Supplementary Material

"The Shared Socioeconomic Pathways and their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview"

In this document, we present additional information to support the results and findings in the main article. This includes additional figures, descriptions of the overall scenario set-up, the participating modeling teams, the implementation of the SSPs, and the implementation of forcing targets and the shared policy assumptions. The original modelling protocols, describing in detail the instructions to the modelling teams for the different aspects of the SSPs are added as Appendix A, B and C.

Contents

1. Additional Figures

Several figures on emissions, forcing, and costs could not be included in the main paper as a result of space constraints and have therefore been included in this Supplementary Information.

Figure S1: Same as Figure 5 in the main paper, but showing emissions and forcing pathways of the SSP mitigation scenarios

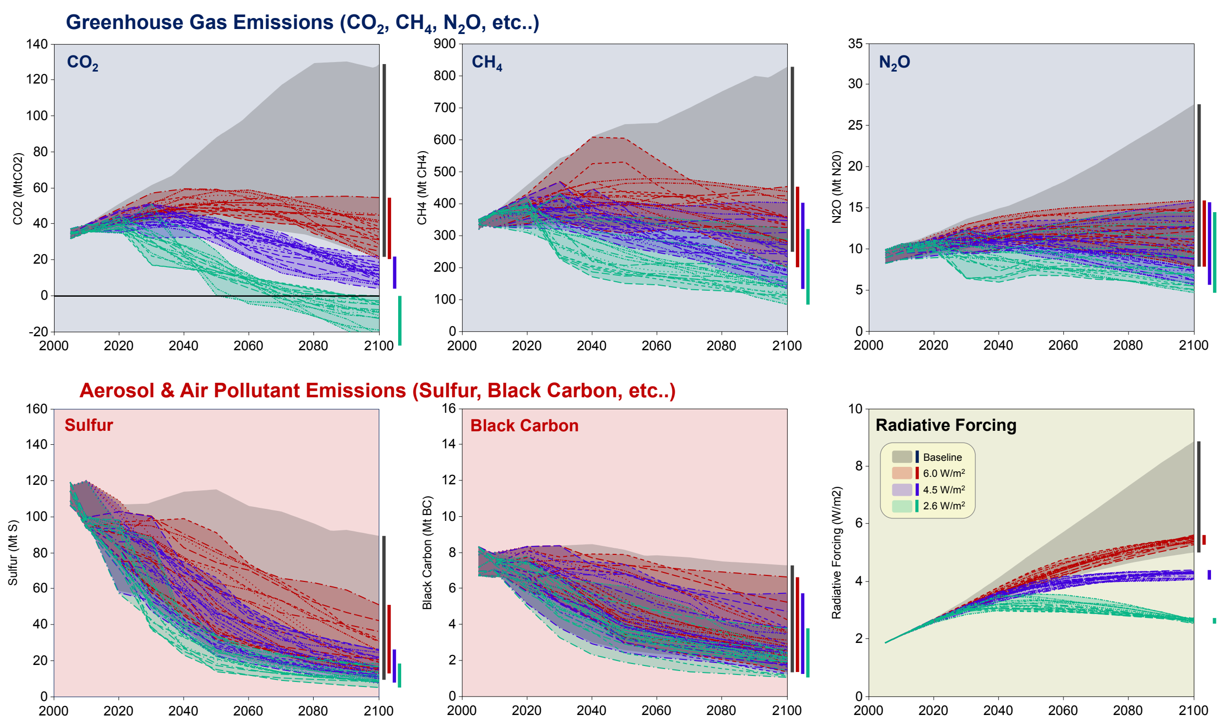


Figure S2: Same Figure as Figure 8 in the main paper, but showing mitigation costs in terms of GDP losses (cumulated between 2010 and 2100 using a discount rate of 5%). The figure includes results from three models reporting GDP losses (MESSAGE-GLOBIOM, REMIND-MAgPIE, AIM-CGE)

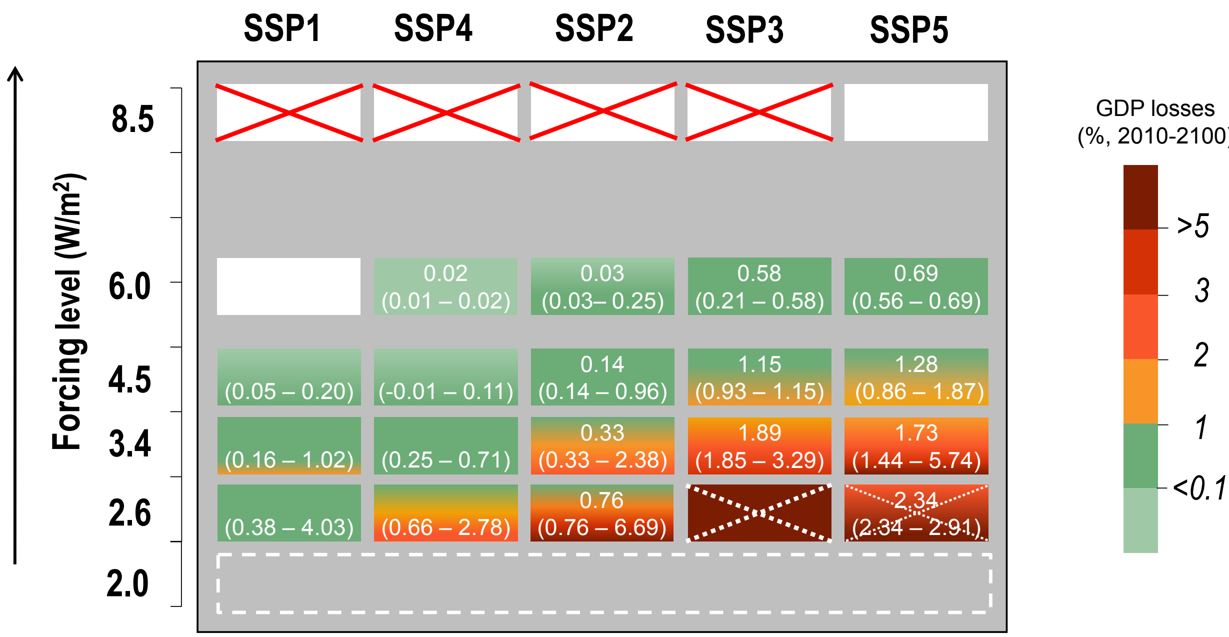


Figure S3: Same Figure as Figure 8 in the main paper, but showing mitigation costs in terms of consumption losses (cumulated between 2010 and 2100 using a discount rate of 5%). The figure includes results from three models reporting consumption losses (MESSAGE-GLOBIOM, REMIND-MAgPIE, AIM-CGE).

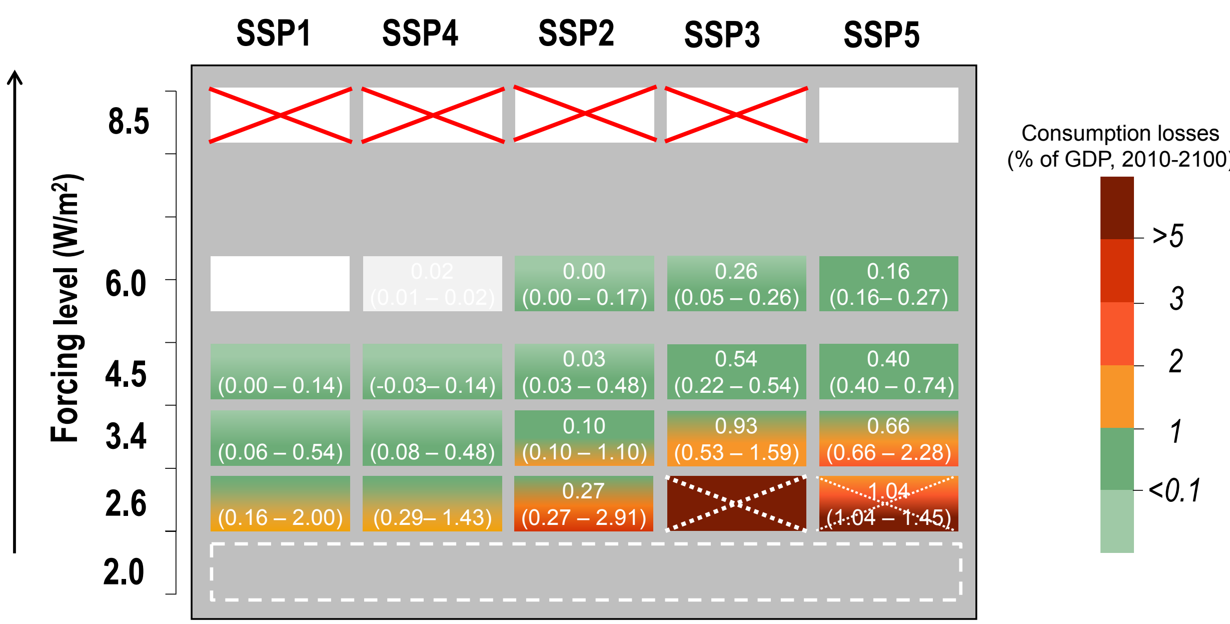
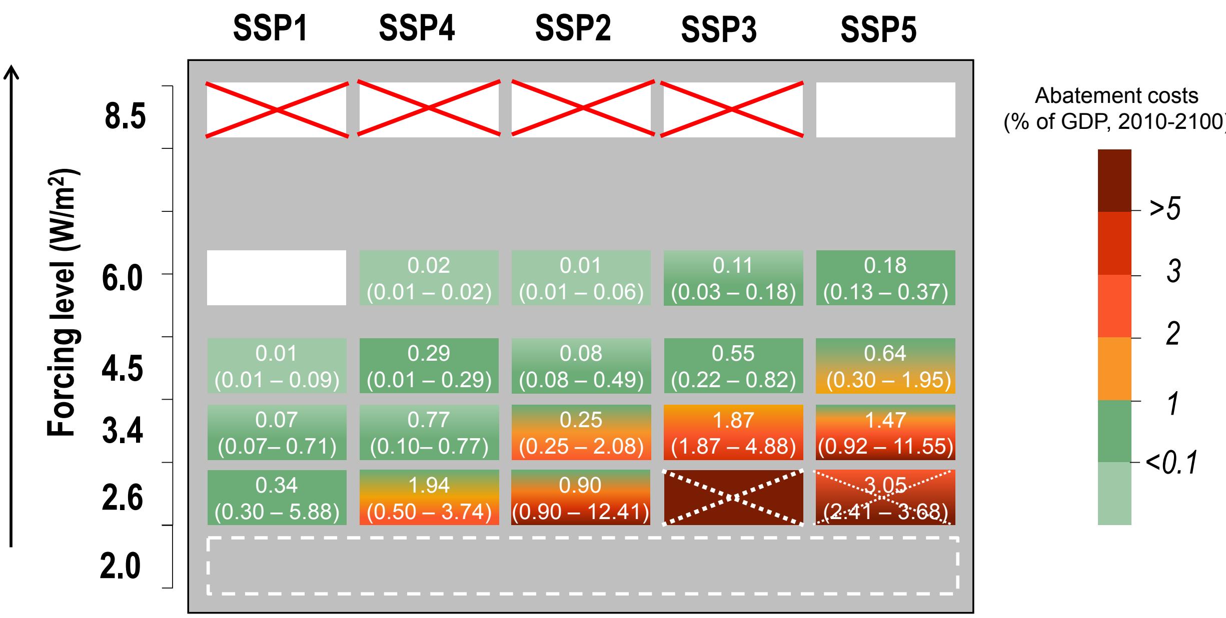


*Figure S4: Same Figure as Figure 8 in the main paper, but showing abatement costs as percent of GDP. Abatement costs are defined as: (carbon price * emissions reduction relative to the baseline) / 2. The division by 2 approximates a linear increase of carbon prices with abatement at a specific point in time. Abatement costs are cumulated between 2010 and 2100 using a discount rate of 5%. The figure includes results from all six models.*



2. Overall scenario set-up and naming convention

The shared socioeconomic pathways (SSPs) describe different socioeconomic reference developments spanning the space of socioeconomic challenges to mitigation and adaptation (O'Neill et al, 2014; van Vuuren et al, 2014). The SSPs consist first-of-all of a narrative, quantified population, GDP and urbanization trajectories, and qualitative assumptions on the energy and land use sectors. These elements served as the starting point for the further quantitative elaboration of the SSPs using integrated assessment models. This draft describes the scenario protocol that was used by the integrated assessment modeling teams for the implementation of the SSPs.

The framework of the Shared Socioeconomic Pathways (SSPs) contains 5 main scenarios from which different reference (baseline) and mitigation scenarios can be developed. In the quantitative elaboration of the mitigation scenarios, three of the four Representative Concentration Pathways (RCPs) forcing targets were used if applicable (6.0, 4.5, 2.6 W/m2). Note that the exact quantified forcing levels of some of the RCPs are slightly different from the original RCP labels (based on MAGICC-6.8, the forcing levels by 2100 of the three RCPs are: 5.4, 4.2, and 2.6 W/m2 respectively). In addition to the aforementioned targets, an intermediate forcing target of 3.4 W/m2 was applied to explore implications of climate policies between 4.5 (4.2) and 2.6 W/m2. The following table summarizes the RCP/SSP combinations and the naming convention of the IAM scenarios that were developed as part of this exercise.

Table 1: IAM scenarios (combining different climate forcing levels and socioeconomic assumptions):

	SSP1	SSP2	SSP3	SSP4	SSP5
Baseline	SSP1-Base	SSP2-Base	SSP3-Base	SSP4-Base	SSP5-Base
6 W/m2 (RCP6)	SSP1-60	SSP2-60	SSP3-60	SSP4-60	SSP5-60
4.5 W/m2 (RCP4.5)	SSP1-45	SSP2-45	SSP3-45	SSP4-45	SSP5-45
3.4 W/m2	SSP1-34	SSP2-34	SSP3-34	SSP4-34	SSP5-34
2.6 W/m2 (RCP2.6)	SSP1-26	SSP2-26	SSP3-26	SSP4-26	SSP5-26

3. Participating modeling teams and available scenarios

In total, six IAM teams from FEEM, IIASA, PBL, NIES, PIK and PNNL have participated so far in the SSP scenarios development process (the teams contributed voluntary to the process; as entrance criteria the ability to report emission and land-use variables was used). Descriptions of each model are included as Appendix D. Each SSP has been implemented by multiple IAM models. Thus, there are alternative interpretations from different IAMs for each of the SSPs and corresponding cells in Table 1. For each SSP, a so-called **Marker Scenario** was selected from the available model interpretations (i.e, there is one marker model for each of the five SSP columns in Table 1). Table 2 provides an overview of all available SSP scenarios including the five selected representative SSP marker scenarios developed by the following models (teams):

- SSP1: IMAGE (PBL)
- SSP2: MESSAGE-GLOBIOM (IIASA)
- SSP3: AIM (NIES)
- SSP4: GCAM (PNNL)
- SSP5: REMIND-MAGPIE (PIK)

Table 2: Available scenarios developed by the participating modeling teams [M = Marker (blue), NR = Not Run (grey), X = Non-Marker (green), No solution = no feasible solution (red) could be found by the modeling team]

	AIM	GCAM	IMAGE	MESSAGE-GLOBIOM	REMIND-MAgPIE	WITCH-GLOBIOM
SSP1-Reference	X	X	M	X	X	X
SSP1-6.0	NR	NR	NR	NR	NR	X
SSP1-4.5	X	X	M	X	X	X
SSP1-3.4	X	X	M	X	X	X
SSP1-2.6	X	X	M	X	X	X
SSP2-Reference	X	X	X	M	X	X
SSP2-6.0	X	X	X	M	X	X
SSP2-4.5	X	X	X	M	X	X
SSP2-3.4	X	X	X	M	X	X
SSP2-2.6	X	X	X	M	X	X
SSP3-Reference	M	X	X	X	NR	X
SSP3-6.0	M	NR	X	X	NR	X
SSP3-4.5	M	NR	X	X	NR	X
SSP3-3.4	M	NR	X	X	NR	X
SSP3-2.6	No solution	NR	No solution	No solution	NR	No solution
SSP4-Reference	X	M	NR	NR	NR	X
SSP4-6.0	NR	M	NR	NR	NR	X
SSP4-4.5	X	M	NR	NR	NR	X
SSP4-3.4	X	M	NR	NR	NR	X
SSP4-2.6	X	M	NR	NR	NR	X
SSP5-Reference	X	X	NR	NR	M	X
SSP5-6.0	X	X	NR	NR	M	X
SSP5-4.5	X	X	NR	NR	M	X
SSP5-3.4	X	X	NR	NR	M	X
SSP5-2.6	X	X	NR	NR	M	No solution

4. Implementation of SSPs

Population and GDP: The scenarios adopt the SSP population projections (KC and Lutz, forthcoming) and the marker SSP GDP projections by the OECD (Dellink et al, forthcoming) for their SSP scenario runs. Those projections are specified on a country level in Power Purchasing Parity (PPP) and have been aggregated to the native model regions. In addition, OECD has provided PPP to Market Exchange Rate (MER) conversion factors to convert PPP projections into MER if needed (see the download section of the SSP database).

Energy and land use: The SSPs also vary with respect to the assumptions on energy and land use changes. Characteristic assumptions of the different SSPs are summarized in the tables given in Appendix A. The tables include qualitative guidance for the modeling implementation for a range of specific areas, including:

- Fossil resources (capturing the essence of the table on energy supply (resources, Table A.2))
- Fossil energy trade (see category trade barriers in energy supply (resources) Table A.2)
- Energy supply technologies (see Table A.2 on energy supply technologies)
- Final energy intensity (capturing the essence of the Table A.1 on energy demand)
- Phase out of traditional biofuels (see category traditional fuel use in energy demand Table A.1)
- Land protection (see category land use change regulation in land use Table A.3)
- Land productivity (see land use Table A.3)
- Food consumption (see category environmental impact in land use Table A.3)
- Trade of agricultural products (see category international trade in land use Table A.3)

The underlying narratives of the SSPs can justify additional variations of input assumptions. Modeling teams are free to introduce such additional variations if they do not conflict with the energy and land use tables.

Regional pollution: The SSPs have different assumptions on regional pollution, in particular air and water. The qualitative guidance for implementation and stringency of regional pollution policies is summarized in Appendix C. The models report emissions of sulfur dioxide (SO2), nitrogen oxides (NOx), organic carbon (OC), black carbon (BC), carbon monoxide (CO), and non-methane volatile organic carbons (NMVOC). The models use different inventories for base year calibration (EDGAR4.2, 2011, Klimont et al., forthcoming, Bond et al., 2007, Lamarque et al., 2010, Smith et al., 2010, Eyring et al., 2009, Cofala et al., 2007) and the reported values are not harmonized to a single source. The future development of pollution controls are based on the near and long-term target levels in wealthy countries (represented by technological frontier), assuming universal availability of technology globally in the long run (Rao et al, 2016, this special issue). A number of factors, including continued cross-country differences in policies and institutions may prevent full convergence to the frontier. Thus in countries currently ‘lagging’, controls will ultimately converge not necessarily to the technological frontier but rather to the (lower) average emission factor levels corresponding firstly to their ‘own’ country group and eventually to that in current OECD countries. These broad pollution control storylines can then be linked to the SSP narratives, assuming that the speed of implementation varies as a function of the difference between current conditions and the target level of pollution control and the income level (affluence) of a region at a given time. The speed and absolute value to which country groups converge is differentiated across the SSPs. In addition, the regional pollution storylines (see Appendix C, Table 3.1) provide for additional differences, with target levels, rate of policy "catch up" and technological innovation levels differing between scenarios as well.

5. Implementation of climate forcing targets

Radiative forcing targets refer to **full** anthropogenic forcing by the end of the century[1]. In order to enhance comparability of climate results between the SSP scenarios and the original Representative Concentration Pathways (RCPs), **the SSP mitigation scenarios have aimed at the same 2100 radiative forcing levels as the original RCPs** in order to allow combined use of existing climate model runs and the new SSP-based mitigation scenarios. For a better comparability of the climate results, the forcing outcomes of all SSP scenarios were calculated thus with a common climate model MAGICC (v6.8). For this purpose, emissions inputs to the MAGICC model were harmonized for the base year. Emissions were harmonized to the RCPs for the year 2005 with exception of N2O and CH4, which were harmonized to EDGAR. Note that also the forcing levels of the original RCPs have been re-calculated using MAGICC 6.8. The RCP climate results are provided together with the SSP IAM scenarios at the SSP database.

For different reasons, 2100 forcing levels of the RCPs based on the current MAGICC model are not directly equal to the number in the RCP name (see box). This means, for example, that the SSP replications of the RCP6 scenarios should reach about 5.5 W/m2 in 2100, which is the forcing level of the original AIM RCP6.0.

Box: RCP forcing levels
The four RCPs were named after long-term forcing levels. RCP4.5 and RCP6.0 were defined as stabilization scenarios. Approaching the stabilization level in a smooth way, the 2100 forcing levels of these RCPs are still below the final stabilization levels at respectively 4.5 and 6.0 W/m2. This impact is most pronounced for RCP6. In contrast, RCP2.6 and RCP8.5 were defined on the basis of their 2100 forcing level. The forcing levels were calculated by the MAGICC-6 model available in 2009 (see Meinshausen et al., 2011). Since 2009, the MAGICC model has been updated on the basis of the CMIP5 results and new insights in the relationship between emissions and forcing levels.

Note that the harmonization aimed only at improving the comparability of the climate forcing results of the scenarios. Hence, the emissions reported in the database represent native results from the different

[1] While albedo changes are included in the radiative forcing, its value is kept constant over time and is thus not modelled dynamically.

models. Details on the different inventories that have been used by the different teams can be found here.

The 2100 forcing levels to be achieved for the various mitigation scenarios are as follows:

- SSP-60: corresponds to ~5.5 W/m2 (no overshoot) from RCP 6.0
- SSP-45: corresponds to ~4.3 W/m2 (no overshoot) from RCP 4.5
- SSP-34: corresponds to ~3.4 W/m2 as an in-between scenario for SSP45 and SSP26
- SSP-26: corresponds to ~2.6 W/m2 from RCP3PD

6. Shared Policy Assumptions (SPAs)

Each of the SSPs is defined by a set of generic and shared assumptions for climate policies (so-called shared policy assumptions). The definitions of these SPAs were derived by considering three main guiding principles:

1) The SPA/SSP combination is selected with the primary aim to reinforce the challenges for mitigation described by the relative position of each SSP in the challenges space.

2) The expected overall impact of the mitigation policy of each SPA is further selected to be consistent with the SSP storyline (i.e., specific sectors or policy measures might be less effective in some of the storylines compared to others – this is particularly relevant for land policies in SSPs that are characterized by large inequality and rural/urban divide. In particularly, land policies are assumed to be more difficult to implement in these SSPs.

3) The SPAs are defined in terms of their overall characteristics (expected impact) only. In order to give modeling teams a high degree of flexibility, each team is free to choose policy instruments for the model implementation that would fit best the modeling approach and would result in the overall policy effectiveness as described by the SPA/SSP combination.

A detailed description of the SPA protocol can be found as Appendix B.

7. Near-term emissions of the SSP scenarios by 2030

The different SPAs and the different underlying socioeconomic and technological assumptions of the SSPs lead to a comparatively wide range for near-term greenhouse gas emissions. For example, the GHG emissions across the SSP marker scenarios aiming at a long-term forcing target of 3.4 W/m^2 ranges from less than 50 GtCO2e in 2030 in the SSP4 marker scenario up to about 63 GtCO2e in the SSP3 marker scenario. Corresponding ranges for each SSP is shown in Figure S5.

These estimates do not take into account yet the recent country pledges for the GHG emissions in 2030 from the Paris Agreement (UNFCCC, 2015). These country pledges, i.e., the so-called INDCs (Intended Nationally Determined Contributions) are often associated with different conditions, for example, on financial support or on action in other countries. Depending on whether these conditions will be met in the future (or not), INDCs are expected to result in different GHG emissions levels by 2030. If conditional

INDCs are assumed, the global emissions are projected to increase to 54 GtCO2e (range 52 to 57) in 2030. If the unconditional INDCs are implemented only, emissions are projected to be higher, leading to 56 GtCO2e (range 54 to 59) in 2030.

Figure S5 compares the GHG emissions levels resulting from the conditional and unconditional INDCs (UNFCCC, 2015) with the near term global GHG emissions levels of the SSPs. It is interesting to note that the SSPs with low mitigation challenge (SSP1 marker and SSP4 marker) show 2030 emissions below those of the conditional INDCs. By the same token, the 2030 emissions of the SSPs with high mitigation challenges (SSP3 marker and SSP5 marker) exceed even the central estimate for the unconditional INDCs. The 2030 emissions of the SSP2 marker are almost identical with the central estimate of the conditional INDC.

The results seem to be consistent with the SPAs and provide an interesting interpretation of the SSP storylines in the context of the current political agreements. The low mitigation challenge has been interpreted in a way that it would allow further strengthening of near-term mitigation measures beyond the INDCs, while in case of high challenges for mitigation it seems to be rather difficult to meet even the unconditional INDCs. This interpretation holds particularly for the marker scenarios. The full range of model results includes some scenarios with lower near-term emissions due to rapid land-use changes.

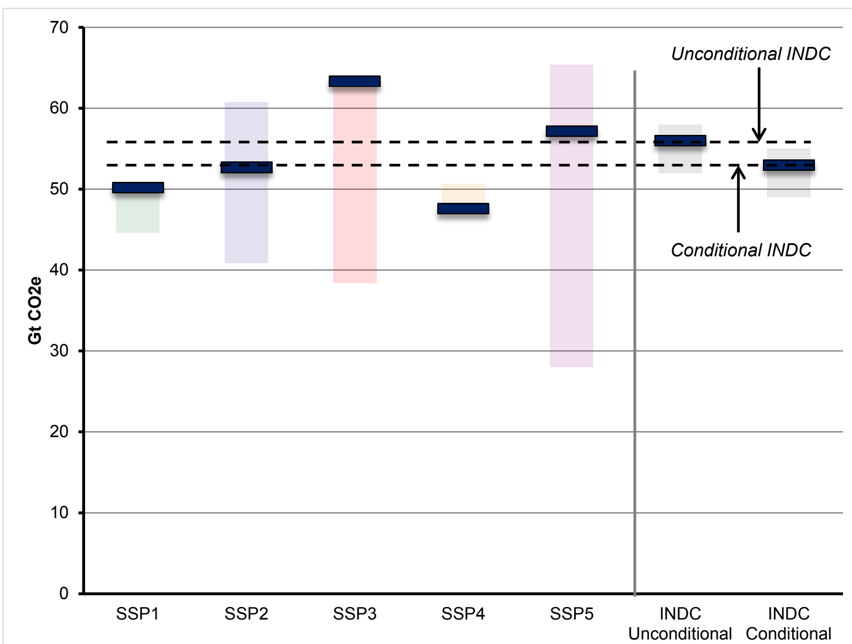


Figure S5: Comparison of global near-term GHG emissions by 2030 associated with the SSP scenarios targeting 3.4 W/m2 and the INDCs (UNEP, 2015). The markers of the SSP scenarios are shown as tick horizontal lines. Colored bars indicate the range across models for each SSP. In addition, the resulting ranges of the conditional and unconditional INDCs are depicted (light grey bars). The horizontal lines for the INDCs show the central estimate from UNEP (2015).

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Appendix A: Energy and land use tables

This appendix describes the model protocol as used by the different teams to implement the SSPs.

A.1: Qualitative assumptions for energy demand

Developments on the energy demand side are directly influenced by several key elements in the basic SSPs and the associated storylines, most notably, demographic trends, economic development, urbanization, consumption patterns, policy orientation and (directional) technological change.

Traditional fuel use in developing countries is phased out rapidly in SSP1 and 5 as a consequence of high economic development, fast urbanization and a focus on sustainable development in SSP1 and overall economic development in SSP5. In contrast, SSP3 as well as SSP4 show continued reliance on traditional fuels in low income rural households given the overall poor economic development in SSP3 and divided income distributions in SSP4. In SSP2 significant progress with solving the energy access problem can be seen, not as fast though as in SSP 1 and 5.

Environmental consciousness and sustainable development objectives lead to acceptance of strong regulatory approaches (e.g., high energy taxes) in SSP1, resulting in only modest energy service demand levels. Adoption of efficient end-use technologies in combination with fast and well planned urbanization enables a transition to low energy intensity of services, in particular in the transportation (high share of public transportation) and buildings sector (building codes). Industrial energy intensity can be kept at low levels due to use of efficient technologies and adoption of recycling and alternative materials.

In SSP5 the general preference for status consumption in combination with prosperous economic development features lifestyles with high energy service demand levels which are also encouraged by low fossil fuel prices and low energy taxes. Despite fast technological change, energy intensity of services tends to be medium or high for structural reasons. In the transportation sector high shares of private transport, partly encouraged by urban sprawl, and air traffic lead to high energy intensity of services as do large infrastructure investments and material intensive consumption patterns in industry.

Despite relatively poor economic development, in SSP3 the demand for energy services is intermediate, because of low environmental standards and little or ineffective regulation, in particular low energy taxes. Energy intensity of services is medium to high in all end-use sectors as a result of inefficient equipment, ineffective regulation (no efficiency standards, etc.) and poorly performing public infrastructure (e.g., public transport, energy grids).

In SSP4, the higher income countries exhibit modest per capita energy service demands as a result of a divided society in which the majority has modest incomes, but more importantly in response to strong regulation (energy taxes). The latter also lead to incentives for reaching low energy intensity of services in all end-use sectors. In contrast, energy intensity of services tends to be much higher in low income countries; with the exception of the transportation sector, where comparatively low energy intensities are also achieved for structural reasons (modal split with high public transport share).. However, given the low income levels the overall demand for services stays low.

In SSP2 service demand levels are intermediate (between SSP1 and SSP5 on a per capita level) and also energy intensity of services is intermediate across all end-use sectors.

Table A.1: Qualitative assumptions for energy demand across SSPs

	SSP 1			SSP 2			SSP 3			SSP 4			SSP 5		
	Country Income Groupings														
SSP Element	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Non-climate Policies															
Traditional Fuel Use	fast phase-out, driven by policies and economic development			intermediate phase-out, regionally diverse speed			continued realiance on traditional fuels			continued traditional fuel use	some traditional fuel use among low income housholds		fast phase-out, driven by development priority		
Energy Demand Side															
Lifestyles	modest service demands (less material intensive)			medium service demands (generally material intensive)			medium service demands (material intensive)			low service demands	modest service demands		high service demands (very material intensive)		
Environmental Awareness	high			medium			low			low	high		medium (low for global level/high for local level)		
Energy Intensity of Services															
Industry	low			medium			high			high	low		medium		
Buildings	low			medium			high			medium	low/medium		medium		
Transportation	low			medium			medium	high		low/medium	low		high		
General Comments				some regional diversity retained											

A.2: Qualitative assumptions for fossil energy supply

The fossil resource supply is mainly relevant for the use of fossil fuels in the energy and industry sector and therefore the related CO2 emissions. The "challenge to mitigation" is largely determined by the baseline emission trajectory and the effort necessary to reduce these emissions by the various options of emission abatement.

SSP2 is the middle of the road scenario and therefore medium assumptions for the availability of fossil fuels are applied. The "Sustainability SSP1" scenario is characterized by a low challenge to mitigation. The technological development and the limited acceptability leading to tight policies and regulations limit the supply and increase the recovery costs. This is consistent with low availability of fossil resources, which also implies relatively low emissions in the baseline and, thus, a low forcing level and a lower challenge to achieve more stringent forcing levels. The "Fossil-fueled Development SSP5" scenario assumes a high challenge to mitigation, which is interpreted as a very high availability of fossil fuels, which is supposed to lead to high baseline emissions. Broad social acceptability and fast technological improvements are the pre-conditions for very plentiful and cheap availability of fossil fuels. Globalization and free trade help to match demand and supply. The relatively low fossil fuel costs also increase the challenge to achieve stronger climate change mitigation targets because the opportunity costs of not using the fossil fuels are low. The "Inequality SSP4" scenario assumes a low challenge to mitigation. The assumptions of fossil fuels are set higher than in the SSP1 scenario, but in combination with other drivers of CO2 emissions the baseline emissions will remain at relatively moderate levels (compared to SSP2) and the storyline assumptions also suggest relatively cheap emission mitigation possibilities. The "Regional Rivalry SSP3" scenario assumes a high challenge to mitigation that is- like SSP5, but to a lesser degree – related to high availability of fossil fuels. Technological progress is less and therefore the potential for cheap recovery of fossil fuels remains limited. Domestic policies towards energy security and lax regulations to support domestic fossil fuel supply will lead to relatively abundant levels of fossil fuels. However, energy security concerns reduce the regional availability of fossil fuels to some degree.

Table A.2: Qualitative assumptions for fossil energy supply across SSPs

	SSP1 Sustainability	SSP2 Middle of the Road	SSP3 Regional Rivalry		SSP4 Inequality			SSP5 Fossil fueled development
			Country grouping		Country grouping by income			
			Exporter	Importer	Low	Medium	High	
Coal								
Macro-economy	cost driver	neutral	cost reducing		cost driver	cost driver	neutral	cost reducing
Technological progress	slow	medium	slow	fast		medium		very fast
National & environmental policy	very restrictive	supportive	very suportive		supportive	supportive	restrictive	very supportive
Conv. hydrocarbons								
Macro-economy	neutral	neutral	neutral		cost driver	neutral	cost reducing	cost reducing
Technological progress	medium	medium	medium			fast		very fast
National & environmental policy	restrictive	supportive	not supportive	supportive	supportive	supportive	restrictive	very supportive
Unconv. hydrocarbons								
Macro-economy	neutral	neutral	neutral		cost driver	neutral	cost reducing	cost reducing
Technological progress	slow	medium	slow	medium		medium		very fast
National & environmental policy	very restrictive	supportive	not supportive	very supportive	supportive	supportive	restrictive	very supportive
General								
Trade barriers	free trade	some barriers	high barriers			barriers		free

A.3: Qualitative assumptions for energy conversion technologies

SSP1: Since this is the world with rapid technological change toward environmental friendly processes, conversion technologies for commercial biomass and non-bio renewables improve relatively rapidly, although social acceptance for commercial biomass is weak because of its anticipated land use impact. Other conventional technologies, such as fossil fuel conversion technologies, nuclear power, and CCS, progress modestly in SSP1, and their social acceptance remains weak.

SSP2: This is the world where energy intensity and fossil fuel dependency continue to decrease at historic rates. Both technology development and social acceptance for all conversion technologies are assumed to be 'middle-of-the-road' among the five SSPs.

SSP3: With little progress in reducing resource intensity and low investments in technology R&D, technological changes of fossil fuel conversion, commercial biomass conversion, and non-bio renewable technologies are slow throughout the world. Nuclear power progresses modestly in high income countries because of energy security concerns although it develops at a slower rate in other countries due to weak global cooperation. Because energy security goals dominate local environmental concerns, social acceptance for fossil fuel and commercial biomass conversion and nuclear power remains strong. However, social acceptance for non-bio renewable technologies is not particularly strong due to their high costs and lack of technological learning. Finally, technological development in technologies for Carbon Dioxide Removal (CDR), such as bio-energy conversion in combination with CCS, are slow, and therefore their potential is limited.

SSP4: In this world, multinational energy corporations invest in R&D as a hedging strategy against resource scarcity and climate change, developing and applying alternative technologies internationally. As a result, low- and no-carbon technologies, such as commercial biomass conversion, non-bio renewables, nuclear power, and CCS, are deployed at low costs throughout the world. Social acceptance for these alternative technologies is strong because the majority of global population remains poor and vulnerable to resource scarcity, although nuclear power and CCS are modestly accepted in medium-to-high income countries because of their associated risks perceived by the high-income global elite. Fossil fuel technologies progress at modest rate only in medium-to-high income countries, but their social acceptance remains weak.

SSP5: Because of the strong preference for rapid conventional development, the world relies heavily on fossil energy and does not actively invest in alternative energy sources. There is modest but continued progress in conventional fossil fuel technologies and, in particular, rapid development in synthetic fuel and gas technologies. Technological changes in alternative conversion technologies are not rapid, although CCS technology progresses relatively rapidly along with fast fossil fuel extraction as a hedging strategy against climate change. Social acceptance for fossil fuel conversion technologies is relatively high, whereas social acceptance for renewable energy is relatively low in this world due to its distinct social preference.

Table A.3: Qualitative assumptions for energy conversion technologies SSPs

	SSP 1			SSP 2			SSP 3			SSP 4			SSP 5		
	Country Income Groupings														
SSP Element	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Conventional and Unconventional Fossil Fuel Conversion (synfuel and syngas in parenthesis if different)															
Technology Development		Med			Med			Low		Low	Med	Med		Med (High)	
Social Acceptance		Low			Med			High		High	Low	Low		High	
Commercial Biomass Conversion															
Technology Development		High			Med			Low		High	High	High		Med	
Social Acceptance		Low			Med			High		High	High	High		Med	
Non-bio Renewables Conversion															
Technology Development		High			Med			Low		High	High	High		Med	
Social Acceptance		High			Med			Med		High	High	High		Low	
Nuclear Power															
Technology Development		Med			Med		Low	Low	Med	High	High	High		Med	
Social Acceptance		Low			Med		High	High	High	High	Med	Med		Med	
CCS (under climate policy only)															
Technology Development		Med			Med			Med		High	High	High		High	
Social Acceptance		Low			Med			Med		High	Med	Med		Med	

A.4 Qualitative assumptions for Land-use change dynamics across SSPs

Table A.4: SSP Storylines "Agriculture and Land use"

SSP1	SSP2	SSP3	SSP4	SSP5
Land use is strongly regulated, e.g. tropical deforestation rates are strongly reduced. Crop yields are rapidly increasing in low- and medium-income regions, leading to a faster catching-up with high income countries. Healthy diets with low animal-calorie shares and low waste prevail. In an open, globalized economy, food is traded internationally.	Land use change is incompletely regulated, i.e. tropical deforestation continues, although at slowly declining rates over time. Rates of crop yield increase decline slowly over time, but low-income regions catch up to a certain extent. Caloric consumption and animal calorie shares converge towards medium levels. International trade remains to large extent regionalised.	Land use change is hardly regulated, i.e. tropical deforestation continues at current rates. Rates of crop yield increase decline strongly over time, due to little investment. While rich countries are characterized by unhealthy diets with high animal shares wasteful treatment of food, risk of hunger remains high in many poor countries. A regionalized world leads to reduced trade flows.	Land use change is strongly regulated in high income countries, but tropical deforestation still occurs in poor countries. High income countries achieve high crop yield increases, while low income countries remain relatively unproductive in agriculture. Caloric consumption and animal calorie shares converge towards medium levels. Food trade is globalized, but access to markets is limited in poor countries, increasing vulnerability for non-connected population groups.	Land use change is incompletely regulated, i.e. tropical deforestation continues, although at slowly declining rates over time. Crop yields are rapidly increasing. Unhealthy diets with high animal shares and high waste prevail. Barriers to international trade are strongly reduced, and strong globalization leads to high levels of international trade.

Table A.5: Qualitative assumptions for agriculture and land-use change across SSPs

	SSP 1			SSP 2			SSP 3			SSP 4			SSP 5		
	Country Income Groupings														
SSP Element	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**	**Low**	**Med**	**High**
Land use change regulation	strong			medium			weak			weak	medium	strong	medium		
Agriculture															
Land productivity growth	rapid	rapid	medium	medium			slow			slow	medium	rapid	rapid		
Environmental Impact of food consumption	low			medium			high			medium			high		
International Trade	globalized			regionalized			regionalized			limited access	globalized	globalized	globalized		

Appendix B: Definition of the Shared Policy Assumptions

This Appendix provides the description of the Shared Policy Assumptions as provided to the different teams as model protocol.

B.1: Introduction

The SPAs define the overall timing of climate policies, accession rules as well as the policy assumptions in different sectors of the SSPs. Definitions include:

1) The time until global cooperative action is achieved in the fossil fuel and industry sector. Three different accession rules (F1/F2/F3) that characterize low/intermediate/high levels of global cooperation and subsequently low to high challenges to mitigation are described below.

2) In addition, the SPAs describe (a) the expected effectiveness of land-use mitigation for each SSP/SPA combination as well as (b) provide guidance with respect to the overall land-use dynamics (particularly for the forest sector). As emphasized above, modeling teams are free to select the exact policy instruments for the implementation (the instruments are not harmonized across models).

3) Each SPA is thus defined in terms of the accession rules for fossil fuels (F) and the respective treatment of land-use mitigation (L).

B.2 Shared Policy Assumptions (SPAs) for fossil fuel and industry emissions

Three generic FF&I SPAs (shorthand F) are distinguished that characterize different levels of global cooperation in terms of policy implementation.

F1 describes a globally concerted effort toward the climate objectives with full cooperation achieved after 2020. F3 combines assumptions about delayed action and a globally fragmented approach in the short term with a large fraction of countries staying outside the global carbon market until 2030 or 2040. F2 represents intermediate assumptions with respect to global policy implementation in between F1 and F3.

The fossil fuel & industry (FFI) SPAs, are generally characterized by three phases:

- *Fragmentation until 2020:* countries aim at some interpretation of actual 2020 (Cancun) pledges, and continue this level of action thereafter. It is modeler's choice how to implement the period of fragmentation in a way consistent with Cancun pledges. The reference / lenient / weak / fragmented policy scenarios of earlier modeling comparison projects, such as AMPERE, LIMITS, or EMF27 can serve as a guideline. However, the 2020 carbon price in the SPA runs should not rise above the carbon price in the SPA0 benchmark case in developing country regions. SPA0 refers to the mitigation scenario with an empty SPA (i.e., mitigation is introduced in a fully efficient and cost-effective way and no specific assumptions with regards of accession, etc.. is made). Also, the carbon price should not exceed the SPA0 price by more than \$15/tCO2 in industrial country regions (this will be relevant particularly in the case of moderate long term forcing targets where the adopted Cancun pledges might be overly ambitious). There should be no anticipation of more stringent action beyond the period of fragmentation. This requires perfect foresight models to pre-run a reference with moderate action throughout the 21st century. This should have the characteristics identified in AMPERE / LIMITS / RoSE / EMF27, i.e. a peaking of global CO2e emissions around 2050 and roughly a return to present day levels by 2100.

- *Accession as of 2020*: countries transition from the carbon price that they come with in the final year of the fragmentation period to a global carbon price at some time during the accession period. There will be a globally uniform carbon price at the end of the accession period. The transition should be formulated such that the SPA carbon prices do not exceed the SPA0 prices before 2030 (obviously this assumption applies to those regions that have carbon prices below the SPA0 price in 2020). *Cooperation*: all countries have adopted the globally uniform carbon price. Its temporal profile (e.g. hotelling) is modeler's choice, but as a general recommendation, the shape of the carbon price in the immediate action case (SPA0) may be adopted and the magnitude of the price trajectory may be scaled up by some percentage so that the long term target is reached despite excess emissions in the periods of fragmentation and accession.

Based on the phases above the three FF&I SPAs are defined as follows:

- **F1:** Fragmentation until 2020, and full regional cooperation thereafter.
- **F2:** Fragmentation until 2020, and linear transition to a globally uniform carbon price by 2040 of all countries. It will be checked in the next round whether the length of the transition period makes RCP2.6 infeasible in some models.
- **F3:** Fragmentation until 2020, after which those model regions with an average per capita income of \$12600\$/yr (see http://data.worldbank.org/about/country-classifications/country-and-lending-groups) or higher in 2020 (depending on the SSP; using PPP GDP scenarios of the OECD) start a linear transition to the global carbon price until 2040. All other countries continue on their fragmented climate policy path until 2030, and start the transition 10 years later, during the period 2030-2050.

B.3: Shared Policy Assumptions (SPAs) for the land-use sector

Three generic SPAs for the land-use sector (shorthand L) are distinguished, which differ in terms of the pricing of emissions from land-use sources:

- **LP** = price all land use emissions at the level of carbon prices in the energy sector (i.e., mitigation is implemented on land at the same level as for the energy/fossil fuel sector). This land-use treatment is consistent with the storylines of SSP1 and SSP5, which are both characterized by high equality and affluence (and thus successful poverty eradication in rural areas). Hence, implementation of land-use policies will be comparatively easy in these SSPs.

- **LN** = limited pricing of land use emissions, due to major implementation barriers and in order to limit impact on food prices. This treatment of mitigation on land is consistent with SSP3 storyline of high inequality and fragmentation. Land-use mitigation is unlikely to be effective in this storyline. Local concerns for food security due to expected bioenergy deployment may be addressed (if needed) through implementation of bioenergy taxes, constraints for bioenergy deployment and/or other land policies (e.g., requirement to deploy bioenergy only on marginal land). Land-use pricing should be set to 0-20% of the GHG price of the energy sector (modeler's choice).
- **LD** = price all land use emissions at the level of carbon prices in the energy sector, unless this leads to afforestation or elimination of deforestation before 2030, in which case the control of CO2 land use emissions (but not the pricing of Non-CO2 agricultural emissions) should be reduced, at least until 2030. This is an intermediate case between LP and LN relevant for SSP2 and SSP4. This land-use policy is suggested for SSP2 since a radical departure from current deforestation trends in the near term would be inconsistent with its (dynamics as usual) storyline. A radical (near-term) departure from current deforestation trends is also inconsistent with SSP4 given its emphasis on inequality (and thus slow rural development). In both storylines land-use policies may become effective in the long term, however (in SSP4 this could be enabled by multi-national food trusts in control of food production – in SSP2 long-term mitigation dynamics for land are not specifically constrained by the storyline).

B.4: Combination of SSPs and SPAs

Consistent with the mitigation challenges described by the SSPs the following combination of F/L policies were defined as the building blocks of five distinct marker SPAs. The expected challenges for mitigation in combining the five SPAs with the respective SSPs are shown in table below. Each modeling team is asked to develop scenarios using the combination of SPAs and SSPs shown in Table 2.

- **SPA1:** F1 + LP
- **SPA2:** F2 + LD
- **SPA3:** F3 + LN
- **SPA4:** F1 + LD or F1 + LN (full convergence on the definition of SPA4 could not be achieved yet. teams are thus encouraged to test two alternative formulations, using either LD or LN for the land policies)
- **SPA5:** F2 + LP

Table A2.1: Combination of F/L policies as the building blocks of five distinct marker SPAs

SSP5-SPA5: F2 + LP (high mitigation challenge due to the combination of high fossil fuel baseline emissions, very high energy demand, and delays in mitigation (for some regions up to 2040) (F2))		**SSP3-SPA3**: F3 + LN (high mitigation challenge due to high baseline emissions, major delays (F3), and very limited participation of land in mitigation (LN)
	SSP2-SPA2: F2 + LD (intermediate mitigation challenge due to intermediate assumptions for i) baseline emissions, ii) energy demand, iii) delays (F2), and iv) land participation (LD)	
SSP1-SPA1: F1 + LP (low mitigation challenge due to the combination of low baseline fossil fuel emissions, low energy demand, no delays beyond 2020 (F1), and full participation of land mitigation)		**SSP4-SPA4**: F1 + LD (or F1 + LN) (low mitigation challenge due to no delays beyond 2020 (F1), relatively low energy demand combined with intermediate assumptions for land mitigation (LD) and intermediate assumptions for baseline emissions). Challenges in SSP4 will most likely be between SSP1 and SSP2.

Appendix C: Regional pollution tables

This Appendix provides the model protocol for implementing the air pollution assumptions in the SSPs as provided to the different model teams. Further details can be found in the paper in this special issue by Rao et al, 2016.

C.1 Qualitative description of Storylines

We propose three alternative assumptions for future pollution controls (strong, medium and weak). The terminology of these variants follows the same convention as other studies used to inform the SSP scenario design process (Kc and Lutz, forthcoming ; Crespo Cuaresma and Cuaresma, 2014).

The **central** pollution control scenario envisions a world that continues following current trends, with countries aiming to control pollution, and respective polices become increasingly effective as incomes increase. Because of diffusion of technology and knowledge, countries achieve levels of emission control and efficiencies of OECD countries earlier (in relation to income levels). Pollution concentration targets decrease over the century as income increase and more value is placed on health outcomes. To reach these targets, some regions will ultimately require high control efficiencies, some perhaps requiring advances over current technology levels. Regions with large population densities, or adverse physical conditions (e.g. geographically features that result in high pollutant concentrations) may not achieve their desired outcomes.

The **strong** pollution control scenarios assume that increasing health and environmental concerns result in successful achievement of pollutant targets substantially lower than current levels in the medium to long term. Associated with this scenario is a faster rate of pollution control technology development, with lower costs and greater effectiveness as compared to current technologies. Low particulate targets in many regions, for example, will likely require new policies to control agriculture and energy related NH_3 emissions in order to limit the contribution of nitrate aerosols. Such a scenario incorporates the possibility that the envisioned rapid improvements in air and water quality would mean that some regions will ultimately require very high control efficiencies, perhaps well beyond the limits of current technologies. Not only do countries converge faster to the frontier levels of the global technology leader regions; technological and institutional developments are assumed to substantially lower the pollution control frontier over time.

Low pollution control scenarios assume that the implementation of pollution controls is delayed compared to the *central* scenario. In some cases this may be due to the large challenges due to a number of factors including for instance, high emission densities in developing country megacities; lack of adequate ground, air or water quality monitoring; concentrations of confined animal feeding operations, or weaker institutions resulting in lax enforcement. International cooperation is weaker, resulting in slower rates of improvements in control technologies and cross-boundary pollution issues result in higher background concentrations in many regions.

Table A3.1: Qualitative Description of Storylines

	Policy Targets		**Technological Innovation**	**Proposed SSP link**	**Key characteristics of SSPs**
Policy Strength	High Income Countries	Medium and Low Income			
Strong	Much lower than current targets in order to minimize adverse effects on both general population, vulnerable groups, and ecosystems.	Comparatively quick catch-up with the developed world (relative to income)	Pollution control technology costs drop substantially with control performance increasing.	SSP1, SSP5	Sustainability driven; rapid development of human capital, economic growth and technological progress; prioritized health concerns
Central	Lower than current targets	Catch-up with the developed world at income levels lower than when OECD countries began controls (but not as quick as in the strong control case).	Continued modest technology advances.	SSP2	the middle of the road scenario
Weak	Regionally varied policies.	High emissions levels and/or institutional limitations substantially slow progress in pollution control.	Lower levels of technological advance overall.	SSP3, SSP4	Fragmentation, Inequalities

Definitions of income country groups (low income (L) countries, middle income (M) countries, and high income (H) countries) derived from the World Bank classifications. High income countries include all countries above 12,275 USD/capita incomes in 2010. Middle income countries combine all World Bank upper-middle income countries, and those lower-middle income countries that have at least 2,750 USD/cap incomes in 2010. Low income countries are all other countries.

Appendix D: Model Description

D.1 Introduction

This document provides an overview of the six models which have so far participated in the development of the SSP scenarios. These models are hosted by IAM teams at FEEM, IIASA, PBL, NIES, PIK and PNNL each of which have contributed on a voluntary basis towards this process. Key criterion in order to par6ticipate in this process included the ability to provide detailed reporting on emission as well as on land-use variables. The initial section of this document briefly describes each of the models. These descriptions highlight some of the main model characteristics and describe relevant linkages to other models applied in the modelling process. In addition to the descriptions, for each model, a table mapping the native regions to the harmonized SSP regions has been provided. Maps have further been included to illustrate the native model regional definitions. The final section provides an overview of the pollution inventories used across the different models.

D.2 Summary descriptions of the models

AIM/CGE (NIES)

The **Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE)** (Fujimori, 2012; Fujimori et al., 2014a; Fujimori et al., 2014b, 2015; Hasegawa et al., 2015) is a recursive-type dynamic general equilibrium model that covers all regions of the world. The AIM/CGE model includes 17 regions and 42 industrial classifications. Likewise other CGE models, AIM/CGE deals with whole economic production and consumption behaviors with particular emphasis on the representation of energy in order to assess energy related CO2 emissions appropriately. In addition, agriculture and land use classifications have also high resolution in order to deal with the bioenergy and land use competition appropriately. The climate component is represented by the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC) and the emissions information generated from AIM/CGE is fed into MAGICC.

The production sectors are assumed to maximize profits under multi-nested constant elasticity substitution (CES) functions and each input price. The capital, labor, intermediate inputs and land are the input for each industrial activity. Household expenditures on each commodity are described by a linear expenditure system function. The saving ratio is endogenously determined to balance saving and investment, and capital formation for each good is determined by a fixed coefficient. The international traded goods are substitutable with the domestic production goods.

In addition to energy-related CO2, CO2 from other sources (land use), CH4, N2O, and F-gases are treated as GHGs in the model. Energy-related emissions are associated with fossil fuel consumption and combustion. The non-energy-related CO2 emissions consist of land use change and industrial processes. Land use change emissions are derived from the difference of the forest area from that of the previous year multiplied by the carbon stock density. Non-energy-related emissions other than land use change emissions are assumed to be in proportion to the level of the activities (such as output). CH4 has various sources, but the main sources are the rice production, livestock, fossil fuel mining, and waste management sectors. N2O is emitted as a result of fertilizer application and livestock manure management, and by the chemical industry. Air pollutant gases (BC, CO, NH3, NMVOC, NOX, OC, sulfur) are also associated with fuel combustion and activity levels. Basically, the emissions factors are changed over time according to the implementation of air pollutant removal technologies and relevant legislation.

Table D.2: Mapping of AIM/CGE regions to SSP regions

Native Regions	**SSP Regions**
JPN	OECD90
CHN	ASIA
IND	ASIA
XSE	ASIA
XSA	ASIA
XOC	OECD90
XE25	OECD90
XER	OECD90
CIS	REF
TUR	OECD90
CAN	OECD90
USA	OECD90
BRA	LAM
XLM	LAM
XME	MAF
XNF	MAF
XAF	MAF
Explanations:	
JPN=Japan	TUR=Turkey
CHN=China	CAN=Canada
IND=India	USA=United States
XSE=Southeast Asia	BRA=Brazil
XSA=Rest of Asia	XLM=Rest of South America
XOC=Oceania	XME=Middle East
XE25=EU25	XNF=North Africa
XER=Rest of Europe	XAF=Rest of Africa
CIS=Former Soviet Union	

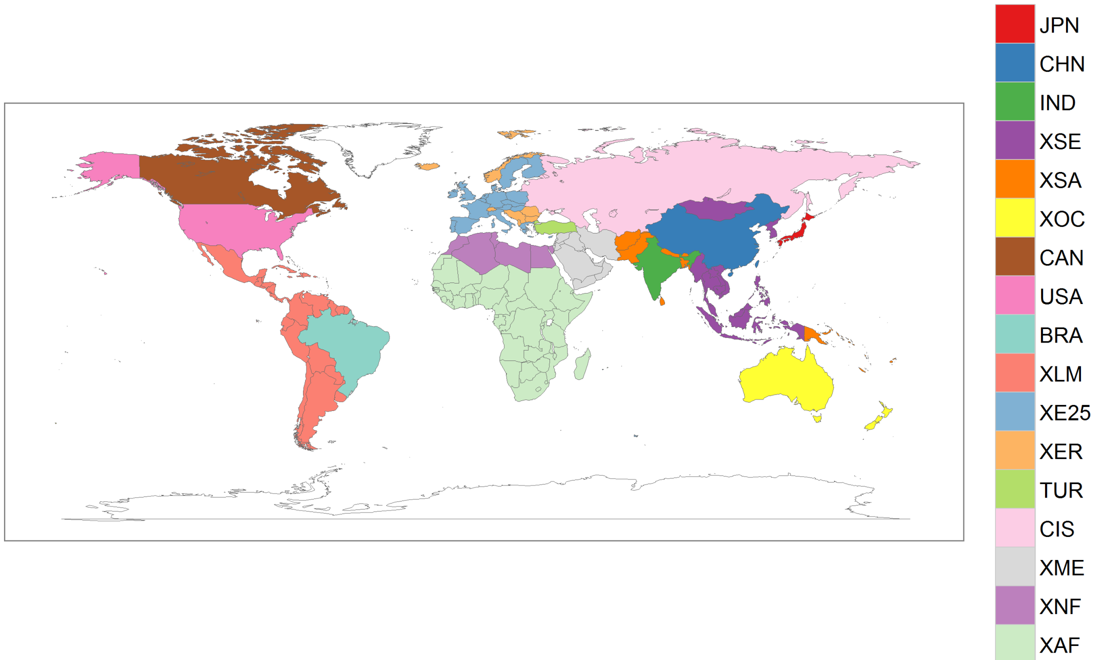

Figure D.1: AIM/CGE model regions

GCAM (PNNL)

The **Global Change Assessment Model (GCAM)** [6] is a global integrated assessment model with particular emphasis on the representation of human earth systems including interactions between the global economic, energy, agricultural, land use and technology systems. The GCAM physical atmosphere and climate are represented by Hector, an open source coupled carbon cycle-climate model (Hartin et al., 2015). The GCAM is global in scope and disaggregated into 32 energy and economic regions and 283 agriculture and land use regions. GCAM is a dynamic-recursive market equilibrium model; as such, prices are adjusted to ensure that supplies and demands of all commodities are equilibrated in each model period. The model operates in 5-year timesteps from 1990 to 2100, with 2010 as its last historical year. The energy system model produces and transforms energy for use in three end-use sectors: buildings, industry and transport. Production is limited by resource availability, which varies by region. Fossil fuel and uranium resources are finite and depletable. Wind, solar, hydro, and geothermal resources are renewable. Bioenergy is also renewable but is treated as an explicit product of the agriculture-land-use portion of the model. The agriculture and land use model computes supply, demand, and land use for a variety of crops and other uses, including natural ecosystems. The model operates using an economic paradigm, where landowners allocate land among competing uses based on profitability. GCAM assumes a distribution of profits across each of the 283 regions, and thus, the fraction of each region allocated to each land use is the probability that use has the highest profit. GCAM computes anthropogenic emissions of 24 GHGs, short-lived species, aerosols, and ozone precursors. Emissions are associated with drivers and change in the future due to changes in drivers, income-driven pollution controls, or carbon-price driven abatement efforts. GCAM is open-source and can be downloaded at: http://www.globalchange.umd.edu/models/gcam/download/.

Table D.3: Mapping of GCAM regions to SSP regions

Native Regions	SSP Regions
Africa	MAF
Australia_NZ	OECD
Canada	OECD
China	ASIA
Eastern Europe	OECD
Former Soviet Union	REF
India	ASIA
Japan	OECD
Korea	ASIA
Latin America	LAM
Middle East	MAF
Southeast Asia	ASIA
USA	OECD
Western Europe	OECD

Explanations:
NZ = New Zealand
Southeast Asia: also including Pakistan
USA = United States of America
Western Europe = Including EU-15, Turkey, EFTA

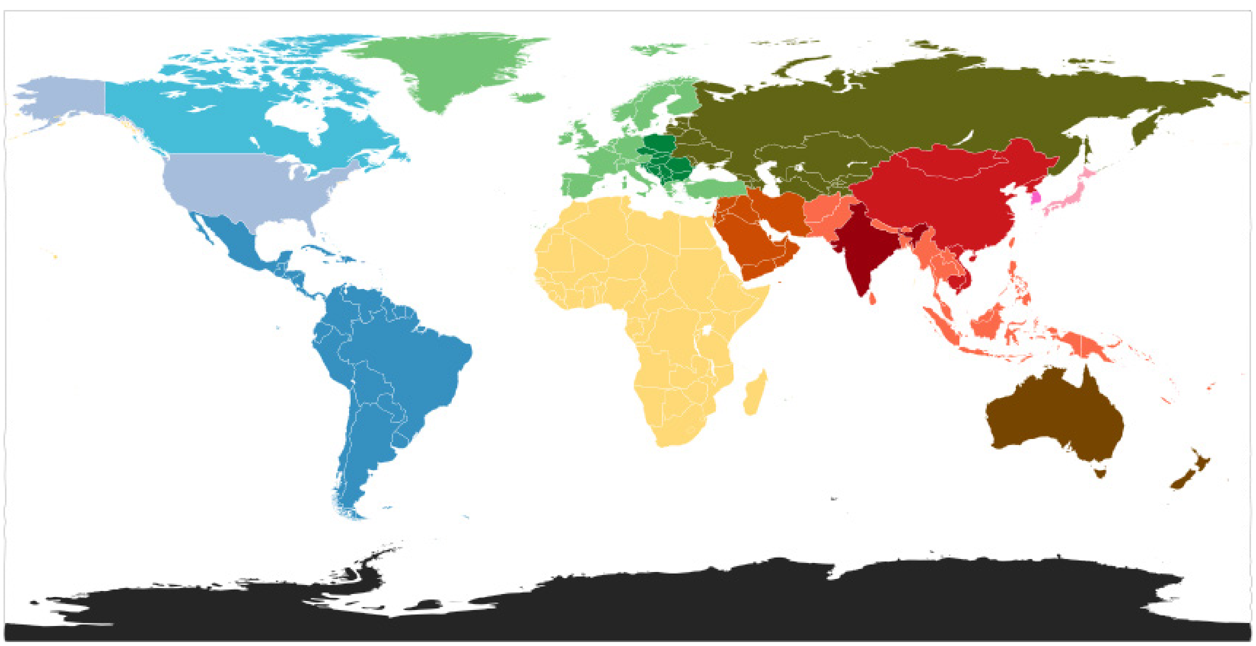

Figure D.2: GCAM model regions

IMAGE (PBL)

The **IMAGE** Integrated Assessment Modelling Framework [7] consists of a set of linked and integrated models that together describe important elements of the long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change. The global energy model that forms part of this framework, TIMER, describes the demand and production of primary and secondary energy and the related emissions of GHGs and regional air pollutants. The land and climate modules of IMAGE describe the dynamics of agriculture and natural vegetation, and resulting climate change. For food and agriculture, the IMAGE system uses projections made by the computable-general-equilibrium MAGNET [8] model. This model describes, in interaction with the main IMAGE framework, changes in food production and trade for a broad set of crops and animal products. The land components of IMAGE [7,9] compute land-use changes based on regional production of food, animal feed, fodder, grass, bio-energy and timber, with consideration of local climatic and terrain properties. Climate change affects the productivity of crops and induces changes in natural vegetation with consequences for biodiversity. The key component of this part of IMAGE is the LPJ-ml model. The potential distribution of natural vegetation and crops is determined on the basis of climate conditions and soil characteristics on a spatial resolution of 5 x 5 minutes. LPJ-ml also estimates potential crop productivity, which is used to determine allocation of cropland to different crops. Emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere are also simulated. The earth system component of IMAGE subsequently calculates changes in atmospheric composition using the emissions from the energy system and land use change, and by taking oceanic carbon dioxide uptake and atmospheric chemistry into consideration. The most important here is the MAGICC model that is included in IMAGE. Subsequently, AOS computes changes in climatic parameters by resolving the changes in radiative forcing caused by greenhouse gases, aerosols and oceanic heat transport.

Table D.4: Mapping of IMAGE regions to SSP regions

Native Regions	SSP Regions
BRA	LAM
CAN	OECD
CEU	OECD
CHN	ASIA
EAF	MAF
INDIA	ASIA
INDO	ASIA
JAP	OECD
KOR	ASIA
ME	MAF
MEX	LAM
NAF	MAF
OCE	OECD
RCAM	LAM
RSAF	MAF
RSAM	LAM
RSAS	ASIA
RUS	REF
SAF	MAF

SEAS	ASIA
STAN	REF
TUR	OECD
UKR	REF
USA	OECD
WAF	MAF
WEU	OECD

Explanations:	
BRA = Brazil	RCAM = Rest of Central America
CAN = Canada	RSAF = Rest of Sub-Saharan Africa
CEU = Central Europe	RSAM = Rest of South America
CHN = China	RSAS = Rest of South Asia
EAF = East Africa	RUS = Russia
INDIA = India	SAF = South Africa
INDO = Indonesia	SEAS = Southeast Asia
JAP = Japan	STAN = Kazakhstan region
KOR = Korea	TUR = Turkey
ME = Middle East	UKR = Ukraine, Belarus, Moldova
MEX = Mexico	USA = United States of America
NAF = North Africa	WAF = West Africa
OCE = Oceania	WEU = Western Europe

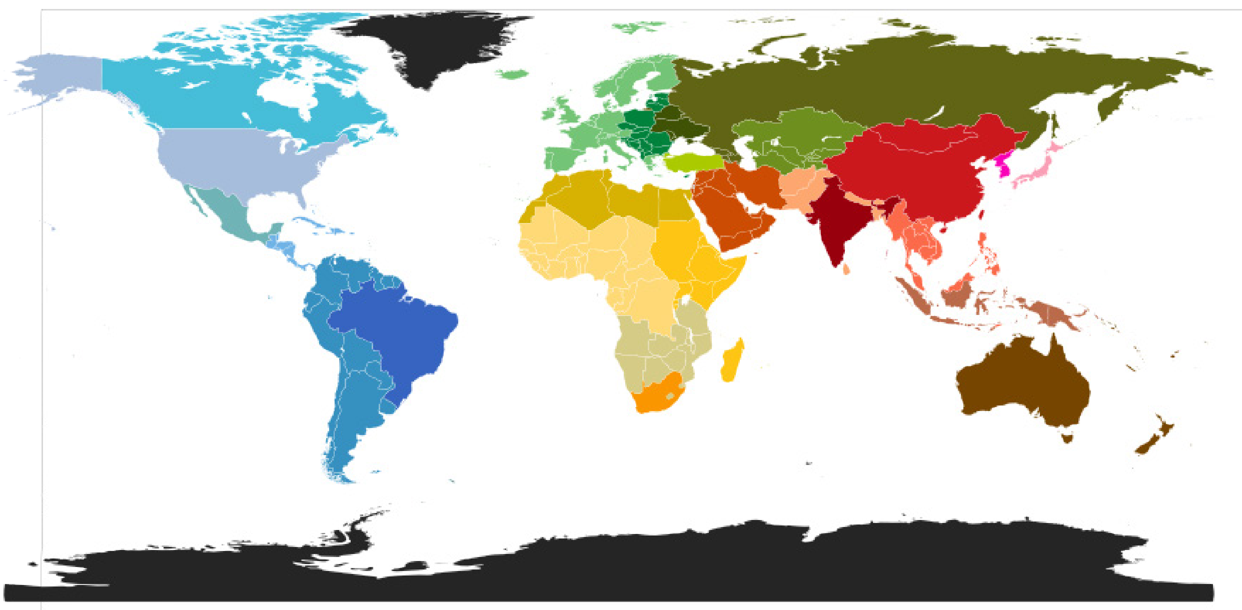

Figure D.3: IMAGE model regions

MESSAGE-GLOBIOM (IIASA)

Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) is an energy engineering model based on a linear programming (LP) optimization approach which is used for medium- to long-term energy system planning and policy analysis [10,11]. The model minimizes total discounted energy system costs, and provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. In addition to the energy system, the model also includes generic representations of agriculture and forestry, which allows incorporation of emissions and mitigation options for the full basket of greenhouse gases and other radiatively active substances [12]. MESSAGE is linked to a macro-economic model -MACRO [13]. In MACRO, capital stock, available labor, and energy inputs determine the total output of the economy according to a nested constant elasticity of substitution (CES) production function. Through the linkage to MESSAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account. MESSAGE is in addition coupled to agricultural model GLOBIOM for consistent projections of land-use. MESSAGE has also been linked to the GAINS model [14,15] to provide estimates of air pollution [16,17,18]. Additional extensive model documentation can be found at https://wiki.ucl.ac.uk/display/ADVIAM/MESSAGE.

The **Global Biosphere Management Model (GLOBIOM)** has been developed at the International Institute for Applied Systems Analysis (IIASA) since the late 2000s. The partial-equilibrium model represents various land-use based activities, including agriculture, forestry and bioenergy sectors. The model is built following a bottom-up setting based on detailed grid-cell information, providing the biophysical and technical cost information. This detailed structure allows taking into account a rich set of environmental parameters. Its spatial equilibrium modelling approach represents bilateral trade based on cost competitiveness. The model was initially developed mostly for integrated assessment of climate change mitigation policies in land based sectors, including biofuels, and is increasingly being implemented also for agricultural and timber markets foresight, and economic impacts analysis of climate change and adaptation. More details on GLOBIOM can be found in [19,20].

Table D.5: Mapping of MESSAGE-GLOBIOM regions to SSP regions[2]

Native Regions	SSP Regions
AFR	MAF
CPA	ASIA
EEU	OECD
FSU	REF
LAM	LAM
MEA	MAF
NAM	OECD
PAO	OECD
PAS	ASIA
SAS	ASIA
WEU	OECD

Explanations:
AFR = Africa
CPA = Centrally-planned Asia, including China, Vietnam and others
EEU = Eastern Europe
FSU = Former Soviet Union
LAM = Latin America and Carribean
MEA = Middle East and North Africa
NAM = North America
PAO = Pacific OECD (Australia, Japan, New Zealand)
PAS = Other Pacific Asia
SAS = South Asia
WEU = Western Europe

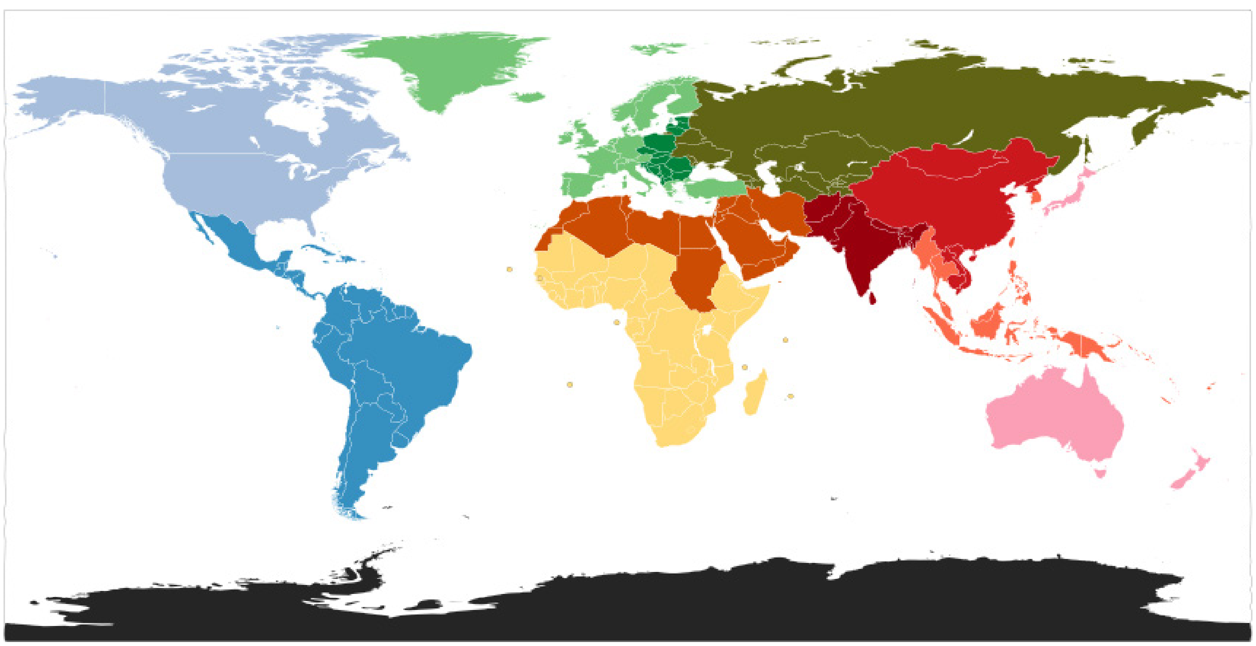

Figure D.4: MESSAGE-GLOBIOM model regions

[2] Note that GLOBIOM model can also be applied as a stand-alone tool, in which case it comprises a number of additional regions.

REMIND-MAgPIE (PIK)

The **Regionalized Model of Investment and Technological Development (REMIND)** [21 (Model description),22,23,24,25,26][3] is a global multi-regional integrated assessment model that couples a top-down macroeconomic growth model with a detailed bottom-up energy system model and a simple climate model. By embedding technological change in the energy sector into a representation of the macroeconomic environment, REMIND combines the major strengths of bottom-up and top-down models. To obtain a detailed evaluation of the climate implications of the scenarios, the model is further coupled with the climate module MAGICC6 [27]. Economic dynamics are calculated through inter-temporal optimization, assuming perfect foresight by economic actors. This implies that technological options requiring large up-front investments that have long pay-back times (e.g. via technological learning) are taken into account in determining the optimal solution. REMIND incorporates a detailed description of energy carriers and conversion technologies, including a wide range of carbon free energy sources as well as fossil and biomass conversion technologies in combination with carbon capture and storage. REMIND also represents trade relations and capital movements between eleven world regions, and also has a detailed representation of global markets for energy resources such as crude oil, coal and gas. Mitigation cost estimates thus take into account technological opportunities and constraints as well as macro-economic feedbacks and trade effects.

Table D.6: Mapping of REMIND regions to SSP regions

Native Regions	**SSP Regions**
AFR	MAF
CHN	ASIA
EUR	OECD
IND	ASIA
JPN	OECD
LAM	LAM
MEA	MAF
OAS	ASIA
ROW	OECD
RUS	REF
USA	OECD
Abbreviations: AFR = Sub-saharan Africa excluding South Africa CHN = China EUR = EU27 IND = India JPN = Japan LAM = Latin America, also including Mexico	MEA = Middle East and North Africa, also including Central Asia OAS = Other Asia, also including Pakistan ROW = Rest of the world RUS = Russia USA = United States of America

[3] Relevant further resources, including a documentation of the equations, can be found on the REMIND webpage at https://www.pik-potsdam.de/research/sustainable-solutions/models/remind/

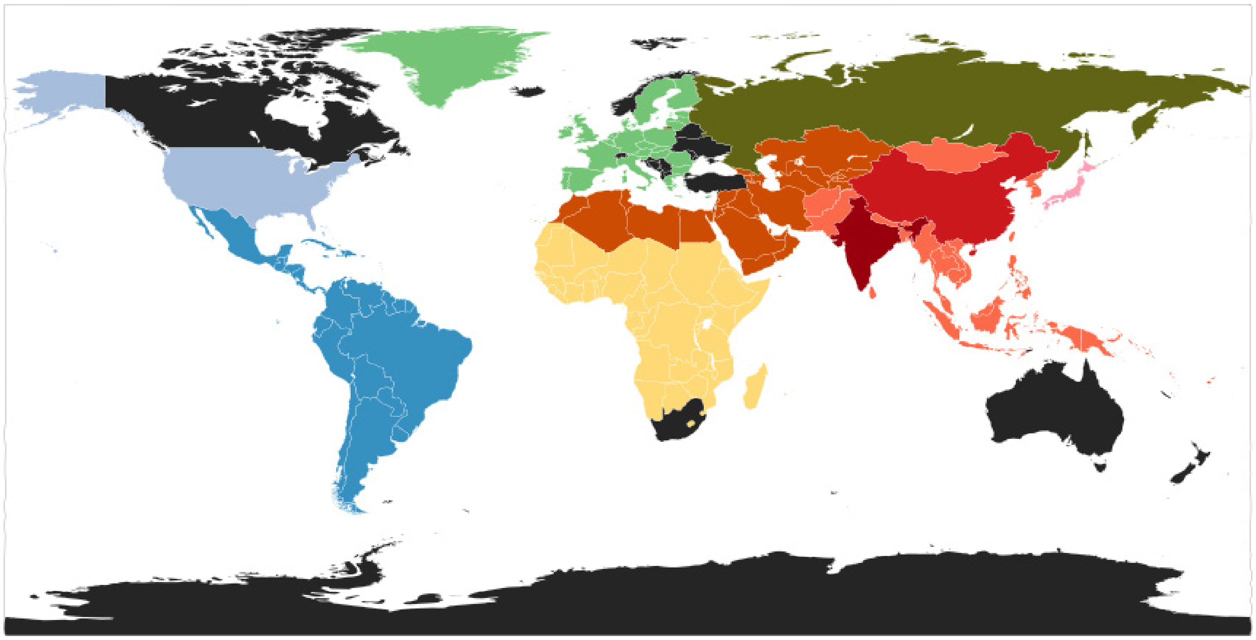

Figure D.5: REMIND model regions

The **Model of Agricultural Production and its Impacts on the Environment (MAgPIE)** is a global multi regional partial equilibrium model of the agricultural sector [28-33]. MAgPIE links demand for 10 economic world regions with spatially explicit biophysical inputs such as land, agricultural yields and water availability. The objective function of MAgPIE is the fulfillment of regional demand at minimum global production costs (cost minimization). Costs accrue for labor, capital, transport, land conversion and R&D investments. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about the level of intensification (yield-increasing technological change), extensification (land-use change) and production relocation (international trade). In climate policy scenarios, GHG emissions from land-use and land-use change are priced. The resulting cost term enters the objective function of MAgPIE, which provides an incentive for endogenous abatement of land-related GHG emissions. MAgPIE is solved in a recursive dynamic mode with a variable time step length of five or ten years on a timescale from 1995 to 2100.

REMIND and MAgPIE are coupled by exchanging price and quantity information on bioenergy and GHGs. First, REMIND is initialized with bioenergy supply curves and a GHG emission baseline derived from MAgPIE. Starting from this initialization, REMIND derives bioenergy demand and GHG prices consistent with a predefined climate target. MAgPIE takes bioenergy demand and GHG prices from REMIND as input and derives bioenergy prices and GHG emissions, which in turn serve as input for the next iteration of REMIND. REMIND and MAgPIE run iteratively until changes in prices and quantities of bioenergy and GHGs are sufficiently small.

Table D.7: Mapping of MAgPIE regions to SSP regions

Native Regions	**SSP Regions**
AFR	MAF
CPA	ASIA
EUR	OECD
FSU	REF
LAM	LAM
MEA	MAF
NAM	OECD
PAO	OECD
PAS	ASIA
SAS	ASIA

Explanations:
AFR = Sub-Saharan Africa
CPA = Centrally planned Asia including China
EUR = Europe including Turkey
FSU = States of the former Soviet Union
LAM = Latin America
MEA = Middle East/North Africa
NAM = North America
PAO = Pacific OECD including Japan, Australia, New Zealand
PAS = Pacific (or Southeast) Asia
SAS = South Asia including India

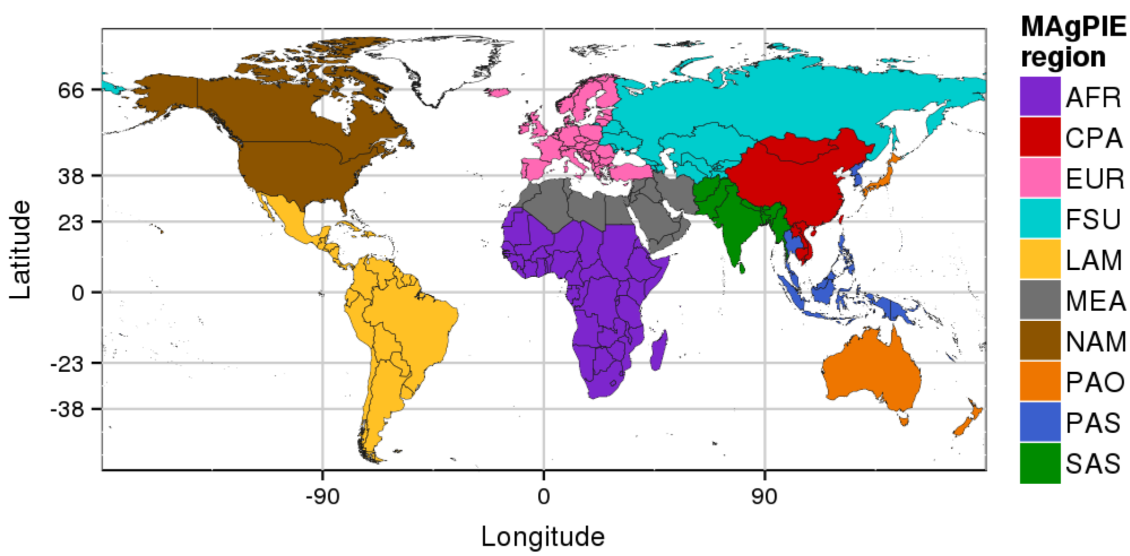

Figure D.6: MAgPIE model regions

WITCH-GLOBIOM (FEEM)

The **World Induced Technical Change Hybrid** model **(WITCH)**, developed by the climate change modelling and policy group at FEEM [34,35] is a hybrid top-down economic model with a representation of the energy sector of medium complexity. Two distinguishing features of the WITCH model are the game-theoretic set-up, which is particularly useful for analyzing fragmented international policy settings, and the representation of endogenous technological change. World countries are grouped into thirteen regions. Innovation spills across regions in the form of knowledge, with important repercussions on the optimal R&D investments that major economic actors decide to undertake. WITCH is an inter-temporal optimization model in which perfect foresight prevails over a time horizon covering the whole century. The model includes a wide range of energy technology options with different assumptions on their future development related to the level of innovation effort undertaken by countries. Special emphasis is put on the emergence of carbon-free energy technologies in the electricity and non-electricity sectors as well as on endogenous improvements in energy efficiency triggered by dedicated R&D investments contributing to a stock of energy efficiency knowledge. WITCH is also coupled to the GLOBIOM model for the land-use sector and includes a module on air pollutant emissions. The full description is available at [36].

Table D.8: Mapping of WITCH-GLOBIOM regions to SSP regions

Native Regions	**SSP Regions**
CAJAZ	OECD
CHINA	ASIA
EASIA	ASIA
INDIA	ASIA
KOSAU	OECD
LACA	LAM
MENA	MAF
NEWEURO	OECD
OLDEURO	OECD
SASIA	ASIA
SSA	MAF
TE	REF
USA	OECD

Explanations:

CAJAZ = Canada, Japan, New Zealand,
CHINA = China
EASIA = Southeast Asia
INDIA = India
KOSAU = Korea, South Africa, Australia
LACA =Latin America
MENA = Middle East, Northern Africa
NEWEURO = EU New Accession States
OLDEURO = EU 15
SASIA = South Asia, also including Pakistan, excluding India
SSA = Sub-Saharan Africa
TE = Russia, Eastern Europe, Turkey, Central Asia
USA = United States of America

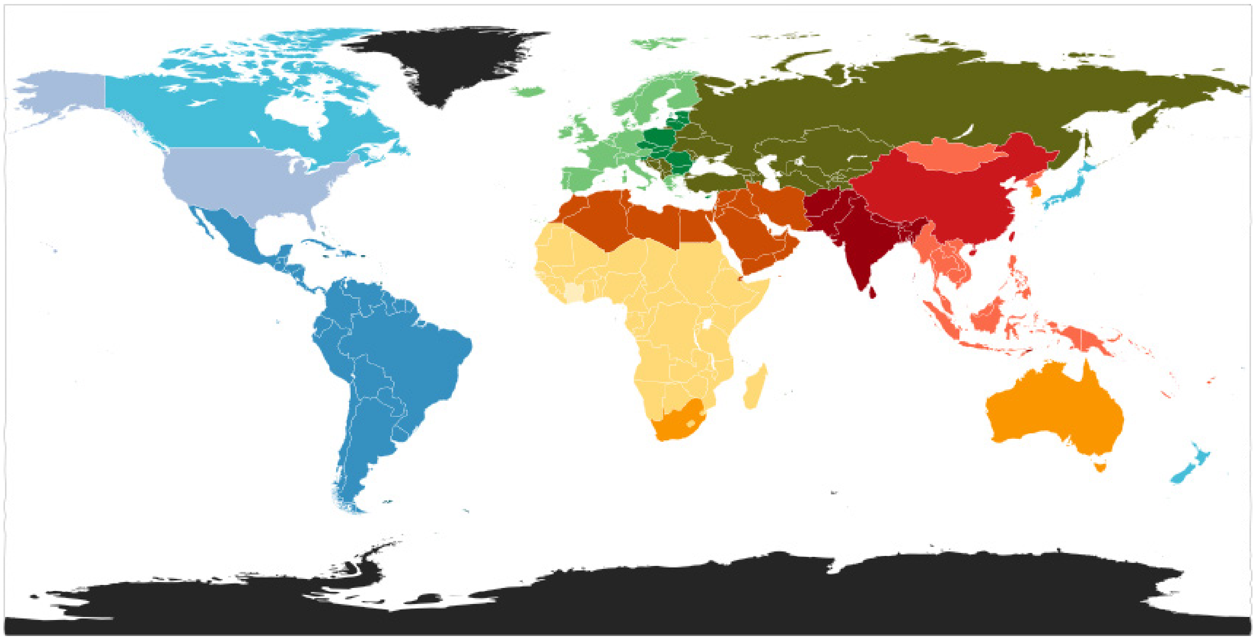

Figure D.7: WITCH model regions

Air Pollution Inventories

The models report emissions of sulfur dioxide (SO_2), nitrogen oxides (NOx), organic carbon (OC), black carbon (BC), carbon monoxide (CO), and non-methane volatile organic carbons (NMVOC). The models use different inventories for base year calibration (Table D.9) and the reported values are not harmonized to a single source. The SSP pathways represent internally consistent representations of future pollution development across the models and reflect institutional and technological constraints in implementation of pollution controls. They include in particular a catch up of all countries to reference target pollutant concentration levels in current OECD countries and an assumed development of pollution control technologies and aspirations over the century.

Table D.9: Inventory Sources for Pollutants

Model	**Base Year Inventories**
AIM/CGE	EDGAR4.2 [37], RCP [38]
GCAM	EDGAR4.2, RCP
IMAGE	EDGAR4.2
MESSAGE-GLOBIOM	GAINS [39], RCP
REMIND-MAGPIE	GAINS, RCP, IPCC 2006 Guidelines for National greenhouse gas inventories [40], GFED3.1 [41]
WITCH-GLOBIOM	RCP

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Appendix E: Definition of SSP regions

The results from the SSP scenarios are shown at regional aggregations for the World or for five macro regions. In addition, the SSP-database hosted at IIASA (https://secure.iiasa.ac.at/web-apps/ene/SspDb/) includes for the main SSP drivers (population, gdp, etc..) also national data as well as data for 32 regions. The regional definitions are provided here.

The five macro-regions are defined as follows:

R5**OECD** = Includes the OECD 90 and EU member states and candidates.
Albania, Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Guam, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, New Zealand, Norway, Poland, Portugal, Puerto Rico, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, The former Yugoslav Republic of Macedonia, Turkey, United Kingdom, United States of America

R5**REF** = Countries from the Reforming Ecomonies of Eastern Europe and the Former Soviet Union.
Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

R5**ASIA** = The region includes most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states.
Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China (incl. Hong Kong and Macao, excl. Taiwan) Democratic People's Republic of Korea, Fiji, French Polynesia, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Micronesia (Fed. States of), Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Republic

of Korea, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Thailand, Timor-Leste, Vanuatu, Viet Nam

R5**MAF** = This region includes the countries of the Middle East and Africa.
Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d`Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Occupied Palestinian Territory, Oman, Qatar, Rwanda, Réunion, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe

R5**LAM** = This region includes the countries of Latin America and the Caribbean.
Argentina, Aruba, Bahamas, Barbados, Belize, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, United States Virgin Islands, Uruguay, Venezuela (Bolivarian Republic of)

The 32 regions are defined as follows:

R32**ANUZ** = This region includes Australia and New Zealand.

R32**BRA** = Brazil.

R32**CAN** = Canada.

R32**CAS** = This region includes the countries of Central Asia.
Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan

R32**CHN** = China (Mainland, Hongkong, Macao; excl. Taiwan).
China, China, Hong Kong SAR, China, Macao SAR

R32**EEU** = Eastern Europe (excl. former Soviet Union and EU member states).
Albania, Bosnia and Herzegovina, Croatia, Montenegro, Serbia, The former Yugoslav Republic of Macedonia

R32**EEU-FSU** = Eastern Europe, former Soviet Union (excl. Russia and EU members).
Belarus, Republic of Moldova, Ukraine

R32**EFTA** = This region includes Iceland, Norway, Switzerland

R32**EU12-H** = New EU member states that joined as of 2004 - high income.
Cyprus, Czech Republic, Estonia, Hungary, Malta, Poland, Slovakia, Slovenia

R32**EU12-M** = New EU member states that joined as of 2004 - medium income.
Bulgaria, Latvia, Lithuania, Romania

R32**EU15** = This region includes European Union member states that joined prior to 2004.
Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom

R32**IDN** = Indonesia.

R32**IND** = India.

R32**JPN** = Japan.

R32**KOR** = Republic of Korea.

R32**LAM-L** = This region includes the countries of Latin America (excl. Brazil, Mexico) - low income.
Belize, Guatemala, Haiti, Honduras, Nicaragua

R32**LAM-M** = This region includes the countries of Latin America (excl. Brazil, Mexico) - medium and high income.
Antigua and Barbuda, Argentina, Bahamas, Barbados, Bermuda, Bolivia (Plurinational State of), Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guyana, Jamaica, Martinique, Netherlands Antilles, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela (Bolivarian Republic of)

R32**MEA-H** = This region includes the countries of Middle East Asia - high income.
Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates

R32**MEA-M** = This region includes the countries of Middle East Asia - low and medium income.
Iran (Islamic Republic of), Iraq, Jordan, Lebanon, Occupied Palestinian Territory, Syrian Arab Republic, Yemen

R32**MEX** = Mexico

R32**NAF** = This region includes the countries of North Africa.
Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Tunisia, Western Sahara

R32**OAS-CPA** = This region includes the countries of Other Asia - former Centrally Planned Asia.
Cambodia, Lao People's Democratic Republic, Mongolia, Viet Nam

R32**OAS-L** = This region includes the countries of Other Asia - low income.
Bangladesh, Democratic People's Republic of Korea, Fiji, Micronesia (Fed. States of), Myanmar, Nepal, Papua New Guinea, Philippines, Samoa, Solomon Islands, Timor-Leste, Tonga, Vanuatu

R32**OAS-M** = This region includes the countries of Other Asia - medium and high income.
Bhutan, Brunei Darussalam, French Polynesia, Guam, Malaysia, Maldives, New Caledonia, Singapore, Sri Lanka, Thailand

R32**PAK** = This region includes Pakistan and Afghanistan.

R32**RUS** = Russian Federation.

R32**SAF** = South Africa.

R32**SSA-L** = This region includes the countries of Subsahara Africa (excl. South Africa) - low income.
Benin, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte d`Ivoire, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Somalia, South Sudan, Sudan, Swaziland, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe

R32**SSA-M** = This region includes the countries of Subsahara Africa (excl. South Africa) - medium and high income.
Angola, Botswana, Equatorial Guinea, Gabon, Mauritius, Mayotte, Namibia, Réunion, Seychelles

R32**TUR** = Turkey.

R32**TWN** = Taiwan.

R32**USA** = United States of America. Includes:
Puerto Rico, United States Virgin Islands, United States of America