

The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP7

ScenarioMIP Scientific Steering Committee and Task Groups

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1. Introduction

2

3 1.1 CMIP and ScenarioMIP

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

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

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

37

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

42

43 1.2 Process of designing a new protocol for CMIP7

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

51
52 The meeting also led to the installation of a final SSC for ScenarioMIP as well as a larger
53 advisory group (see <https://wcrp-cmip.org/model-intercomparison-projects-mips/scenariomip/>)
54 and a proposal on how to develop a new protocol for ScenarioMIP. At this point in time, the
55 envisioned pathway is as follows:

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

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

69 2. Overall design

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Box 2.1: Role of ScenarioMIP in CMIP6

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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).

95 2.1 General design principles

96 In view of the multiple aims of the ScenarioMIP scenarios, the following general design

97 characteristics are proposed. Please note that these scenarios are not intended to

98 represent confined storylines, rather they are illustrative pathways.

99

100 *Wide and plausible range*

101 The scenarios should encompass a wide range of policy-relevant emission trajectories
102 considered to be plausible (i.e. not impossible for technical/geophysical reasons or for other
103 reasons beyond the range relevant for exploring various climate policy responses). This range,
104 however, could be smaller than assessed before. On the high-side, the plausibility of the CMIP6
105 high emissions levels (quantified by SSP5-8.5) have been questioned (Hausfather & Peters,
106 2020). On the low side, some emission trajectories in the period 2020-2030 have become
107 implausible or even impossible.

108

109 *If possible, scenarios are to be run in emission-driven mode (for CO₂)*

110 If possible, most simulations should be run in emission-driven mode – in contrast to the use of a
111 concentration-driven approach in CMIP6. A wider range of model outcomes for the same
112 emission trajectory is expected, which may add further challenges to interpretation and
113 actionability of the results but will better represent the real uncertainty range as it would include

114 both the uncertainty from the carbon cycle and from the climate system and have more direct
115 relevance to the study of mitigation options. The runs would also be more consistent with
116 current ESM capabilities, especially regarding the outcomes of land-based mitigation solutions,
117 which are heavily dependent on feedbacks that are not represented in concentration-driven
118 experiments.

119
120 This will mean that all/most scenario runs are to be preferably emission-driven, (i.e., letting the
121 carbon-cycle in the ESM determine the concentration of CO₂ in the atmosphere that ensues
122 from the prescribed emissions), but concentration data will also be provided for ESMs/GCMs
123 that can only run in concentration mode (without an active carbon cycle) (some discussion on
124 the capabilities of ESMs can be found here(Hajima et al., 2024) (Séférian et al., 2020). Here,
125 the proposal is for those ESMs/GCMs to run median estimates of the concentrations created by
126 SCMs (emulators) (see Box 2.2).

127
128 Regarding CDR options, only reforestation will be based on endogenous representation of land-
129 based mitigation solutions in ESM; for all other options we will include the emission impact in
130 the IAM emission output (see Section 6). To better assess the impact of running in emission-
131 driven mode over the range of responses ensuing from the multi-model ensemble, we also
132 propose that models run one of the ScenarioMIP scenarios (M) both in emission-driven mode
133 and in concentration-driven mode for comparison.

134

135 **Box 2.2: Concentration-driven runs**

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

149

150 While we encourage the research and modeling community to experiment with full emission
151 driven runs, it is proposed that under the ScenarioMIP protocol models be run in emission-
152 driven mode for CO₂ only and not for all GHGs as it is expected that choosing the latter would
153 significantly reduce the number of models participating in emission-driven mode and too little
154 experience has been built up with such runs (the final protocol will be decided after surveying
155 the modelling teams). The use of concentration-driven data for non-CO₂ GHGs and air
156 pollutants requires running a preliminary step using a limited set of models with full
157 representation of air chemistry to create the concentration data. This could include the use of
158 emulators and an atmospheric chemistry model. While the proposal is to use one consistent
159 method for all scenarios in ScenarioMIP, it might be interesting to research the relevant

160 uncertainty by adding more atmospheric chemistry models and even use the output as forcing
161 for ESMs (e.g. in AerChemMIP or in research projects).

162

163 *Scenarios*

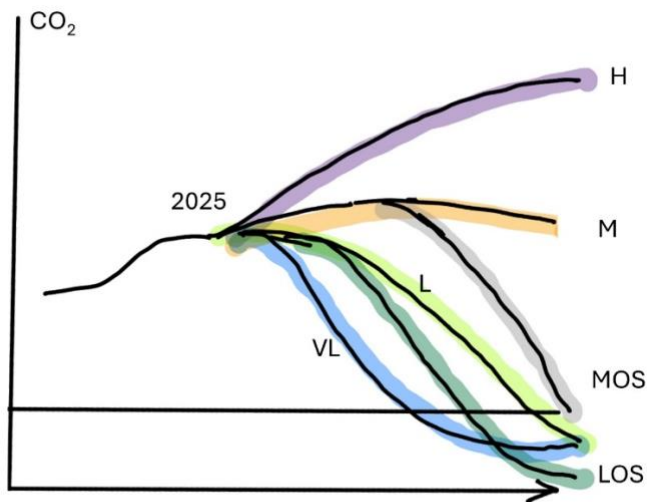
164 The consensus from the Reading meeting formed around a set of 6 scenarios.

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

185

186

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



189

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

194

195 2.2 Other design criteria

196 *Scenario period*

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

207

208 *Air pollution control*

209 Decisions need to be made on air pollution control (Short Lived Climate Forcers (SLCFs),
 210 among which aerosols – from sulfur emissions -- are particularly critical because of their cooling
 211 effect). The high scenario is a logical candidate for high sulfur emissions, partly because of a
 212 strong correlation between GHG mitigation policy effects and air quality outcomes (i.e., air
 213 pollutant emissions are expected to be low in stringent GHG mitigation cases). However, high
 214 aerosol emissions in the high scenario would also slow down warming. Therefore, the proposal

215 is to have a high scenario with the expected decrease (because of historical trends in
216 implementation of air quality controls on pace with economic development) in aerosol emissions
217 (i.e., using standard emission factors) and have a variant of it with deliberately high aerosol
218 emissions (based on higher emission factors) in AerChemMIP.

219

220 *Ensembles*

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

233

234 *IAM model runs*

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

243

244 The IAM community will be asked to explore different scenarios as pilots until the June-August
245 2024 time frame and after that start making further decisions on the exact characteristics. The
246 Scenario working group of IAMC will be the conduit through which the plan and its timeline will
247 be vetted and finalized.

248

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

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<p>Box 2.3: Different mitigation strategies</p> <p>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).</p>
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271

272 *Impacts and adaptation*

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

284

285 *Modeling assumptions*

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

296

297 *The role of complex climate models vs emulators*

298 Some further discussion is needed on the role of different tools (especially ESMs vs emulators
299 of climate model output). The use of emulators can be attractive both to fill in gaps in the design
300 and to accelerate some of the outcomes of new scenarios, given the unavoidable time
301 constraints. Thus, it is useful to consider how emulator use can further reduce the
302 computational load on climate models for scenario exercises and the expectation is that, given

303 the rapid developments in the emulation space of the last few years, the use of emulators to
 304 fully substitute for ESM output may become better actionable in a not-so-distant future. As of
 305 now, however, no emulator can address the provision of outputs from an ESM in their entirety
 306 and for all types of scenarios (with overshoot/peak-and-decline constituting particularly open
 307 questions given the scarcity of existing scenario simulations having these characteristics, on
 308 which emulators could be trained). At this point in time, therefore, it is envisioned that all
 309 scenarios will be run using ESMs.

310

311 *Input variables for ScenarioMIP model runs*

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

318

319 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) CH ₄ , N ₂ O, CO, NO _x , H ₂ , VOC, SO ₂ 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

320

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

326 *Output variables from ESMs*

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

333

334 *Consistency with earlier scenario sets*

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

344

345

346 **2.3 In depth elaboration of specific scenarios**

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

- 351 1. High and medium emission scenarios
- 352 2. Low emission scenarios
- 353 3. Extensions
- 354 4. Representation of negative emissions in IAMs and ESMs

355

356

357 'Table 2.2: Scenarios and proposed naming

358

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	<i>High, Concentration driven (MC)</i>	<i>Variant of H, concentration-driven for models that also run the emission-driven variant</i>	2
	<i>Medium, Concentration driven (MC)</i>	<i>Variant of M, concentration-driven for models that also run the emission-driven variant</i>	1
	Low-concentration driven (LC)	<i>Variant of L, concentration-driven for models that also run the emission-driven variant</i>	2

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362 **3. Towards the design of the high- and medium** 363 **emission scenarios for CMIP7**

364

365 3.1 Introduction

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

369

370 3.2 Scenario Design of the high emission scenario

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

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

389 In this scenario, the rapid cost decrease in renewable energy of the past decade is followed by
390 a period of slowdown of cost declines, as a result of regional scarcity and limited tradability in
391 materials for solar, wind technologies and EV batteries (IEA, 2021; Schlichenmaier & Naegler,
392 2022) as well as lack of public support and the remaining strong position of fossil fuel industries.
393 Critical mineral mining projects may lead to price spikes, local opposition and investment risks,
394 hampering the global energy transition. Such a situation might be combined with the SSP5 or
395 SSP3 scenario (in the SSP5 scenario it might be at odds with relatively high technology
396 development (O'Neill et al., 2017; Riahi et al., 2017) but possibly consistent with the rapid
397 economic growth and energy intensive lifestyles; in SSP3 the lack of international collaboration
398 and generally stagnating technological progress might be consistent with the scenario).

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

408 An additional issue is the treatment of fossil fuel reserves and resources and their tradeability.
409 The cumulative amount of fossil fuel use is likely to be considerably larger than the estimated
410 total reserves (these are known deposits that are extractable at current prices and technologies)
411 (Bauer et al., 2015; Rogner, 1997). Future technologies or market prices would make current
412 resources (estimates of undiscovered and/or not recoverable at current prices) recoverable to
413 some extent. The IAM models already include decision criteria about the use of such energy
414 resources⁴. How these play out in the two different scenarios needs to be transparent.

415

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

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

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

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

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

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

453 Extreme events in many forms such as climate and other environmental, social, geopolitical,
454 financial or economic shocks can happen in the short-term whereas some drivers or outcomes
455 of the extremes may happen over longer periods of time⁵. Extremes may act to push the
456 emission pathway upward. However, not all feedbacks are included in IAMs; social
457 fragmentation, energy insecurity, or policy breakdown are theoretically possible in the high-end
458 storylines.

459 3.3 Scenario Design of the medium emission scenario

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

470 To distinguish between the medium scenario and the lower mitigation scenarios, we make an
471 assumption that mitigation actions in a medium scenario must be established in policy with
472 some legislation to back them up, and ideally a plan for implementation. We don't include
473 announcements of future policy goals which come with no current basis in policy. We
474 recommend using the existing policies because including either Nationally Determined
475 Contributions (NDCs) pledges or net zero announcements involves making significant
476 judgements on implementation. Furthermore, taking only the existing policies appears most
477 consistent with the concept of the “frozen policy” approach. This still leaves a range of possible
478 options based on the literature and ambiguity of interpreting current policies (Rogelj et al.,
479 2023).

480 We consider several options for the treatment of policy assumptions that have a bearing on
481 emissions over time for the medium scenario. In the IAM community already several rules are
482 used to extend current policies beyond 2030 (van Soest et al., 2021). There are various

483 alternatives in terms of specific policies of countries, but the progression of policies in the real
484 world is clearly unknown. This could argue for an assumption of no progression in mitigation
485 policy beyond 2050. Giving the medium scenario this idealized aspect also helps to reinforce
486 the point that it is not a “most likely” scenario.

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

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

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

509 3.4 Scenario Design of the medium emission scenario

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

520

521 3.5 Summary

522 IAM teams are requested to produce scenarios with the characteristics as indicated in Table
523 3.1.

524

525 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.

526

527 4 Towards the design of the low emission scenarios for CMIP7

528 529 4.1 Introduction

530 The ScenarioMIP meeting in Reading concluded that on the low side of the temperature
531 spectrum three scenarios should be analyzed (L, VL, LOS). These scenarios would broadly fall
532 into the range of scenarios that have been associated with the Paris climate goals in the
533 literature. We explicitly take no position on Paris-consistency of the low emission scenarios in
534 this protocol. Instead, we broadly define them in terms of expected global temperature
535 outcomes. In doing so, we acknowledge that associated global temperature projections will not
536 be known before ESMs have run the emissions scenarios as part of scenarioMIP. The
537 temperature response will ultimately depend on carbon cycle feedbacks and climate sensitivity
538 as represented by the ESMs. However, expectations about potential temperature outcomes can
539 be formulated based on existing knowledge informing simple climate models (SCMs) and
540 carbon budget estimates in combination with deep reductions in non-CO₂ emissions. IAM teams
541 should take these expectations as guidance to design their emissions modelling for the low
542 scenarios.

543
544 The low scenarios include 1) a scenario that limits warming to below 1.5°C median warming by
545 2100 with a temporary overshoot that is as low as can still be plausible, 2) a scenario with
546 higher overshoot at peak warming that attempts to return to below 1.5°C median warming by
547 2100, and 3) a scenario which remains likely below 2°C throughout the 21st century. It is
548 actually a research question of ScenarioMIP how the updated emission projections can be
549 categorized in terms of the categories used by IPCC WGIII in 2022 (IPCC, 2022b)¹.

550

551 4.2. Design of the very low (VL) emission scenario

552 *General considerations*

553 The lowest emission pathway among the ScenarioMIP pathways should be designed such that
554 the resulting temperature outcomes at the time of peak warming are as low as can still be
555 plausibly achieved. We define plausibility as (1) within geophysical and techno-economic
556 feasibility limits, particularly regarding ramp-up rates of mitigation and CDR technologies, and
557 (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%.

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

565 Critical design elements of the very low scenario are reducing CO₂ emissions rapidly and
566 deeply, reaching net zero CO₂ emissions between 2045-2060, while also reducing the non-CO₂
567 emissions deeply. Aerosol emissions are determined by associated changes in energy and land
568 use and assumptions about air pollution control policies. IAM teams should make ambitious
569 assumptions about air pollution controls in line with sustainable development objectives. After
570 the point of net zero CO₂ emissions, the pathway will be designed to transition to sustained net
571 negative CO₂ emissions in order to increase the likelihood of limiting warming to 1.5°C in the
572 second half of the century (initial assessments will be computed by climate emulators). This
573 should entail reaching net zero GHG emissions in the second half of the 21st century. The
574 scenario should also consider other Sustainable Development Goals (SDGs), including
575 protecting biodiversity and reducing global inequalities, to the extent feasible. IAM teams should
576 explore measures that minimize the trade-offs and exploit synergies (e.g. dietary change for
577 land use) when designing the emission scenarios.

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

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

- 592 1. Until 2025: match historic trends until 2023 and implement expected developments for
593 2024 and 2025 based on current trends. This holds for emissions and technology
594 deployments (see also overall design).
- 595 2. From 2025 to 2030: IAM teams are asked to make their own judgment of as low as
596 plausible mediating between (1) feasibility limits and (2) plausibility considerations given
597 broad technology and policy trends / constraints, as well as (3) stated policy objectives
598 (including commitments beyond NDCs such as the Renewable Energy and Energy

599 Efficiency pledge, the deforestation pledge, the Global Methane Pledge, etc.) up to
600 2030. Too strong reductions lead to non-actionable counterfactuals: the scenarios
601 should still be policy-relevant in 2028. This means estimates are needed up to 2030 of
602 somewhat likely trends.

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

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

- 613 ● reduction in final energy demand
- 614 ● rapid decarbonization of electricity supply (as measured by carbon intensity of electricity
615 based on gross CO₂ emissions)
- 616 ● deep electrification of industry, transport and buildings
- 617 ● deep decarbonization of residual non-electric fuel mix in industry, transport and buildings
- 618 ● widespread behavioral changes in diet, transportation and consumption
- 619 ● deep reduction of industrial process emissions, including also reducing Fluorinated
620 greenhouse gases in line with Kigali amendment
- 621 ● deep reduction of non-CO₂ gases, in particular methane
- 622 ● elimination of net CO₂ emissions from land use and rapid deployment of land-based
623 CDR measures (within sustainability limits) to move to net negative Agriculture, Forestry
624 and Other Land Uses (AFOLU) CO₂ emissions in the medium to long term
- 625 ● deployment of CDR measures with geological storage, or storage in materials , within
626 sustainability limits

627
628 Some of these levers (alternative fuels, AFOLU) may have implications for SLCF emissions and
629 air pollution.

630
631 An important question that the lowest ScenarioMIP scenario would address is how strongly
632 peak warming can still be constrained given the lack of emissions reductions thus far. The
633 overshoot of 1.5 °C in the very low scenario should be limited to the lowest level plausible as
634 defined above.

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

642

643 4.3 Design of the very low overshoot (LOS) scenario

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

647

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

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

661 .

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

665

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

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

678

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

- 680 - Start time/approximate Global Mean Surface Temperature/Global Surface Air
681 Temperature (GMST/GSAT) level when net-negative emissions are initially realised.
- 682 - Attempted rate of net-negative emissions and plausible maximum rate.
- 683 - End target GMST/GSAT level and net-negative emissions in the long-term (King et al.,
684 2022).
- 685 - Composition of continuing greenhouse gas emissions (proportions of CO₂, CH₄, etc.
686 with different lifetimes).

- 687 - Mode of net-negative emissions and roles of land use change, DAC, etc.
688 - The overall levels of residual emissions and carbon dioxide removal technologies (e.g.
689 high residual emissions with greater CDR or lower residual emissions with less CDR).
690
691

692 In order to see differences in climate outcomes above the noise of internal variability, separation
693 between the lowest scenario and the overshoot might need to be large enough. For CMIP6, a
694 separation of 0.25-0.3 deg C was proposed (Tebaldi et al., 2015); it might be useful whether
695 lower differentiations might be possible. (McKenna et al., 2021; Pfleiderer et al., 2018) although
696 the emission-driven mode might lead to an even larger overlap. We can illustrate the possible
697 design of the scenario with some simple calculation. In terms of CO₂ emissions, the required
698 temperature gap equals about 400-600 GtCO₂, depending on the contribution of SLCFs and
699 non-CO₂ gases to the overshoot (the less rapid reductions of CH₄ may contribute up to about
700 0.15 deg C to the peak temperatures). Assuming that the design of the overshoot scenario
701 would be a continuation along the emissions pathway of current policies (likely close to constant
702 emissions), emissions should follow that pathway for a time period sufficiently long enough to
703 create the above mentioned emission wedge. Thereafter, emissions would start dropping
704 rapidly to net zero and then net negative levels to draw down temperatures in the long term.
705 During this last phase, the overshoot scenario would 'catch-up' to the very low scenario. If the
706 maximum CDR rate were around 10 GtCO₂ per year, it would take more than 50 years to catch
707 up (as also the very low scenario might result in negative emissions).
708

709 The extent and duration of the overshoot will depend on the difference of CO₂ and non-CO₂
710 emissions between the scenarios. The mechanisms and extent of attempted CDR deployment
711 will have ESM-specific efficacies which will impact the degree to which the attempted high
712 overshoot is realized in some members of the ESM ensemble. This may cause larger
713 intermodel uncertainty for the LOS scenario than for other scenarios of the ScenarioMIP set.
714

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

- 718 ● Different SLCF trajectories and in particular methane that has been identified as a key
719 lever for the very low scenario above.
- 720 ● Different assumptions about land futures and respective emissions as well as land cover
721 changes. The very low pathway may be linked to a sustainable land future in line with
722 the SDG narrative including reduced pressure from agricultural land and considering
723 environmental constraints. The high overshoot scenario could contrast that - in line with
724 a need for very large scale and rapid upscaling of CDR needs in such a scenario.
725 Strongly differentiated land futures can lead to noticeable biophysical (local and
726 nonlocal) and carbon cycle effects. At the same time, introducing too many differences
727 would limit the capability to interpret the differences in terms of overshoot; that is, the
728 ability to assign differences in climate outcomes to the occurrence of overshoot. As the
729 scenarios are mostly interpreted in terms of overshoot, it is proposed to be careful about
730 adding additional design criteria - but only look into the additional demand for CDR in
731 the overshoot scenario (in the second half of the century).
732

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

735
736 ScenarioMIP will discuss with LUMIP whether runs can be done with alternative land use
737 patterns.

738

739 4.4 Design of the low emissions scenario

740 The third scenario in the low category is a scenario aimed at staying well-below 1.5 °C,
741 comparable to the C3 category of IPCC (and is thus also relevant for discussions on the Paris
742 Agreement). This scenario will have a slower emission reduction trajectory than the very low
743 scenario. In 2030, emissions might be similar to the current emission pledges. After that,
744 emissions are projected to be reduced further and reach net-zero CO₂ emissions around 2070.
745 Before 2070, some CDR use might compensate for hard-to-abate emission sectors. After 2070,
746 a decision can be made about how long and how deep emissions will remain negative. One
747 needs to consider the overshoot character of this scenario versus the very low scenario with
748 overshoot case (LOS) in order to increase the expected difference in climate outcomes from
749 climate model runs.

750

751

752 4.5 Summary

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

754

755 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.

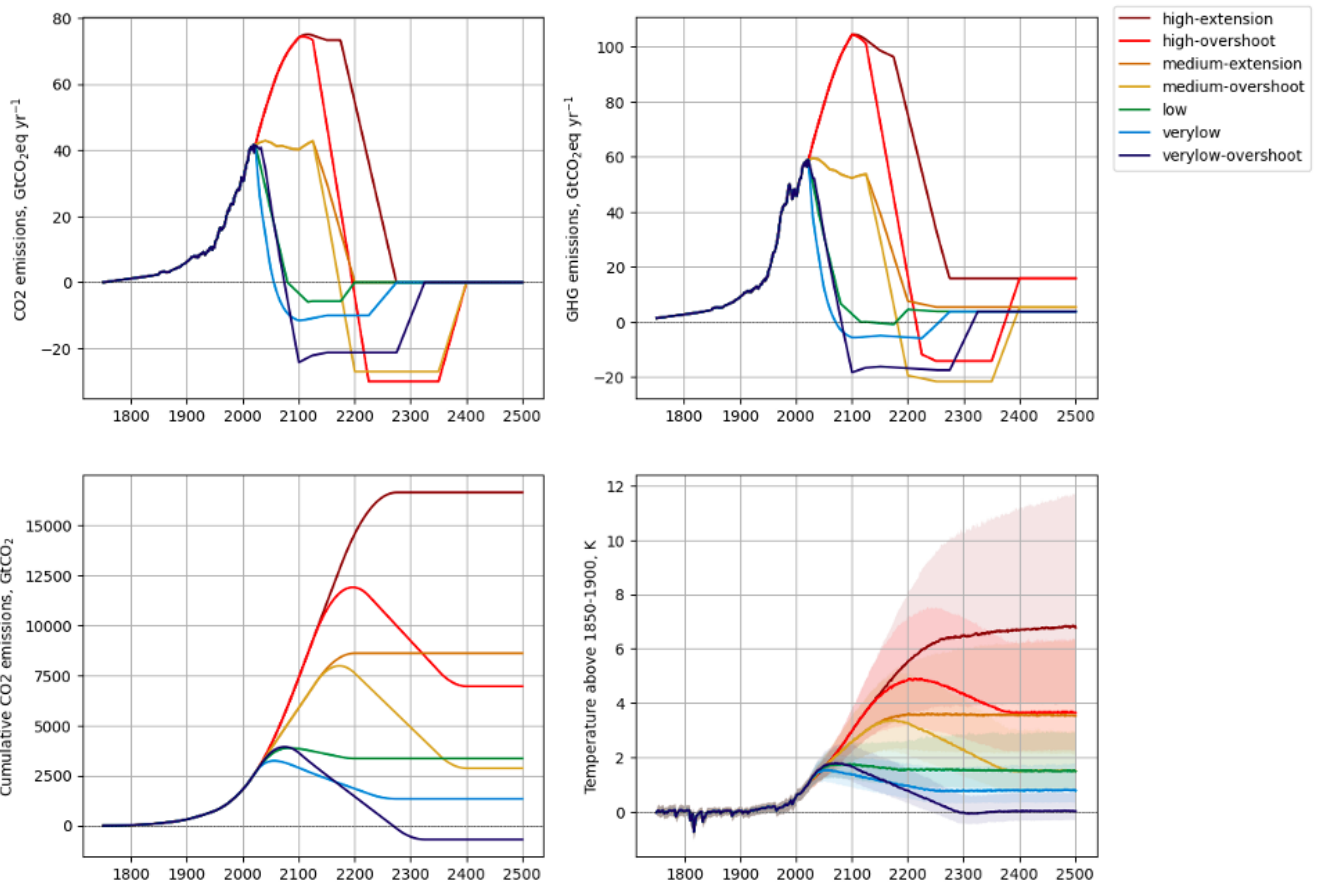
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5. Scenario extensions beyond 2100/2125

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.



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Figure 5.1. Preliminary extensions for ScenarioMIP in CMIP7. Top middle and bottom plots show total GHG emissions using AR6 GWP100 estimates, cumulative CO₂ 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.

774

775 Table 5.1: Main characteristics of the scenario extensions
 776

	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

777

778 As has been the case under the CMIP6 ScenarioMIP design, the scenario extensions will
 779 consist of emission and concentration trajectories to 2300 that are idealized, rather than being
 780 the outcome of IAM model simulations. While IAMs are useful in generating plausible evolution
 781 of greenhouse gas emissions in the shorter-term, beyond about a century's time the
 782 uncertainties that increasingly affect the socio-economic drivers of these trajectories end up
 783 limiting the usefulness of IAMs for scenario design. Forcings will be harmonised to the end year
 784 of the IAM scenarios (2100 or 2125) and will then follow stylized trajectories with a coherent
 785 narrative (e.g., constant positive CO₂ emissions, zero or negative CO₂ emissions, declining CO₂
 786 emissions, with additional simplified assumptions about non-CO₂ forcing, land cover change,
 787 etc.). The idealized nature of these extensions also means that the current proposal can be
 788 easily adapted to further input or rationales, not requiring the same time commitment by the IAM
 789 groups as the 21st century scenarios described in the previous sections.

790

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

794 extensions of the medium, low and very low overshoot scenarios as low priority, with the
795 extensions for the high and medium overshoot given medium priority.

796

797 The long-term extensions are designed to achieve temperature stabilization post-2300. This
798 stabilization is assessed here using an ensemble of the FaIR simple climate model, but in
799 practice involves achievement of net zero CO₂ (rather than net zero GHG), given that on multi-
800 centennial timescales, non-CO₂ forcing stabilises at constant emissions levels.

801

802 5.1a High scenario (H) - high priority

803 It is proposed to have two extensions for the high scenario. The highest extension will explore
804 the risk of long-term changes in slow components of the Earth system, also helping to assess
805 the linearity of the transient climate response to cumulative emissions (TCRE) under high level
806 of CO₂ emissions. It will keep emissions constant at their 2125 level until 2175, then emissions
807 would follow a moderate linear reduction, reaching net zero CO₂ by 2275. The scenario would
808 be ensured that total cumulative emission will be within the known fossil resources (Rogner,
809 1997).

810

811

812 5.1b High overshoot scenario (HOS) – medium priority

813 The high overshoot scenario extension will explore the risk of irreversibility/hysteresis in slow
814 components of the Earth system (e.g., ice sheets) beyond 2125. It will also help to assess the
815 linearity of (TCRE) under high level of negative CO₂ emissions. The scenario will adopt a strong
816 linear emissions reduction from 2125 onward, starting from the 2125 emissions level, achieving
817 zero CO₂ emissions by 2200 and negative CO₂ emissions post 2200. The long-term
818 temperature objectives would be to reach the warming levels of the Medium Scenario in the
819 2300s.

820

821 5.2a Medium scenario (M) - low priority

822 The medium scenario extension will assess the long-term implications of current policy,
823 addressing the potential for a high-overshoot scenario to reverse the 21st century warming from
824 current policies. The medium scenario would be extended beyond 2125 with strong linear
825 emissions reduction, reaching net zero CO₂ by 2200, followed by net zero CO₂ until 2300.

826

827 5.2b Medium overshoot scenario (MOS) – medium priority

828 The medium overshoot scenario will explore the potential to meet Paris targets on a multi-
829 century timescale from a current policy scenario. Strong emissions reductions will begin in 2125
830 to zero CO₂ around 2175 and strongly negative in 2200. Emissions will remain negative for
831 ~150 years to bring cumulative emissions down to a level consistent with returning
832 temperatures to around the levels of the L scenario in the 24th century.

833

834 5.3 Low scenario (L) - low priority

835 The low scenario extension will serve the purpose of assessing the long-term climate and Earth
836 system commitments under what is seen as a realistic, strong, 21st century mitigation scenario.
837 The low scenario extension would first bring emissions from their anticipated negative 2125
838 level to net zero CO₂ around 2200, followed by net zero CO₂ until 2300. The design would be for
839 long-term warming to stabilize at around 1.5-2°C above preindustrial level.

840 5.4 Very low scenario (VL) – high priority

841 Similarly to the low scenario extension, the very low scenario extension will explore the long-
842 term climate commitment of the anthropogenic perturbation following the most ambitious 21st
843 century mitigation scenario. Starting from the negative emissions level achieved in 2125, the
844 very low scenario extension would linearly return to net zero CO₂ by 2275, followed by net zero
845 CO₂ until 2300. The design would be for long-term warming to stabilize at around 1°C above
846 1850-1900 levels.

847

848 5.5 Very low with overshoot (LOS) - low priority

849 The very low with overshoot scenario extension support an assessment of complete reversibility
850 under overshoot, including exploring the potential for climate restoration, i.e. aiming to returning
851 near pre-industrial conditions by 2300. The extension would keep a level of negative CO₂
852 emission from 2125 until 2300, necessary to bring the 2300 anthropogenic forcing near the
853 preindustrial level. The design would be for long-term warming to stabilize at the 1850-1900
854 levels.

855

856

857 As for the 21st century scenarios in ScenarioMIP, emission driven simulations are favoured for
858 the extensions, with prescribed CO₂ emissions, prescribed land cover change, and prescribed
859 non-CO₂ concentrations. The specific of the extensions of non-CO₂ forcings, land use cover and
860 CDR (see Section 6) will be finalised once the IAM-produced scenarios are developed up to
861 2125, the rationale being to have the forcings of the extensions harmonised to the 2125 values,
862 with a 2125-2300 evolution consistent with the overall storyline of the scenario extension, noting
863 that non-CO₂ emissions will probably remain positive for most extensions (see Figure 5.1).

864 6. Representation of carbon dioxide removal

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

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

892 Of the CDR methods listed above,

- 893 ● DACCS (and comparable flows) could be directly reported from IAMs to ESMs. The
894 proposal is to report the DACCS flow separately (and harmonize and downscale
895 separately) from total emissions. The total CO₂ emissions would be still reported
896 including DACCS activity.
- 897 ● There are several components to consider with BECCS:
 - 898 ○ the land-use change associated with increasing or decreasing areas of bioenergy
899 crops,
 - 900 ○ the emissions from bioenergy that replace other emissions in the energy system,
901 and
 - 902 ○ the emissions removed via carbon capture and storage.

903 For CMIP7, we suggest that ESM teams run in emissions-driven mode but directly use the
904 provided BECCS emissions (or resulting concentrations), rather than computing these

905 emissions within their own models. Biogenic carbon removed by BECCS will be harmonized
906 and downscaled separately from energy related emissions with forcings provided as additional
907 gridded data layers. Regional BECCS-related removals will also be harmonized and reported. In
908 addition, to relay key information around BECCS to ESMs, IAMs will need to report at the
909 gridded level, the land-use change areas associated with first and second-generation bioenergy
910 crop deployment. Irrigation and fertilizer usage associated with bioenergy crops will also be
911 provided.

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

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

922

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1037

1038 **Appendix A: Acronyms**

1039	AerChemMIP Aerosol Chemistry Model Intercomparison Project
1040	AFOLU Agriculture, Forestry and Other Land Use
1041	BECCS Bioenergy with Carbon Capture and Storage
1042	CCS Carbon Capture and Storage
1043	CMIC Climate Model of Intermediate Complexity
1044	CMIP Coupled Model Intercomparison Project
1045	CDR Carbon Dioxide Removal
1046	DAC Direct Air Capture
1047	DACCS Direct Air Capture with Carbon Storage
1048	DECK Diagnostics, Evaluation and Characterization of Klima
1049	ESM Earth System Model
1050	EV Electric Vehicle
1051	GCM Global Circulation Model/Global Climate Model
1052	GHG Green-house gas
1053	GMST Global Mean Surface Temperature
1054	GSAT Global-mean Surface Air Temperature
1055	GWP100 Global Warming Potential over 100 years
1056	H High scenario
1057	IAM Integrated Assessment Model
1058	IAMC Integrated Assessment Modeling Consortium
1059	IEA International Energy Agency
1060	input4mip CMIP activity tasked with the processing and availability of input data for ESM
1061	experiments under CMIP
1062	IPCC Intergovernmental Panel on Climate Change
1063	L Low Scenario
1064	LUMIP Land Use Model Intercomparison Project
1065	M Medium Scenario
1066	MIP Model Intercomparison Project
1067	MOS Medium scenario with Overshoot
1068	NDC Nationally Determined Contributions
1069	OS Overshoot
1070	RAMIP Regional Aerosol Model intercomparison Project
1071	RCP Representative Concentration Pathway
1072	SCM Simple Climate Model
1073	SDG Sustainable Development Goal
1074	SLCF Short-Lived Climate Forcer
1075	SSC Scientific Steering Committee
1076	SSP Shared Socio-economic Pathways
1077	TCRE Transient Climate Response to cumulative Emissions

1078 VIA Vulnerability, Impacts and Adaptation
1079 VIACCS Vulnerability, Impacts, Adaptation and Climate Services
1080 VL Very Low scenario
1081 LOS Very Low scenario with Overshoot
1082 WGI/II/II Working Group I/II/III
1083
1084