Integrated Assessment Modeling of Shared Socio Economic Pathways – Study protocol for IAM runs

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[1] The names represent one contact person for each modeling team

Overall scenario set-up and naming convention

The shared socio-economic pathways (SSPs) describe different socio-economic reference developments spanning the space of socio-economic 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 scenarios. 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 Socio-economic 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 RCPs forcing targets were used if applicable (6.0, 4.5, 2.6 W/m2). In addition, an intermediate forcing target of 3.4 W/m2 was applied to explore implications of climate policies between 4.5 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 socio-economic assumptions):

	SSP1	SSP2	SSP3	SSP4	SSP5
Reference	SSP1-ref	SSP2-ref	SSP3-ref	SSP4-ref	SSP5-ref
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

Participating modeling teams and available scenarios

In total, six IAM teams from FEEM, IIASA, PBL, NIES, PIK and PNNL participated so far in the SSP scenarios development process (the teams contributed voluntary to the process; as entrance criterion the ability to report emission and land-use variables was used). Each SSP has been implemented by multiple IAM models. There are thus alternative interpretations from different IAM models 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, NR = Not Run, X = Non-Marker, No solution = no feasible solution could be found by the modeling team]

	AIM	GCAM	IMAGE	MESSAGE-GLOBIOM	REMIND-MAgPIE	WITCH-GLOBIOM
SSP1-Reference	X	X	M	X	X	X
SSP1-4.5	X	X	M	X	X	X
SSP1-3.7	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
SSP2-3.7	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
SSP3-3.7	M	NR	X	X	NR	X
SSP3-2.6	No solution	NR	No solution	X	NR	No solution
SSP4-Reference	X	M	NR	NR	NR	X
SSP4-6.0	X	M	NR	NR	NR	X
SSP4-4.5	X	M	NR	NR	NR	X
SSP4-3.7	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
SSP5-3.7	X	X	NR	NR	M	X
SSP5-2.6	X	X	NR	NR	M	No solution

Implementation of SSPs

Population and GDP: Models have adopted 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 PPP and have been aggregated to the native model regions. In addition, OECD has provided PPP to MER conversion factors to convert PPP projections in MER if needed (see the download section of the SSP database).

Energy and land use: The SSPs vary also 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 I. 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))
- Fossil energy trade (see category trade barriers in energy supply (resources) table)
- Energy supply technologies (capturing the essence of the table on energy supply (technologies))
- Final energy intensity (capturing the essence of the table on energy demand)
- Phase out of traditional biofuels (see category traditional fuel use in energy demand table)
- Land protection (see category land use change regulation in land use table)
- Land productivity (see land use table)
- Food consumption (see category environmental impact of food consumption in land use table)
- Trade of agricultural products (see category international trade in land use table)

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 III. The models report emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), 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. A number of factors, including continued cross- country differences in policies and institutions may prevent full convergence to the frontier. Thus in current 'lagging' countries, controls will ultimately converge not necessarily to the technological frontier but rather to the (lower) average emission factor levels firstly in 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 III, Table 3.1) provide for additional differences, with target levels, rate of policy "catch up" and technological innovation levels differing between scenarios as well.

Implementation of climate forcing targets

Radiative forcing targets refer to **full** anthropogenic forcing by the end of the century[2]. 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**. 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.

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.

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

The 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

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

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 II.

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Appendix I: Energy and land use tables

Qualitative assumptions for energy demand

The development on the energy demand side is 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 were structural reason (modal split with high public transport share) also lead to comparatively low energy intensity levels. 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/mediu m	low			high	
General Comments					some regional diversity retained										

Qualitative assumptions for fossil energy supply

The design for the specification of the extended SSP for fossil resource availability[3] was derived from the specific statements as well as the general narratives of the basic SSPs,[4] hence, it is a specific interpretation of the SSPs for this particular sector. 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. Economically the challenge of mitigation reflects the opportunity cost of not using the fossil fuels and emitting the CO2 freely into the atmosphere. The scenario assumptions on fossil resource supply largely influence the baseline emissions and the prices of final energy. If the baseline CO2 emissions are high and the costs of alternatives are also high compared with the fossil fuel alternative, the challenge to mitigation is high and *vice versa*.

The scenario "continuation 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. 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 "Conventional 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. The relatively low fossil fuel costs also increase the challenge to achieve stronger climate change mitigation targets because the costs of fossil fuels are low. The "Inequality

[3] The „availability of fossil fuels" refers in first place to the cumulative amount that is available and also the economic costs that are necessary for the extraction of these fuels. The availability is determined by technological, macro-economic and policy factors. In a second place, also the dynamic flexibility to bring new resources online to supply them to the market can be covered by the term availability.

[4] The electronic form of Table XXX contains as comments the relevant text passages and also indicates some short-comings in deriving the extended SSP assumptions from the basic SSP storylines.

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 CO_2 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 “Fragmentation SSP3” scenario assumes a high challenge to mitigation that is- like SSP5, but to a lesser degree – related to high availability of fossil fuels. Here also the domestic policies towards energy security and lax regulations to support domestic fossil fuel supply will lead to relatively abundant levels of fossil fuels.

Table A.2: Qualitative assumptions for fossil energy supply 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
Coal							
Macro-economy	cost driver	neutral	cost reducing	cost reducing	neutral	cost driver	cost reducing
Technology	medium	medium	high		medium		very high
National & environmental policy	very restrictive	supportive	very supportive	supportive	supportive	restrictive	very restrictive
Conv. Hydrocarbons							
Macro-economy	neutral	neutral	neutral		cost driver		cost reducing
Technology	medium	medium	medium		fast		very high
National & environmental policy	restrictive	supportive	mixed (not supported in MEA/FSU)	supportive	supportive	restrictive	very restrictive
Non-conv. Hydrocarbons							
Macro-economy	neutral	neutral	neutral		cost driver		cost reducing
Technology	slow	medium	medium		medium		very high
National & environmental policy	very restrictive	supportive	very supportive	supportive	supportive	restrictive	very restrictive
General							
Trade barriers	Free	Barriers	High Barriers		Barriers		Free

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 impacts on land utilization and crop prices.

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		

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. Unhealthy diets with high animal shares and high waste prevail. 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 II: Definition of the Shared Policy Assumptions

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).

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 AMPERE / LIMITS / RoSE / EMF7 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, and 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.

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).

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 III: Regional pollution tables

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; 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.