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SUPPLEMENTARY INFORMATION

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Sensitivity of projected long-term CO_2 emissions across the Shared Socioeconomic Pathways

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Supplementary Text

Contribution to the existing literature

This paper goes beyond the literature on three main issues: the use of SSP scenarios, the multi-model ensemble, and the algorithm used for the sensitivity analysis. We review the existing literature on these so far separate topics in what follows.

Several emission scenarios have been generated by the research community over the years. The IPCC Special Report on Emission Scenarios [1] described scenarios (SRES) which have been used since the third IPCC assessment report. SRES provided four qualitative stories (families A1, A2, B1, B2) spanning different socio-economic and technical assumptions. Six scenario groups were drawn from the four families. Altogether 40 SRES scenarios were developed by six modeling teams. SRES have been very influential, accumulating almost 3000 citations (according to Google Scholar). However, by now the SRES (published in 2000) are outdated. A new set of future scenario narratives has been recently developed to be used as baseline scenarios. These scenarios, called Shared Socio-economic development Pathways SSPs [2, 3, 4, 5] describe five future evolutions of the world spanning different challenges to mitigation and adaptation. A set of 6 process-based[1] models have interpreted and implemented the SSPs storylines, generating new long-term projections of GHG emissions scenarios [6, 7, 8, 9, 10]. The SSP narratives are summarized in Table S2. We limit this study to the first 3 SSPs, which would be located on the main diagonal of a space with increasing mitigation and adaptation challenges as dimensions. The other two available SSPs (i.e. SSP4 and SSP5) would instead be placed off of this diagonal.

Regarding existing studies exploring the sensitivities of future emissions with IAMs, these focused on either a small set of models, or on individual sensitivities. [11] assessed the sensitivity of the social cost of carbon and GHG emissions to 8 exogenous inputs in the DICE model, a simple and one of the most popular IAMs. [12] explored the uncertainty of baseline emissions as the result of the uncertainty of several inputs conditionally to the SRES scenarios, using the TIMER energy model. [13] provide a recent 4-model exploration of economic and fossil fuel drivers of emissions, focusing on direct OFAT effects. [14] is one of the closest contribution, assessing the role of population, total factor productivity, and climate sensitivity with 6

[1]As opposed to stylized, reduced-form approaches of another class of IAMs, often used for cost-benefit analyses.

IAMs. They also focus on direct OFAT impacts alone, and on a subset of drivers.

Some studies have employed rigorous Global Sensitivity Methods. [15] and [16] provide a large-scale model diagnostic evaluation that explicitly accounts for the parametric interactions and dependencies between coupled climate and economic components. They use the DICE IAM. [17] is the first global sensitivity study featuring multiple (3) models. Their contribution is focused on the costs or performance of five low carbon technologies. [18], using the IMACLIM-R IAM, propose a different 'backwards' approach involving an a-priori identification of drivers, a modelling exercise to transform these drivers into a large set of scenarios, and an a-posteriori selection of a few SSPs using statistical cluster-finding algorithms.

The approach underlying this analysis is similar but unrelated to methods of Index Decomposition Analysis (IDA), like Logarithmic Mean Divisia index (LMDI) [19]. An extensive literature review on the application of IDA to energy-related CO_2 emissions is offered in [20]. Through IDA, it is possible to quantify drivers of change in CO_2 emissions for a certain sector and country, given past data on related quantities. LMDI can be used also on "future" data, e.g. to identify drivers of future emissions reductions, using a dataset of scenarios implemented by an ensemble of IAMs [21]. In our case, since we have access to the data generating process, the perspective is reversed. Models are run for specific sensitivity scenarios, optimized to clearly reveal the role of drivers we consider. Moreover, the LMDI expansion is exact when the decomposition is applied to models like Kaya, which implicitly assume an additive or multiplicative structure. The present decomposition is, instead, model-independent and exact also when the input-output mapping is not multilinear. It is also important to observe that a factor in our analysis is a group of model inputs, that refers to several variables that vary simultaneously (and this is one additional technical difficulty of our analysis compared to previous works).

Methodology

In this analysis, we are dealing with M models, where each model, in principle, has its own input space and input-output mapping. Then, we write $\mathbf{y} = h_m(\boldsymbol{x})$, $\mathbf{y} : \mathcal{X}_m \mapsto \mathcal{Y}^m$, where $\mathcal{X}_m \subseteq R^{n_m}$, and $\mathcal{Y}^m \subseteq R^{q_m}$ are the model input space and model output spaces, and n_m and q_m the number of model inputs and model outputs of model m, respectively. To illustrate the method, let us focus on a single model output $y \in \mathbb{R}$, e.g. global cumulative fossil fuels and industry CO_2 emissions in the period 2010-2050, which is computed by all models and for all values of $\boldsymbol{x} \in \mathcal{X}_m, m = 1, 2, ..., M$.

To find a common ground, we identify a scenario space, i.e. a space with setups implementable across the different IAMs in a consistent way. We describe such scenario space by discrete vectors $\boldsymbol{z} = [z_1, z_2, \ldots, z_n] \in \{0, 1\}^n$. Each component z_i is a factor, or scenario feature, which is model-independent, and can either be at its nominal value (i.e. 0) or deviate to an alternative value (i.e. 1). Here, the factors are POP, GDPPC, END, FF and LC. Nominal levels correspond to SSP2 assumptions, while alternative levels correspond to either SSP1 or SSP3 assumptions. Then, a map is needed to translate these common scenarios to implementable model inputs combinations. We denote this function through $t_m(\cdot) : \{0, 1\}^N \mapsto \chi_m$ for each model. That is $\boldsymbol{x} = t_m(\boldsymbol{z})$. Hence, we can associate each scenario $\boldsymbol{z}$ with a model response $y_m = h_m(t_m(\boldsymbol{z})) = g_m(\boldsymbol{z})$.

When moving from the nominal scenario $\boldsymbol{z}^0 = [0, \ldots, 0]$ to its alternative counterpart $\boldsymbol{z}^1 = [1, \ldots, 1]$, we observe a finite change in the output $\Delta y = g_m(\boldsymbol{z}^1) - g_m(\boldsymbol{z}^0)$. To understand the contributions of the i-th scenario feature z_i to this change, we exploit the link between Placket-Burmann design of experiments and finite change expansion [22, 23]. Dropping the model index m for brevity, we have:

$$\Delta y = g(\boldsymbol{z}^1) - g(\boldsymbol{z}^0) = \sum_{i=1}^{n} \Delta_i g + \sum_{i<j}^{n} \Delta_{i,j} g + \cdots + \Delta_{1,2,\ldots,n} g \qquad (1)$$

where:

- $\Delta_i g = g([z_1^0, z_2^0, \ldots, z_{i-1}^0, z_i^1, z_{i+1}^0, \ldots, z_n^0]) - g(\boldsymbol{z}^0)$ is the observed change in output due to the individual change in the i-th scenario input;
- $\Delta_{i,j} g = g([z_1^0, z_2^0, \ldots, z_{i-1}^0, z_i^1, z_{i+1}^0, \ldots, z_{j-1}^0, z_j^1, z_{j+1}^0, \ldots, z_n^0]) - \Delta_i g - \Delta_j g - g(\boldsymbol{z}^0)$ is the change in output due to the simultaneous change in scenario inputs i and j net of the sum of the individual effects of i and j;
- and likewise for higher order terms such as $\Delta_{i,j,k} g$.

This expansion is strictly related to Efron and Stein's functional ANOVA expansion of a multivariate mapping [24].

One then summarizes the individual, interaction and total effect of each model input in the following sensitivity indices:

- $\phi_l^1 = \Delta_l g$ and its normalized version $\Phi_l^1 = \dfrac{\phi_l^I}{\Delta y}$ will be referred to as the *individual effect* of input l;

- $\phi_i^T = \sum_{k=1}^n \sum_{i \in i_1, i_2, \ldots, i_k; i_1 < \ldots < i_k} \Delta_{i_1, \ldots, i_k} g$ and its normalized version $\Phi_i = \dfrac{\phi_i^T}{\Delta y}$ will be referred to as the *total effect* of input i, including all the finite changes terms involving that input;

- $\phi_i^{\mathcal{I}} = \phi_l^T - \phi_l^1$ will be referred to as the *interaction effect* of input i, and will be equal to the sum of all contributions to Δy involving a change in model input i.

The number of interacting terms determining the total effect is exponential in the number of inputs (equal to $2^n - 1$, in principle). Nonetheless, a shortcut exists to evaluate the total effects with a number of evaluations of y (and thus runs of a model) linear in the number of inputs. This depends on the fact that total effects can be also calculated as [22, 23]:

$$\phi_i^T = g(\boldsymbol{z}^1) - g([z_1^1, z_2^1, \ldots, z_{i-1}^1, z_i^0, z_{i+1}^1, \ldots, z_n^1]) \qquad (2)$$

Then, it is possible to compute all ϕ_i^1, ϕ_i^T and $\phi_i^{\mathcal{I}}$ at $2n+1$ model evaluations. This design motivates the table of runs of each model (see Table S4).

Individual and total indices are useful in sensitivity analysis, because we can answer questions such as:

1. What is the direction of change associated with the individual variations in the z_i's?

2. Is the presence of interactions relevant?

3. Do alternative IAMs respond to the same changes in the same way?

4. What is the factor that drives the changes the most?

Coming back to the comparison with LMDI, we note that, while both approaches aim to specify the relationship between the output (CO_2 emissions) and the key model drivers, the chosen method turns out to be more suitable for the present evaluation.

Climate policy

In the CPRICE scenarios, a global carbon price equal to 30 US$2005/tCO2eq in 2040, starting in 2020 and increasing at 5%/yr is applied. Figure S5 illustrates the resulting temporal evolution until 2050, and compares it with the range of average carbon prices between 2025 and 2030 compatible with NDC and AR5 2C scenarios, as reported in [25]. Figure S6 compares the corresponding emissions profiles. The adopted climate policy can be considered as consistent with the climate stringency of NDC in the short-term, and with a possible continuation of a similar level of stringency in the long-run. However, this is likely not enough to keep global warming in the 2C threshold by the end of the century. The difference in emissions with SSP2 is shown in Figure S7.

Elasticities

To account for the different magnitude of the factor changes, we performed a further analysis utilizing elasticities as sensitivity measures. Such elasticities provide an indication of the response of the model to a unitary variation in a factor, assuming a constant slope in the response (a restricting but much used assumption). The composite nature of the factors we consider does not allow a straightforward definition of unit changes in those factors and, consequently, an evaluation of their relative unitary effects on emissions. As usual, we focus on percentage changes in global cumulative CO_2 emissions from fossil fuels and industry, when passing from SSP2 to either SSP1 or SSP3. Then, for each factor, we normalize by the percentage change in a correlated scalar variable: for POP we choose global population, for GDPPC global GDP per capita, for END global final energy per unit of GDP, and for FF and LC global emissions per unit of GDP. Change is considered both when moving either a single factor or all the other factors together, as already done for the calculation of individual and total effects. We just focus on absolute quantities. These ratios, or elasticities, are shown for the year 2050 and the BASE policy in Figure S13. Population remains a marginal driver. Resource and technological assumptions have in general a greater impact on emissions per unit of carbon intensity increased (for FF) or reduced (for LC). GDPPC seems less impacting in SSP1 per unit of GDP per capita. A different exercise would be needed to further elaborate on this topic.

Robustness to different time horizons and climate policies

Figure S10 and S12 provide a different perspective on the changes in sensitivity measures when considering different time horizons or climate policies, extending Table 1 and the tornado Figures S9 and S11. The left-hand side of each subplot illustrates the average movement across models of the sensitivities. When moving from BASE to CPRICE (Figure S10), emissions reduce, and the magnitude of total effects of drivers tend to shrink. In SSP3 we find some exceptions, as GDPPC and LC become marginally more important in magnitude. When moving to a more challenging world, a climate policy seems to stress the importance of reduced wealth and low-carbon availability in determining future emissions.

When considering the second half of the century (Figure S12), the effect on emissions is amplified across all factors. The change which is more visible and consistent across models and SSPs is an increse in the interaction effects of GDPPC. Over time, the inter-dependence of economic growth assumptions with all the other assumptions in affecting emissions becomes greater. This translates into a greater total effect of GDPPC in SSP3 (i.e. interactions amplify the total effect), and a relatively lower total effect in SSP1 (i.e. interactions dampen the total effect), with the same opposite dynamics we discussed in the main text for the short-term. On average, also the total effect of END grows relatively more than FF, LC and POP, with the main findings of paper relative to the period 2010-2050 being reinforced as we look further into the future.

Supplementary Figures

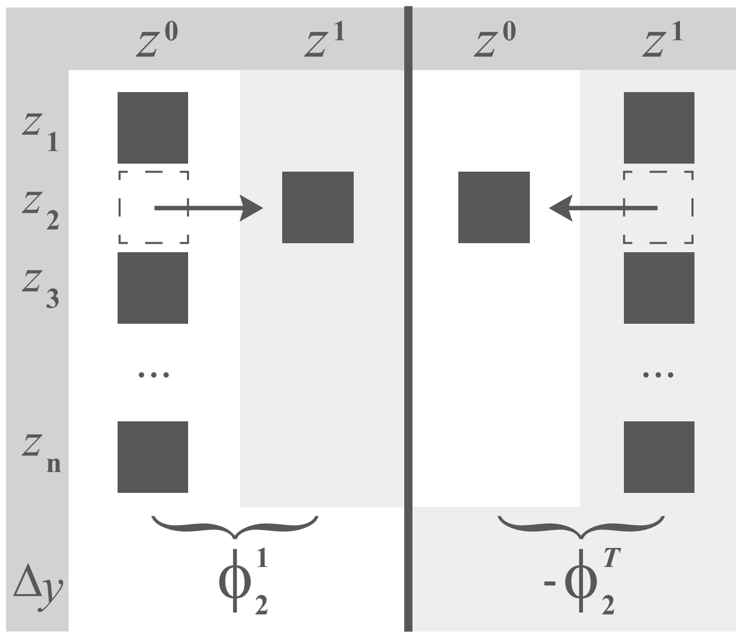

Figure S1: Logic underlying the scenario design for the sensitivity analysis [23]. Left: a given factor z_l (e.g. GDPPC) among the n considered (i.e. the 5 factors) is moved from a reference level of scenario $\boldsymbol{z}^0$ (i.e. SSP2) to an alternative level of scenario $\boldsymbol{z}^1$ (i.e. SSP1 or SSP3). The difference in outputs (e.g. cumulative emissions) yields the individual effect ϕ_l^1 of factor l on the output. Right: all factors but z_l are moved to the alternative level from the reference level. With a change in sign, the difference in outputs yields the total effect ϕ_l^T. The difference between total and individual effects are the interactions.

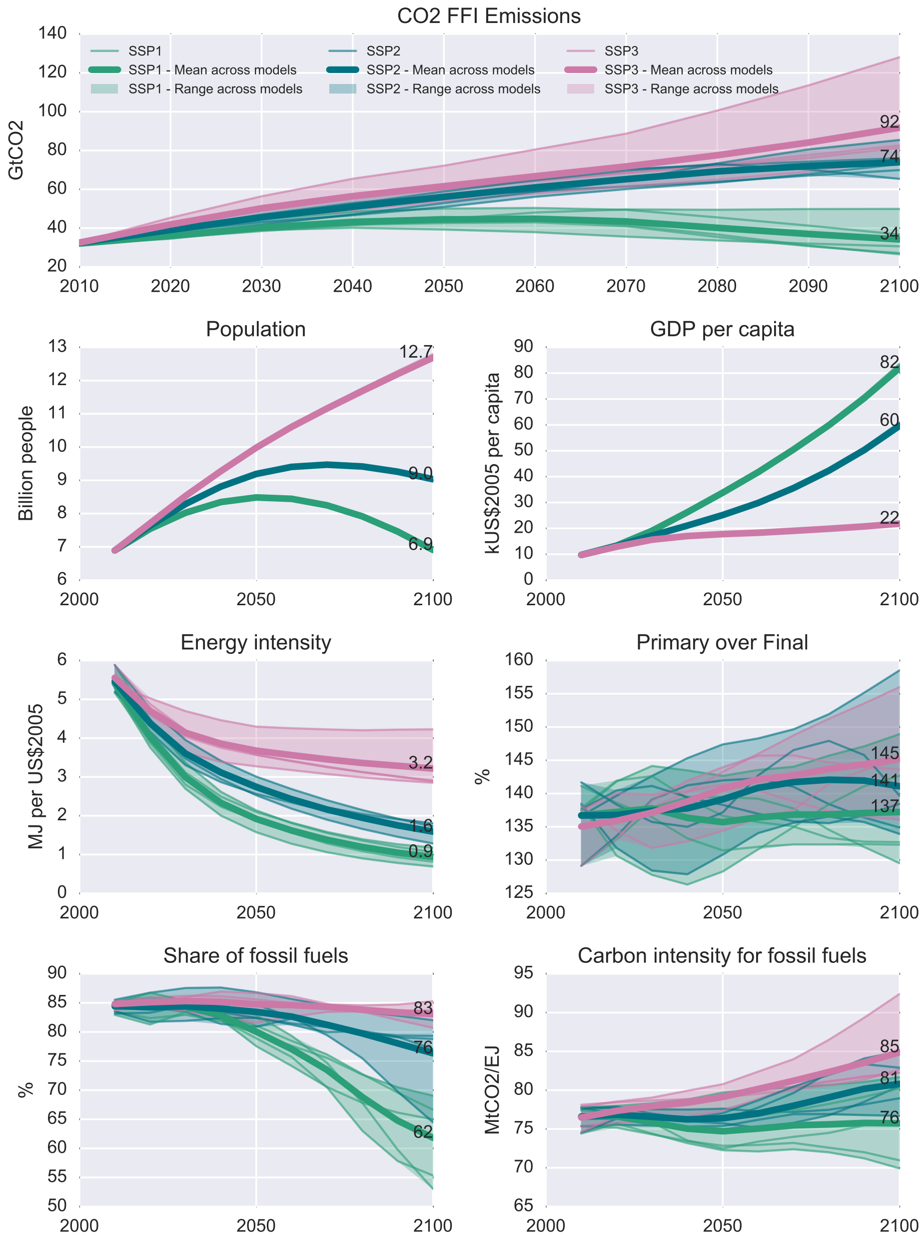

Figure S2: CO_2 emissions from Fossil Fuels and Industry with potential drivers as quantified by the 5 SSP marker models and reported in the SSP online database. First row: yearly CO_2 FFI emissions throughout the century. Second row: yearly world population (left); yearly GDP (PPP) per capita (right). Third row: yearly final energy per unit of GDP (PPP) (left); yearly primary energy over final energy (right). Fourth row: yearly share of primary oil, coal and gas supply over all primary energy supply (left); yearly CO_2 FFI emissions per unit of primary fossil supply (right).

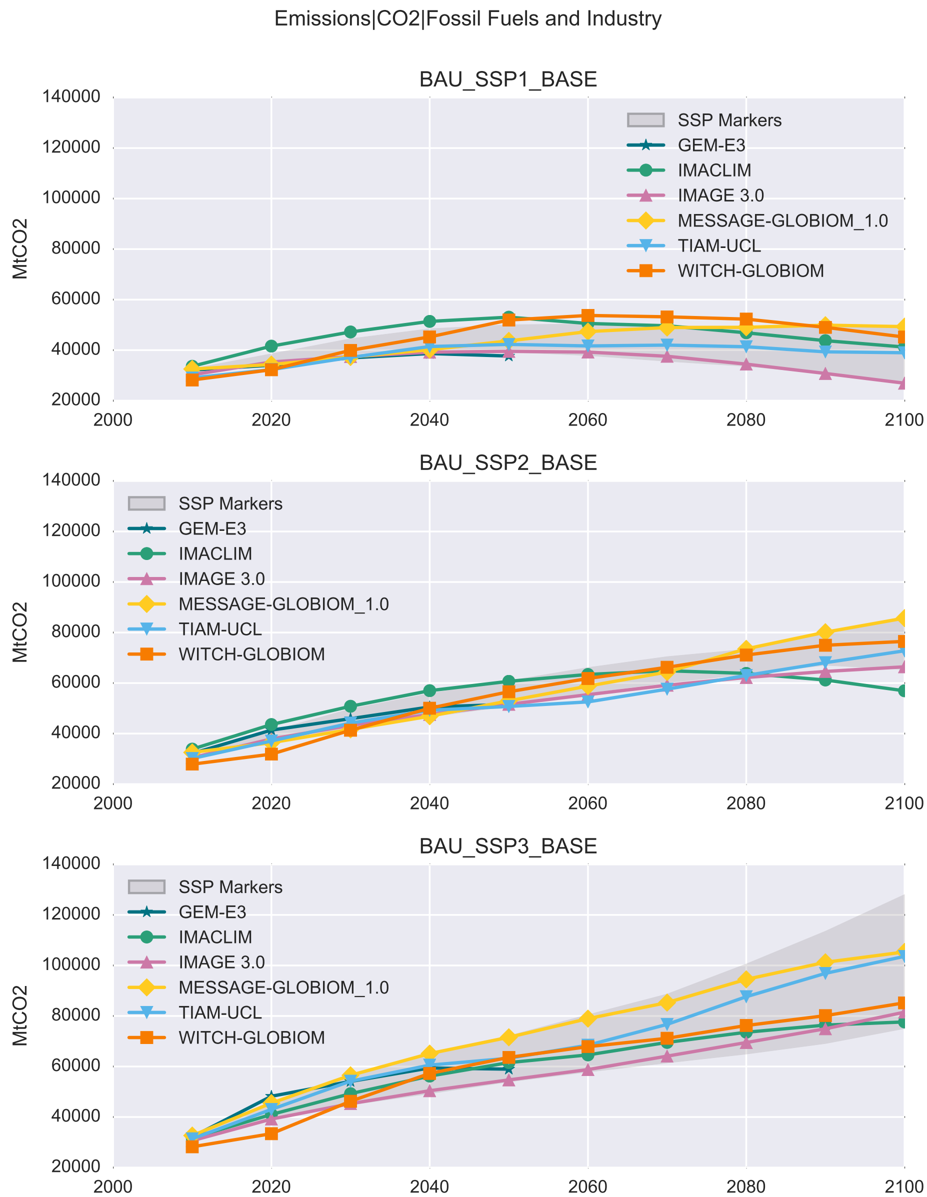

Figure S3: CO_2 emissions from Fossil Fuels and Industry across BASE SSP1, SSP2 and SSP3 scenarios, as implemented in this exercise.

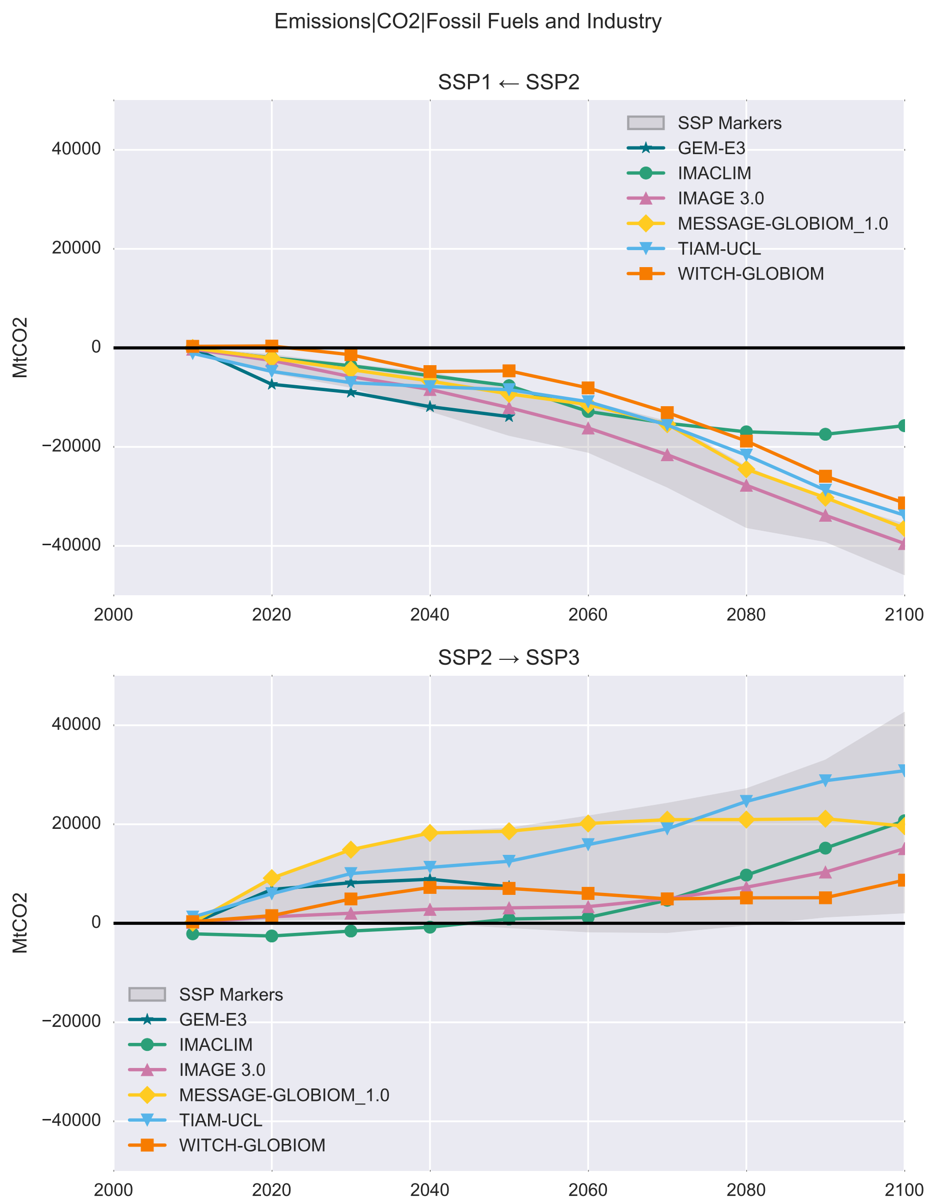

Figure S4: CO_2 emissions from Fossil Fuels and Industry difference between BASE SSP2 and either SSP1 or SSP3 scenarios, as implemented in this exercise. With solid colored lines: results from the 6 models. Black line: 0 difference with SSP2. In dark grey: min-max range for the SSPDB.

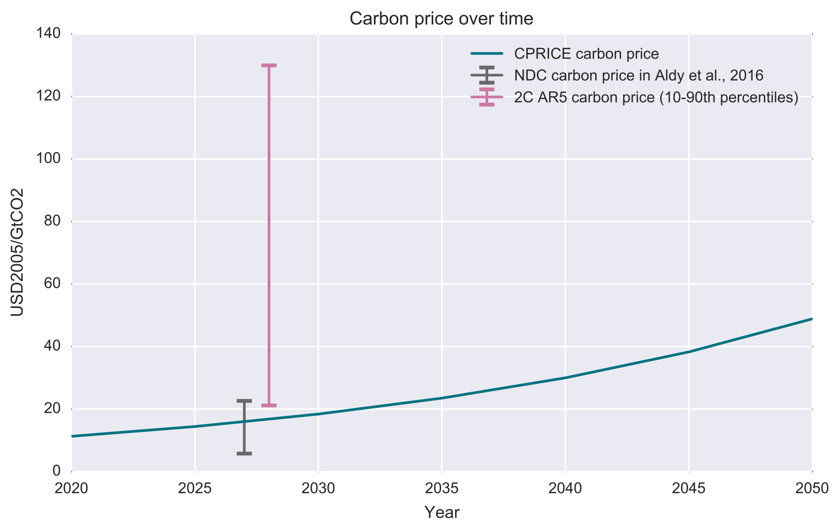

Figure S5: Global carbon price over time applied in the CPRICE scenarios of this study, in comparison with that of AR5 2C and NDC scenarios of [25].

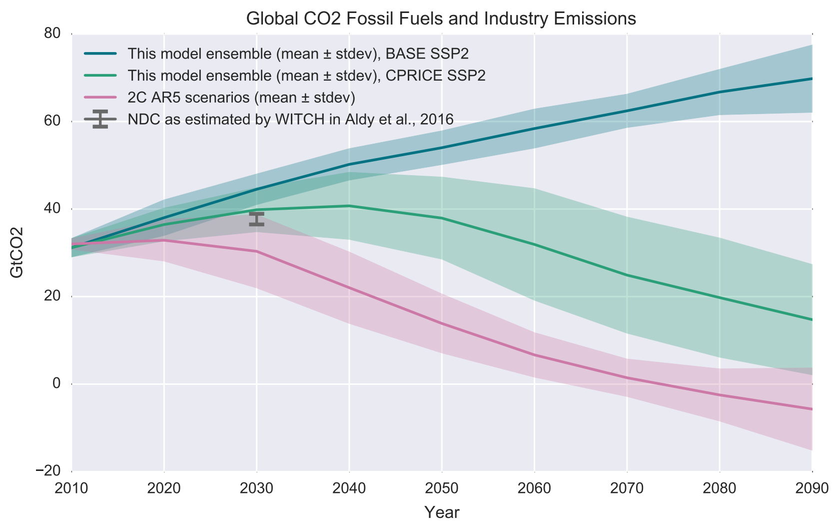

Figure S6: CO_2 emissions from Fossil Fuels and Industry over time, comparing BASE SSP2 and CPRICE SSP2 reference scenarios in this study with AR5 2C and NDC scenarios of [25].

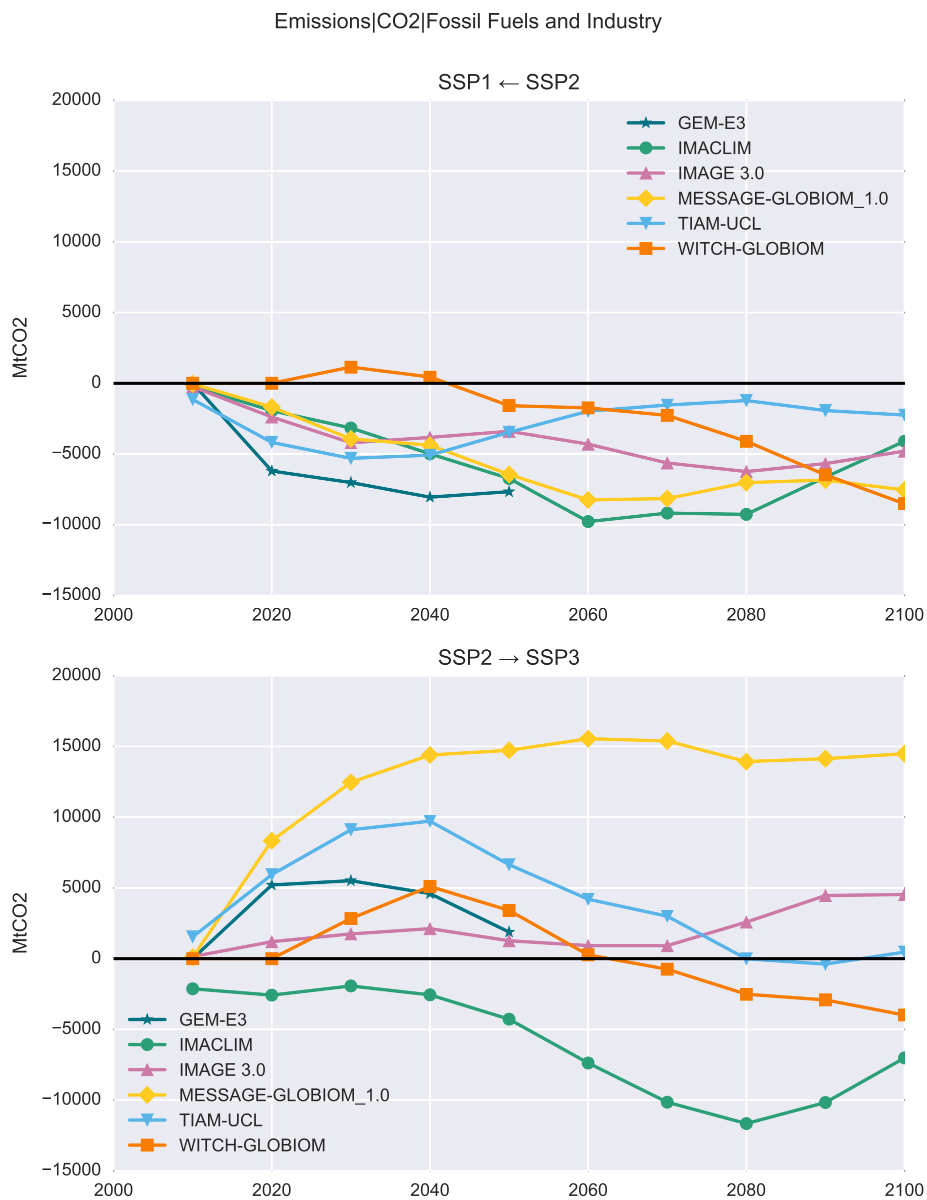

Figure S7: Difference in CO_2 emissions from Fossil Fuels and Industry between CPRICE SSP2 and either SSP1 or SSP3 scenarios, as implemented in this exercise. With solid colored lines: results from the 6 models. Black line: 0 difference with SSP2.

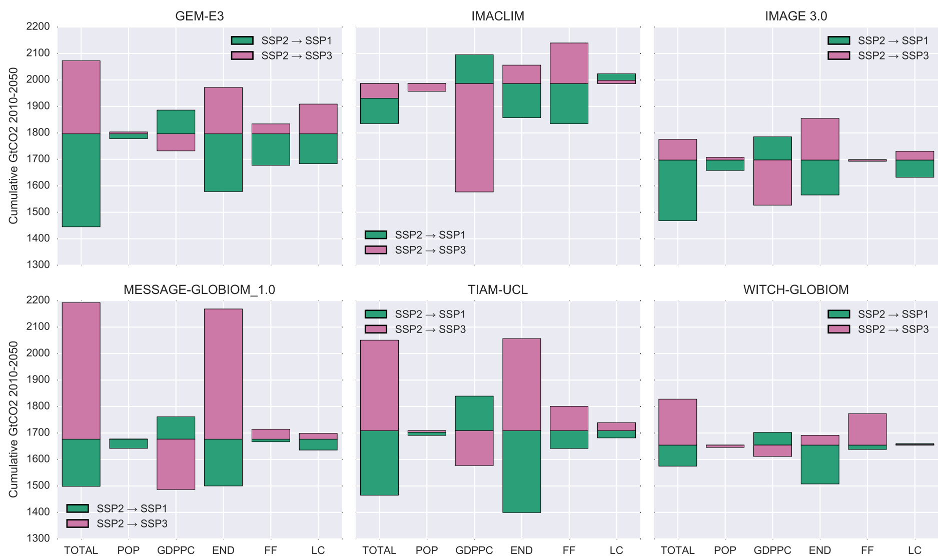

Figure S8: Total effects on cumulative CO_2 Fossil Fuels and Industry till 2050 under BASE, in $GtCO_2$, for each model.

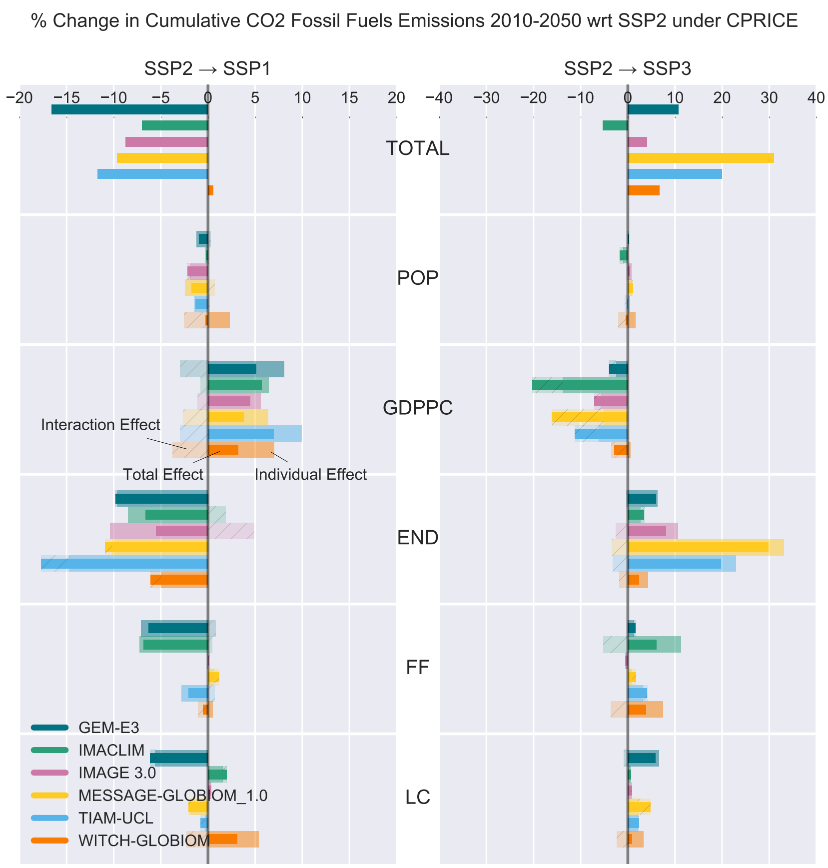

Figure S9: Generalized tornado plot of cumulative CO_2 Fossil Fuels and Industry emissions (2010-2050) change from SSP2 to either SSP1 (left) or SSP3 (right) under CPRICE, for each of the 6 IAMs. TOTAL refers to total emission changes, and the rows below show emission changes for each of the five factors. Individual effects are reported with transparent thicker bars, total effects with solid thinner bars and interaction effects with striped bars.

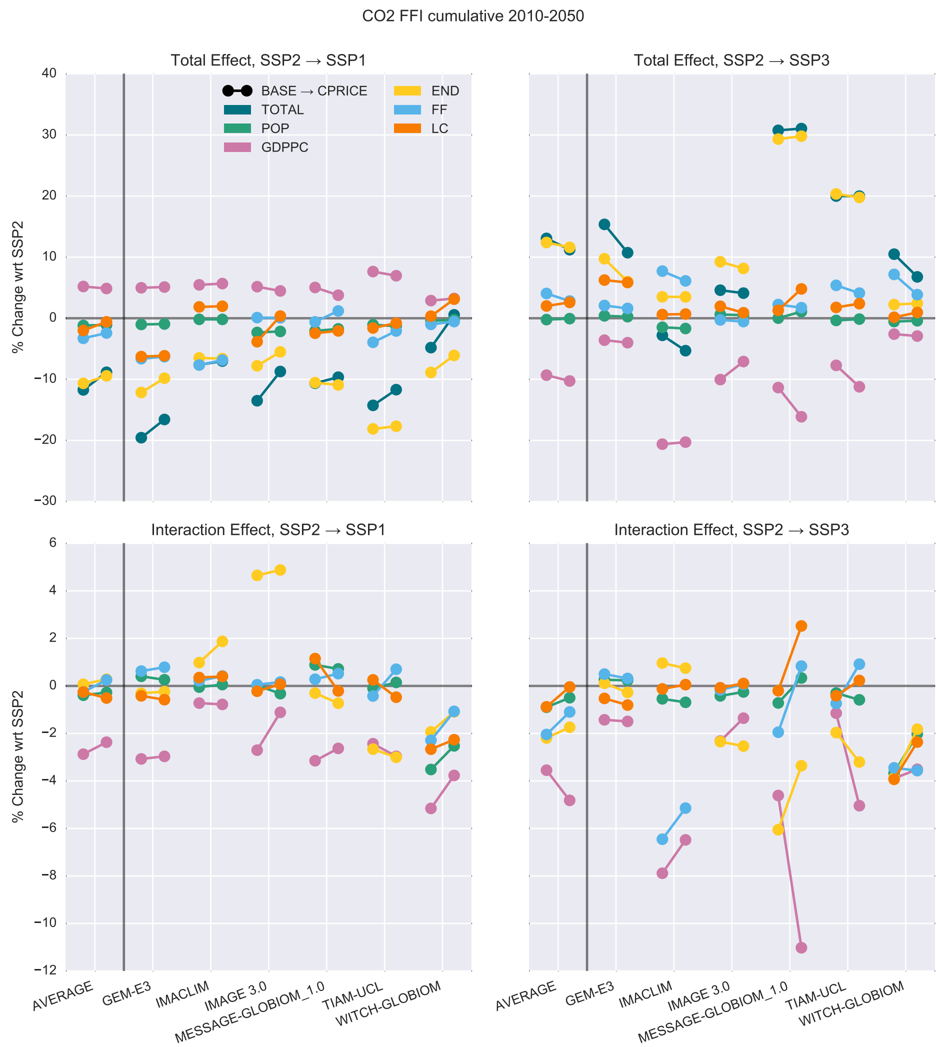

Figure S10: Total and interaction effects on cumulative CO_2 Fossil Fuels and Industry emissions till 2050, when moving from BASE to CPRICE case, for each model. Average effects across models are added on the left of each subplot.

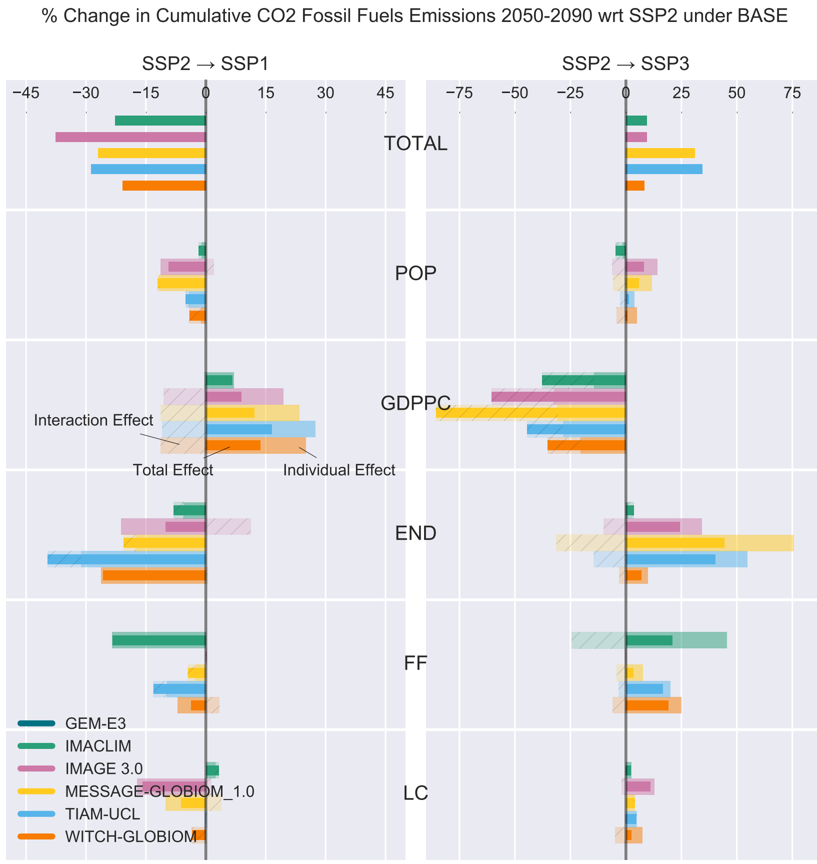

Figure S11: Generalized tornado plot of cumulative CO_2 Fossil Fuels and Industry emissions (2050-2090) change from SSP2 to either SSP1 (left) or SSP3 (right) under BASE, for each of the 6 IAMs. TOTAL refers to total emission changes, and the rows below show emission changes for each of the five factors. Individual effects are reported with transparent thicker bars, total effects with solid thinner bars and interaction effects with striped bars.

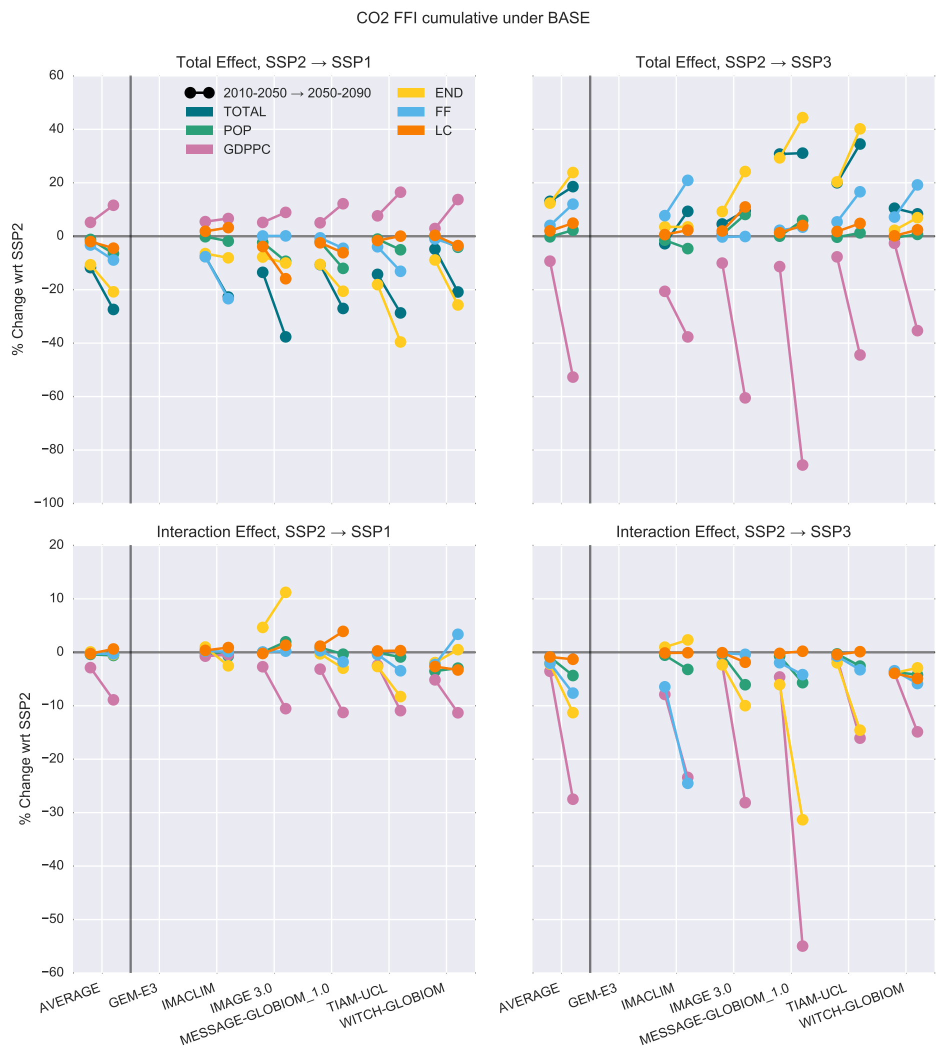

Figure S12: Total and interaction effects on cumulative CO_2 Fossil Fuels and Industry emissions under BASE, when moving from period 2010-2050 to 2050-2090, for each model. Average effects across models are added on the left of each subplot.

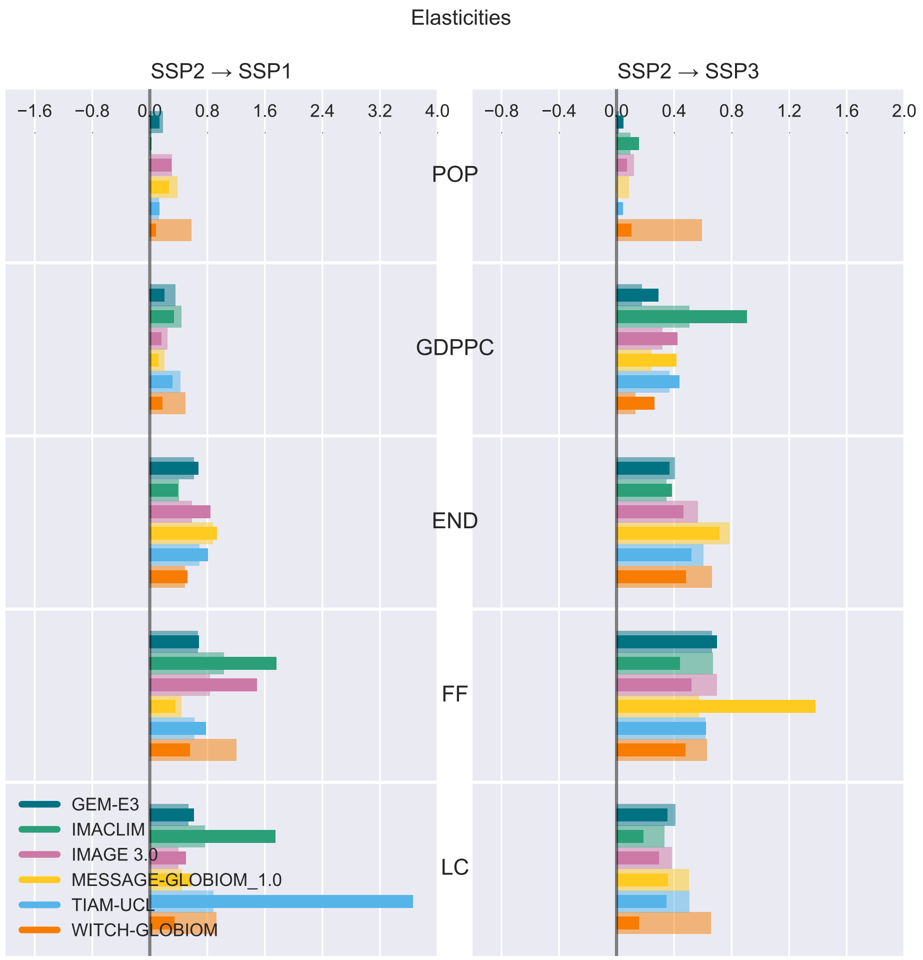

Figure S13: Normalized sensitivities. Percentage change of cumulative CO_2 Fossil Fuels and Industry emissions divided by percentage change of population (POP), GDP per capita (GDPPC), final energy per unit of GDP (END), and emissions per unit of GDP (FF, LC). These ratios provide normalized results on the magnitude of the drivers in parenthesis, and bring some evidence on the elasticities of the factors in parethensis. All quantities are evaluated in 2050 at the global level under the BASE scenario, considering both individual and total effects, in absolute terms.

Supplementary Tables

Table S1: The set of models involved in the experiment.

Model	GEM-E3 [26]	IMACLIM [27]	IMAGE [28]	MESSAGE-GLOBIOM [7, 29]	TIAM-UCL [30]	WITCH [31]
Institute	NTUA, E3M Lab	CIRED	PBL, UU	IIASA	UCL	FEEM, CMCC
Model concept	General equilibrium	Hybrid: general equilibrium with technology explicit modules	Simulation	General equilibrium soft-linked with energy engineering partial equilibrium model	Energy partial equilibrium	Optimal economic growth model + Bottom-up energy sector + Nash game
Solution concept	Recursive dynamic	Recursive dynamic	Recursive dynamic	Optimization (linear for energy, non-linear for economy)	Linear optimization	Non-linear optimization + Tatonnement for Nash equilibrium
Model anticipation	Myopic	Myopic		Perfect foresight	Perfect foresight	Perfect foresight
Regions	38	12	26	11	16	13
Time horizon	2004-2050	2001-2100	1970-2100	1990-2110	2005-2100	2005-2150
Time step (# of years)	5	1	5	5 (until 2010), 10 (after 2010)	10	5
Economic sectors[3]	Energy and Non-energy	Energy and Non-energy	Energy	Energy	Energy	Energy
Energy Service sectors	All	All	All	All	All	Transport vs Rest
GHGs	All	CO2	All	All	CO2, CH4, N2O	All

[3]We distinguish models that have a single economic sector coupled with a detailed representation of the energy sector ("Energy" in the table), from those that model multiple economic sectors beyond the energy one.

Table S2: SSP narratives description, from [10].

#	Narrative
SSP1	Sustainability - Taking the Green Road (Low challenges to mitigation and adaptation) The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
SSP2	Middle of the Road (Medium challenges to mitigation and adaptation) - The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.
SSP3	Regional Rivalry - A Rocky Road (High challenges to mitigation and adaptation) A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

Table S3: List of parameters belonging to the five factor changed across SSP levels, according to the implementation of each modelling team.

Model	POP	GDPPC	END	FF	LC
GEM-E3	Total population; subsistence minima parameters.	Technical change factors of skilled and unskilled labor (adjusted to get target GDP per capita).	Technical change and energy intensity factors in firms and households.	Reserves of crude oil; regional prices of coal and gas (adjusted to different levels starting from ROSE project estimates).	Maturity and learning-by-doing rates of renewable energy technologies.
IMACLIM	Total and active population.	Labor productivity growth.	Motorisation rate; residential space; industrial goods consumption increase with wealth.	Extraction costs and availability of unconventional oil/gas.	Learning-by-doing rates and maximum potential of renewable energy technologies (changed in the opposite direction for nuclear).
IMAGE	Total population.	GDP.	Preference factor for low carbon or traditional fuels; energy intensity for services.	Learning factors; trade barriers.	Learning factors of renewable energy technologies and hydrogen (opposite preference for nuclear); support for renewables capacity.
MESSAGE-GLOBIOM	Total population (directly used in the parameterization of energy demands).	Growth rates of total labor in MACRO (macro-economic model soft-linked with MESSAGE), representing the combined effect of labor force and labor productivity growth (recalibrated in the scenarios that directly influence energy demands by changing POP, GDPPC, END, also using sector-specific AEEI coefficients in addition to labor productivity change parameters).	Energy intensity improvement; maximum fuel shares (e.g., rate of electrification in transport); availability and cost of end-use technologies (e.g., hydrogen fuel cell availability, cost of industrial boilers).	Extraction costs and availability of oil/gas/coal; cost and availability of fossil conversion technologies (including technologies with carbon capture and storage).	Investment, operation and maintenance costs renewable energy technologies, as well as resource availability; plant load factors of nuclear power plants.
TIAM-UCL	Total population.	GDP.	Demand curves exponents.	Extraction costs for fossil fuels; temporal trajectory of the cost trends (without changing total cumulative availability).	Maximum annual nuclear growth rate; capital costs of non-biomass renewables; biomass availability and supply costs.
WITCH-GLOBIOM	Total population.	Labor productivity growth.	Factor productivity of energy in final good production; transport fuel efficiency; travel intensity.	Reserves and extraction costs of fossil fuels.	Learning-by-doing rates of renewable energy technologies and battery; investments, operation and maintenance costs of nuclear.

Remark for MESSAGE-GLOBIOM in Table S3. In all scenario variants explored in this global sensitivity analysis, the GLOBIOM land-use representation from SSP2 has been used. As a result, only SSP2 BASE is consistent with the SSP implementation of MESSAGE-GLOBIOM while SSP1 and SSP3 are by design deviating from the official SSP implementations as documented in [7] and [10]. While the internal consistency of the SSPs is affected by this approach, a systematic comparison of these scenarios with the original SSP implementation show that impacts on overall fossil fuel use in baseline scenarios is very modest and also the resulting changes in fossil fuel and industrial CO2 emissions, the primary variable of interest in this study, are small (some 2% by 2100). By contrast quite significant impacts on biomass use are observed for two reasons, (i) the traditional biomass potential is factored into the cheapest category and when pairing this with higher/lower traditional biomass demand the remaining biomass for commercial applications change, and (ii) in particular in the long run the demographic effect and the resulting difference in pressure on land are quite significant in the SSPs.

Table S4: Names and details of the scenarios needed for the decomposition analysis and implemented by modellers. Each number under an input column refers to the SSP base scenario from which the setup for that input is taken.

#	Scenario Name	POP	GDPPC	END	FF	LC
1	SSP2_BASE	2	2	2	2	2
2	SSP2_POP1	1	2	2	2	2
3	SSP2_GDPPC1	2	1	2	2	2
4	SSP2_END1	2	2	1	2	2
5	SSP2_FF1	2	2	2	1	2
6	SSP2_LC1	2	2	2	2	1
7	SSP2_POP3	3	2	2	2	2
8	SSP2_GDPPC3	2	3	2	2	2
9	SSP2_END3	2	2	3	2	2
10	SSP2_FF3	2	2	2	3	2
11	SSP2_LC3	2	2	2	2	3
12	SSP1_BASE	1	1	1	1	1
13	SSP1_POP2	2	1	1	1	1
14	SSP1_GDPPC2	1	2	1	1	1
15	SSP1_END2	1	1	2	1	1
16	SSP1_FF2	1	1	1	2	1
17	SSP1_LC2	1	1	1	1	2
18	SSP3_BASE	3	3	3	3	3
19	SSP3_POP2	2	3	3	3	3
20	SSP3_GDPPC2	3	2	3	3	3
21	SSP3_END2	3	3	2	3	3
22	SSP3_FF2	3	3	3	2	3
23	SSP3_LC2	3	3	3	3	2

References

[1] Nakicenovic, N. *et al.* Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. Tech. Rep., Pacific Northwest National Laboratory, Richland, WA (US), Environmental Molecular Sciences Laboratory (US) (2000). URL http://www.osti.gov/scitech/biblio/15009867. 02912.

[2] Moss, R. H. *et al.* The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756 (2010). URL http://www.nature.com/nature/journal/v463/n7282/abs/nature08823.html.

[3] van Vuuren, D. P. *et al.* A new scenario framework for climate change research: scenario matrix architecture. *Climatic Change* **122**, 373–386 (2013). URL http://dx.doi.org/10.1007/s10584-013-0906-1.

[4] O'Neill, B. C. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* **122**, 387–400 (2013). URL http://dx.doi.org/10.1007/s10584-013-0905-2.

[5] Kriegler, E. *et al.* A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change* **122**, 401–414 (2014). URL http://dx.doi.org/10.1007/s10584-013-0971-5.

[6] van Vuuren, D. P. *et al.* Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change* (2016). URL http://www.sciencedirect.com/science/article/pii/S095937801630067X. 00002.

[7] Fricko, O. *et al.* The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change* (2016). URL http://www.sciencedirect.com/science/article/pii/S0959378016300784. 00001.

[8] Fujimori, S. *et al.* SSP3: AIM implementation of shared socioeconomic pathways. *Global Environmental Change* (2016). URL http://dx.doi.org/10.1016/j.gloenvcha.2016.06.009.

[9] Bauer, N. *et al.* Shared socio-economic pathways of the energy sector – quantifying the narratives. *Global Environmental Change* (2016). URL http://dx.doi.org/10.1016/j.gloenvcha.2016.07.006.

[10] Riahi, K. *et al.* The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* (2016). URL http://dx.doi.org/10.1016/j.gloenvcha.2016.05.009.

[11] Nordhaus, W. D. *A question of balance: economic modeling of global warming* (Yale University Press New Haven, 2008). 00163.

[12] van Vuuren, D. P., de Vries, B., Beusen, A. & Heuberger, P. S. C. Conditional probabilistic estimates of 21st century greenhouse gas emissions based on the storylines of the IPCC-SRES scenarios. *Global Environmental Change* **18**, 635–654 (2008). URL http://www.sciencedirect.com/science/article/pii/S0959378008000460. 00035.

[13] Kriegler, E. *et al.* Will economic growth and fossil fuel scarcity help or hinder climate stabilization? *Climatic Change* 1–16 (2016). URL http://link.springer.com/article/10.1007/s10584-016-1668-3. 00000.

[14] Gillingham, K. *et al.* Modeling Uncertainty in Climate Change: A Multi-Model Comparison. Tech. Rep., National Bureau of Economic Research (2015). URL http://www.nber.org/papers/w21637. 00003.

[15] Anderson, B., Borgonovo, E., Galeotti, M. & Roson, R. Uncertainty in Climate Change Modeling: Can Global Sensitivity Analysis Be of Help? *Risk Analysis* **34**, 271–293 (2014). URL http://onlinelibrary.wiley.com/doi/10.1111/risa.12117/abstract. 00000.

[16] Butler, M. P., Reed, P. M., Fisher-Vanden, K., Keller, K. & Wagener, T. Identifying parametric controls and dependencies in integrated assessment models using global sensitivity analysis. *Environmental Modelling & Software* **59**, 10–29 (2014). URL http://www.sciencedirect.com/science/article/pii/S1364815214001327.

[17] Bosetti, V. *et al.* Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy* **80**, 244–263 (2015). URL http://www.sciencedirect.com/science/article/pii/S0301421514006776. 00007.

[18] Rozenberg, J., Guivarch, C., Lempert, R. & Hallegatte, S. Building SSPs for climate policy analysis: a scenario elicitation methodology to map the space of possible future challenges to mitigation and adaptation. *Climatic Change* **122**, 509–522 (2013). URL http://link.springer.com/article/10.1007/s10584-013-0904-3. 00021.

[19] Ang, B. LMDI decomposition approach: A guide for implementation. *Energy Policy* **86**, 233–238 (2015). URL http://dx.doi.org/10.1016/j.enpol.2015.07.007.

[20] Xu, X. & Ang, B. Index decomposition analysis applied to CO2 emission studies. *Ecological Economics* **93**, 313–329 (2013). URL http://dx.doi.org/10.1016/j.ecolecon.2013.06.007.

[21] Marcucci, A. & Fragkos, P. Drivers of regional decarbonization through 2100: A multi-model decomposition analysis. *Energy Economics* **51**, 111–124 (2015). URL http://dx.doi.org/10.1016/j.eneco.2015.06.009.

[22] Borgonovo, E. Sensitivity analysis with finite changes: An application to modified EOQ models. *European Journal of Operational Research* **200**, 127–138 (2010). URL http://www.sciencedirect.com/science/article/pii/S0377221708010631. 00028.

[23] Borgonovo, E. A methodology for determining interactions in probabilistic safety assessment models by varying one parameter at a time. *Risk Analysis* **30**, 385–399 (2010). URL http://dx.doi.org/10.1111/j.1539-6924.2010.01372.x.

[24] Efron, B. & Stein, C. The jackknife estimate of variance. *The Annals of Statistics* 586–596 (1981).

[25] Aldy, J. *et al.* Economic tools to promote transparency and comparability in the paris agreement. *Nature Climate Change* (2016). URL http://dx.doi.org/10.1038/nclimate3106.

[26] Capros, P. *et al.* GEM-E3 model documentation. *JRC Scientific and Policy Reports* **26034** (2013). URL ftp://s-jrcsvqpx102p.jrc.es/pub/EURdoc/EURdoc/JRC83177.pdf. 00014.

[27] Waisman, H., Guivarch, C., Grazi, F. & Hourcade, J. C. The Imaclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change* **114**, 101–120 (2012). URL http://link.springer.com/article/10.1007/s10584-011-0387-z. 00050.

[28] Stehfest, E. *et al.* *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, in, PBL Netherlands Environmental Assessment Agency The Hague* (2014). 00002.

[29] Krey, V. *et al.* Message-globiom 1.0 documentation. Tech. Rep., International Institute for Applied Systems Analysis (IIASA) (2016). URL http://data.ene.iiasa.ac.at/message-globiom/.

[30] Anandarajah, G., Pye, S., Usher, W., Kesicki, F. & Mcglade, C. TIAM-UCL Global Model Documentation (2011). URL http://discovery.ucl.ac.uk/1413198/.

[31] Emmerling, J. *et al.* The WITCH 2016 Model-Documentation and Implementation of the Shared Socioeconomic Pathways (2016). URL http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2800970.