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Report

The MESSAGEix-GLOBIOM model and scenarios for transition risk analysis.

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Based on the MESSAGEix-GLOBIOM model documentation and inputs of all authors of underlying documents:

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Abstract

This report provides background information to the MESSAGEix-GLOBIOM scenarios that were selected to support transition risk analysis for the Task-Force for Climate Related Financial Disclosures (TCFD) Banking Pilot Phase II. The first part provides an overview of the MESSAGEix-GLOBIOM integrated assessment model, its core methodology, main components and definitions. The second part discusses the selected scenarios and motivation for this selection. The selected scenario cover a range of emission reductions that vary in stringency and pace of emission reduction. We selected the following types of scenarios: Current policy scenarios that limit climate policy to currently implemented or announced policies (NPi: National implemented policies and NDC: Nationally Determined Contributions for 2030) and scenarios with immediate global climate action based on a carbon budget (Immediate2C and Immediate1p5C). Finally, scenarios with delayed global climate action scenarios based on carbon budgets (Delayed2C) and immediate global climate action based on a peak-temperature goal (LowCDR2C and LowCDR1p5C) represent cases with steep emission reductions either immediately or after 2030.

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The MESSAGEix-GLOBIOM integrated assessment model

The IIASA Integrated Assessment Modeling framework

During the past a few decades, IIASA has developed a comprehensive Integrated Assessment Modeling framework (Figure 1). The MESSAGEix model, at the core of this IAM framework, was originally developed to represent global/regional energy systems and be used as an energy planning tool. Over the years, the system boundaries were extended to answer new and broader research questions, so that the current version allows for a detailed representation of the technical-engineering, socio-economic, and biophysical processes in energy and land-use systems. The land-use sector is incorporated using an emulator of IIASA's GLOBIOM model and the detailed emissions accounting is based on the GAINS model. Through the link with the GLOBIOM model, the carbon emission from land use changes and biomass supply potentials can be integrated into the energy system and GHG emission analysis; through the combination with the GAINS model, the air pollution emissions of energy system and their health effects can be further evaluated. In addition to these two large-scale models, three other key models are also closely related to the use of the MESSAGE model, namely "MAGICC" and "MACRO".

The short description in this report is based on the detailed documentation of the MESSAGEix-GLOBIOM model[1], which can be found at https://data.ene.iiasa.ac.at/message-globiom. The source code of the model is open-source and available at [https://github.com/iiasa/message_ix.](https://github.com/iiasa/message_ix) Table 1 includes an overview of links to the full documentation on different components of the MESSAGE-GLOBIOM framework.

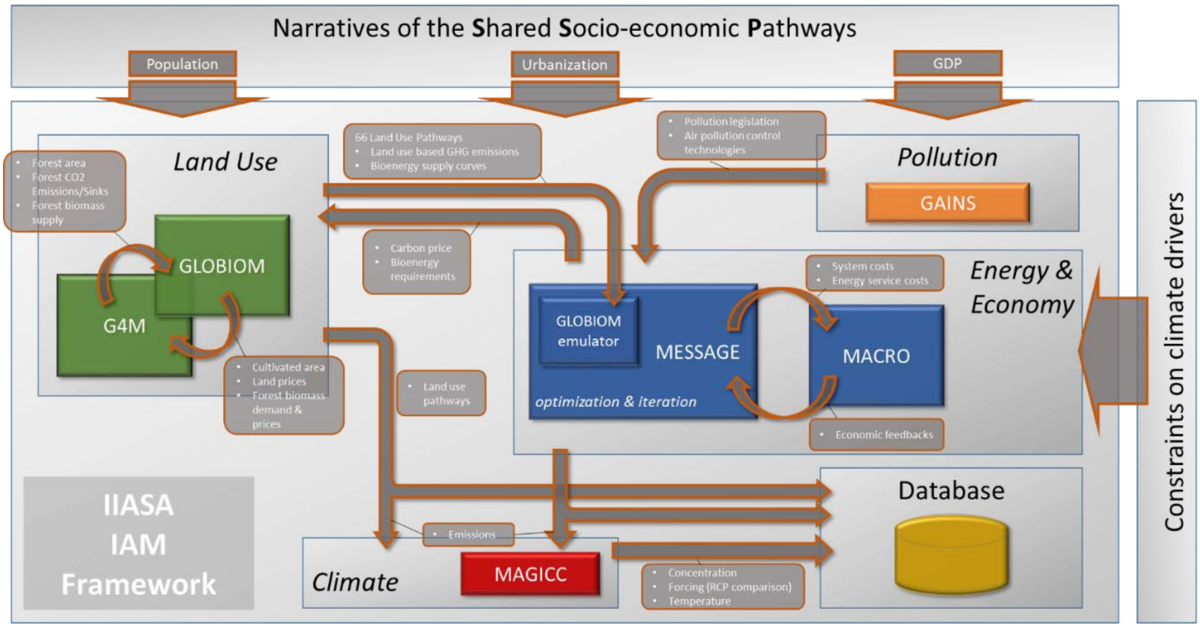

Figure 1: Overview of the IIASA IAM framework

Linking the energy model MESSAGE with the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change)[2] allows the integrated analysis of (probabilistic) climate outcomes that result from detailed energy system transformations. The framework is used for the development of internally consistent energy-economic greenhouse gas mitigation scenarios. MAGICC is a reduced-complexity coupled global climate and carbon cycle model which calculates projections for atmospheric concentrations of GHGs and other atmospheric climate drivers like air pollutants, together with consistent projections of radiative forcing, global annual-mean surface air temperature, and ocean-heat uptake. MAGICC is an upwelling-diffusion, energy-balance model, which produces outputs for global- and hemispheric-mean temperature. MAGICC receives inputs from the MESSAGE model with respect to anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur dioxide (SO_2), reactive gases (CO, NOx, VOCs), and halocarbons. MAGICC then relates GHG emissions and their outputs (physical and chemical sink processes) to changes in the atmospheric carbon concentration. From these inputs, the MAGICC model estimates net carbon flows and atmospheric CO_2 concentrations, as well as changes in radiative forcing, temperature, and sea level.

The MESSAGEix model is soft-linked to an aggregated, single-sector macro-economic model (MACRO)[3]. The reason for linking the two models is to consistently reflect the influence of energy supply costs, as calculated by MESSAGE, the mix of production factors considered in MACRO, and the effect of changes in energy prices on energy service demands. The combined MESSAGEIX-MACRO model can generate a consistent macro-economic response to changes in energy prices and estimate overall economic consequences (on GDP or consumption) of energy or climate policies. MACRO is a macroeconomic model maximizing the intertemporal utility function of a single representative producer-consumer in each world region. The optimization result is a sequence of optimal savings, investment, and consumption decisions. The main variables of the model are the capital stock, available labor, and energy inputs, which together determine the total output of an economy according to a nested CES (constant elasticity of substitution) production function.

Table 1: links to full documentation of different components of the MESSAGE-GLOBIOM model

Component	Link
Overview	https://message.iiasa.ac.at/projects/global/en/latest/overview/index.html
Socioeconomic development	https://message.iiasa.ac.at/projects/global/en/latest/socio_econ/index.html
Energy (MESSAGE)	https://message.iiasa.ac.at/projects/global/en/latest/energy/index.html
Macro-economy (MACRO)	https://message.iiasa.ac.at/projects/global/en/latest/macro.html
Land use (GLOBIOM)	https://message.iiasa.ac.at/projects/global/en/latest/land_use/index.html
Water	https://message.iiasa.ac.at/projects/global/en/latest/water/index.html
Emissions	https://message.iiasa.ac.at/projects/global/en/latest/emissions/index.html
Climate (MAGICC)	https://message.iiasa.ac.at/projects/global/en/latest/climate/index.html
Mathematical formulation	https://message.iiasa.ac.at/projects/global/en/latest/annex/index.html

We use this MESSAGEix-GLOBIOM for the analysis (also integrated with MAGICC and MACRO). The energy system module of MESSAGEix-GLOBIOM is formulated as a dynamic linear least-cost optimization model. The model seeks to satisfy exogenously given demand levels by energy commodity (secondary and primary energy) and node (region, country, etc.) while minimizing total energy system cost. The objective function aggregates costs and expenditures across all components of the model. Aggregate costs include investment and operational costs for technologies, costs for exhaustible resource extraction and power generation from renewable energy sources, as well as emissions taxes and other expenditures. The model determines the optimal configuration of the energy system within various technical-engineering, socio-economic, or biophysical constraints. The model assumes perfect foresight until the end of the optimization horizon.

In the following, a detailed introduction to the MESSAGE model is presented.

The MESSAGE model

MESSAGE has been frequently applied to pertinent questions at the interface between science and policy in the context of energy system transitions and environmental questions. In the past decade alone, the MESSAGE model was used in a number of highly visible projects: it underpinned a substantial part of the *Global Energy Assessment*[4]; it contributed one of the marker scenarios for the *Representative Concentration Pathways*[5]; and it was used as a marker scenario for the *Shared Socio-economic Pathways*[6,7] and the innovative Low Energy Demand scenario[8]. Scenarios developed using the MESSAGE model were also included in the analysis of the *Intergovernmental Panel on Climate Change (IPCC)*.

Structure and modules

In the MESSAGE model, the energy system is organized at five levels, namely resources, primary energy, secondary energy, final energy and demand (useful energy). Figure 2 shows a partial and illustrative reference energy system (RES) for MESSAGE, indicating how these five levels relate to each other and how technologies can be used to convert energy carriers from one level to another. MESSAGE is mathematically formulated around technologies (represented in the RES as rectangles between levels) that use and produce/generate (energy) commodities. These commodities can be modeled at different levels to depict a RES that includes primary extraction, conversion to secondary energy carriers and consumption of final or useful energy. Dedicated modules within the MESSAGE model handle specific aspects that are common in energy-environmental systems models such as exhaustible and renewable resources or emissions.

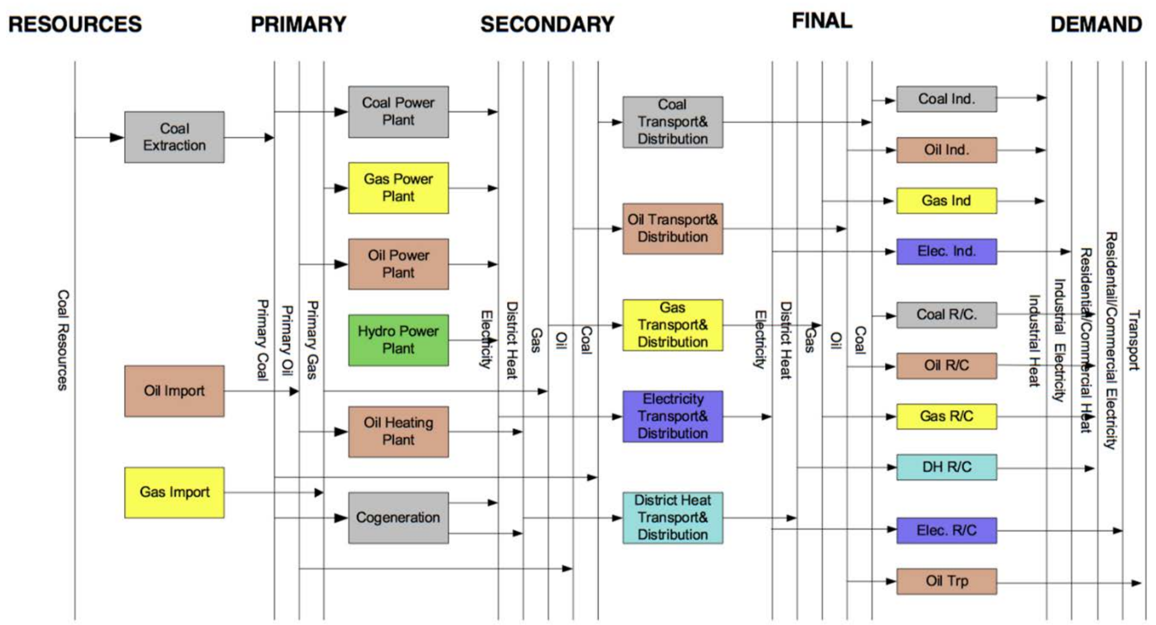

Figure 2: Partial and illustrative Reference Energy System (RES) in MESSAGE to clarify how levels of energy carriers relate to each other and how/which technologies can be used to convert energy between levels.

Technologies

Technologies are the key building blocks of the MESSAGE model, representing steps along the supply chain of a reference energy system. Energy technologies are characterized by numerical model inputs describing their economic (e.g., investment costs, fixed and variable operation and maintenance costs), technical (e.g., conversion efficiencies), ecological (e.g., GHG and air pollutant emissions), and sociopolitical characteristics. An example for the sociopolitical situation in a world region would be the decision by a country or world region to ban certain types of technologies (e.g., nuclear power plants). Model input data reflecting this situation would be constraining the use of these technologies or, equivalently, their omission from the data set for this region altogether.

Technologies can also have other technical-engineering parameters, such as upper and lower bounds on capacity or activity. Technologies can also include dynamic constraints, in which the capacity expansion or activity level in one period constrains the feasible options at a later point in the model horizon. This can be used to represent the inertia in a system or economic-engineering limitations to the diffusion of a technology beyond a certain rate.

Each technology in the MESSAGE model is represented by a detailed vintage structure of installed capacity. Through this structure, characteristics of installed technology can change over time, such as decreasing efficiency or increased operation-and-maintenance costs towards the end of a plant's technical lifetime. The model endogenously determines the optimal point in time for retiring a plant, based on the specific representation of both fixed costs (per unit of installed/maintained capacity) and variable/operating costs (per unit of activity). This allows distinguishing between the "technical lifetime" of an installation (which is an engineering parameter) and the "economic lifetime", which is a model outcome depending on the market environment (i.e., when future revenue is lower than fixed and operating costs, making it cost-optimal to retire a plant).

Exhaustible resources

Non-renewable resources are at the first level of the energy system, before the 'primary energy' level. The availability and costs of fossil fuels influences the future development of the energy system, and therewith future mitigation challenges. Understanding the variations in fossil fuel availability and the underlying extraction cost assumptions across the SSPs is hence important. Our fossil energy resource assumptions in MESSAGE are derived from various sources[4,9] and are aligned with the storylines of the individual SSPs. While the physical resource base is identical across the SSPs, considerable differences are assumed regarding the technical and economic availability of overall resources, for example, of unconventional oil and gas. What ultimately determines the attractiveness of a particular type of resource is not just the cost at which it can be brought to the surface, but the cost at which it can be used to provide energy services. Assumptions on fossil energy resources should thus be considered together with those on related conversion technologies. For SSP2 (the basis for all scenarios selected in this report) we assume a continuation of recent trends, focusing more on developing extraction technologies for unconventional hydrocarbon resources, thereby leading to higher potential cumulative oil extraction than in the other SSPs.

Estimates of available uranium resources in the literature vary considerably, which could become relevant if advanced nuclear fuel cycles (e.g., the plutonium cycle including fast breeder reactors, the thorium cycle) are not available. In MESSAGE, advanced nuclear cycles such as the plutonium cycle and nuclear fuel reprocessing are in principle represented, but their availability varies following the scenario narrative.

In the model, commodities are distinguished by different grades, to reflect the cost characteristics of fossil fuels and the typical extraction path across multiple deposits. Each grade has an upper limit on cumulative extraction over the entire model horizon. In addition, constraints on total extraction in a period can be specified either in absolute terms (as an upper bound) or as a maximum share of remaining resources (i.e., the initial endowment at the beginning of the model horizon minus extraction in previous periods). These equations allow to implement the characteristic resource supply curves, where cheap deposits are used first, but not necessarily exclusively. If parametrized appropriately, the formulation ensures extraction from a range of deposits (or grades) in every time period. The extraction shifts gradually over time to costlier options or to other locations if a basin is depleted.

Renewable resources

The supply of renewable energy resources is based on a formulation developed by Sullivan et al.[10] This formulation assumes that high-quality locations for wind and solar power generation are exploited first and consecutive capacity is installed in locations with lower quality resource (also through grade structure explained above). As a result, increased exploitation of renewable resources results in increased capacity requirements per amount of energy generated. Renewables differ from non-exhaustible resources in this regard, where exploitation of deposits over time leads to increasing extraction costs.

Emissions and pollutants

The MESSAGE model is often applied for the evaluation of energy pathways under greenhouse gas emissions constraints. The implementation therefore includes a dedicated formulation for upper bounds on emissions and pollutants. This formulation aggregates emissions across spatial scales such that an upper bound defined at the regional level constrains the total emissions from all subregions. The formulation is also flexible as to only account for emissions from specific categories of technologies or land-use scenarios, or to constraint the (average) emissions over a number of model periods.

Land-use model emulator

Interactions between the land-use sector and the energy sector are at the core of integrated assessment modeling, as land-use provides both bioenergy and food to the human system, and acts as a source and sink of emissions. However, agriculture and forestry do not fit naturally into the formulation of energy system models based on technologies. Therefore, the MESSAGE implementation incorporates a generic land-use emulator, where the model can determine a linear combination of land-use scenarios or trajectories depending on cost characteristics, emissions profiles, output of commodities (e.g. crops, bioenergy), and input requirements (e.g. fertilizer). The parametrization of the land-use scenarios is intended to be provided by other models specific to the agriculture sector. The default model that is used with MESSAGE is the GLOBIOM model, which is developed and maintained at IIASA as well.

Energy demand

Energy service demands are exogeneous to the MESSAGE model, although they can be responsive to changes in energy prices as result of the iterations with the MACRO economic model (see Figure 3). The iteration between the linear MESSAGE equations and the non-linear MACRO model may experience numerical problems, therefore, the iterative procedure also contains checks on oscillation of the solution without converging to a joint result.

The MESSAGE model distinguishes seven different energy demands across thermal and electric (specific) loads in three economic sectors (industry, buildings and transport) complemented by demands for feedstock and non-commercial biomass. The seven useful demand categories are “specific industrial”, “thermal industrial”, “feedstocks”, “non-commercial biomass”, “thermal residential and commercial”, “specific residential and commercial”, and “transport”. The demand projections for each of these seven categories are developed with a scenario generator. The scenario generator uses country-level historical data of GDP per capita (PPP) and final energy use as well as projections of GDP (PPP) and population to extrapolate the energy service demands into the future.

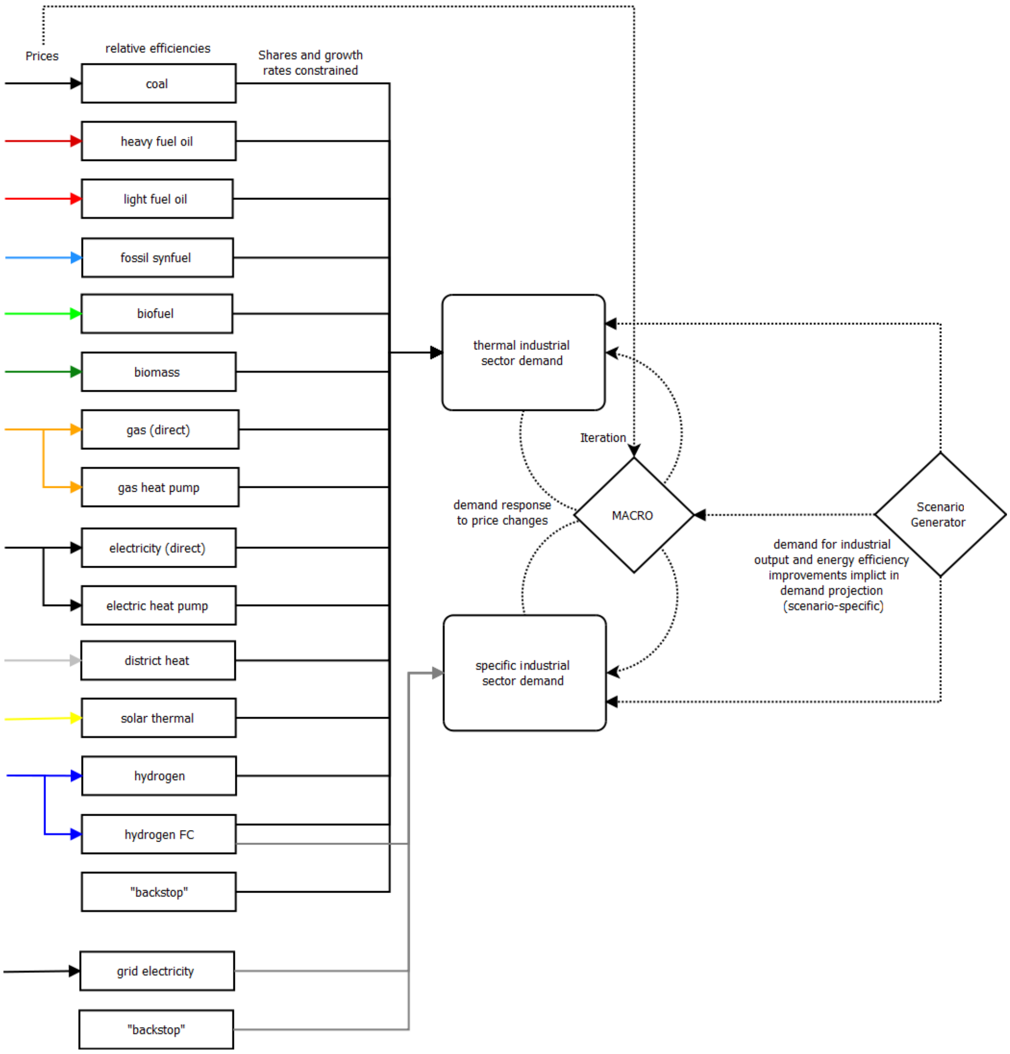

Figure 3: Overview of the iterative linking between MESSAGE and MACRO for the industry sector. The transport and the building sectors also similar iteration flows.

Spatial and temporal definitions

An efficient treatment of spatial and temporal disaggregation levels is paramount to conducting relevant scenario analysis for future research questions. For this reason, the MESSAGE implementation includes a native consideration of technologies and other aspects across hierarchical spatial and time disaggregation levels. In this way, it is possible to develop data sets for MESSAGE model instances where some technologies or commodities are considered at a regional and annual average level, while other aspects are considered at a much finer spatial and/or temporal resolution level. One example for the first category of highly aggregated technology is coal extraction, where seasonal variability and local transport infrastructure are usually of lesser concern. In contrast, power generation or water consumption along a river basin often require a high level of detail to accurately identify system-wide impacts and interdependencies across sectors. This feature facilitates an effective scenario development process and reduces the processing burden on the numerical solvers, because only the relevant sectors are modeled at a high level of detail. The current spatial resolution of the MESSAGE model is 11 global regions (see Figure 4).

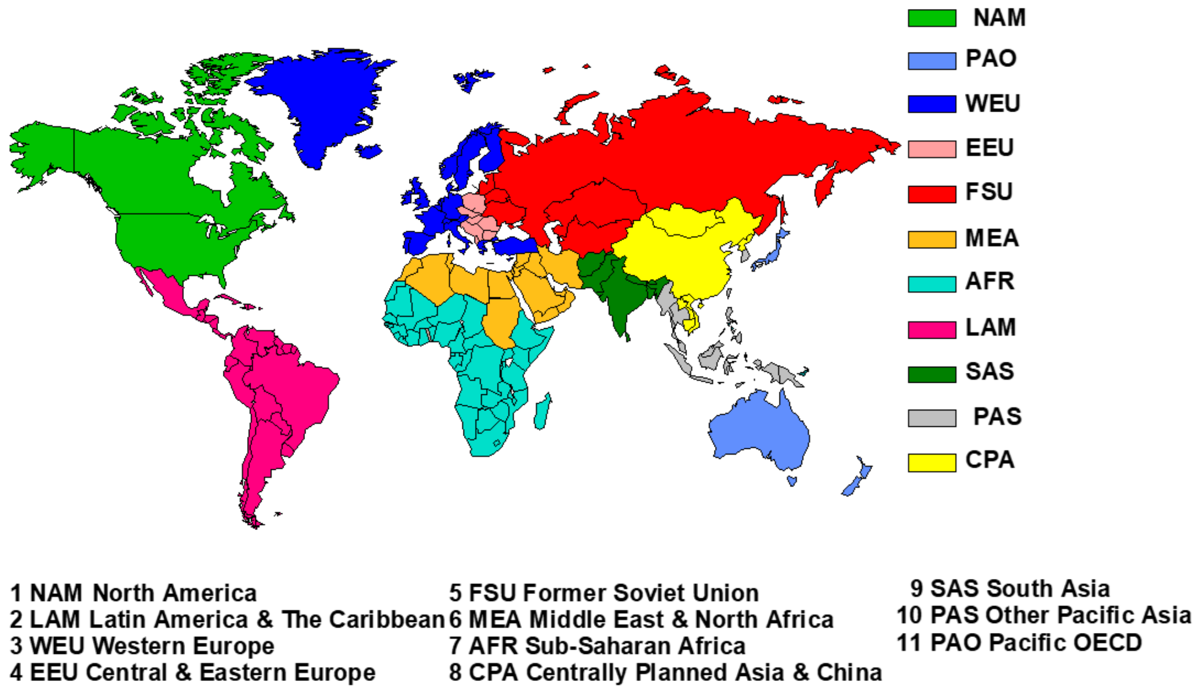

Figure 4: Spatial resolution of the MESSAGE model.

MESSAGEix-GLOBIOM scenarios for transition risk analysis

Selected scenarios

In consultation with UNEP and the participants in the UNEP-FI project, we selected a set of seven transition scenarios that cover a range of emission reductions that vary in stringency and pace. We distinguish four types of scenarios containing the specific scenarios as defined as follows:

1) Current policy scenarios

   - **NPi**: National implemented policies
   - **NDC**: Nationally Determined Contributions for 2030

2) Immediate global climate action based on carbon budget

   - **Immediate2C**: global climate action after 2020 to limit cumulative emissions between 2011-2100 to 1000 GtCO2 (67% chance of limiting warming to 2 degrees)
   - **Immediate1p5C**: global climate action after 2020 to limit cumulative emissions between 2011-2100 to 400 GtCO2 (67% chance of limiting warming to 1.5 degrees)

3) Delayed global climate action based on carbon budget

   - **Delayed2C**: delayed global climate action after 2030 to limit cumulative emissions between 2011-2100 to 1000 GtCO2 (67% chance of limiting warming to 2 degrees), following NDCs until 2030
   - **Delayed1p5C**: delayed global climate action after 2030 to limit cumulative emissions between 2011-2100 to 400 GtCO2 (67% chance of limiting warming to 1.5 degrees), following NDCs until 2030. **Such scenario is not feasible in the MESSAGEix-GLOBIOM model**

4) Immediate global climate action based on a peak-temperature goal

   - **LowCDR2C**: global climate action after 2020 to reach net-zero emissions in 2060 and remain at net-zero emissions afterwards, limiting peak warming to below 2 degrees.
   - **LowCDR1p5C**: global climate action after 2020 to reach net-zero emissions in 2050 and limit negative emissions to 2PgC/year afterwards, limiting peak warming to below 1.5 degrees.

Motivation for the scenario choices

The selected scenario cover a range of emission reductions that vary in stringency and pace, reflecting more orderly and disorderly transitions to a low-carbon future at both 1.5 and 2 degrees warming (see Figure 5).

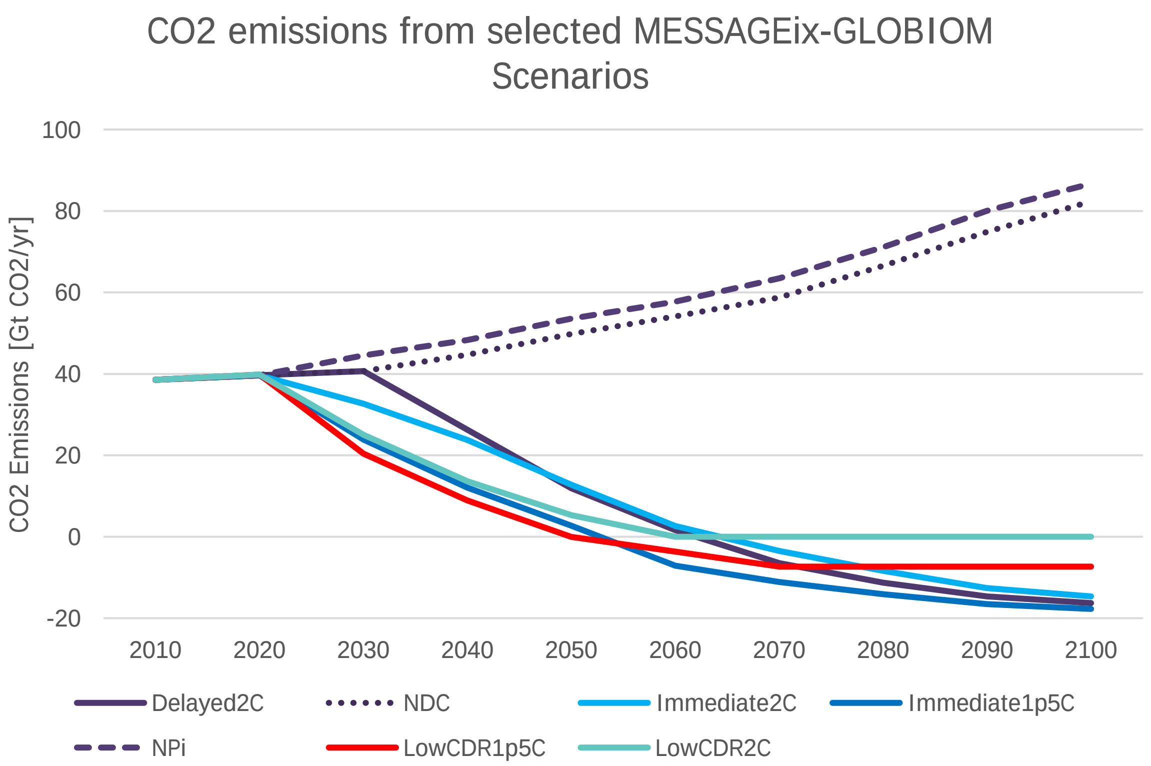

Figure 5: CO2 emissions trajectories of the selected scenarios.

First, the NPi and NDC represent scenarios in which climate action is not becoming more stringent then the currently implemented policies or then the announced emission reductions for 2030. Under these cases, there will be no transition to a low-carbon future.

Second, the Immediate2C and Immediate1p5C scenarios represent globally coordinated transitions to a low-carbon future, taking a globally cost-optimal emission trajectory into account that compensates higher emissions on the short term with negative emissions in the second half of the century. These scenarios are rather idealized in their assumption on both the immediate implementation of global emission reductions and the scale up of negative emissions technologies over the next few decades. Therefore, the final variants in the scenario set explicitly deal with these two aspects.

Third, the Delayed2C scenario represents a delay in global climate action until 2030, as countries first only live up to the NDCs and then converge on a global trajectory towards a low-carbon future. In order to limit temperature increase to 2 degrees in this scenario, the emission reductions after 2030 need to be steeper then in the immediate2C scenario and this scenario requires more negative emissions to compensate for the lack of emission reduction on the short term. A 1.5 degree scenario following this design proved not to be feasible with the MESSAGE scenario.

Finally, the two low CDR scenarios limit Carbon Dioxide Removal from the atmosphere, so called "negative emissions". These CDR-technologies pull CO2 from the atmosphere and store it underground (direct air capture) or in the biosphere (afforestation) or rely on both (biomass with CCS). The key-idea behind these scenarios is that they do not allow positive emissions in the first half of the 21st century to be compensated by negative emissions in the second half of the century, leading to a similar temperature change by the year 2100. Due to the lack of CDR in the second half of the century, these scenarios require steeper emission reductions on the short term, leading to a fast transition to a low-carbon energy system.

Depending on the reason for exploring a low-CDR scenario, there are a few ways to design such scenarios:
- One could remove or limit all CDR technologies in the model
- One could remove or limit key-inputs to important CDR technologies, because one doubts that these will materialize at large scale in the future (e.g. limiting bioenergy availability or limiting storage capacity for CCS)
- One could explicitly assume a certain emission trajectory of reaching net-zero emissions at a certain timepoint and staying at net-zero emissions afterwards (the approach followed in the MESSAGE low-CDR scenarios), as this focuses on the moment of peak-warming once emissions are net-zero and avoids the compensation of slower emission reduction on the short term with negative emissions later in the century. The idea behind these scenarios is described in Rogelj et al., 2019.

Detailed assumptions behind each scenario are described below.

Scenario descriptions

Reference scenarios

The **National implemented Policies scenario (NPi)** describes energy, climate and economic projections for the period until 2030, based on currently implemented national policies relevant for achieving the internationally pledged INDC (Intended Nationally Determined Contributions) targets. The emission development after 2030 assumes that countries will pursue equivalent effort. This is represented by assuming constant relative CO_2-equivalent emission reductions between NoPolicy (a scenario without any climate policies) and NPi between 2030 and 2100. The starting point for NPi scenario is the climate policy database containing climate, energy and development policies in G20 countries with cut-off year of 2015. These policies can be policy targets from national policy documents (e.g. National Communication, strategy documents) or policy instruments (e.g. ETS, feed-in-tariff, renewable portfolio standard). In practice, policy instruments are often implemented to achieve national (often aspirational) policy targets. As it might be difficult to implement specific policy instruments in IAMs, we included aspirational policy targets as currently implemented policies, but only if they are backed by effective policy instruments. If the policy instrument ends before the policy target year, we assume continuation of the policy instrument, but only for around five years. This leads to the definition of implemented policy as either a policy adopted by the government (through legislation), or a non-binding target backed by effective policy instruments.

The **NDC scenario (NDC)** assumes implementation of NDCs by 2030, but no further intensification of emission reduction commitments beyond the NDCs after 2030. The focus of this scenario is the year 2030, which is the target year of most submitted NDCs. However, we assume that post-2030, countries will implement equivalent effort in the same way as for NPi scenario (so by assuming constant relative CO2eq emission reductions between a NoPolicy (scenario without any climate policies) and INDCi between 2030 and 2100). It thus assumes a continuation of fragmented and highly diversified action and does not represent an intensification of efforts toward the achievement of the 1.5-2°C target as envisioned by the Paris Agreement, but rather the floor of ambition implied by the submitted INDCs. It thus represents a scenario of moderate, fragmented action in which the (conditional) commitments made in the INDCs are realized, but where the international community fails to ratchet-up 2030 targets and increase long-term ambition relative to the effort implied by the INDCs. This scenario will serve as a point of comparison for the 1.5°C and 2°C scenarios.

Budget-based scenarios

Then, there are two sub-groups of scenarios achieving 1.5-2°C limits under a set of long-term carbon budget constraints. The **DelayedXX** scenarios explore the feasibility of achieving 1.5-2°C-limits in a global cost-effective way, starting from INDC-based near-term pathways under the cumulative (between 2011-2100) budget constraint of *n* Gt CO2. The **ImmediateXX** scenarios explore the feasibility of achieving the same long-term goals in the most cost-effective way under the same constraint, by starting from today's policies and allowing for overachieving of INDC targets. These pathways are composed of two distinct phases: in the first phase until 2020 (Immediate) or 2030 (Delayed), they follow the developments of the NPi or INDCi scenario (i.e. NPi2020 achieves the currently implemented policies included in NPi scenario up till the year 2020, and INDC2030i achieves the INDC targets up till 2030). In the second phase starting from 2020 (Immediate) or 2030 (Delayed), they assume stylized, comprehensive climate policies (CO2 prices equalized across regions and sectors) limiting cumulative 2011-2100 CO2 budgets at three discrete levels (1600, 1000, 400 Gt CO2 cumulative 2011-2100) as indicated in Table 1, in line with long-term stabilization in the 1.5-2°C range. The carbon budget of 1600 GtCO2 for the period 2011-2100 would limit global warming below 2°C relative to pre-industrial levels with at least 50% probability, and the budget of 1000 GtCO2 would limit warming below 2°C with at least 66% probability during the entire course of the 21st century. The budget of 400 GtCO2 for the period 2011-2100 explores the effort necessary to limit global warming to 1.5°C with 66% probability by the end of the 21st century (in 2100). During the 21st century this probability is generally lower than 66% (temperature overshoot). The same CO2 -price shall be applied to non-CO2 greenhouse gases to ensure comparable mitigation efforts across gases.

Low CDR scenarios

The low CDR scenarios are built on a different perspective from those above. The budget-based scenarios above (DelayedXX and ImmediateXX) are designed to achieve the target temperature at the end of the century. It means that the scenario can temporarily exceed the temperature target (which is referred to as 'overshoot') for a period and, near the end of the century, can bring down the temperature by relying on substantial deployment of negative emissions technologies. This may appear inconsistent with the idea of the Paris Agreement or, in some cases, be considered undesirable because of concerns over sustainability and intergenerational equity [12,13]. Hence, one can design an emission trajectory that explicitly limits the temperature change at peak warming and limits negative emissions afterwards, following the new logic suggested by Rogelj et al., 2019. This new approach meets the Paris Agreement's targets and caps the overshoot at a specific level while considering the future deployment of negative emissions and intergenerational trade-offs as explicit design criteria. In the **LowCDR1p5C**, global net-zero emissions are achieved by 2050, with an average of 4 GtC/yr emissions between 2020 and the net-zero year. After reaching net-zero, net-negative emissions in this scenario are limited to a maximum of 2 GtC/yr. In the **LowCDR2C** scenario, global net-zero emissions are achieved by 2060, with an average of 4 GtC/yr emissions between 2020 and the net-zero year. After reaching net-zero, no net-negative emissions are allowed in this scenario.

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