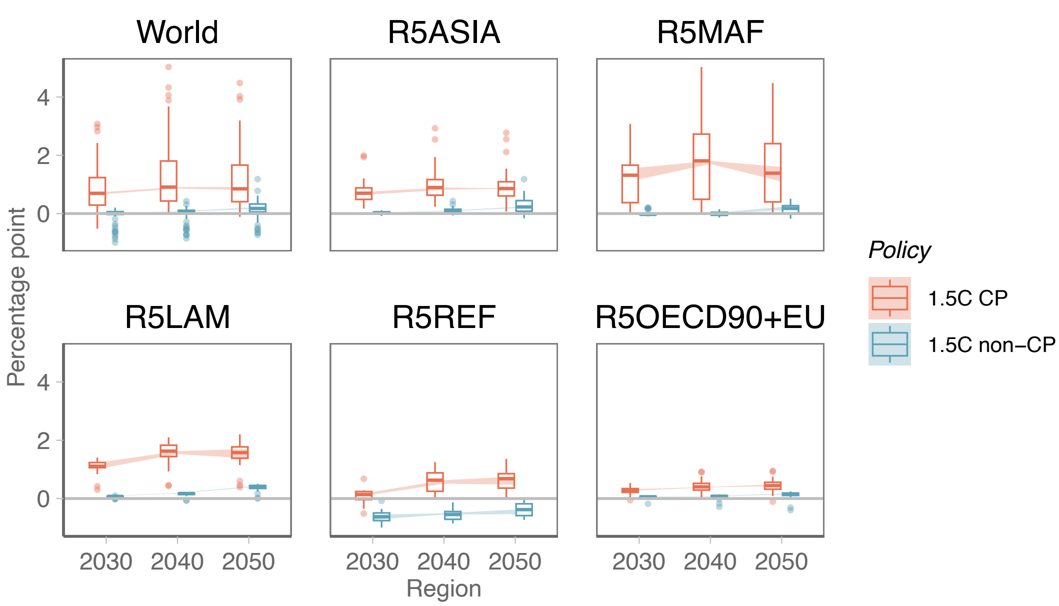
SI. Fig. 7 Regional hunger risk projections. a) Hunger risk and b) regional composition of the hunger risk projection in the SSP2-based scenario. In a), shades indicate the range of SSP variations. Like poverty projections, hunger risk is greatest in Asia, where the population is large, and Africa, where the poverty rate is high. In b), Asia contributes over 50% of the population at risk of hunger in the baseline scenario, and that proportion expands under mitigation scenarios and in the long term, mainly due to population growth. Organisation for Economic Co-operation and Development and European Union countries are not shown due to a lack of hunger risk in our projection.

SI 4. Inequality

SI 4.1 Gini coefficient

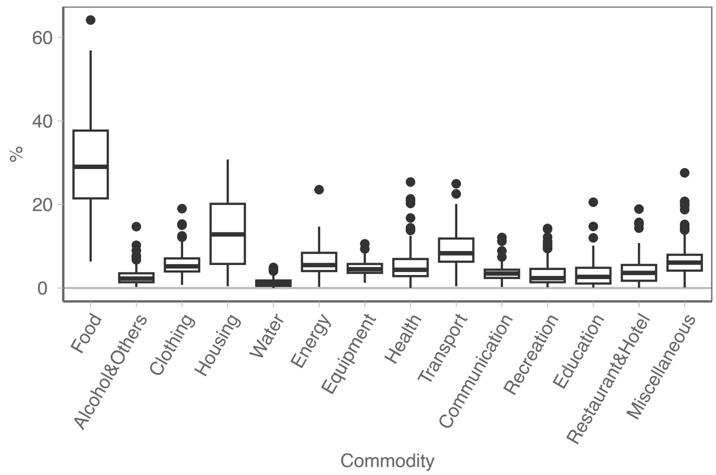


SI. Fig. 8 Baseline Gini coefficient uncertainty. Boxes indicate the interquartile range. Whiskers show the 1st and 4th quartiles of data. Points are outliers. Shades show the range of median estimates in different SSPs.

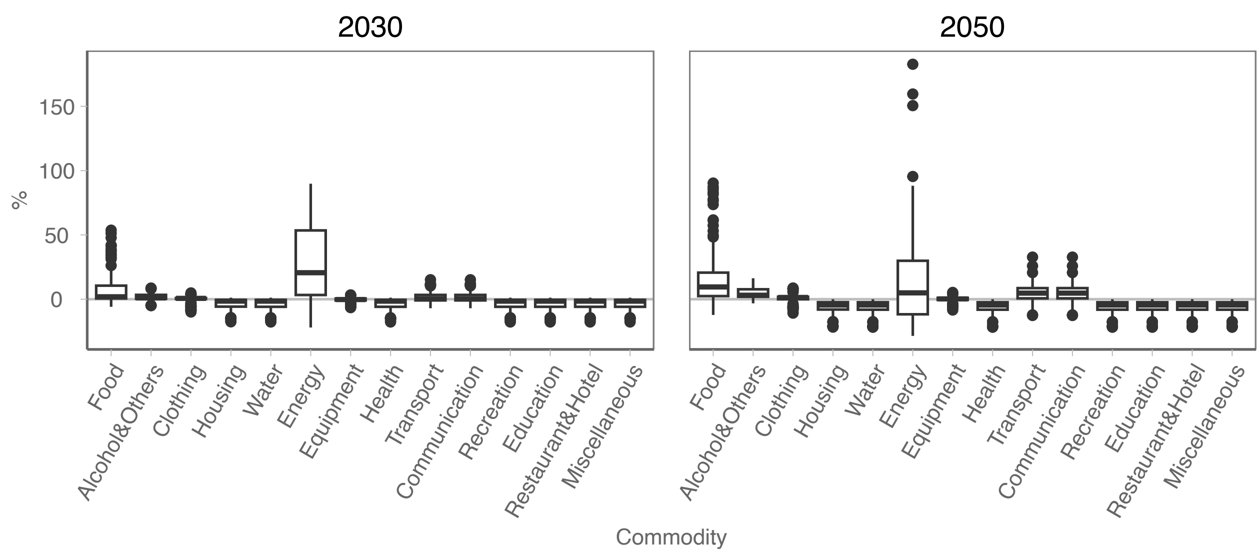


SI. Fig. 9 Percentage change in Gini coefficient under policy scenarios. 1.5˚C scenarios used in the robustness test are included. Plots are labelled as described for SI Fig. 8.

SI 5. Expenditure share and price changes in the household consumption basket



SI. Fig. 10 Household consumption share (national average, cross-country) in 2015, taken from the historical household budget survey (HBS) dataset of AIM-PHI. The historical HBS dataset in AIM-PHI includes the Global Consumption Database managed by the World Bank [20], the EUROSTAT HBS database [21], and multiple national HBS datasets [22–27]. Food expenditure accounts for the largest share of the total household consumption budget.



SI. Fig. 11 Percentage change in prices in the main scenarios compared to baseline prices. Food and energy are the two commodities suffering from the largest price increases. Energy expenditure makes up a smaller share of the household consumption budget than food expenditure, as shown above, supporting our choice of robustness testing for agricultural productivity, which is closely related to food prices.

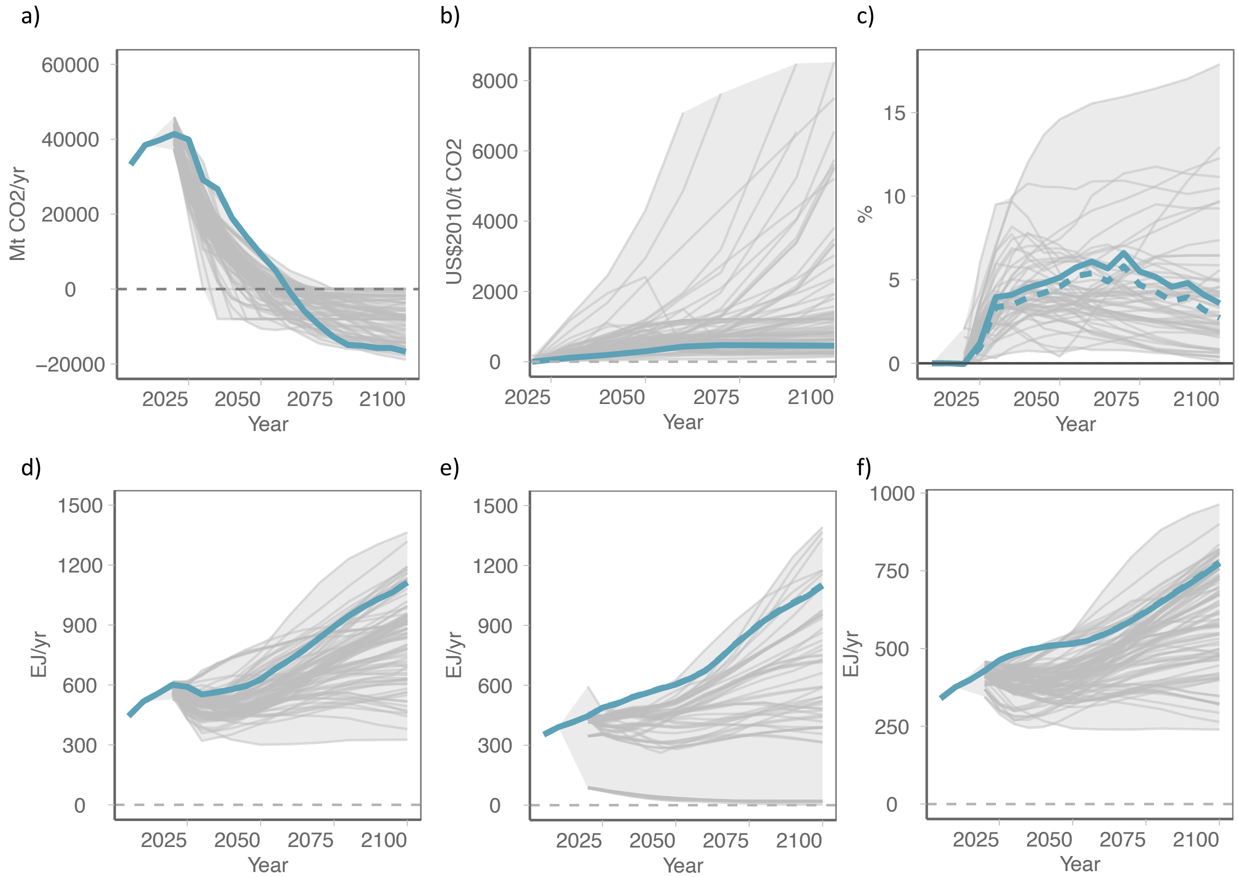
SI 6. Situating our scenarios in the IPCC AR6 scenario ensemble

We compared our 1.5˚C scenarios with the C1 category of scenarios (global pathways that limit warming to 1.5°C (> 50%) with no or limited overshoot assuming immediate action) [28] that passed historical vetting in the IPCC Assessment Report 6 (AR6) database maintained by the International Institute of Applied Systems Analysis [29].

The carbon price trajectories in the carbon pricing scenarios are in the lower range of the scenario ensemble (SI. Fig. ***12*** a). Primary and secondary energy supply and final energy demand fall within the upper range of the scenario ensemble due to the coupling with AIM-Technology. Macroeconomic losses (SI. Fig. ***12*** b, c) and other key energy-related indicators (SI. Table ***3***) are within the middle-upper range.

SI. Table 3 Comparison of key energy-related indicators.

	Year	AR6 C1 scenarios	Our 1.5˚ C scenarios
Final energy demand (EJ/yr)	2020	419 (367-457)	428
	2030	399 (293-447)	483
	2050	410 (325-540)	516
	2100	612 (321-818)	777
Final energy intensity of GDP index (2020 = 100)	2030	71 (59-81)	85.2
	2050	46 (34-60)	60.4
	2100	26 (14-45)	43.0
Electricity share in final energy (%)	2020	20(18-25)	17.8
	2030	27 (23-35)	22.3
	2050	52 (40-64)	46.7
	2100	66 (50-78)	91.8



SI. Fig. 12 Comparison between our main scenarios to the IPCC AR6 scenario ensemble. a) CO_2 emissions trajectory, b) carbon price, c) consumption loss, d) total primary energy supply, e) total secondary energy supply, and f) total final energy demand (summing up all sectors). The grey lines in the background show the trajectories in line with the 1.5C target (C1) in the IPCC AR6 scenario database. The colorful lines show the projections in our scenarios. Carbon price in a) is only relevant in 1.5C CP scenario.

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