The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP7

ScenarioMIP Scientific Steering Committee and Task Groups

For questions: detlef.vanvuuren@pbl.nl, claudia.tebaldi@pnnl.gov,
brian.oneill@pnnl.gov

1. Introduction

1.1 CMIP and ScenarioMIP

Scenarios represent a critical tool in climate change analysis. They are used by different research communities to explore potential future avenues in socio-economic conditions, assess the effects of different drivers of climate change, characterize future climatic conditions, and assess impacts of climate change as well as adaptation and mitigation responses. Scenarios also connect these research communities. In this paper, we are specifically concerned with those scenarios that are used as external forcings to climate models, i.e. Earth System Models (ESMs), General Circulation Models (GCMs), Climate Models of Intermediate or Reduced Complexity (CMICs) and Simple Climate Models (SCMs). These external forcings encompass elements such as emissions and atmospheric concentrations of greenhouse gases, chemically reactive gases, and aerosols, and land use. Such scenarios play a pivotal role not only in climate research but as integrating tools for scientific assessment processes and policy analysis.

The Climate Modelling Intercomparison Project (CMIP) has been organising scenario experiments for several phases. The Scenario Model Intercomparison Project (ScenarioMIP) forms a primary activity within CMIP that facilitates multi-model climate projections based on alternative plausible forcing scenarios that are directly relevant to societal concerns regarding climate change mitigation, adaptation, and impacts. In this role, ScenarioMIP's goal is the design of a limited set of scenario-based experiments, with three important aims:

- *Service*: Providing information about future changes in climate variables (such as temperature, precipitation, humidity, etc.) and related direct human forcings (such as population) to a diverse set of user communities that can be used for further research and analysis to better understand climate change, its impacts, risks, and response options, including mitigation choices. Such research communities include, for instance, researchers on impacts and vulnerability or real-world practitioners, who might use this information for national risk assessment or adaptation planning.
- *Science*: Providing information used to study and understand climate processes in and of themselves, and how their response to past and future anthropogenic forcings emerges from internal variability and model structural uncertainties.
- *Policy*: Providing information that helps support climate policy development and communication in line with national and international climate policy developments. This includes the use of ScenarioMIP outputs as part of forthcoming assessments of the IPCC. This means that the scenarios also need to comply with IPCC's mandate to provide policy relevant, but not prescriptive information.

Computational expenses associated with setting up, running and archiving output from climate model experiments pose strict constraints on the number of scenarios that ScenarioMIP's protocol can include. Therefore, a set of scenarios needs to be selected as a compromise that satisfies these three critical goals as best as possible.

1.2 Process of designing a new protocol for CMIP7

On June 20-22, 2023, the first meeting of the ScenarioMIP project under the new phase of the Coupled Model Intercomparison Project, CMIP7, was held in Reading, UK. During the discussions in plenary and the various break-out sessions, a clear consensus on several main characteristics of the scenario set emerged. Based on the meeting report, the Scientific Steering Committee (SSC) of ScenarioMIP and several task groups have continued to work on an experimental design for the next round of ScenarioMIP. The results so far are captured in this document.

The meeting also led to the installation of a final SSC for ScenarioMIP as well as a larger advisory group (see https://wcrp-cmip.org/model-intercomparison-projects-mips/scenariomip/) and a proposal on how to develop a new protocol for ScenarioMIP. At this point in time, the envisioned pathway is as follows:

- First presentation of the ideas for ScenarioMIP and envisioned process by ScenarioMIP leadership (September 2023)
- Formulation of a draft proposal for a protocol based on the work of various task forces by ScenarioMIP Scientific Steering Committee (Late 2023)
- Review of the draft proposal by the ScenarioMIP advisory board (February 2024)
- External review of the draft proposal (April 2024)
- Further definition of exact characteristics of the scenarios (June-August 2024)
- Intended submission of the proposal to GMD (June-August 2024)
- Finalisation of the data and harmonisation with historical data (June-August 2025)
- Start of climate model runs: Last quarter of 2025

The process will include a period in which the emission/land use scenarios can be tested in ESMs for quality control.

2. Overall design

Box 2.1: Role of ScenarioMIP in CMIP6

In CMIP6, ScenarioMIP specified four Tier 1 and four Tier 2 scenarios to be run by ESMs/GCMs, and these experiments (especially those in Tier 1) were run by most modelling teams participating in CMIP6 and are by far the most used scenario-based runs of CMIP6 (O'Neill et al., 2016; Tebaldi et al., 2021). The use of the ScenarioMIP experiments resulted in physical science papers describing changes in climate characteristics, but also a very large number of papers characterizing the impacts of those changes. Further, ScenarioMIP results contributed to the assessment reports of all Working Groups of IPCC, supplying a dimension of integration that is reflected in the Synthesis Report of AR6 (IPCC 6th Assessment Report). The most direct use was in WGI, where ScenarioMIP runs formed the backbone of the assessment (IPCC, 2021). The use in WGII was more limited because of issues related to timing (IPCC, 2022a). In WGIII, ScenarioMIP results had an indirect but fundamental contribution via the calibration of SCMs that allowed characterization of probabilistic global temperature projections and the resulting classification of a large set of baseline and mitigation scenarios produced by Integrated Assessment Models (IPCC, 2022b). There were some issues related to the process. As under earlier phases, there were delays in data production (by Integrated Assessment modeling teams), its translation into inputs for ESMs and its harmonisation to historical forcings. This also meant that data could not be tested earlier, and for some ESM modeling teams this translated to significant time before they were successfully able to run their models using the new forcing data fields. Also, over time, critiques emerged about the plausibility of some scenarios (SSP5-8.5 and its precursor, RCP8.5; SSP1-1.9).

2.1 General design principles

In view of the multiple aims of the ScenarioMIP scenarios, the following general design characteristics are proposed. Please note that these scenarios are not intended to represent confined storylines, rather they are illustrative pathways.

Wide and plausible range

The scenarios should encompass a wide range of policy-relevant emission trajectories considered to be plausible (i.e. not impossible for technical/geophysical reasons or for other reasons beyond the range relevant for exploring various climate policy responses). This range, however, could be smaller than assessed before. On the high-side, the plausibility of the CMIP6 high emissions levels (quantified by SSP5-8.5) have been questioned (Hausfather & Peters, 2020). On the low side, some emission trajectories in the period 2020-2030 have become implausible or even impossible.

If possible, scenarios are to be run in emission-driven mode (for CO_2)

If possible, most simulations should be run in emission-driven mode – in contrast to the use of a concentration-driven approach in CMIP6. A wider range of model outcomes for the same emission trajectory is expected, which may add further challenges to interpretation and actionability of the results but will better represent the real uncertainty range as it would include both the uncertainty from the carbon cycle and from the climate system and have more direct relevance to the study of mitigation options. The runs would also be more consistent with current ESM capabilities, especially regarding the outcomes of land-based mitigation solutions, which are heavily dependent on feedbacks that are not represented in concentration-driven experiments.

This will mean that all/most scenario runs are to be preferably emission-driven, (i.e., letting the carbon-cycle in the ESM determine the concentration of CO_2 in the atmosphere that ensues from the prescribed emissions), but concentration data will also be provided for ESMs/GCMs that can only run in concentration mode (without an active carbon cycle) (some discussion on the capabilities of ESMs can be found here(Hajima et al., 2024) (Séférian et al., 2020). Here, the proposal is for those ESMs/GCMs to run median estimates of the concentrations created by SCMs (emulators) (see Box 2.2).

Regarding CDR options, only reforestation will be based on endogenous representation of land-based mitigation solutions in ESM; for all other options we will include the emission impact in the IAM emission output (see Section 6). To better assess the impact of running in emission-driven mode over the range of responses ensuing from the multi-model ensemble, we also propose that models run one of the ScenarioMIP scenarios (M) both in emission-driven mode and in concentration-driven mode for comparison.

Box 2.2: Concentration-driven runs

Several climate models may choose not to run in emission-driven mode. It is proposed to therefore provide median values of the expected concentration outcomes (using simple climate models (=emulators) calibrated on CMIP6 results to simulate the carbon cycle) for all ScenarioMIP scenarios. It is expected that within the total set of model results, the concentration-driven models will have a reduced outcome space compared to the emission driven set - which will have consequences for interpretation and use of certain variables. An alternative could have been to run concentration-driven models multiple times using low/medium/high estimates of the concentrations, derived by alternative values of the parameters affecting carbon cycle uncertainty. However, this would complicate and burden the ScenarioMIP design excessively. It is recognized that this type of exploration would be an important contribution to the uncertainty quantification of model projections, and we suggest that it should be the object of a research project.

While we encourage the research and modeling community to experiment with full emission driven runs, it is proposed that under the ScenarioMIP protocol models be run in emission-driven mode for CO_2 only and not for all GHGs as it is expected that choosing the latter would significantly reduce the number of models participating in emission-driven mode and too little experience has been built up with such runs (the final protocol will be decided after surveying the modelling teams). The use of concentration-driven data for non-CO_2 GHGs and air pollutants requires running a preliminary step using a limited set of models with full representation of air chemistry to create the concentration data. This could include the use of emulators and an atmospheric chemistry model. While the proposal is to use one consistent method for all scenarios in ScenarioMIP, it might be interesting to research the relevant uncertainty by adding more atmospheric chemistry models and even use the output as forcing for ESMs (e.g. in AerChemMIP or in research projects).

Scenarios

The consensus from the Reading meeting formed around a set of 6 scenarios.

- *High emission scenario*: There was an interest in a high emission scenario based on assuming developments in an adverse direction, including, e.g., high demographic growth and slow technology development. This high emission scenario is, however, expected to result in forcings below SSP5-8.5. (See Section 3)
- *Medium emission scenario:* There was an interest in a middle scenario to explore consequences of continuing current policies without modification. (See Section 3)
- *Overshoot.* Strong interest was also expressed for an additional scenario that would follow the medium scenario until mid-century, with rapidly decreasing emissions afterwards, representing delayed mitigation action. (See Section 3)
- *Low emission scenarios:* There was an interest in a set of scenarios at the low end that would inform policies consistent with the Paris Agreement (i.e. the range from 1.5 to below 2°C). One of the scenarios should remain as low as possible given feasibility constraints (consistent with a majority of the participants indicating that ScenarioMIP should only prescribe plausible scenarios, leaving idealized/counterfactual pathways to different research exercises or MIPs).This scenario is thus relevant for the low end of the Paris range (i.e. as close to the 1.5°C goal as possible). The second trajectory would be a scenario with an overshoot of the 1.5°C goal, followed by a deployment of Carbon Dioxide Removal (CDR) intended to return to lower levels, thus supporting research into the reversibility of climate outcomes and their impacts. The last scenario would be consistent with the pursuit of warming levels below 2°C. (See Section 4)

Figure 2.1 shows a stylized, qualitative design for the CMIP7 ScenarioMIP scenarios as discussed and agreed upon in Reading

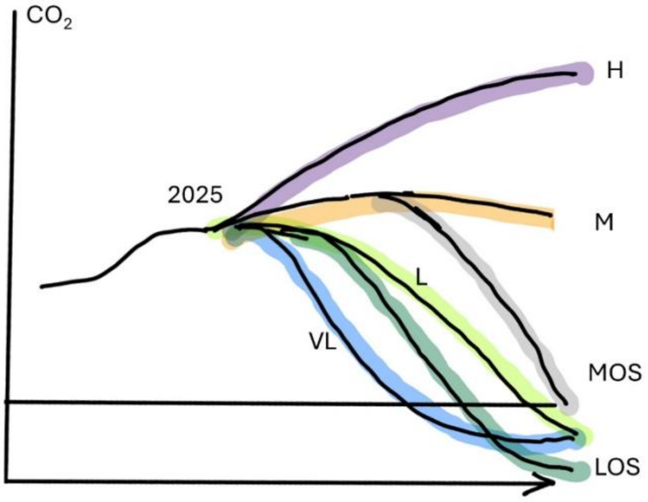

Figure 2.1: Draft outline scenarios developed on final day of work at the Reading meeting (the lines are only meant as illustration, e.g., decisions on timing still need to be taken). The dashed line was at the time of the Reading meeting considered as a possible additional scenario to the set of five, but received strong endorsement in the intervening time since that discussion, by the SSC and the Advisory Group.

2.2 Other design criteria

Scenario period

The scenario period starts in 2025 (for CMIP7, historical forcings will be finalized up to the end of 2024). There are important reasons to investigate long-term dynamics beyond the end of the century, and therefore the need for extensions was voiced. But first, a survey of the Integrated Assessment Modeling teams is planned to determine whether their output could cover the period up to 2125 in recognition that the traditional 2100 horizon is naturally becoming increasingly shorter. In any case, long-term extensions (assumed not to be reliant on Shared Socio-economic Pathways (SSPs) drivers and Integrated Assessment modelling) would start from the end of the Integrated Assessment Model (IAM) scenario output (2100 or 2125) and cover the period out to 2200 or, preferably, 2300 (See Section 5). Particular interest in the longer term was expressed by the icesheet/sea level rise researchers.

Air pollution control

Decisions need to be made on air pollution control (Short Lived Climate Forcers (SLCFs), among which aerosols – from sulfur emissions -- are particularly critical because of their cooling effect). The high scenario is a logical candidate for high sulfur emissions, partly because of a strong correlation between GHG mitigation policy effects and air quality outcomes (i.e., air pollutant emissions are expected to be low in stringent GHG mitigation cases). However, high aerosol emissions in the high scenario would also slow down warming. Therefore, the proposal is to have a high scenario with the expected decrease (because of historical trends in implementation of air quality controls on pace with economic development) in aerosol emissions (i.e., using standard emission factors) and have a variant of it with deliberately high aerosol emissions (based on higher emission factors) in AerChemMIP.

Ensembles

Decisions need to be made on the use/size of initial condition ensembles. These are particularly relevant at the low end of the scenario range where the emergence of a climate signal is expected to require relatively larger ensembles but are also important to enable sampling of longer return period events (rarer events) at all levels of forcing. Under CMIP6, teams were asked to run each scenario at least once -and to run an initial condition ensemble of at least 10 members for a specific scenario (SSP3-7.0). For CMIP7, we request running ensembles (e.g. 3 members, or more according to modeling centers capacities) for each scenario, which will help to reduce uncertainty. The Strategic Ensemble Design Task Team may be asked for further advice. It is still an open question if climate model emulators could be used to complement this part of the design. Emulators have not been adequately trained and tested for peak and decline scenarios, and it is still unclear whether any emulator would be able to fully replace the comprehensive set of outputs from an ESM.

IAM model runs

Based on the - mostly qualitative - formulation of the different scenarios in this document, it is envisioned to ask the IAM community to provide alternative (i.e., ideally more than one) quantitative interpretations of the scenarios. Subsequently, marker scenarios could be selected for ScenarioMIP (realizing also the possible impacts on the climate outcomes). The full set of alternative scenarios can still provide flexibility for users other than ScenarioMIP models (e.g. scenario analysts), certainly if key parameters are varied (such as CDR use). The alternative scenarios could also include variants with and without climate change impacts. Decisions will also need to be made regarding the choice of underlying SSPs.

The IAM community will be asked to explore different scenarios as pilots until the June-August 2024 time frame and after that start making further decisions on the exact characteristics. The Scenario working group of IAMC will be the conduit through which the plan and its timeline will be vetted and finalized.

The expectation is that the CMIP results will be used in IPCC assessments finalised in 2028. This means that studies will be published in the 2026-2027 time frame - while the scenarios need to be useful to policy discussions in the subsequent years. It is therefore proposed that the scenarios do not diverge before 2025 (and implement expected developments up to 2025 based on current implemented policies). For the period up to 2027, it is also expected that differences would remain within a relatively narrow plausibility range.

Box 2.3: Different mitigation strategies

Mitigation strategies can differ in choice of reduction measures, timing, geographic location and underlying baseline (SSPs). For instance, climate impacts can be different for negative emissions originating from bio-energy-and-carbon-capture-and-sequestration (CCS) or reforestation. The same can be the case for a SSP1 or SSP3 based scenario staying well below 1.5 °C. Mitigation action can also differ in terms of the contribution of various sectors and countries, strongly related to justice issues. The latter will also be further explored in IAM research – summarized in subsequent IPCC WGIII reports. In ScenarioMIP, the focus is on the climate response of different forcing trajectories. It will be interesting to further research whether differences in mitigation strategies lead to clearly identifiable physical responses in climate model runs. This can also inform the exchangeability of climate model runs for different impact studies. It should be noted that solar radiation management is not included in these experiments as it is covered in a separate MIP (GeoMIP).

Impacts and adaptation

The proposal will request the IAM teams to produce simulations that do not include climate change impacts on anthropogenic systems (e.g. agriculture, energy use or economic growth). At this point of time, there are several pragmatic reasons for this. First, the scenarios are also used to estimate impacts by impact models (combination of climate and direct human drivers) – leading to possible double counting. Moreover, not all IAM can represent the breadth and detail of many regional impacted systems and adaptation strategies. The scenarios are therefore intended to be augmented by impacts and adaptation studies that complete the picture of potential future worlds with climate shifts, mitigation, adaptation, and development. At the same time, demand for fully consistent scenarios is growing. It is, therefore, encouraged that IAM models produce additional scenarios in which impacts are accounted for. This work may also lead to different scenario protocols for future ScenarioMIP exercises.

Modeling assumptions

The modeling paradigms and assumptions underlying IAM implementations relate to questions of mitigation preferences and climate justice. Exploring the implications of these assumptions, and alternative implementations, is of critical importance to provide policy relevant science to inform the deliberations on mitigation efforts and their regional distribution. These important questions, however, are outside the scope of ScenarioMIP that is focussed on providing scenario forcing data for ESMs. The use of IAMs within ScenarioMIP is limited to provide emissions and land use forcing time series that allow to explore different global climate futures in a policy neutral way. An exploration of alternative implementations of the ScenarioMIP scenario narratives using different modeling paradigms and normative assumptions is explicitly encouraged.

The role of complex climate models vs emulators

Some further discussion is needed on the role of different tools (especially ESMs vs emulators of climate model output). The use of emulators can be attractive both to fill in gaps in the design and to accelerate some of the outcomes of new scenarios, given the unavoidable time constraints. Thus, it is useful to consider how emulator use can further reduce the computational load on climate models for scenario exercises and the expectation is that, given the rapid developments in the emulation space of the last few years, the use of emulators to fully substitute for ESM output may become better actionable in a not-so-distant future. As of now, however, no emulator can address the provision of outputs from an ESM in their entirety and for all types of scenarios (with overshoot/peak-and-decline constituting particularly open questions given the scarcity of existing scenario simulations having these characteristics, on which emulators could be trained). At this point in time, therefore, it is envisioned that all scenarios will be run using ESMs.

Input variables for ScenarioMIP model runs

Input data for ScenarioMIP model runs needs to be made available both for climate models and for the Impacts, Adaptation and Vulnerability research community. Decisions will also need to be made regarding the forcings/additional data that will be provided. Table 2.1 illustrates what type of data could be made available, but it is proposed that ScenarioMIP requests the CMIP panel (and, via the panel, the modeling teams) as well as the Vulnerability Impacts Adaptation and Climate Services (VIACS) advisory board to CMIP to provide further guidance.

Table 2.1: Possible input data into ScenarioMIP (further input requested)

	Climate models	Vulnerability, Impact and adaptation community
Based on previous round	CO_2 emissions (fossil + land use) + concentrations (harmonised with historical data) Land use change (harmonised with historical data) CH4, N2O, CO, NOx, H2, VOC, SO2 emission data (harmonised with historical data and run via an atmospheric chemistry model)	Population maps Energy system parameters Land use maps/crop data (in addition to land cover) Water consumption and irrigation [gridded]
Additional data	Data on CDR activity (reforestation; negative emissions)	Urban area Economic variability and poverty/inequality
	Water consumption [gridded] Fertiliser use Crop yields Gridded energy consumption Other	Fertiliser use Crop yields Gridded energy consumption

Further, the CMIP7 Forcings Task Team is in place to address some of these issues (required forcing input files, harmonization) and coordinate the provision of ESM forcings through the input4mip effort. This include, for instance, also harmonization of historical emission data and providing consistent gridded land use data. For this, ScenarioMIP will work closely together with the Forcing Task Team.

Output variables from ESMs

An inquiry will be sent to relevant actors for required output data, in cooperation with the CMIP7 data request team (data request is being sent out through a series of papers). In this context it might be useful to also evaluate the previous set of output data (including possibly the download records). Many variables were produced from the last set of scenario runs but a smaller number were broadly used. The data collected in other areas could go beyond the CMIP6 set, including for instance atmospheric composition and chemistry and data on extreme events.

Consistency with earlier scenario sets

In CMIP6, one of the scenario design's stated goals was to facilitate comparison with CMIP5 and some studies were published that attributed changes in temperature range to changes in scenarios vs models. It is assumed, however, that for the study of consistencies and differences from model development, the experiments prescribed as part of CMIP's Diagnostics, Evaluation and Characterization of Klima (DECK) is more suitable. ScenarioMIP will contact the CMIP panel to ask for their opinion on the suitability of the DECK runs for consistency checks. In the final design, it would be useful to consider how to further improve consistency (e.g., scenarios could end up - when run by simple climate models - at similar forcing or warming levels to previous scenarios).

2.3 In depth elaboration of specific scenarios

In the rest of the document, we will further explore ideas and considerations relevant to the various scenarios. This is based on the results of discussions undertaken by the SSC since Reading, and research within four task groups that were formed after Reading to address open questions with regard to:

1. High and medium emission scenarios
2. Low emission scenarios
3. Extensions
4. Representation of negative emissions in IAMs and ESMs

'Table 2.2: Scenarios and proposed naming

Scenario group	Scenario name	Brief description	Priority
High/Medium	High (H)	High emission scenario to explore possible high end impacts	1
	Medium (M)	Medium emission scenario consistent with current policies	1

2 °C	Medium Overshoot (MO)	Scenario follows medium scenario and mid-century diverts rapidly leading to an overshoot of 2 °C	1
Low scenarios	Low (L)	Scenario consistent with staying with high probability below 2 °C	1
	Very Low (VL)	Scenario consistent with limited overshoot of 1.5 °C (as low as possible)	1
	Low Overshoot (LOS)	Scenario with similar end-of-century impact to VL, but with overshoot	1
Concentration-driven	*HIgh, Concentration driven (MC)*	*Variant of H, concentration-driven for models that also run the emission-driven variant*	2
	Medium, Concentration driven (MC)	*Variant of M, concentration-driven for models that also run the emission-driven variant*	1
	Low-concentration driven (LC)	*Variant of L, concentration-driven for models that also run the emission-driven variant*	2

3. Towards the design of the high- and medium emission scenarios for CMIP7

3.1 Introduction

The high and medium scenarios (H&M) are interesting to study possible impacts, challenges to adaptation and mitigation as well as climate dynamics. Below, we discuss the main scenario characteristics and narratives.

3.2 Scenario Design of the high emission scenario

The high-emission scenario explores a plausible future world that weakens or even abandons mitigation policies and actions. It is important for addressing questions such as: what are the physical, socio-economic, and ecological impacts associated with a scenario in which climate policy largely fails? What is the risk of reaching possible tipping points in the Earth system over a wide range of future warming levels? How large might the climate change risks be to which society will have to adapt? Do non-linear responses alter the nature of extreme events as the world reaches higher warming levels? How far beyond current conditions are known adaptations viable? How much might mitigation policies reduce risks relative to a future with high warming?

The scenario includes events and outcomes that may not be likely given current trends but are still plausible enough to occur. The world view it represents is consistent with policy roll-back, the lack of coordination and cooperation for addressing global environmental concerns, societies and industries depending on and even reverting to fossil fuel resources, the adoption of resource and energy intensive production technologies and lifestyles, and unforeseen technological barriers. This scenario is not meant to represent a “business-as-usual” or no-policy reference scenario for the other cases. The scenario is intended to explore the upper end of GHG emissions resulting from deep political, technological and structural deviation from current trends.

In this scenario, the rapid cost decrease in renewable energy of the past decade is followed by a period of slowdown of cost declines, as a result of regional scarcity and limited tradability in materials for solar, wind technologies and EV batteries (IEA, 2021; Schlichenmaier & Naegler, 2022) as well as lack of public support and the remaining strong position of fossil fuel industries. Critical mineral mining projects may lead to price spikes, local opposition and investment risks, hampering the global energy transition. Such a situation might be combined with the SSP5 or SSP3 scenario (in the SSP5 scenario it might be at odds with relatively high technology development (O'Neill et al., 2017; Riahi et al., 2017) but possibly consistent with the rapid economic growth and energy intensive lifestyles; in SSP3 the lack of international collaboration and generally stagnating technological progress might be consistent with the scenario).

Since the emission outcomes of the pathways will not be fully known until run by IAMs, we recommend that IAM modeling teams develop two storylines, using both SSP3 and SSP5 baselines updated with recent data and trends, and then select a preferred, plausible high-emission scenario. Further specification of the scenario protocol may happen in parallel with the IAM test runs. We note also that according to the scenario framework design, climate impacts are not included in the scenarios produced for ScenarioMIP, to avoid double counting of impacts in IAV studies. If climate impacts were large enough to modify global emissions and land use trajectories, a possibility especially in a high scenario, this would introduce an inconsistency in the scenario.

An additional issue is the treatment of fossil fuel reserves and resources and their tradeability. The cumulative amount of fossil fuel use is likely to be considerably larger than the estimated total reserves (these are known deposits that are extractable at current prices and technologies) (Bauer et al., 2015; Rogner, 1997). Future technologies or market prices would make current resources (estimates of undiscovered and/or not recoverable at current prices) recoverable to some extent. The IAM models already include decision criteria about the use of such energy resources[4]. How these play out in the two different scenarios needs to be transparent.

In support of the plausibility of a high emission scenario it is crucial to document and motivate the techno-economic, political and socioeconomic assumptions that drive the transformation. Over the past decade several developments and trends have diverted the transformation pathway away from very high-emission levels. In particular, progress in the fields of renewable energy technologies and electrification of end-uses have substantially eroded the competitive advantages of fossil fueled technologies. Therefore, the causes and drivers that lead towards fossil fuel-based development need to be clarified and motivated.

Another key factor is aerosol forcing. Aerosol emissions have been observed to shape regional climate and will be one of the major drivers to influence climate change in coming decades (Persad et al., 2022). Aerosols will be included in all SSP scenarios and sensitivity to aerosols will be tested for the high scenario. Following the SSP storylines, the recommendation might be to use low aerosol levels for SSP5 and high for SSP3. However, using high aerosols would lead to less warming and also a different ratio between warming and precipitation, which might be less useful for impact assessment (Shiogama et al., 2023). Therefore, we propose to use default or low aerosol levels in the high scenario, an assumption also supported by the potential for air pollution control in developing countries (e.g. as currently happening in China). A high aerosol variant could be run in AerChemMIP and RAMIP (Wilcox et al., 2023).

To maintain plausibility of the scenario and keep consistency in the near term with other scenarios, we recommend considering a high-emission situation that takes account of the benefits of existing emission reductions through 2025 and deviates thereafter. The near-term developments would be constrained to be consistent with the overall scenario set, i.e. implement expected developments until 2025 with rapid roll-back of climate policy after 2026. The narrative storylines of the high scenario would follow the original storylines of the driving SSPs. How policy roll-back could come about in both scenarios are as follows:

- In SSP3, a resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or regional issues.

Policies shift to become increasingly oriented toward national and regional security issues, including barriers to trade. A low international priority for addressing climate concerns leads to collapse of international and national climate policies.

- In SSP5, there is little effort to avoid global environmental concerns due to a perceived tradeoffs with progress on economic development while local environmental impacts (e.g. aerosols related to air pollutant emissions) are addressed effectively by technological solutions. Technological progress and investments focus on fossil fuels while low investment in low-carbon technologies leads to relatively high barriers to development and dissemination in renewables and other low-carbon technologies. The strong reliance on fossil fuels and the lack of global environmental concern leads to ineffectiveness of international and national climate policies.

Extreme events in many forms such as climate and other environmental, social, geopolitical, financial or economic shocks can happen in the short-term whereas some drivers or outcomes of the extremes may happen over longer periods of time[5]. Extremes may act to push the emission pathway upward. However, not all feedbacks are included in IAMs; social fragmentation, energy insecurity, or policy breakdown are theoretically possible in the high-end storylines.

3.3 Scenario Design of the medium emission scenario

The medium-emission scenario is a benchmark that shows the consequences of some measure of the current policy situation continuing over the century, and we refer to this as a “current or frozen policy scenario”. It should not be considered as a “most likely” scenario. The scenario will be used to explore a future world in the case of continuing currently implemented climate policies and/or emission pledges and can be used to address questions such as: what future physical, socio-economic, and ecological risks are implied by current levels of climate change policy (Roelfsema et al., 2020; Rogelj et al., 2023)? In comparison to lower scenarios, what are the relative benefits and costs of taking further mitigation actions? What are the needs for adaptation implied by current policy levels? What limits to adaptation would be encountered in future decades without additional mitigation actions?

To distinguish between the medium scenario and the lower mitigation scenarios, we make an assumption that mitigation actions in a medium scenario must be established in policy with some legislation to back them up, and ideally a plan for implementation. We don’t include announcements of future policy goals which come with no current basis in policy. We recommend using the existing policies because including either Nationally Determined Contributions (NDCs) pledges or net zero announcements involves making significant judgements on implementation. Furthermore, taking only the existing policies appears most consistent with the concept of the “frozen policy” approach. This still leaves a range of possible options based on the literature and ambiguity of interpreting current policies (Rogelj et al., 2023).

We consider several options for the treatment of policy assumptions that have a bearing on emissions over time for the medium scenario. In the IAM community already several rules are used to extend current policies beyond 2030 (van Soest et al., 2021). There are various alternatives in terms of specific policies of countries, but the progression of policies in the real world is clearly unknown. This could argue for an assumption of no progression in mitigation policy beyond 2050. Giving the medium scenario this idealized aspect also helps to reinforce the point that it is not a “most likely” scenario.

Another complexity is whether to focus only on national policies, or to include corporate pledges, which is consistent with the need for public, private and citizen responses to the climate challenge. In the recommendation for initial scenarios for earth system model simulations we take the pragmatic choice of focusing on national policies but recommend further work on the sensitivity of current policy outcomes to a broader interpretation of emission reduction pledges.

We recommend that the underlying storyline continues to use a middle of the road SSP2 case, updated for CMIP7. Emission policy choices are frozen at present day (taken as the latest time that still allows the IAM and then earth system models to be run in time to inform the global stocktake). Non-climate-related environmental policies (e.g. forest protection, air pollution) are still allowed to improve within the scenario. In addition, underlying technology assumptions are allowed to evolve and the sensitivity of results to these assumptions should be assessed. A pragmatic choice is for IAM modelers to agree on a single definition of current policies to freeze, and then to implement this in the different IAMs. The scenario to then take forward into CMIP7 would come from the median climate outcome from this range. As a starting point we recommend using an updated version of the reasoning from the “CurPol” scenario assumptions used in Working Group III of IPCC AR6 (IPCC, 2022b). The frozen policy scenario provides a benchmark against which additional future mitigation policies can be assessed.

For consideration in the longer term, we would recommend exploration of the climate response for alternative IAM responses to the current policy assumptions above, and potentially a wider consideration of other interpretations of current policy, including alternative views on policies around air quality.

3.4 Scenario Design of the medium emission scenario

The last scenario (see Figure 2.1) follows the medium scenario until mid-century and subsequently starts to implement rapid and deep action to reduce emissions. The scenario correspond to a lack of policy action in the next decades. The scenario fills the gap between the medium scenario and the low scenarios and represents a moderate action interpretation of the world that fails to implement the Paris Agreement. The scenario will lead to a peak in temperature followed by a decline after emissions reach net zero. The exact form of this overshoot scenario will be further explored as part of the model experiments also looking at the other scenarios. In principle, design criteria are similar to the very-low-overshoot scenario discussed in the next chapter, i.e. following the medium scenario, followed by rapid but feasible climate action leading to negative emissions – but limited by sustainability constraints.

3.5 Summary

IAM teams are requested to produce scenarios with the characteristics as indicated in Table 3.1.

Table 3.1: Main characteristics of the scenarios

	Description
H	Scenario that explores roll-back of existing climate policy; low technology development on renewables and thus high emissions (SSP3/SSP5 based)
M	Scenario that explores emission trajectory consistent with current policies (SSP2 based)
MOS	Scenario that deviates from the medium (M) scenario mid-century – followed by rapid and deep climate action.

4 Towards the design of the low emission scenarios for CMIP7

4.1 Introduction

The ScenarioMIP meeting in Reading concluded that on the low side of the temperature spectrum three scenarios should be analyzed (L, VL, LOS). These scenarios would broadly fall into the range of scenarios that have been associated with the Paris climate goals in the literature. We explicitly take no position on Paris-consistency of the low emission scenarios in this protocol. Instead, we broadly define them in terms of expected global temperature outcomes. In doing so, we acknowledge that associated global temperature projections will not be known before ESMs have run the emissions scenarios as part of scenarioMIP. The temperature response will ultimately depend on carbon cycle feedbacks and climate sensitivity as represented by the ESMs. However, expectations about potential temperature outcomes can be formulated based on existing knowledge informing simple climate models (SCMs) and carbon budget estimates in combination with deep reductions in non-CO_2 emissions. IAM teams should take these expectations as guidance to design their emissions modelling for the low scenarios.

The low scenarios include 1) a scenario that limits warming to below 1.5°C median warming by 2100 with a temporary overshoot that is as low as can still be plausible, 2) a scenario with higher overshoot at peak warming that attempts to return to below 1.5°C median warming by 2100, and 3) a scenario which remains likely below 2°C throughout the 21st century. It is actually a research question of ScenarioMIP how the updated emission projections can be categorized in terms of the categories used by IPCC WGIII in 2022 (IPCC, 2022b)[1].

4.2. Design of the very low (VL) emission scenario

General considerations

The lowest emission pathway among the ScenarioMIP pathways should be designed such that the resulting temperature outcomes at the time of peak warming are as low as can still be plausibly achieved. We define plausibility as (1) within geophysical and techno-economic feasibility limits, particularly regarding ramp-up rates of mitigation and CDR technologies, and (2) accounting for technology and policy trends / constraints in the short-run (see below for a

---

[1] According to AR6 WG3 Annex III Table 14: C1: Limit warming to 1.5°C (>50%) with no or limited overshoot (Reach or exceed 1.5°C during the 21st century with a likelihood of ≤67%, and limit warming to 1.5°C in 2100 with a likelihood >50%. Limited overshoot refers to exceeding 1.5°C by up to about 0.1°C and for up to several decades). C2: Return warming to 1.5°C (>50%) after a high overshoot (Exceed warming of 1.5°C during the 21st century with a likelihood of >67%, and limit warming to 1.5°C in 2100 with a likelihood of >50%. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1°C– 0.3°C for up to several decades). C3: Limit warming to 2°C (>67%) Limit peak warming to 2°C throughout the 21st century with a likelihood of >67%.

detailed description of assumptions for the period until 2030). In ScenarioMIP, scenarios will preferably be run in emission driven mode. This means that in the design phase, it will not be (fully) known what concentration or temperature level the set of Earth system models (ESMs) will reach at their peak, at the end of the century, or afterwards (initial assessments will be computed in the IAMs by climate emulators). Concentration and temperature levels are also conditional on the effectiveness of those CDR measures which are implemented in the ESMs (likely a subset of the CDR measures represented in IAMs in CMIP7).

Critical design elements of the very low scenario are reducing CO_2 emissions rapidly and deeply, reaching net zero CO_2 emissions between 2045-2060, while also reducing the non-CO_2 emissions deeply. Aerosol emissions are determined by associated changes in energy and land use and assumptions about air pollution control policies. IAM teams should make ambitious assumptions about air pollution controls in line with sustainable development objectives. After the point of net zero CO_2 emissions, the pathway will be designed to transition to sustained net negative CO_2 emissions in order to increase the likelihood of limiting warming to 1.5°C in the second half of the century (initial assessments will be computed by climate emulators). This should entail reaching net zero GHG emissions in the second half of the 21st century. The scenario should also consider other Sustainable Development Goals (SDGs), including protecting biodiversity and reducing global inequalities, to the extent feasible.IAM teams should explore measures that minimize the trade-offs and exploit synergies (e.g. dietary change for land use) when designing the emission scenarios.

In order to achieve these outcomes, the very low scenario should consider a range of measures and underlying trends that would permit rapid emissions reductions based on plausible assumptions about the underlying pace of the system transformations (see e.g. Brutschin et al., 2021) general characteristics of low-carbon technology innovation (Malhotra & Schmidt, 2020; Wilson et al., 2020) and the dynamics of socio-technical innovation (Jewell & Cherp, 2023). Achieving this low pathway is also strongly linked to sustainable land futures, including shifts towards low greenhouse gas emitting diets (e.g. the Lancet Planetary diet) (Humpenöder et al., 2024). There could be clear differences between the lowest scenario and the overshoot scenario, for instance in their long-term CDR use and near-term land-use.

The IAM modeling teams will be asked to develop an ensemble of scenarios, representing alternative interpretations of each of the three low-emission ScenarioMIP scenarios (see also further in this document). Specifically for the lowest scenario, it is important to avoid assuming implausible reductions in the very near term. Modeling teams should constrain (very) near term developments in the scenarios as follows:

1. Until 2025: match historic trends until 2023 and implement expected developments for 2024 and 2025 based on current trends. This holds for emissions and technology deployments (see also overall design).
2. From 2025 to 2030: IAM teams are asked to make their own judgment of as low as plausible mediating between (1) feasibility limits and (2) plausibility considerations given broad technology and policy trends / constraints, as well as (3) stated policy objectives (including commitments beyond NDCs such as the Renewable Energy and Energy

Efficiency pledge, the deforestation pledge, the Global Methane Pledge, etc.) up to 2030. Too strong reductions lead to non-actionable counterfactuals: the scenarios should still be policy-relevant in 2028. This means estimates are needed up to 2030 of somewhat likely trends.

3. After 2030, mitigation trends should be framed in terms of reaching the long-term climate target. This ambition is bounded by considerations of techno-economic feasibility of low carbon technology deployment and where relevant sustainable development goals (see above).

For the development of the lowest plausible emissions trajectories, it is recommended that the modeling teams consider a wide portfolio of options but also explore different options that would enable rapid transitions towards low GHG emissions. The following design elements were identified (the list is non-exhaustive and can be amended by the modeling teams). These design elements broadly cover complementary levers (groups of measures) that are available to reduce emissions:

- reduction in final energy demand
- rapid decarbonization of electricity supply (as measured by carbon intensity of electricity based on gross CO_2 emissions)
- deep electrification of industry, transport and buildings
- deep decarbonization of residual non-electric fuel mix in industry, transport and buildings
- widespread behavioral changes in diet, transportation and consumption
- deep reduction of industrial process emissions, including also reducing Fluorinated greenhouse gases in line with Kigali amendment
- deep reduction of non-CO_2 gases, in particular methane
- elimination of net CO_2 emissions from land use and rapid deployment of land-based CDR measures (within sustainability limits) to move to net negative Agriculture, Forestry and Other Land Uses (AFOLU) CO_2 emissions in the medium to long term
- deployment of CDR measures with geological storage, or storage in materials , within sustainability limits

Some of these levers (alternative fuels, AFOLU) may have implications for SLCF emissions and air pollution.

An important question that the lowest ScenarioMIP scenario would address is how strongly peak warming can still be constrained given the lack of emissions reductions thus far. The overshoot of 1.5 °C in the very low scenario should be limited to the lowest level plausible as defined above.

A number of particularly relevant scenario dimensions for Earth System Models (ESMs) were identified: 1) Land use and afforestation policy, 2) Land- and Ocean-based CDR strategies, 3) Regionally defined emissions, for greenhouse gases and aerosols, 4) resolved biofuel growth, transport, consumption and CCS, 5) treatment of carbon storage reservoirs and assumptions on loss rates, 6) regionally defined renewable energy production. An explicit representation of these dimensions in the IAM scenarios would thus help representation of the pathways by ESMs and permit improved linkages among IAMs and ESMs.

4.3 Design of the very low overshoot (LOS) scenario

Global greenhouse gas emissions are not declining and continue to follow a near-constant trend. Looking into scenarios with overshoot of the low-end goals of the Paris Agreement are thus an important point of comparison to the very low emissions scenario discussed above.

Design of overshoot scenarios may be undertaken with different priorities in mind and the ultimate design should account for these different considerations: ·

- Analyzing the geophysical and technological uncertainties. This will result in a better understanding of the viability of achieving climate overshoot in the first place, exploiting (limited) process resolution of emissions-driven ESMs. This includes identifying hysteresis in the climate system - both globally (e.g., through simulations of Zero Emissions Commitment scenarios) and regionally.
- Assessing the impacts of temperature overshoot, and the benefits of avoided overshoot.
- Gaining a better understanding of the near- and long-term consequences of delaying emission reductions. This will help inform ongoing policy discussions around plausibility and implications of overshoot resulting from delayed actions.
- Understanding the benefits, costs, and trade-offs of achieving declining temperatures in the long term.

·

Given these considerations, the overshoot scenario proposed is an attempted high-overshoot in contrast to the minimal overshoot that may result from the design of the lowest ScenarioMIP emissions pathway discussed in detail in the last section.

There are several considerations in how an overshoot scenario may be designed:

- In order to compensate for the high level of overshoot, this pathway will need to achieve higher CDR levels than the very low ScenarioMIP pathway. Hence, sustainability considerations will likely have to be relaxed compared to the very low pathway. Despite the difficulty in assessing future CDR technologies, however, the attempted use of CDR should still be within the assessed plausible range in the literature.
- The scenario needs to be sufficiently different from other scenarios in ScenarioMIP, in terms of resolving differences between ESM runs. Differences are measured not only in terms of IAM estimated temperature and concentration pathways, but also in terms of CDR measures implemented (volume and type) (leading possibly also to additional impacts).
- The scenario needs to be relevant in the context of the Paris Agreement.

Other specific elements to be considered in design of overshoot scenarios include:

- Start time/approximate Global Mean Surface Temperature/Global Surface Air Temperature (GMST/GSAT) level when net-negative emissions are initially realised.
- Attempted rate of net-negative emissions and plausible maximum rate.
- End target GMST/GSAT level and net-negative emissions in the long-term (King et al., 2022).
- Composition of continuing greenhouse gas emissions (proportions of CO_2, CH4, etc. with different lifetimes).

- Mode of net-negative emissions and roles of land use change, DAC, etc.
- The overall levels of residual emissions and carbon dioxide removal technologies (e.g. high residual emissions with greater CDR or lower residual emissions with less CDR).

In order to see differences in climate outcomes above the noise of internal variability, separation between the lowest scenario and the overshoot might need to be large enough. For CMIP6, a separation of 0.25-0.3 deg C was proposed (Tebaldi et al., 2015); it might be useful whether lower differentiations might be possible.(McKenna et al., 2021; Pfleiderer et al., 2018) although the emission-driven mode might lead to an even larger overlap. We can illustrate the possible design of the scenario with some simple calculation. In terms of CO_2 emissions, the required temperature gap equals about 400-600 $GtCO_2$, depending on the contribution of SLCFs and non-CO_2 gases to the overshoot (the less rapid reductions of CH4 may contribute up to about 0.15 deg C to the peak temperatures). Assuming that the design of the overshoot scenario would be a continuation along the emissions pathway of current policies (likely close to constant emissions), emissions should follow that pathway for a time period sufficiently long enough to create the above mentioned emission wedge. Thereafter, emissions would start dropping rapidly to net zero and then net negative levels to draw down temperatures in the long term. During this last phase, the overshoot scenario would ‘catch-up’ to the very low scenario. If the maximum CDR rate were around 10 $GtCO_2$ per year, it would take more than 50 years to catch up (as also the very low scenario might result in negative emissions).

The extent and duration of the overshoot will depend on the difference of CO_2 and non-CO_2 emissions between the scenarios. The mechanisms and extent of attempted CDR deployment will have ESM-specific efficacies which will impact the degree to which the attempted high overshoot is realized in some members of the ESM ensemble. This may cause larger intermodel uncertainty for the LOS scenario than for other scenarios of the ScenarioMIP set.

It might be desirable to consider dimensions additional to peak warming to differentiate the very low emission scenario from the overshoot scenario. These dimensions may include among other factors:

- Different SLCF trajectories and in particular methane that has been identified as a key lever for the very low scenario above.
- Different assumptions about land futures and respective emissions as well as land cover changes. The very low pathway may be linked to a sustainable land future in line with the SDG narrative including reduced pressure from agricultural land and considering environmental constraints. The high overshoot scenario could contrast that - in line with a need for very large scale and rapid upscaling of CDR needs in such a scenario. Strongly differentiated land futures can lead to noticeable biophysical (local and nonlocal) and carbon cycle effects. At the same time, introducing too many differences would limit the capability to interpret the differences in terms of overshoot; that is, the ability to assign differences in climate outcomes to the occurrence of overshoot. As the scenarios are mostly interpreted in terms of overshoot, it is proposed to be careful about adding additional design criteria - but only look into the additional demand for CDR in the overshoot scenario (in the second half of the century).

As discussed previously, it is important for these scenarios to follow a plausible emissions pathway to 2030 so as to not be non-actionable counterfactuals.

ScenarioMIP will discuss with LUMIP whether runs can be done with alternative land use patterns.

4.4 Design of the low emissions scenario

The third scenario in the low category is a scenario aimed at staying well-below 1.5 °C, comparable to the C3 category of IPCC (and is thus also relevant for discussions on the Paris Agreement). This scenario will have a slower emission reduction trajectory than the very low scenario. In 2030, emissions might be similar to the current emission pledges. After that, emissions are projected to be reduced further and reach net-zero CO_2 emissions around 2070. Before 2070, some CDR use might compensate for hard-to-abate emission sectors. After 2070, a decision can be made about how long and how deep emissions will remain negative. One needs to consider the overshoot character of this scenario versus the very low scenario with overshoot case (LOS) in order to increase the expected difference in climate outcomes from climate model runs.

4.5 Summary

IAM teams are asked to explore the following scenarios as indicated in Table 4.1.

Table 4.1: Main characteristics of the scenarios

	Description
L	Scenario that has the characteristics of the C3 scenario in IPCC WGIII; reaching net-zero CO_2 around 2070. Emissions in 2030 at the level of current pledges.
VL	Very low scenario, relevant for the low end of the Paris temperature range staying as close as possible to 1.5 deg C. The scenario will explore near-term methane reduction. The scenario most likely reaches net-zero emissions around the middle of the century.
LOS	Emission reduction is constrained to current policies in 2030 and remains relatively high for some period of time (leading to overshoot). After that mitigation policies kick-in rapidly. CDR use in the second half of the century draws down temperature.

5. Scenario extensions beyond 2100/2125

During the ScenarioMIP meeting in Reading, the desire to consider a set of scenario extensions going beyond the 21st century was expressed. The purpose of these extensions is twofold. For the high and medium emission scenarios the extensions will explore the long-term Earth System response to high level of warming, including the risk of breaching tipping points and triggering large scale irreversible changes. For the low, very low and very low overshoot scenarios, the extension will aim to explore the long-term commitment and potential reversibility, possibly to pre-industrial levels, of the anthropogenic perturbation.

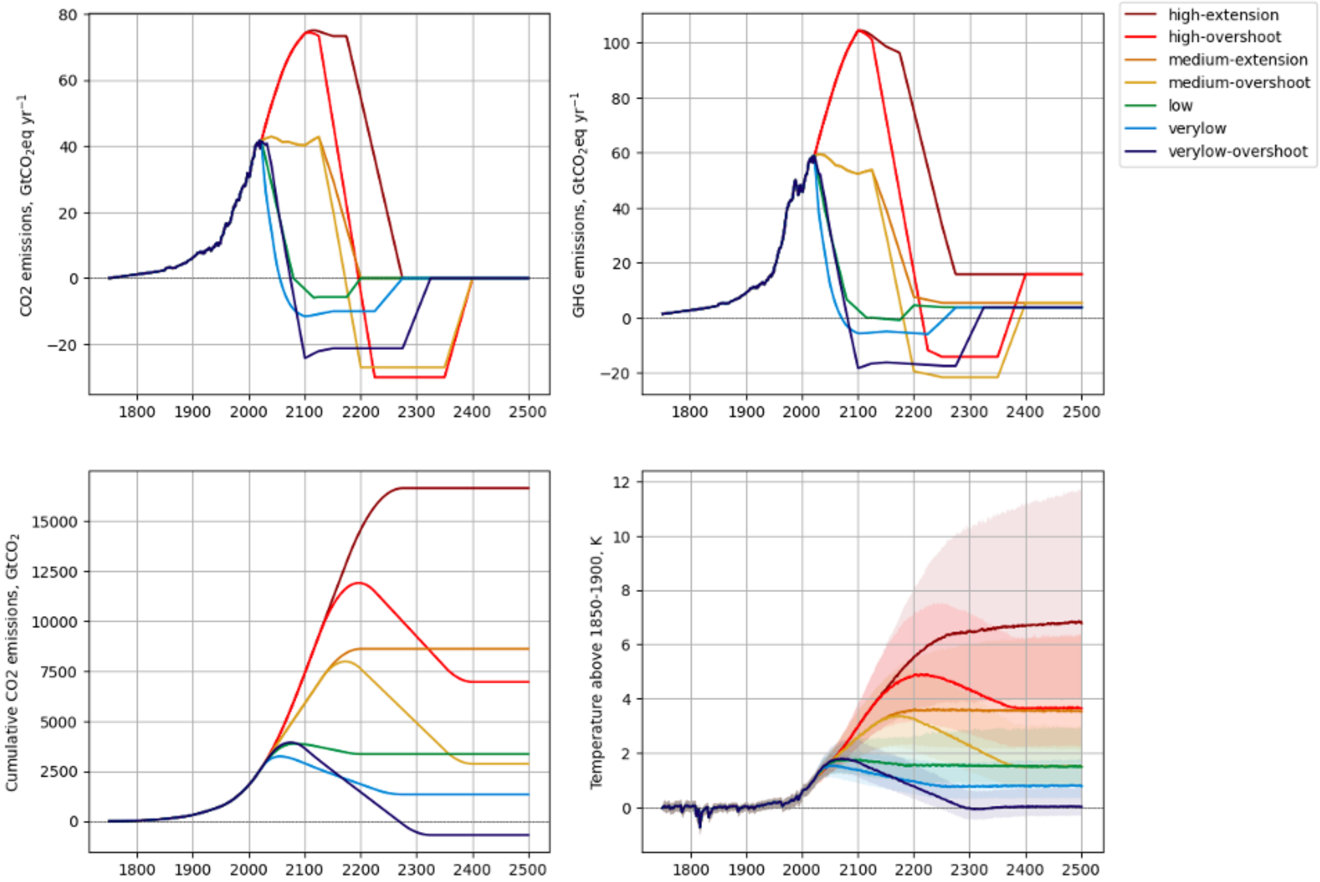

Figure 5.1. Preliminary extensions for ScenarioMIP in CMIP7. Top middle and bottom plots show total GHG emissions using AR6 GWP100 estimates, cumulative CO_2 emissions and global mean temperature respectively. Temperatures are calculated using the probabilistic AR6 ensemble of the FaIR simple climate model, with shaded area representing the 5-95% percentiles.

Table 5.1: Main characteristics of the scenario extensions

	H	HOS	M	MOS	L	VL	LOS
Tier	High priority	Medium Priority	Low priority	Medium Priority	Low priority	High priority	Low priority
Purpose	Assessment of risk of large irreversible changes in slow components of the Earth system	Assessment of reversibility from a very high warming state	Assessment of long-term implications of current policy, including large overshoot and reversibility	Assessment of potential to meet Paris targets on a multi-century timescale from a current policy scenario	Assessment of long-term commitment under strong mitigation	Assessment of long-term commitment under highest mitigation	Assessment of reversibility, including climate restoration
Storyline	Constant CO_2 emissions from 2125 to 2175, linear reduction reaching net zero CO_2 by 2275 and zero CO_2 emissions thereafter	Radical emissions reductions after 2125 to negative CO_2 emissions after 2200	Emission reduction to net-zero CO_2 by 2200	Emission reduction in 2125, zero CO_2 by 2175, to strongly negative in 2200 and thereafter.	Emissions reaches net-zero CO_2 around 2200, followed by zero CO_2 emissions until 2300	Return from net-negative to net-zero CO_2 emissions around 2275, followed by zero CO_2 emissions	Continue negative CO_2 emissions, returning to preindustrial forcing by 2300

As has been the case under the CMIP6 ScenarioMIP design, the scenario extensions will consist of emission and concentration trajectories to 2300 that are idealized, rather than being the outcome of IAM model simulations. While IAMs are useful in generating plausible evolution of greenhouse gas emissions in the shorter-term, beyond about a century's time the uncertainties that increasingly affect the socio-economic drivers of these trajectories end up limiting the usefulness of IAMs for scenario design. Forcings will be harmonised to the end year of the IAM scenarios (2100 or 2125) and will then follow stylized trajectories with a coherent narrative (e.g., constant positive CO_2 emissions, zero or negative CO_2 emissions, declining CO_2 emissions, with additional simplified assumptions about non-CO_2 forcing, land cover change, etc.). The idealized nature of these extensions also means that the current proposal can be easily adapted to further input or rationales, not requiring the same time commitment by the IAM groups as the 21st century scenarios described in the previous sections.

The rationale and proposed GHG emissions (or concentration) trajectories for the extensions of the main scenarios (Figure 2.1) are described here, and summarised in Table 5.1. The proposal is to have the extensions of the high and the very low scenarios as high priority, and the extensions of the medium, low and very low overshoot scenarios as low priority, with the extensions for the high and medium overshoot given medium priority.

The long-term extensions are designed to achieve temperature stabilization post-2300. This stabilization is assessed here using an ensemble of the FaIR simple climate model, but in practice involves achievement of net zero CO_2 (rather than net zero GHG), given that on multi-centennial timescales, non-CO_2 forcing stabilises at constant emissions levels.

5.1a High scenario (H) - high priority

It is proposed to have two extensions for the high scenario. The highest extension will explore the risk of long-term changes in slow components of the Earth system, also helping to assess the linearity of the transient climate response to cumulative emissions (TCRE) under high level of CO_2 emissions. It will keep emissions constant at their 2125 level until 2175, then emissions would follow a moderate linear reduction, reaching net zero CO_2 by 2275. The scenario would be ensured that total cumulative emission will be within the known fossil resources (Rogner, 1997).

5.1b High overshoot scenario (HOS) – medium priority

The high overshoot scenario extension will explore the risk of irreversibility/hysteresis in slow components of the Earth system (e.g., ice sheets) beyond 2125. It will also help to assess the linearity of (TCRE) under high level of negative CO_2 emissions. The scenario will adopt a strong linear emissions reduction from 2125 onward, starting from the 2125 emissions level, achieving zero CO_2 emissions by 2200 and negative CO_2 emissions post 2200. The long-term temperature objectives would be to reach the warming levels of the Medium Scenario in the 2300s.

5.2a Medium scenario (M) - low priority

The medium scenario extension will assess the long-term implications of current policy, addressing the potential for a high-overshoot scenario to reverse the 21st century warming from current policies. The medium scenario would be extended beyond 2125 with strong linear emissions reduction, reaching net zero CO_2 by 2200, followed by net zero CO_2 until 2300.

5.2b Medium overshoot scenario (MOS) – medium priority

The medium overshoot scenario will explore the potential to meet Paris targets on a multi-century timescale from a current policy scenario. Strong emissions reductions will begin in 2125 to zero CO_2 around 2175 and strongly negative in 2200. Emissions will remain negative for ~150 years to bring cumulative emissions down to a level consistent with returning temperatures to around the levels of the L scenario in the 24th century.

5.3 Low scenario (L) - low priority

The low scenario extension will serve the purpose of assessing the long-term climate and Earth system commitments under what is seen as a realistic, strong, 21st century mitigation scenario. The low scenario extension would first bring emissions from their anticipated negative 2125 level to net zero CO_2 around 2200, followed by net zero CO_2 until 2300. The design would be for long-term warming to stabilize at around 1.5-2°C above preindustrial level.

5.4 Very low scenario (VL) – high priority

Similarly to the low scenario extension, the very low scenario extension will explore the long-term climate commitment of the anthropogenic perturbation following the most ambitious 21st century mitigation scenario. Starting from the negative emissions level achieved in 2125, the very low scenario extension would linearly return to net zero CO_2 by 2275, followed by net zero CO_2 until 2300. The design would be for long-term warming to stabilize at around 1°C above 1850-1900 levels.

5.5 Very low with overshoot (LOS) - low priority

The very low with overshoot scenario extension support an assessment of complete reversibility under overshoot, including exploring the potential for climate restoration, i.e. aiming to returning near pre-industrial conditions by 2300. The extension would keep a level of negative CO_2 emission from 2125 until 2300, necessary to bring the 2300 anthropogenic forcing near the preindustrial level. The design would be for long-term warming to stabilize at the 1850-1900 levels.

As for the 21st century scenarios in ScenarioMIP, emission driven simulations are favoured for the extensions, with prescribed CO_2 emissions, prescribed land cover change, and prescribed non-CO_2 concentrations. The specific of the extensions of non-CO_2 forcings, land use cover and CDR (see Section 6) will be finalised once the IAM-produced scenarios are developed up to 2125, the rationale being to have the forcings of the extensions harmonised to the 2125 values, with a 2125-2300 evolution consistent with the overall storyline of the scenario extension, noting that non-CO_2 emissions will probably remain positive for most extensions (see Figure 5.1).

6. Representation of carbon dioxide removal

Carbon dioxide removal (CDR) methods are an important component of climate mitigation plans and have a unique role in reducing emissions via their potential to enable net-negative emissions. How these methods are deployed will affect both land use and land management, as well as energy system compositions, impacting broader sustainable development and biodiversity considerations (Mace et al., 2021). Currently, a broad range of CDR methods are being discussed within the policy communities and considered as part of climate action plans, however IAMs only represent a subset of these approaches. The main CDR methods represented in IAMs are Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture and Storage (DACCS), and afforestation. In addition, IAMs are exploring new CDR methods such as biochar, soil carbon sequestration, enhanced weathering, and ocean-based CDR, although these are not likely to be included in scenarios for ScenarioMIP as part of CMIP7. These methods will be investigated in ScenarioMIP future scenarios, as well as within other related MIPs such as CDR-MIP, LUMIP, and geoMIP. The CDR methods used in these scenarios are intended to be plausible but do represent a wide range of uncertainty and assumptions about underlying drivers (e.g. socio-economic and technological conditions).

An important need across this modeling process is for as much consistency as possible between models (from IAMs to harmonization to use within ESMs) for areas of land-use change as well as emissions and reductions resulting from CDR activities. In addition, full transparency and clarity about which processes are included in models (and the related intentions and considerations of IAMs), the steps involved in translating this information between models, and how this gets implemented in ESMs needs to be recorded to provide a clear understanding for the community about how to use ScenarioMIP runs in an impacts model or other studies to understand the impacts and trade-offs of CDR. This includes details on which type of CCS is used, and assumptions about total life-cycle emissions. When possible, underlying information on drivers of land-use change (especially food production vs bioenergy crop production) should also be provided, even if only at regional scales (and can potentially be downscaled either within the harmonization process or within ESMs themselves).

Of the CDR methods listed above,

- DACCS (and comparable flows) could be directly reported from IAMs to ESMs. The proposal is to report the DACCS flow separately (and harmonize and downscale separately) from total emissions. The total CO_2 emissions would be still reported including DACCS activity.
- There are several components to consider with BECCS:
    - the land-use change associated with increasing or decreasing areas of bioenergy crops,
    - the emissions from bioenergy that replace other emissions in the energy system, and
    - the emissions removed via carbon capture and storage.

For CMIP7, we suggest that ESM teams run in emissions-driven mode but directly use the provided BECCS emissions (or resulting concentrations), rather than computing these emissions within their own models. Biogenic carbon removed by BECCS will be harmonized and downscaled separately from energy related emissions with forcings provided as additional gridded data layers. Regional BECCS-related removals will also be harmonized and reported. In addition, to relay key information around BECCS to ESMs, IAMs will need to report at the gridded level, the land-use change areas associated with first and second-generation bioenergy crop deployment. Irrigation and fertilizer usage associated with bioenergy crops will also be provided.

An important goal of ScenarioMIP is for ESMs to be able to compute BECCS-related emissions within their own models. However, these experiments are currently best handled as research projects or within another MIP for CMIP7. ScenarioMIP calls for continued research on the best approaches for IAMs to provide BECCS-related data for use in emission-driven ESMs and for ESMs to use that data in a way that is consistent with the original IAM intentions.

Afforestation for negative emissions will be provided as gridded areas of land-use for new forest plantations in previously non-forested locations. This will be reported separately from reforested areas and existing forest areas (by both IAMs and ESMs) which will enable support for downstream biodiversity and impacts analysis. It is critical for a meaningful representation in ESM that they can represent managed forests.

References

Bauer, N., Bosetti, V., Hamdi-Cherif, M., Kitous, A., McCollum, D., Méjean, A., Rao, S., Turton, H., Paroussos, L., Ashina, S., Calvin, K., Wada, K., & van Vuuren, D. (2015). CO2 emission mitigation and fossil fuel markets: Dynamic and international aspects of climate policies. *Technological Forecasting and Social Change*, *90*(PA), 243-256. https://doi.org/10.1016/j.techfore.2013.09.009

Brutschin, E., Pianta, S., Tavoni, M., Riahi, K., Bosetti, V., Marangoni, G., & Van Ruijven, B. J. (2021). A multidimensional feasibility evaluation of low-carbon scenarios [Article]. *Environmental Research Letters*, *16*(6), Article 064069. https://doi.org/10.1088/1748-9326/abf0ce

Hajima, T., Kawamiya, M., Ito, A., Tachiiri, K., Jones, C., Arora, V., Brovkin, V., Séférian, R., Liddicoat, S., Friedlingstein, P., & Shevliakova, E. (2024). Consistency of global carbon budget between concentration- and emission-driven historical experiments simulated by CMIP6 Earth system models and suggestion for improved simulation of CO2 concentration. *EGUsphere*, *2024*, 1-49. https://doi.org/10.5194/egusphere-2024-188

Hausfather, Z., & Peters, G. P. (2020). Emissions – the ‘business as usual’ story is misleading. *Nature*, *29 January 2020*.

Humpenöder, F., Popp, A., Merfort, L., Luderer, G., Weindl, I., Bodirsky, B. L., Stevanović, M., Klein, D., Rodrigues, R., Bauer, N., Dietrich, J. P., Lotze-Campen, H., & Rockström, J. (2024). Food matters: Dietary shifts increase the feasibility of 1.5°C pathways in line with the Paris Agreement. *Science Advances*, *10*(13), eadj3832. https://doi.org/doi:10.1126/sciadv.adj3832

IEA. (2021). *The Role of Critical Minerals in Clean Energy Transitions*. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

IPCC. (2021). *Climate Change 2021 - The Physical Science Basis. Summary for Policymakers*.

IPCC. (2022a). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* C. U. Press.

IPCC. (2022b). Climate Change 2022: Mitigation of Climate Change. Contribution of of WGIII to the IPCC Sixth Assessment Report.

Jewell, J., & Cherp, A. (2023). The feasibility of climate action: Bridging the inside and the outside view through feasibility spaces [Review]. *Wiley Interdisciplinary Reviews: Climate Change*, *14*(5), Article e838. https://doi.org/10.1002/wcc.838

King, A. D., Peel, J., Ziehn, T., Bowen, K. J., McClelland, H. L. O., McMichael, C., Nicholls, Z. R. J., & Sniderman, J. M. K. (2022). Preparing for a post-net-zero world. *Nature Climate Change*, *12*(9), 775-777. https://doi.org/10.1038/s41558-022-01446-x

Mace, M., Fyson, C., Schaeffer, M., & Hare, W. (2021). Large-Scale Carbon Dioxide Removal to Meet the 1.5°C Limit: Key Governance Gaps, Challenges and Priority Responses. *Global Policy*, *12*, 67-81 https://doi.org/https://doi.org/10.1111/1758-5899.12921

Malhotra, A., & Schmidt, T. S. (2020). Accelerating Low-Carbon Innovation [Review]. *Joule*, *4*(11), 2259-2267. https://doi.org/10.1016/j.joule.2020.09.004

McKenna, C. M., Maycock, A. C., Forster, P. M., Smith, C. J., & Tokarska, K. B. (2021). Stringent mitigation substantially reduces risk of unprecedented near-term warming rates. *Nature Climate Change*, *11*(2), 126-131. https://doi.org/10.1038/s41558-020-00957-9

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century [Article]. *Global Environmental Change*, *42*, 169-180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6 [Article]. *Geoscientific Model Development*, *9*(9), 3461-3482. https://doi.org/10.5194/gmd-9-3461-2016

Persad, G. G., Samset, B. H., & Wilcox, L. J. (2022). Aerosols must be included in climate risk assessments. *Nature*, *611*(7937), 662-664. https://doi.org/10.1038/d41586-022-03763-9

Pfleiderer, P., Schleussner, C. F., Mengel, M., & Rogelj, J. (2018). Global mean temperature indicators linked to warming levels avoiding climate risks [Article]. *Environmental Research Letters*, *13*(6), Article 064015. https://doi.org/10.1088/1748-9326/aac319

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., . . . Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview [Article]. *Global Environmental Change*, *42*, 153-168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Roelfsema, M., van Soest, H. L., Harmsen, M., van Vuuren, D. P., Bertram, C., den Elzen, M., Höhne, N., Iacobuta, G., Krey, V., Kriegler, E., Luderer, G., Riahi, K., Ueckerdt, F., Després, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Gidden, M., . . . Vishwanathan, S. S. (2020). Taking stock of national climate policies to evaluate implementation of the Paris Agreement [Article]. *Nature Communications*, *11*(1), Article 2096. https://doi.org/10.1038/s41467-020-15414-6

Rogelj, J., Fransen, T., den Elzen, M. G. J., Lamboll, R. D., Schumer, C., Kuramochi, T., Hans, F., Mooldijk, S., & Portugal-Pereira, J. (2023). Credibility gap in net-zero climate targets leaves world at high risk [Article]. *Science*, *380*(6649), 1014-1016. https://doi.org/10.1126/science.adg6248

Rogner, H. H. (1997). An assessment of world hydrocarbon resources [Article]. *Annual Review of Energy and the Environment*, *22*(1), 217-262. https://doi.org/10.1146/annurev.energy.22.1.217

Schlichenmaier, S., & Naegler, T. (2022). May material bottlenecks hamper the global energy transition towards the 1.5 °C target? . *Energy Reports*, *8*, 14875-14887.

Séférian, R., Berthet, S., Yool, A., Palmiéri, J., Bopp, L., Tagliabue, A., Kwiatkowski, L., Aumont, O., Christian, J., Dunne, J., Gehlen, M., Ilyina, T., John, J. G., Li, H., Long, M. C., Luo, J. Y., Nakano, H., Romanou, A., Schwinger, J., . . . Yamamoto, A. (2020). Tracking Improvement in Simulated Marine Biogeochemistry Between CMIP5 and CMIP6. *Current Climate Change Reports*, *6*(3), 95-119. https://doi.org/10.1007/s40641-020-00160-0

Shiogama, H., Fujimori, S., Hasegawa, T., Hayashi, M., Hirabayashi, Y., Ogura, T., Iizumi, T., Takahashi, K., & Takemura, T. (2023). Important distinctiveness of SSP3–7.0 for use in impact assessments [Note]. *Nature Climate Change*, *13*(12), 1276-1278. https://doi.org/10.1038/s41558-023-01883-2

Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J., Friedlingstein, P., Knutti, R., Lowe, J., O'Neill, B., Sanderson, B., Van Vuuren, D., Riahi, K., Meinshausen, M., Nicholls, Z., Tokarska, K., Hurtt, G., Kriegler, E., Meehl, G., Moss, R., . . . Ziehn, T. (2021). Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6 [Article]. *Earth System Dynamics*, *12*(1), 253-293. https://doi.org/10.5194/esd-12-253-2021 van Soest, H. L., Aleluia Reis, L., Baptista, L. B., Bertram, C., Després, J., Drouet, L., den Elzen, M., Fragkos, P., Fricko, O., Fujimori, S., Grant, N., Harmsen, M., Iyer, G., Keramidas, K., Köberle, A. C., Kriegler, E., Malik, A., Mittal, S., Oshiro, K., . . . van Vuuren, D. P. (2021). Global roll-out of comprehensive policy measures may aid in bridging emissions gap [Article]. *Nature Communications*, *12*(1), Article 6419. https://doi.org/10.1038/s41467-021-26595-z

Wilcox, L. J., Allen, R. J., Samset, B. H., Bollasina, M. A., Griffiths, P. T., Keeble, J., Lund, M. T., Makkonen, R., Merikanto, J., O'Donnell, D., Paynter, D. J., Persad, G. G., Rumbold, S. T., Takemura, T., Tsigaridis, K., Undorf, S., & Westervelt, D. M. (2023). The Regional Aerosol Model Intercomparison Project (RAMIP) [Article]. *Geoscientific Model Development*, *16*(15), 4451-4479. https://doi.org/10.5194/gmd-16-4451-2023

Wilson, C., Grubler, A., Bento, N., Healey, S., de Stercke, S., & Zimm, C. (2020). Granular technologies to accelerate decarbonization: Smaller, modular energy technologies have advantages [Review]. *Science*, *368*(6486), 36-39. https://doi.org/10.1126/science.aaz8060

Appendix A: Acronyms

AerChemMIP Aerosol Chemistry Model Intercomparison Project
AFOLU Agriculture, Forestry and Other Land Use
BECCS Bioenergy with Carbon Capture and Storage
CCS Carbon Capture and Storage
CMIC Climate Model of Intermediate Complexity
CMIP Coupled Model Intercomparison Project
CDR Carbon Dioxide Removal
DAC Direct Air Capture
DACCS Direct Air Capture with Carbon Storage
DECK Diagnostics, Evaluation and Characterization of Klima
ESM Earth System Model
EV Electric Vehicle
GCM Global Circulation Model/Global Climate Model
GHG Green-house gas
GMST Global Mean Surface Temperature
GSAT Global-mean Surface Air Temperature
GWP100 Global Warming Potential over 100 years
H High scenario
IAM Integrated Assessment Model
IAMC Integrated Assessment Modeling Consortium
IEA International Energy Agency
input4mip CMIP activity tasked with the processing and availability of input data for ESM experiments under CMIP
IPCC Intergovernmental Panel on Climate Change
L Low Scenario
LUMIP Land Use Model Intercomparison Project
M Medium Scenario
MIP Model Intercomparison Project
MOS Medium scenario with Overshoot
NDC Nationally Determined Contributions
OS Overshoot
RAMIP Regional Aerosol Model intercomparison Project
RCP Representative Concentration Pathway
SCM Simple Climate Model
SDG Sustainable Development Goal
SLCF Short-Lived Climate Forcer
SSC Scientific Steering Committee
SSP Shared Socio-economic Pathways
TCRE Transient Climate Response to cumulative Emissions

VIA Vulnerability, Impacts and Adaptation
VIACCS Vulnerability, Impacts, Adaptation and Climate Services
VL Very Low scenario
LOS Very Low scenario with Overshoot
WGI/II/II Working Group I/II/III