NGFS Climate Scenarios Technical Documentation

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Contents

Acknowledgements

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Executive Summary

Established in 2017, the Network for Greening the Financial System (NGFS) today represents a major hub for the promotion of analytical work and best practices in the field of green finance. Currently (June 2024), the NGFS consists of 141 central banks and supervisors (and 21 observers) from across five continents committed to sharing best practices, contributing to the development of climate- and environment-related risk management in the financial sector and mobilising mainstream finance to support the transition toward a sustainable economy.[1]

One of the key initiatives of the NGFS is the development of climate-related scenarios that can be used by financial institutions to assess and manage climate-related risks. These scenarios are intended to be forward-looking and consider various climate-related factors, as well as policy and technology developments. Hypothetical future pathways of climate change are used for analysing and assessing the potential impacts and risks associated with different climate outcomes. The scenarios are not intended to predict the exact future climate but rather provide a set of plausible pathways that can help policymakers, researchers, financial institutions, and private sector businesses explore impacts and evaluate adaptation and mitigation strategies in the face of climate change.

The NGFS climate scenarios have been developed in partnership with a consortium of academics from the Potsdam Institute for Climate Impact Research (PIK), International Institute for Applied Systems Analysis (IIASA), University of Maryland (UMD), Climate Analytics (CA) and the National Institute of Economic and Social Research (NIESR). This work was made possible by grants from the ClimateWorks Foundation.

[1] See https://www.ngfs.net/en/about-us/membership

Introduction

This document provides technical information on the NGFS long-term climate scenarios and the underlying modelling infrastructure. It includes updated technical information from previously published material[2], and expands the scope and the level of detail of the information provided to highlight key modelling assumptions and comparisons between models, scenarios, and vintages for key variables. As accompanying material to the NGFS scenarios, this document aims to answer conceptual and technical questions for a wide range of stakeholders, from scenario users interested in performing analyses on the datasets themselves to interested readers who would like to better understand the NGFS scenarios.

Following a layered structure, this document has been designed to target readers with different levels of technical expertise. On the one hand, readers interested in gaining high-level information about the NGFS scenarios will benefit from a comprehensive high-level overview, non-technical summaries prefacing each section, as well as explainer boxes included throughout the document to provide relevant background information. On the other hand, readers with advanced technical knowledge who are interested in detail will find the extensive description of the NGFS modelling framework useful, with the specifics of each model being presented in separate chapters and technical insights being highlighted in thematic boxes.

The remainder of this document is organised into 8 modules. **Module 1** provides a high-level overview of the NGFS scenarios, their rationale, and their broader context. The following modules describe in detail the NGFS modelling framework and methodology to generate the NGFS scenarios. **Modules 2, 3 and 4** outline the three Integrated Assessment Models (IAMs) used to generate the transition pathways for the NGFS scenarios: REMIND-MAgPIE, MESSAGE-GLOBIOM, and the GCAM models respectively. **Modules 5 and 6** describe the modelling for physical risk and its relationship with transition policies, with focus on acute and chronic physical risk respectively. **Module 7** discusses the downscaling methodology applied to produce country-level results. **Module 8** covers the National Institute Global Econometric Model (NiGEM) and describes how this macro-financial model has been specifically modified for the purpose of producing the NGFS scenarios to understand the consequences of transition and physical risk on the key macro-financial fundamentals.

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[2] The previous version of the Technical Documentation for NGFS Phase IV scenarios, published in November 2023, can be found here.

Module 1: High-level overview

The NGFS scenarios have been developed to provide a common starting point for analysing climate risks to the economy and financial system.

Key messages

- **The NGFS scenarios have been created as a tool to shed light on potential future risks, and to prepare the financial system for the shocks that may arise**. Importantly, the NGFS scenarios are not forecasts. Instead, they aim at exploring the bookends of plausible futures (neither the most probable nor desirable) for financial risk assessment.
- **The NGFS scenarios explore a range of plausible outcomes.** They provide a common language for how climate change (physical risk) and climate policy and technology trends (transition risk) could evolve in different futures.
- **The NGFS scenarios present unique features that make them particularly suitable for a wide range of applications.** They provide a common starting point for climate risk assessment, they produce internally consistent results applicable at the global level that combine transition, physical and macro-financial risks, and they are freely accessible through a public online platform.

1. Introduction

Since 2018, an increasing number of central banks and supervisors around the world have joined forces in the Network for Greening the Financial System (NGFS) to help build a common understanding of how climate change affects our economies and financial systems. While governments and legislators are primarily responsible for the implementation of climate policies, central banks and supervisors can also play an important role in addressing climate change within their mandates. In addition, in line with their objectives and functions, central banks and supervisors need to be able to identify climate-related risks and quantify their impact via rigorous analysis. The NGFS has thus developed, together with leading academic climate institutions[3], a common picture of what our economies might look like under different assumptions in terms of transition policies and physical risks. These are called "climate scenarios".

The NGFS climate scenarios[4] have been created as a tool to shed light on potential future risks, and to prepare the financial system for the shocks that may arise. They answer crucial questions like "what can happen?" or "what should happen?" to enable a common understanding of how climate change and climate mitigation can impact our economies in the long run (until 2100). Since its first vintage, published in 2020, the NGFS scenarios have offered a useful guide to climate risks, as they combine the analysis of transition, physical and macro-financial risks to reveal the long-term trade-offs between the costs of climate mitigation and the consequences of unfettered climate change. The NGFS scenarios have three essential features:

- They take a **long-term perspective**, providing a **common starting point** for analysing climate-related risks and their impact on the economy and financial system.

3 See modelling teams of the NGFS Academic Consortium in the Acknowledgements section.

4 Referred to as "NGFS scenarios" in the rest of the document.

- They cover the **global economy**, producing results that are internally consistent, applicable at the global level and comparable across regions.

- They represent a **global public good** as they are the product of an international collaboration among leading academic institutions that (i) combine state-of-the-art climate models to capture the interactions between transition, physical and macro-financial risk, and (ii) make the results available as a set of climate pathways accessible to anyone, anywhere in the world on the NGFS Scenarios Portal

It is important to note that the NGFS scenarios are not forecasts. Instead, they aim at exploring plausible futures (neither necessarily the most probable nor the most desirable) for financial risk assessment making them particularly suitable for a wide range of applications. To reflect the uncertainty inherent to modelling climate-related macroeconomic and financial risks, the NGFS scenarios use different models, and explore a wide range of scenarios across regions and sectors.

The NGFS scenarios are regularly updated and enhanced in line with evolving expectations. The first vintage of NGFS climate scenarios was released in 2020, and three more followed in fall 2021, 2022, and 2023. This documentation has been published together with the fifth vintage of the scenarios. Over time, the NGFS scenarios have become deeper, broader, and richer in terms of modelling tools, output results, risk coverage and geographical scope. Continuous progress and refinements reflect the innovative nature of climate scenario development, which lies at the frontier between climate science, macroeconomic analysis, and policy assessment.

Explainer box 1

What is a scenario and scenario analysis, and what are climate scenarios and climate modelling?

- **In a world of uncertainty, a scenario is a hypothetical construct that describes a path of development leading to a particular future outcome**. Scenarios are not forecasts or predictions, and do not provide a full description of the future, but rather highlight central elements of a possible future.

- **Scenario analysis is a tool to enhance critical strategic thinking.** It is a process of examining and evaluating possible future events and is used in a forward-looking assessment of risks and opportunities.

- **Climate scenarios explore a different set of assumptions about how climate policy, emissions, and temperatures evolve**. They help to identify impacts from a changing climate and the necessary policies for and opportunities from a green transition. They can help our understanding of how climate-related risks could evolve and what the implications might be for the economy and the financial system.

- **Climate modelling refers to the use of quantitative methods to simulate and analyse the interactions of climate variables**, both to understand the dynamics of the climate system and to project the future climate. Climate models may also be qualitative to provide descriptive narratives of possible futures.

1.1 NGFS scenarios as a useful guide to climate risks

Climate change affects the way that our economy functions. In recent years, we have experienced a multitude of climate disasters, from wildfires in North America, to floods in Brazil, to heatwaves with new record temperatures in Europe. These are examples of more severe and more frequent extreme weather events that are already visible today. However, in the transition to a less polluting economy, other events, including less visible ones, could affect the profitability of businesses or the prosperity of households. Thus, climate change affects our economy and financial system through a range of different transmission channels that can be classified into two types of risks:

- The **physical risks** of a changing climate, including more frequent or severe weather events like floods, droughts, and storms, as well as other risks stemming from an increase in global temperature, and

- The **transition risks** from moving towards a low-carbon economy, the timing and speed of which will depend on policy and regulation, technology development and changes in consumer preferences.

Policymakers and supervisors have identified climate change as a significant source of financial risk for several years now[5]**, but assessing its effects remains a daunting task for many, as they differ from the traditional sources of financial distress**. Capturing climate-related risks means considering their unique and complex features, such as assessing an unprecedented combination of impacts spread over a long-term horizon and bridging persisting climate data gaps[6]. While uncertainty is inherent in climate-related risks, this is not reason enough to shy away from this fundamental challenge.

Scenario analysis is one approach to tackle this uncertainty. On the one hand, the NGFS scenarios provide plausible future developments, because they are constructed with models designed to simulate the complex and non-linear dynamics of the energy, economy, and climate systems. On the other hand, they account for various possible policy and technology assumptions. Therefore, they allow a rich exploration of various plausible future developments and an understanding of the trade-offs between various policy and technology choices.

The NGFS scenarios provide a common starting point for understanding how climate change (physical risk) and climate policy and technology trends (transition risk) could evolve in different futures. In the newly released Phase V, the NGFS scenario framework explores a set of seven scenarios characterised by different levels of physical and transition risk, primarily driven by the level of policy ambition, policy timing, coordination, and technology levels. The main technical features include:

- **different climate pathways** that depict potential future trajectories of greenhouse gas emissions and global temperature increases,

- **macro-economic variables** that are influenced by climate change, such as GDP growth, inflation, interest rates and employment,

- **sectoral breakdown**, including energy, transportation, and agriculture,

- **geographical coverage**, accounting for regional and country-level variations in climate risk,

- a **time horizon** spanning multiple decades and long-term perspectives to capture the gradual nature of climate change impacts, and

- **policy assumptions**, such as the implementation of carbon pricing mechanisms, renewable energy targets and other mitigation and adaptation measures.

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5 Network for Greening the Financial System (2018), "First progress report", Banque de France, October. Carney, M., Villeroy de Galhau, F. and Elderson, F. (2019), "Open letter on climate-related financial risks", Bank of England, April.

6 Baranović, Ivana, Busies, Iulia, Coussens, Wouter, Grill, Michael and Hempell, Hannah S., (2021), "The challenge of capturing climate risks in the banking regulatory framework: is there a need for a macroprudential response?", ECB Macroprudential Bulletin, issue 15, number 1.

The NGFS scenarios combine the analysis of transition, physical and macro-financial risks. To make this possible, the NGFS scenarios bring together a global, harmonised set of transition pathways, physical climate change impacts and economic indicators. A combination of models is used to capture separately but consistently climate, macroeconomic, and financial contingencies. This methodology will later be referred to as the suite-of-model approach. As shown in **Figure 1**, the models used to derive the NGFS scenarios can be classified into three broad categories: **physical risk models**, **transition risk models** and a **macro-financial model**[7].

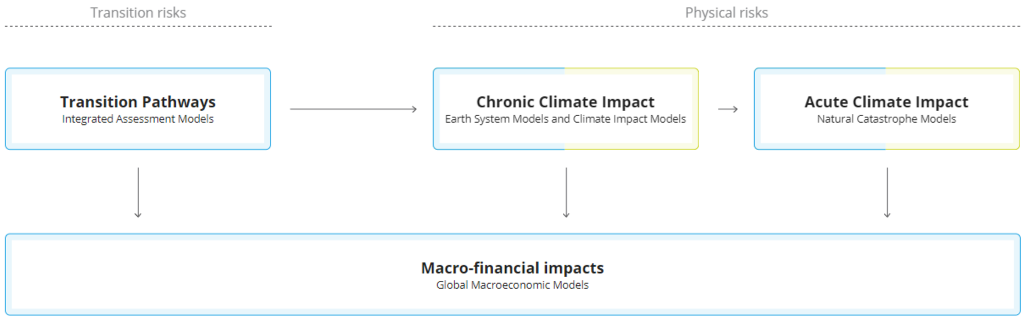

Figure 1. NGFS suite-of-models approach

- **Physical risk models** include all models that are participating in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)[8] and CLIMADA[9] and provide climate and economic indicators accounting for changes in climate.

- **Transition risk models** include three Integrated Assessment Models (IAMs), specifically REMIND-MAgPIE, GCAM and MESSAGEix-GLOBIOM, that derive the impacts of different policy ambitions on the energy sector, emissions, and land use.

- The **macro-financial model** consists of the NiGEM model (a version specifically modified for the purpose of producing the NGFS scenarios), to understand the consequences of transition and physical risk on the key macro-financial fundamentals.

The NGFS suite of models produces a range of internally consistent data on transition risks, physical risks, and economic impacts. The NGFS scenarios consist of a set of climate-related and macro-financial variables available for each model, scenario, and geography (**Figure 2**). The data can be accessed freely online:

7 More details on the NGFS modelling approach are provided in **NGFS modelling** approach of this module.
8 More information about ISIMIP can be found here.
9 CLIMADA stands for climate adaptation and is a probabilistic natural catastrophe damage model that also calculates averted damage (benefit) thanks to adaptation measures of any kind (from grey to green infrastructure, behavioural, etc.). More information here.

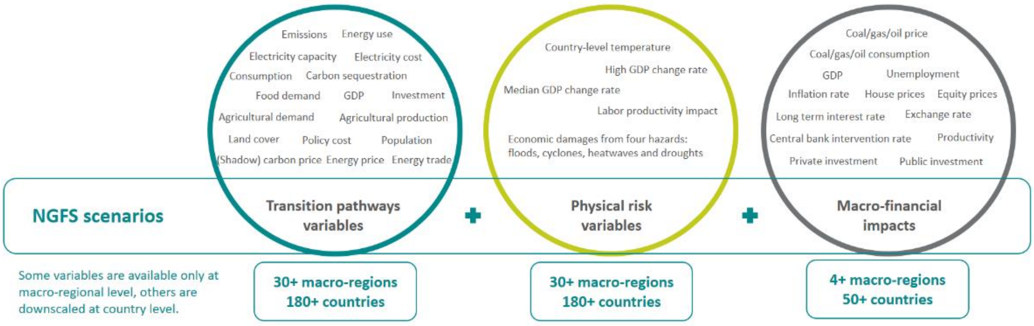

Figure 2. Overview of the range of data provided by NGFS scenarios.
Note: this visual does not contain the full list of variables and is for illustrative purposes only. The names of the variables do not necessarily correspond to the ones used in the databases. The number of countries/regions available varies significantly depending on the variable. Downscaled climate-related and macro-financial variables are available for 180+ and 50+ countries, respectively.

- **Physical risk variables** can be explored through the **NGFS Climate Impact Explorer** hosted by Climate Analytics. More granular data are available via the ISIMIP project. Physical risk analysis was supported by Climate Analytics, ETH Zurich and PIK.

- **Transition pathway and macro-financial impact variables** are made available in the **NGFS Scenarios Database** hosted by IIASA. The transition pathways were produced by three IAM teams: PIK (REMIND-MAgPIE model), IIASA (MESSAGEix-GLOBIOM model) and UMD (GCAM model). Economic variables were produced by the National Institute for Economic and Social Research (NIESR) (NiGEM model).

- **Key data and resources** can be explored interactively on the **NGFS Scenarios Portal**.

1.2 Comparison with other existing climate scenarios

The NGFS scenarios share some commonalities with other existing climate scenarios, such as the ones developed by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA). For instance, all three sets of climate scenarios **rely on** Integrated Assessment Models (**IAMs)** to provide transition pathways for various narratives (with different but consistent results). Moreover, another shared feature of the IPCC, the IEA and the NGFS scenarios is that they are all **neither predictions nor forecasts** but instead explore a range of future climate pathways and/or green transition policies to estimate their future economic implications.

Despite having similar objectives, the NGFS scenarios have some unique features that make them particularly suitable for a wide range of applications. The **main differences** to other existing climate scenarios can be summarized in three categories:

- **Scope**. The NGFS scenarios assess the consequences of both transition and physical risks globally, while the IEA scenarios focus on transition risk only[10], and IPCC focus on the possible evolution of greenhouse gas emissions[11]. The NGFS Scenarios also include more macroeconomic details.

[10] For more details on the IEA scenarios, see here.
[11] IPCC (2000), Special Report on Emissions Scenarios, Working Group III of the Intergovernmental Panel on Climate Change, see here.

- **Time horizon**. The NGFS scenarios look at the trade-offs between a green transition and a no-transition scenario until the end of the century (2100), while the IEA scenarios focus on the implications of a green transition until 2050.

- **Applications**. For the reasons above, the NGFS scenarios are mostly used by central banks, supervisory authorities, and financial institutions to assess the costs and benefits of a green transition for the financial sector, while the IEA scenarios are mostly used to better understand the implications of different green policies in the short run.

The combination of transition, physical and macroeconomic models has been confirmed by scenario users as one of the key strengths of the NGFS scenarios. The results of the first public NGFS survey on climate scenarios underline that scenario users rate the NGFS scenarios framework positively compared to other existing climate scenarios and highlight the number and relevance of output variables as an additional unique selling point of the NGFS scenarios[13].

Explainer box 2

Modeling structure example: how do NGFS scenarios compare with IEA [12] and IPCC scenarios?

More technically, the NGFS, IEA and IPCC scenarios also differ in terms of modelling and narrative:

- **The NGFS produces a wider set of scenarios.** The NGFS scenarios explore seven possible future pathways, looking at both transition and physical risk, while the IEA scenarios explore only three scenarios, abstracting from the implications of physical risk.

- **The NGFS offers sets of scenarios that have been created using the REMIND-MAgPIE model** that integrates the macro-economic climate damages into the optimization procedure.

- **The NGFS scenarios combine three model categories in a consistent manner to assess the costs and benefits of a green transition**: the Integrated Assessment Models (IAMs) to assess the economic implications of a green transition; climate damage models to understand the consequences of physical risk; a macro-economic model (NiGEM) to assess the macroeconomic implications of climate policies and unfettered climate change. The IEA scenarios, instead, rely on a single model, i.e., the World Energy model. The NGFS suite-of-model approach allows for exploring the uncertainty related to model structures and techno-economic and potentially other assumptions.

- **Moreover, the types of models and variables (e.g., endogenous vs exogenous) are different from IEA scenarios, which lead to different results.**

[12] There are three main IEA scenarios in the World Energy Outlook 2023: Stated Policies scenario (STEPS) ("the trajectory implied by today's policy settings"), Announced Pledges Scenario (APS) ("all aspirational targets announced by governments are met on time and in full"), and Net Zero Emissions by 2050 (NZE) Scenario ("a way to achieve a 1.5 °C stabilization in the rise in global average temperatures, alongside universal access to modern energy by 2030").

[13] NGFS (2023), "NGFS Survey on Climate Scenarios: key findings", June

1.3 Scenario applications

The NGFS scenarios have become a key ingredient for exploratory stress test and scenario analysis exercises worldwide. Originally designed as a tool to advise policymakers on potential future risks, their user community continues to grow substantially beyond central banks and supervisors. Since their first vintage in 2020, the NGFS scenarios have been repeatedly refined with the release of three improved vintages and made available as a public good. While evolving to cater for new needs, the NGFS scenarios' unique features as a financial risk assessment tool have made them particularly well suited for an increasing range of applications. In other words, not only the number of users continues to grow, but also the variety of their applications:

- **Risk assessment, scenario analysis and stress testing.** Central banks, supervisors and financial institutions can use the scenarios to assess the resilience of portfolios, individual institutions or the entire financial system under different climate scenarios. This helps to identify potential vulnerabilities and allows for the appropriate risk management strategies, as well as assessing the trade-offs of different options.

Explainer box 3

Carbon pricing example: how do NGFS scenarios compare with IEA and IPCC scenarios?

Since the NGFS scenarios were developed for risk assessment purposes, they do not always have equivalents in the IEA or IPCC models, as the latter focus on exploring transition pathways. To illustrate this, let us look at the example of carbon pricing.

- **Carbon prices are structurally different in the NGFS and IEA scenarios.** In the case of the NGFS scenarios, the carbon price is calculated endogenously within each IAM, whereas in the case of the IEA, the carbon price is set exogenously depending on national carbon pricing policy and commitments and the degree of emission reductions in each scenario.
- **In other words, in the NGFS scenarios, carbon prices are shadow prices that reflect the policy ambition specified by the scenario (e.g., Net Zero by 2050) and serve as a measure of overall policy intensity.** They are sensitive to factors such as the level of ambition to mitigate climate change, the timing of policy implementation, the distribution of policy measures across sectors and regions, and assumptions regarding technology (e.g., the availability and feasibility of carbon dioxide removal).
- **In addition to (actual) carbon pricing, the scenarios developed by the IEA separately consider a wide range of other policy measures that can contribute to emission reductions, and the carbon price is not a marginal abatement cost that is derived through an optimization calculation.** Carbon prices that are linked to emission reductions through formulation under IAMs and carbon prices that are set in a situation where policy measures other than carbon pricing are in place are different in nature. In the presence of other policy measures, the carbon prices implicit in the IAMs tend to be higher (CRIEPI, 2022).

- **Climate disclosures.** Granular data on transition pathways, climate impacts and macro-financial indicators can enhance strategic thinking and form a key part of climate-related financial disclosures. Climate scenarios support harmonisation efforts in this field.

- **Strategy and policy alignment**. While many actors in the private and public sectors are revising their strategies and policies to align with particular goals, the NGFS scenarios highlight some key themes that can be used to help guide decision-making and set more granular targets. For example, NGFS scenarios can help financial institutions develop their net zero transition plan and manage associated risks, as well as support the alignment of climate targets.

- **Investor engagement:** Investors can use the scenarios as a basis for dialogue with companies and assess the long-term sustainability of their investment portfolios.

- **Further academic research**: The NGFS scenarios can be used as a starting point for researchers and technical specialists who wish to extend them to include higher granularity and other channels and/or feedback effects.

The NGFS scenarios are helping a wide range of public and private sector players to identify climate risks globally. The results of a stocktaking exercise[14] on climate scenarios, models, data, and metrics used by members of the Financial Stability Board (FSB) and the NGFS show that the vast majority of the 53 members that have completed, are conducting, or plan to conduct a climate scenario analysis exercise rely on the NGFS scenarios. The report argues that the NGFS scenarios are at the core of these exercises, with most of the sampled institutions worldwide making use of them, either with or without adjustments in some of their components or outcomes. (See FSB-NGFS, 2022).[15]

Furthermore, survey results[16] confirm that the NGFS scenarios have become an essential tool among both private and public sector actors in understanding the financial risks stemming from a changing climate, as well as the opportunities of climate mitigation action. The NGFS survey finds that over 70% of 213 respondents from 57 countries use them, mostly to better understand the impacts of climate risks and to build internal capacity. In addition, the richness and granularity of the scenarios make them useful also for a wide range of audiences including consultancies, academics, international organisations, or civil society organisations, among others (See NGFS,2023).[17]

The NGFS scenarios can also help policymakers and central banks understand the impacts of transition policies on the macroeconomic outlook, which in turn can feed into relevant policy decisions. Alongside the impact of climate change and climate policies on the key macroeconomic indicators (such as GDP, commodity prices, inflation, and interest rates), the NGFS scenarios also give insights that can inform policymakers. For example, they provide estimates of the investments needed across energy sectors to reach the climate targets. The scenarios show how much all these variables differ across regions and can thus support the calibration of country-specific climate policies and risk assessment exercises. The NGFS scenarios are also an important tool to assess the forward-looking impact of climate change on macroeconomic fundamentals, which can support central banks' policy decisions.

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[14] Information on a total of 66 climate scenario analysis exercises was obtained.

[15] Climate Scenario Analysis by Jurisdictions: initial findings and lessons, November 2022

[16] Most of the respondents come from financial institutions, central banks, and consulting firms; and use NGFS scenarios to better understand the impact of climate risks on the respective organisation, individual financial institutions, or financial stability. In addition, 95% of the respondents that have already concluded exercises based on NGFS scenarios are (at least partially) satisfied with the outcome.

[17] NGFS Survey on Climate Scenarios: key findings, June 2023

The NGFS scenarios have evolved from a policy tool for selected users to a common language for climate risks for all. Although they were originally developed by central banks and supervisors to help inform and guide policy across the globe, they are used, by now, for an increasing variety of applications by financial institutions, policymakers, and other key stakeholders to assess the financial risks associated with climate change and support the transition to a more sustainable and resilient economy.

2. NGFS scenario narratives

The NGFS scenarios explore the impacts of climate change and climate policy with the aim of providing a common reference framework.

Key messages

- **The NGFS scenarios explore a set of seven climate scenarios that can be grouped into four categories (quadrants): orderly transition, disorderly transition, hot world, and too little, too late**. Each scenario is characterized by its overall level of physical and transition risk, which are driven by the level of policy ambition, policy timing, coordination, and technology levers.
- **In this fifth vintage, the NGFS scenarios have been enriched and updated in several aspects:**
  - **The NGFS scenarios have been brought up to date with new economic and climate data, policy commitments, and model versions**: the scenarios use the latest release - i.e., version 3.0 - of the Shared Socioeconomic Pathways (SSPs). In addition, the NGFS scenarios account for the most recent country-level commitments announced by March 2024.
  - **A new damage function has been applied to enhance physical risk modelling.** The new damage function incorporates the latest climate science findings, and it is calibrated using state-of-the-art climate datasets. Consequently, it captures climate change impacts in a comprehensive manner beyond increases in mean temperature and assesses their persistence effects on the economy. The new damage function helps better prepare the financial system to the economic impacts of global warming.

The NGFS scenarios framework explores a set of possible transition pathways, depending on different levels of ambition and coordination in terms of climate policies. As shown in the NGFS scenarios framework (Figure 3), the NGFS scenarios can be grouped into four quadrants: orderly transition, disorderly transition, hot house world, and too little, too late scenarios.

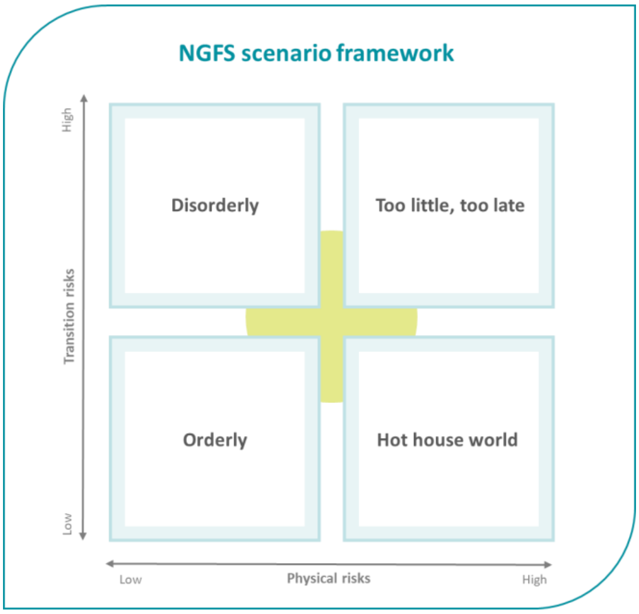


Figure 3. Overview of the NGFS scenario framework

- **Orderly** scenarios assume that ambitious climate policies are introduced early and become gradually more stringent. Both physical and transition risks are relatively subdued.

- **Disorderly** scenarios assume that climate policies are delayed or divergent across countries and sectors. These scenarios are associated with subdued physical but high transition risks, as, for instance, carbon prices might need to rise sharply and abruptly.
- **Hot house world** scenarios assume that global warming cannot be limited due to insufficient global efforts. As a result, critical temperature thresholds are exceeded, leading to severe physical risks and irreversible impacts like sea-level rise.
- **Too little, too late** (TLTL) scenarios assume that a late and uncoordinated transition fails to limit physical risks.

2.1 Description of narratives

In this fifth vintage, the NGFS scenarios explore a set of seven possible transition pathways, depending on different levels of ambition and coordination in terms of climate policies. The scenarios are mapped in the NGFS scenario framework in Figure 4 and can be summarised as follows.

Orderly

- **Low Demand** (LD) explores the global efforts needed to be able to limit global warming to below 1.5°C by 2050 in an orderly fashion, aligned with the Paris Agreement, driven by lower energy demands.
- **Net Zero 2050** limits global warming to 1.5°C through stringent climate policies and innovation, reaching global net zero CO_2 emissions around 2050. Some jurisdictions such as the US, EU, UK, Canada, Australia, and Japan reach net zero for all GHGs.
- **Below 2°C** gradually increases the stringency of climate policies. Countries with net zero targets reach them partially (80% of the target), giving a 67% chance of limiting global warming to below 2°C.

Disorderly

- **Delayed transition** assumes annual emissions do not decrease until 2030. Strong policies are needed to limit warming to below 2°C. Negative emissions are limited.

Hot house world

- **Nationally Determined Contributions (NDCs)** includes all pledged targets even if not yet backed up by implemented effective policies.
- **Current Policies** assumes that only currently implemented policies are preserved, leading to high physical risks.

Too little, too late

- **Fragmented World** assumes a delayed and divergent climate policy response among countries globally, leading to high physical and transition risks. Countries without zero targets follow current policies, while other countries achieve them only partially (80% of the target).

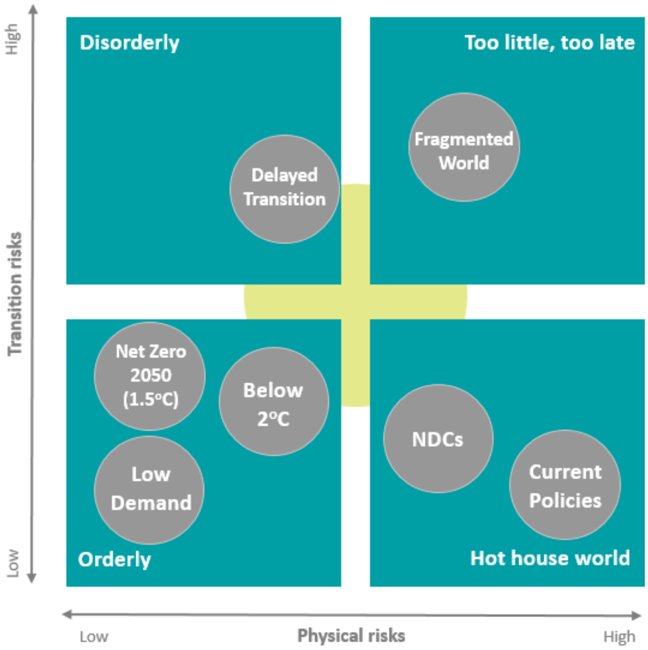


Figure 4. The NGFS scenario framework in Phase V

The transition pathways for the NGFS scenarios show a range of higher and lower risk outcomes that explore a different set of assumptions about the evolution of climate policy, emissions, and temperatures. Each scenario is based on several key design choices relating to policy ambition (captured by specific end-of-century temperature targets or policy packages), short-term policy, overall policy coordination and technology availability. **Table 1** highlights the various assumptions underlying these design options, which are explained in more detail below. **Table 3** compares the key assumptions across scenarios.

The main driving forces of the scenarios are the evolution of carbon prices and the evolution of CO_2 emissions, which are strictly related.

Table 1. Overview of NGFS scenario narratives

Quadrant	NGFS scenario	Narrative explained
Orderly	**Low Demand (1.5°C)**	**This scenario includes significant behavioural changes in energy generation and consumption activities to ensure an orderly, Paris-aligned transition**[18]. • Global CO_2 emissions reach or approach net zero in 2050. Countries with a political commitment to a net zero target defined before end of March 2024 meet this target before or after 2050. • Some jurisdictions such as the US, EU, UK, Canada, Australia, and Japan reach net zero for all GHGs. • Additional levers in end-use sectors (e.g., behavioural changes, reducing energy demand, inducing faster electrification, and substitution through renewables) mitigate the pressure on carbon taxes to induce the transition and are the distinguishing feature of this scenario compared to the Net Zero scenario by 2050.
	Net Zero 2050 (1.5°C)	**Global warming is limited to 1.5°C (with a 50% chance) through stringent climate policies and innovation, reaching global net zero CO_2 emissions around 2050.** • Global CO_2 emissions reach or approach zero in 2050. Countries with a political commitment to a net zero target defined before end of March 2024 meet this target before or after 2050. • Some jurisdictions such as the US, EU, UK, Canada, Australia, and Japan reach net zero for all GHGs.
	Below 2°C (2°C)	**The stringency of climate policies is gradually increased, giving a 67% chance of limiting global warming to below 2°C by the end of the century.** • Global CO_2 emissions evolve such that the end-of-century temperature goal of 2°C warming is reached (with a 67% chance). • Countries who have net zero targets follow through on 80% of them, others follow less ambitious trajectories.

[18] "Paris-aligned" refers to achieving the 1.5-degree target of the Paris Climate Agreement by reducing greenhouse gas emissions: "limiting the global temperature increase to no more than 1.5 degrees Celsius by the year 2100 compared to pre-industrial times."

Disorderly	**Delayed Transition**	**Annual emissions do not decrease until 2030. Strong policies are needed to limit warming to below 2°C.** • Countries stick to current policies until 2030 and experience a "fossil recovery", after which they transition such that the end-of-century temperature goal of 2°C warming is reached. This change of regime in 2030 is unanticipated and therefore disruptive. Countries with net-zero policy target commitments are assumed to follow-through on 80% of them. Negative emissions are limited.
Hot house world	**Nationally Determined Contributions (NDCs)**	**All pledged targets are assumed to be implemented, even if they are not yet backed up by effective policies.** • Countries implement pledged policies in addition to current policies and keep their level of ambition beyond the NDC horizon. The cut-off date for targets being considered here is those published by the UNFCCC until end of March 2024[19].
	Current Policies	**Only currently implemented policies are preserved, leading to high physical risks.** • Existing climate policies remain in place but there is no strengthening of ambition level of these policies[20].
Too little, too late	**Fragmented World**	**A delayed and divergent climate policy response among countries globally leads to high physical and transition risks.** • Only currently implemented policies are maintained until 2030 (delayed transition); thereafter, countries that have set themselves a net zero target only reach an 80% reduction by 2050, while others continue with current policies (divergent transition).

[19] See https://unfccc.int/NDCREG

[20] The detail of policy representation differs across models and across different sectors. Policy implementation has been included in as much detail as possible, but due to limited granularity of sector representation, all models also represent some policies as proxies, for example via aggregate final energy reductions instead of explicit implementation of efficiency standards, or a carbon price.

Table 2. Overview of NGFS scenarios by key assumptions. The table maps out key features of the scenario narrative and their macro-financial risk implications stemming from transition or physical risk. Green means "low risk", yellow means "medium risk", red means "high risk".

Category	Scenario	End of century (peak) warming	Policy reaction	Technology change	Carbon dioxide removal -	Regional policy variation +
Orderly	Low Demand	1.1°C (1.6°C)	Immediate and smooth	Fast change	Medium use	Medium Variation
	Net Zero 2050	1.4°C (1.7°C)	Immediate and smooth	Fast change	Medium-high use	Medium Variation
	Below 2°C	1.8°C (1.8°C)	Immediate and smooth	Moderate change	Medium use	Low variation
Disorderly	Delayed Transition	1.7°C (1.8°C)	Delayed	Slow/ Fast change	Low-medium use	High variation
Hot house world	Nationally Determined Contributions (NDCs)	2.3°C (2.3°C)	NDCs	Slow change	Low-medium use	Medium variation
	Current Policies	3.0°C (3.0°C)	None - current policies	Slow change	Low use	Low variation
Too-little-too-late	Fragmented World	2.4°C (2.4°C)	Delayed and Fragmented	Slow/ Fragmented change	Low-medium use	High variation

2.2 What is new in the NGFS scenario framework?

As in each iteration, the NGFS scenarios have been brought up to date with new economic and climate data, policy commitments and model versions. All NGFS scenarios have been updated to account for changes in the broad geopolitical and climate policy situation, including delays in government climate action and lock-in of fossil fuel technologies in many jurisdictions. Specifically, Phase V accounts for targets and pledged policies published by the UNFCCC until end of March 2024. This results in a total of 36 new sumbissions from multiple countries including Brazil, the EU, Azerbaijan, United Arab Emirates, Kazakhstan and Egypt. Updates have also been made to the use of Carbon Dioxide Removal (CDR) technologies, which has been limited compared to the Phase IV scenarios. Overall, all scenarios are mode disorderly in Phase V.

Phase V employs a new damage function to capture physical risk impacts on the economy. The damage function is based on the newly published paper of Kotz et al. (2024) "The economic commitment of climate change". The new damage function has been calibrated using the newest state-of-the-art climate datasets and models, relying on high granular climate and economic data from 1979 to 2019. The new damage function, contrarily to the previous one, considers other effects of climate change beyond increases in mean temperature. Included in the model are average annual temperature, daily temperature variability, total annual precipitation, number of wet days, and extreme daily rainfall. In addition, the new damage function captures lagged effects of climate shocks on economic output, indicating how the impact of climate shocks persists up to 10 years after their occurrence.

2.3 Shared model input assumptions

All scenarios share the same underlying assumption on key socio-economic drivers, such as harmonised population and economic developments, which are taken from the Shared Socioeconomic Pathway SSP2 (Dellink et al., 2017; Fricko et al., 2017; KC & Lutz, 2017; O'Neill et al., 2017; Riahi, van Vuuren, et al., 2017). The fifth vintage of the NGFS scenarios uses the updated version 3.0 of the SSP scenarios (https://data.ece.iiasa.ac.at/ssp/#/about).Thus, all NGFS scenarios are to a great extent aligned with the Middle of the Road Shared Socioeconomic Pathway, which is neither optimistic, nor very pessimistic.

Further drivers such as food and energy demand are also harmonised, though not at a precise level but in terms of general patterns.

The transition pathways do not incorporate the anticipation of potential future economic damages from physical risks (except for REMIND-MAgPIE scenarios with integrated damages). In other words, damages to infrastructure systems and the economy in the future, caused by emissions today, have no feedback mechanism that affects current choices. We provide acute and chronic physical damages for each scenario, but they are not incorporated in the transition models.

3. NGFS modelling approach

This section explains the modelling choices made by the NGFS, and describes the models used to generate the NGFS Scenarios.

Key messages

- To reflect the uncertainty inherent to modelling climate-related macroeconomic and financial risks, the NGFS scenarios use different models, and explore a wide range of scenarios across regions and sectors. This is called the NGFS suite-of-model approach.
- The NGFS suite-of-models is internally aligned in a coherent way and produces a range of data on transition risks, physical risks, and economic impacts.

The NGFS scenarios bring together a global, harmonised set of transition pathways, physical climate change impacts and economic indicators. They combine the analysis of transition, physical and macro-financial risks to shed light on the long-term trade-offs between the costs of climate mitigation and the consequences of unfettered climate change. They take a **long-term perspective**, which is necessary to assess the benefits of reduced physical risk over the next decades driven by effective climate policies: a scenario focussed on the next few years would, in fact, only capture the costs of climate action, while omitting the future but long-lasting benefits of meeting the Paris temperature targets – which is the very reason why climate action is needed.

Climate risks and their transmission channels

Climate risks could affect the economy and financial system through a range of different transmission channels. To understand the potential macroeconomic impacts of climate risks, we can distinguish between risks related to the transition to a lower-carbon economy (transition risks) and risks related to the physical impacts of climate change (physical risks), as shown in Figure 5.

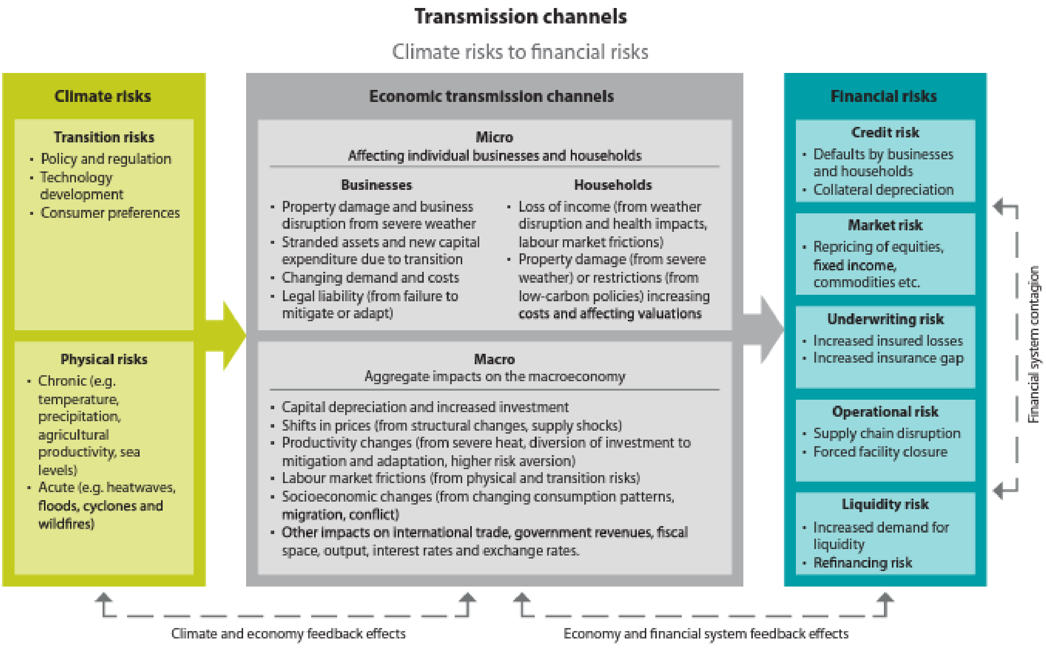


Figure 5. Transmission channels: climate risks to financial risks. Source: NGFS (2022)

- **Transition risks** affect the profitability of businesses and wealth of households, creating financial risks for lenders and investors. They also affect the broader economy through investment, productivity, and relative price channels, particularly if the transition leads to stranded assets.

- **Physical risks** affect the economy in two ways: **Acute impacts** from extreme weather events can lead to business disruption and damages to property. There is some evidence that with increased warming they could also lead to persistent longer-term impacts on the economy. These events can increase underwriting risks for insurers, possibly leading to lower insurance coverage in some regions, and impair asset values. **Chronic impacts**, particularly from increased temperatures, may affect labour, capital, land, and natural capital in specific areas. By affecting individual businesses, households and the broader macroeconomy, climate risks could translate into financial risks and affect the financial system.

Seven different academic institutions or initiatives joined forces under the aegis of the NGFS to ensure the overall consistency of the scenario framework while still relying on state-of-the-art and peer-reviewed academic literature. The NGFS therefore uses existing models, each of them being specialised and advanced in capturing one single part of the framework. This allows deep diving in the reactions of economic sectors to climate change and/or climate policies with a higher level of granularity, coverage, and precision than otherwise possible. The models chosen for the NGFS scenarios also inform the IPCC reports, thus ensuring a high level of consistency between the NGFS and the IPCC frameworks. Furthermore, this collaboration has facilitated dialogues across specialised institutions, that has allowed a cross-fertilisation of ideas and skills to improve existing methodologies and advance our understanding of climate scenarios further.

NGFS suite-of-model approach

The NGFS scenarios are based on a modular, suite-of-model approach to capture separately but consistently climate, macroeconomic, and financial contingencies. The models used to derive the NGFS scenarios can be classified into three broad categories:

- **Physical risk models** include all physical risk models that are participating in ISIMIP and CLIMADA and provide climate and economic indicators because of changes in climate.

- **Transition risk models** include three Integrated Assessment Models (IAMs), specifically **REMIND-MagPIE, GCAM** and **MESSAGEix-GLOBIOM**, that derive the impacts of different policy ambitions on the energy sector, emissions, and land use.

- The **macroeconomic model** consists of the **NiGEM model** (a version specifically modified for the purpose of producing the NGFS scenarios), to understand the consequences of transition and physical risk on key macro-financial fundamentals.

The transition pathways for the NGFS scenarios have been generated with these three well-established IAMs and linked to a macroeconomic model (NiGEM) to extend the macro-economic information. The IAMs have been used in a vast number of peer-reviewed scientific studies on climate change mitigation and their results feature in several assessment reports (Clarke et al., 2014; Forster et al., 2018; Jia et al., 2019; Rogelj, Shindell, et al., 2018; UNEP, 2018, IPCC 2022a). They allow the estimation of global and regional mitigation costs (Kriegler et al., 2013, 2014, 2015; Luderer et al., 2013; Riahi et al., 2015; Tavoni et al., 2013), the analysis of emissions pathways (Riahi, van Vuuren, et al., 2017; Rogelj, Popp, et al., 2018, Riahi et al., 2021), associated land use (Popp et al., 2017) and energy system transition characteristics (Bauer et al., 2017; GEA, 2012; Kriegler et al., 2014; McJeon et al., 2014), the quantification of investments required to transform the energy system (GEA, 2012; McCollum et al., 2018; Bertram et al., 2021) and the identification of synergies and trade-offs of sustainable development pathways (Bertram et al., 2018; TWI2050, 2018). In short, they optimize energy systems and land/water use in the face of long-run population and production trends. To shed light on the potential macroeconomic impacts, the IAMs have been linked to the macro-economic model NiGEM. Put simply, this mid-term global econometric model takes in energy-related and carbon tax inputs from the IAMs and generates macro-financial series such as inflation, unemployment, and house price index (HPI) that would be more typically used in financial modelling.

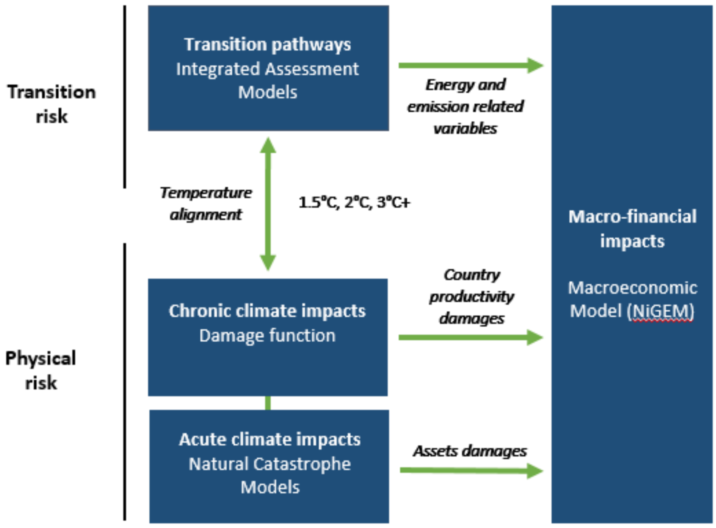


Figure 6. Interactions between the three model categories in the NGFS framework

The NGFS suite of models is aligned in a coherent way to produce results that are internally consistent. **Figure 6** illustrates the NGFS suite of models and how models interact with each other. Transition and physical risk models have been aligned in terms of temperature pathways, to ensure that both their impacts on the economy are consistent and comparable. The way transition and physical models are combined with the macro-financial model NiGEM is instead sequential. Energy- and emission-related variables produced by the three IAMs are used as input by NiGEM. Similarly, NiGEM obtains input variables from the physical risk models.

Explainer box 4

What are benefits and challenges of the NGFS suite of models?

The NGFS suite of models contrasts with the single model approach in that it builds on the strengths of each type of model, but at the same time there are challenges to be considered.

Main benefits

- **The strength of the NGFS suite of models is in their global coverage and integrated assessment of risks**. Where possible, multiple models have been used for each scenario and warming level to represent uncertainty.
- **Comparable outputs.** The three NGFS IAMs produce comparable outputs for energy and land-use series, although sometimes with varying methodologies, and can be equally interchanged when used downstream in NiGEM.
- **Flexibility.** Users can choose from comparable IAM outputs in macroeconomic models.
- **Openness.** Users can examine the sensitivity of using different methodological assumptions at the energy and land/water use system level on lower-level economic drivers, increasing transparency and robustness.

Main challenges

- **This modular approach makes sacrifices in terms of unity** (although there is a reconciliation process between common endogenous outputs).
- **While significant research advances have been made** recently, care should be taken in using the results, particularly at the most granular levels.

Modelling the macro-financial effects of climate scenarios is an exercise that sits in the nexus of two distinct fields 1) climate, energy, and land use, and 2) the macroeconomy. The first is usually modelled using an engineering approach since energy systems (and emissions) dynamics are determined by long-run investment in different vintages of technologies that convert resources into energy, such as coal-fired power plants or windmills, and are constrained by physical resource endowments inherent in each region due to factors such as geology or wind patterns. On the other hand, higher-frequency macroeconomic dynamics are typically modelled by understanding the relationship of purely economic series in history and are agnostic on energy mix or land/water use. Producing climate scenarios most useful for financial analysis would entail integrating these two contrasting frameworks' data and key methodological elements. Modelers can address this challenge by either designing a holistic model that can represent both long-term energy use and mid-term macroeconomic outcomes or utilize a modular approach by linking two separate frameworks. Both methods have their upsides and downsides to consider. While a modular approach gains in specificity, openness, and flexibility, it also sacrifices in consistency. A single unified model on the other hand may need to make sacrifices in terms of detail on certain, potentially key, subcomponents, but would find it easier to maintain conceptual soundness and overall consistency.

The NGFS scenarios take the modular approach as a starting point, following the trend in the energy systems field to tackle complexity by leveraging the individual strengths of a variety of models.[21] Indeed, the IAMs also follow this strategy, as they were developed to model phenomena that were studied in different disciplines. For example, within the IAMs, separate macroeconomic modules exist mainly to generate long-run aggregate energy and resource demand, with energy and land-use modules calculating the optimal structure of these systems to fulfil this demand and climate modules calculating the subsequent effects on temperature. Key inter-module interactions, such as price feedback, are modelled with hard links.

Utilizing the IAMs (GCAM, MESSAGEix-GLOBIOM, and REMIND-MAgPIE) for key energy, land/water use, and carbon tax series ensures these components are modelled most accurately, providing energy transition and other dynamics that have been used in hundreds of peer-reviewed scientific studies on climate change mitigation. On the other side, the modelling of the impact of these series on the macroeconomy with NiGEM, the leading global macroeconomic model, leverages its considerable strengths in this area as well. Both policymakers and private sector organizations across the globe rely on these models for economic forecasting, scenario building, and stress testing.

The modular approach also carries the benefit of flexibility, additionally leading to further transparency and robustness. If intermediate series are consistent in interpretation, models that interact with them can be switched in or out. A concrete example is in the presence of 3 options of IAMs to generate energy and land-use series. They all produce comparable outputs, although sometimes with varying methodologies, and can be equally interchanged when used downstream in NiGEM. This enables users to examine the sensitivity of using different methodological assumptions at the energy and land/water use system level on lower-level economic drivers, increasing transparency and robustness. In addition, users can directly use IAM outputs in macroeconomic models of their choice. This contrasts with a single model approach which would be more difficult to disentangle modularly.

While the outputs of the two modelling frameworks mostly do not intersect, with energy and land/water use on the IAM side and macro-financial variables from NiGEM, both sides of the framework do generate endogenous or semi-endogenous GDP estimates. IAMs' baseline GDP is exogenous and based on SSP2 variables. GDP then changes semi-endogenously due to transition costs in each scenario. To ensure consistency, NiGEM sets demand and supply-side shocks such that its baseline GDP matches the GDP target from the IAMs (GDP then deviates from baseline in each scenario). In addition to the above, each scenario also includes chronic physical risks shocks via demand and supply-side shocks (see **Figure 8**). Based on scenario temperature outcomes, GDP shocks for chronic physical risks are computed using a damage function, and subsequently fed as input to NiGEM.

[21] See https://papers.ssrn.com/sol3/papers.cfm?abstract_id=318680.

Explainer box 5

What are Integrated Assessment Models?

Integrated assessment models (IAMs) are simplified representations of complex physical and social systems, focusing on the interaction between economy, society, and the environment.

- **IAMs represent the coupled energy-economy-land-climate system to varying degrees.** In some ways, IAMs can differ from each other: there can be significant variation in geographical, sectoral, spatial and time resolution; they rely on different technological representation; they can use partial or general equilibrium assumptions; and they can assume perfect foresight or recursive-dynamic methodology. The difficulty in fully representing the extent of climate damages in monetary terms may be the most important and challenging limitation of IAMs.
- **IAMs integrate knowledge from two or more domains into a single framework**. They are one of the main tools for undertaking integrated assessments. The IAMs used by the NGFS include representations of multiple sectors of the economy, such as energy, land use and land-use change; interactions between sectors; the economy as a whole; associated GHG emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social, and technological development and the evolution of the climate system. Other types of IAMs additionally include representations of the costs associated with climate change impacts. These can be used to assess impacts and mitigation in a cost-benefit framework and have been used to estimate the social cost of carbon. The NGFS does not use such models and relies on other methods to compute the cost of transition and physical risks.

3.1 The NGFS IAMs – process-based modelling of the energy transition

Even though the NGFS IAM models were developed by different research groups, with each model having its own unique features, strengths, and limitations, they all have in common a similar modular structure and set of shared assumptions, with scenarios based on the widely used Shared Socio-economic Pathways (SSPs), and harmonized population and economic development trajectories. They combine macro-economic, agriculture and land-use, energy, water, and climate systems into common numerical frameworks that enable the analysis of the complex and non-linear dynamics in and between these components.

In contrast to simpler cost-benefit IAMs like Dynamic Integrated Climate-Economy models (DICE) and Regional Integrated Climate-Economy models (RICE), the IAMs used by the NGFS cover more systems with a finer granularity and process detail, which leads them to be referred to as process-based IAMs. For instance, they offer highly granular representations of the energy system, taking an engineering-style approach to modelling the conversion of raw natural resources into energy using various competing technologies. An overview of their high-level structure can be pictured in **Figure 8**.

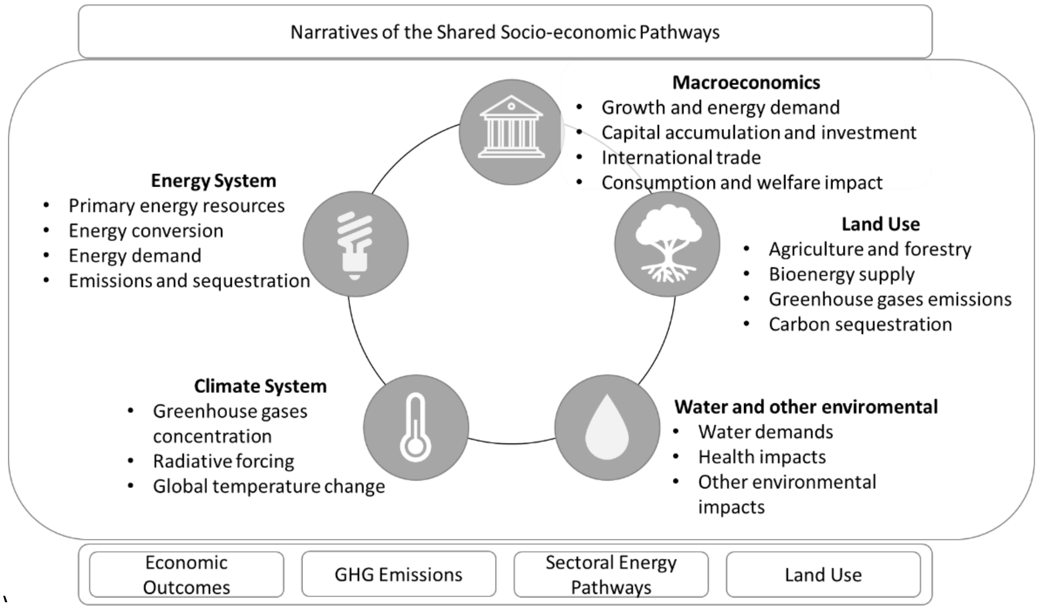


Figure 8. Simplified diagram of the elements that integrate the IAM models

As one of the key outputs from the IAMs is the energy transition path induced by a policy change, such as a carbon tax, we will outline the key modules used in all the IAMs to produce this output and highlight where differences occur. Since all the models produce a cost-minimizing or approximately cost-minimizing energy mix given demand derived in the macroeconomy, we trace through the system from the top down.

- **Macroeconomy:** This module provides assumptions or modelling of high-level GDP or population trends at the regional level. IAMs' baseline GDP is exogenous and based on SSP2 variables. GDP then changes semi-endogenously due to transition costs in each scenario. MESSAGEix and REMIND utilize Ramsey-type growth models where capital investment and energy are chosen to maximize intertemporal welfare given energy costs (model parameters are calibrated to match exogenous GDP). In contrast, GCAM GDP is set to an exogenous baseline and adjusts according to the labour force, population, and energy price changes.

    - **Sectoral energy demand** is determined by the level of economic activity in the macroeconomic modules which in turn, is determined within the macroeconomic optimization problem given energy costs (in REMIND), calibrated to exogenous baseline projections with endogenous deviations due to changes in energy costs (in MESSAGE and GCAM), or set according to exogenous projections (in GCAM). [22] When demand is endogenous, assumptions are made regarding substitutability of sectors in aggregate production using constant elasticity of substitution (CES) production functions. Sectors differ between models but include, at the very least, Buildings, Transport, Industry, and Agriculture/Land-use.

[22] MESSAGE can also determine energy demand fully endogenously using price feedback between the MACRO and MESSAGE modules (see MESSAGEix-GLOBIOM documentation, page 49). However, in Phase IV scenarios, energy demand is generated from exogenous material demand projections. Keeping energy demand endogenous allows for substitution between inputs.

- **Energy Systems.** In all three IAMs, these are represented in a separate module. Sectoral final energy demand is derived in the previous step and used here as an input. This module then calculates the lowest-cost method of supplying this energy. REMIND-MAgPIE features a feedback mechanism where this derived cost is fed back into the macro model to generate a new sectoral energy demand, iterating until convergence.

    - **Energy conversion technologies.** This is the process of converting raw resources (also known as *primary energy*) into *secondary energy*, such as electricity. Secondary energy is then subsequently also converted into *final energy.* All 3 IAMs model technological investment in vintages. Each vintage is associated with fixed costs associated with the initial investment, variable costs associated with the running of the investment, costs from early retirement, and depreciation from age. This feature introduces frictions that prevent instantaneous switching between technologies and represents capital stock inertia. MESSAGEix and REMIND explicitly model cost minimization between these technologies either using constant elasticity of substitution (CES) production functions in REMIND or linear substitution in MESSAGE. In contrast, GCAM models the discrete choice using logit functions. This means that even if the cost is unambiguously lower in one technology vs. the other, a certain share will mechanically remain with the less efficient technology depending on logit exponent.

    - **Raw energy supply curves.** This determines the cost of extracting raw resources both in the case of renewables as well as fossil fuel and other non-renewable resources. In each model, higher *grades* of resources reflect those that are easiest to exploit, such as land with high solar irradiance or easily accessible fossil fuel reserves. In the case of the models that linearly optimize energy cost at some level, REMIND and MESSAGEix, this introduces convexities that further prevent corner solutions in cost minimization, i.e., 100% adoption of the lowest cost technology.

Carbon prices are the primary channel for which transition scenarios are implemented in the IAMs, where, roughly speaking, the price is set such that the emissions constraints applied to the scenario are satisfied. This occurs through substitution effects, where the emissions price raises the cost of operating the given emitting technology. In REMIND-MAgPIE, MESSAGEix-GLOBIOM and GCAM this triggers an endogenous shift in investment in energy conversion technologies, with increased capacity for cheaper technologies and reduced usage and early retirement for more expensive technologies.

Water and land-use systems such as GLOBIOM in MESSAGEix, MAgPIE in REMIND, and integrated modules in GCAM operate parallel to the core energy and economic modules, optimizing agriculture, forestry, and other land use (AFOLU) in concert with policy changes. For example, greater production and population demands would negatively impact forest cover, reducing carbon uptake in forests and changing the supply of biomass for bioenergy and lumber. This, in turn, affects emissions and estimates of the carbon price for any given scenario.

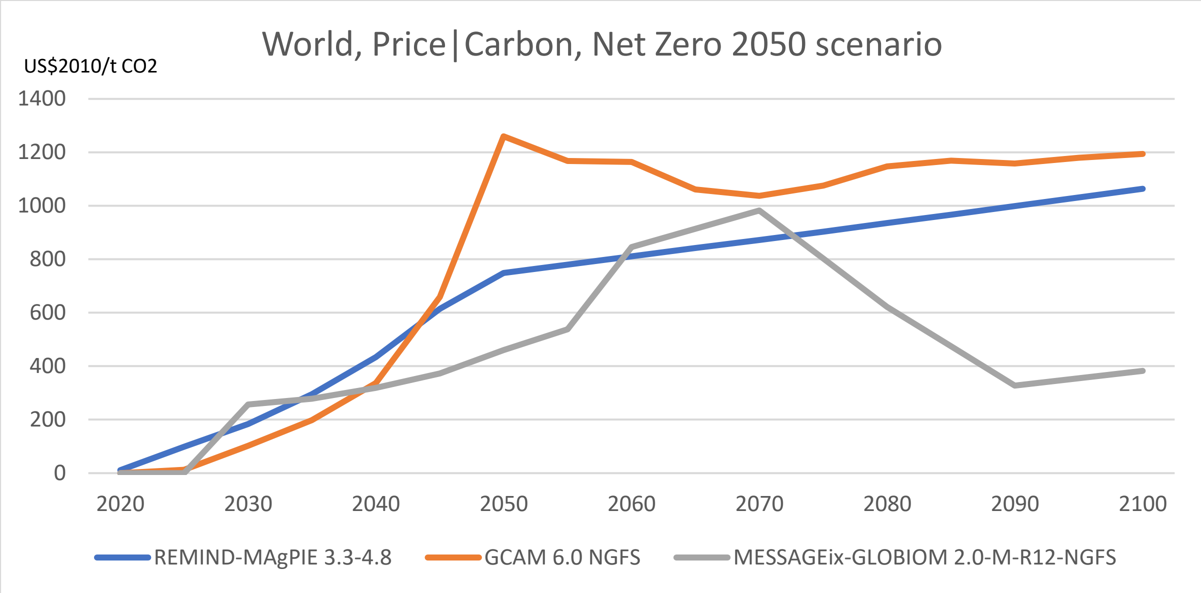


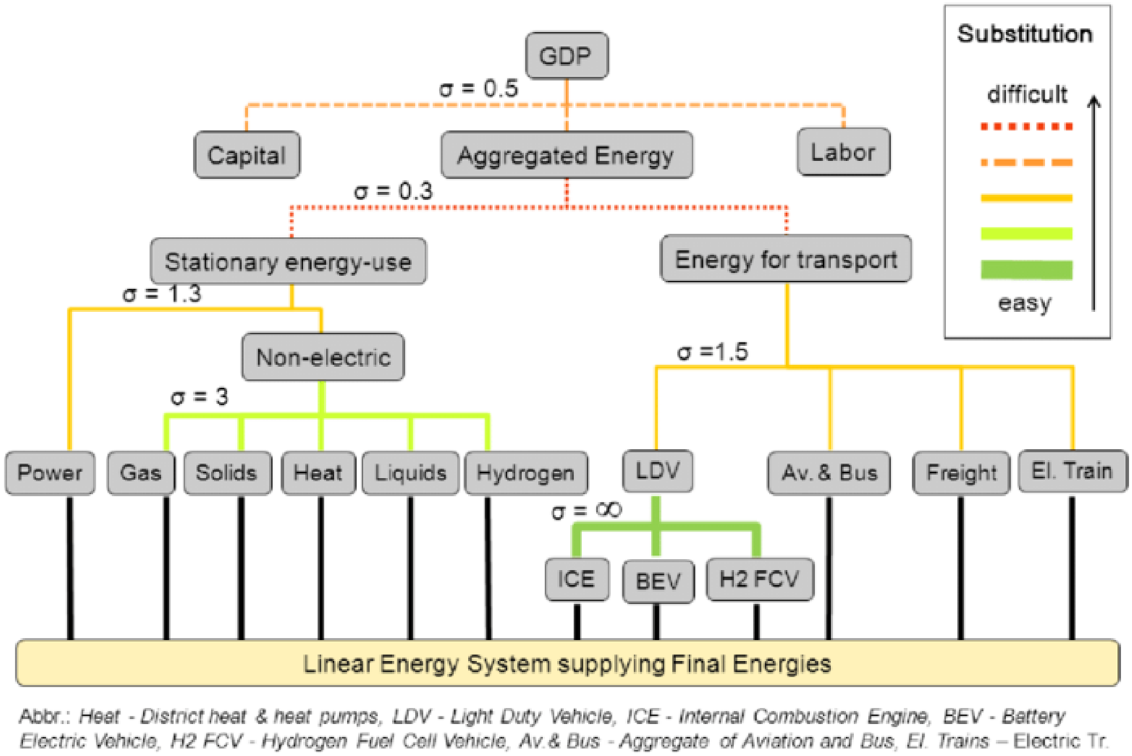
Figure 9: Carbon price IAM comparison in Net Zero Scenario.

A visualization of the derived carbon tax trajectories for the Net Zero 2050 scenario is shown in **Figure 9**, with REMIND and GCAM broadly consistent in initial years and MESSAGEix diverging on the entire path. The MESSAGE price path here is strongly determined by the peak-warming/net-zero definition of the scenarios. The prices increase strongly until net-zero CO_2 emissions are reached, after which the emissions remain stable at net-zero, which happens at lower costs. The following section identifies the most critical shared drivers in determining how each IAM would model this transition.

3.2 The NGFS IAMs – key dynamics driving an energy transition

Each model has different effective substitutability of energy sources, which is crucial in determining the speed of energy transition and carbon prices for each scenario. This is both due to explicit assumptions and differing structure.

For instance, MESSAGEix and REMIND determine energy technology through **optimization using constant elasticity of substitution (CES) production functions**. The CES parameters of this function, as well as the nesting structure of the CES goods, determine the substitutability of the energy sources. For example, REMIND assumes perfect substitution at the lowest level of energy good, such as power, following the intuition that electrons from fossil fuel or renewables are indistinguishable in their ability to fulfil electricity demand and similar for liquids, gases, and others. However, this energy demand is still segmented by sector. So, power to the transport sector cannot be substituted for power to stationary energy-use sectors, as seen in **Figure 10**. Conversely, imperfect substitution is only explicitly modelled at the sectoral energy demand level in MESSAGE. Instead, more detailed process-based modelling of frictions at the lower level drives imperfect substitution of energy sources.



Production structure of REMIND. Linear production functions describe the conversion of primary energy (lowest level) to final energy carriers. Nested CES structures describe the aggregation of final energy carriers for end-use.

Figure 10: REMIND production structure. σ refers to the CES substitution parameter.

In contrast, GCAM uses a vintage capital model of capital investment and utilization. Existing vintages are assumed to operate throughout their useful life as long as the vintage is able to cover its operating costs. Costs include energy and other operating costs such as labor, water and new investments compete based on expected levelized cost of production. The distribution of investments into new capital is modelled using a **discrete choice logit model** that determines the share of new investment based on expected cost. Technologies with the lowest expected cost of production receive the largest share of the portfolio, with more expensive technology options garnering a smaller share of the portfolio, with the size of this portion depending on an exogenously set exponent parameter. In this framework, this parameter explicitly controls substitution between technologies, although other factors would also modify this implicitly. The scale of investment in the new vintage is set by the expected need for new capacity, which in turn is determined by difference between expected demand for the sector's output and capacity available from existing vintages of capital. For example, see **Figure 11** for an illustration of hydrogen transmission, distribution, and end-use.

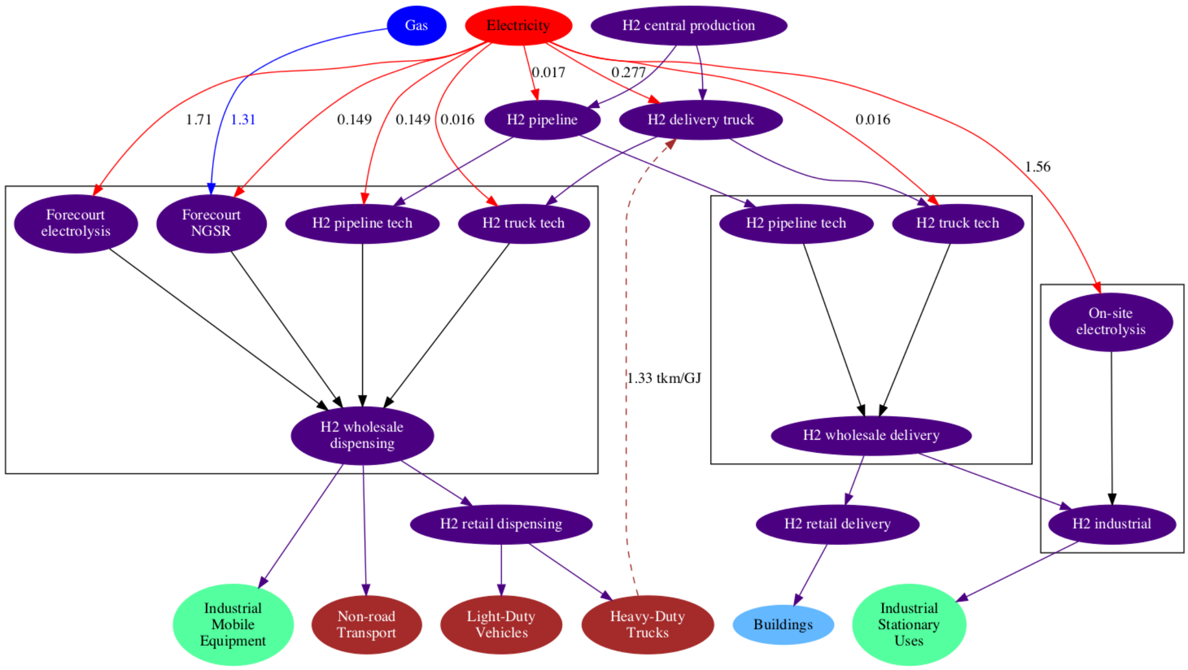


Figure 11: GCAM hydrogen technology nesting structure, including approximate energy requirements at each stage.

Even with full substitutability assumed for an energy input, several frictions at the lower level in the IAMs would continue to impede instantaneous switching to the lower-cost option. The first is associated with the **vintage-style modelling** of energy conversion technologies. This feature represents the inertia in the energy system due to its long-lived capital stock. It includes both fixed costs in installing new capacity and hard constraints on the early retirement of old capacity. The second is the presence of **convex resource supply curves**, representing the increasing marginal costs of extracting resources as quantity increases. For example, using larger quantities of specific resources, such as coal, would entail mining in more difficult-to-access regions, represented as *grades*. These energy resource endowment curves are derived from the bottom up, using sources such as the US Geological Survey and various energy institutes and agencies. An example of oil in MESSAGE is given in **Figure 12**.

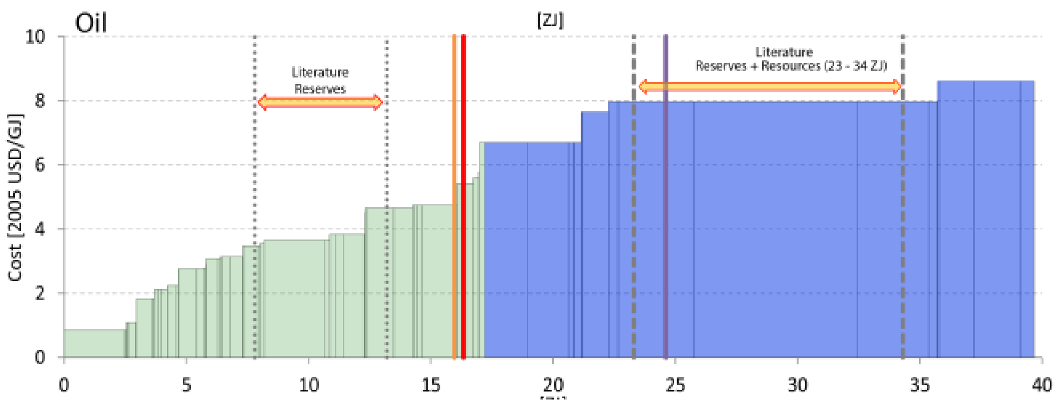


Figure 12: Oil resource endowment curve, MESSAGE.

A final component essential for the determination of endogenous energy mix is **technological change and diffusion**. In REMIND, this is partly endogenous through a model of "learning-by-doing," with global learning curves and internalized spillovers for wind and solar power, and advanced vehicle and energy storage technology. This causes capital costs to decrease while cumulated capacity increases. In MESSAGE, there is a modelling of technology diffusion that produces a similar effect, with dynamic constraints that relate the construction of a technology added in period *t* to the construction or activity in period *t-1*. In all models, exogenous paths for cost and efficiency parameters in each scenario follow assumptions implied by the SSPs.

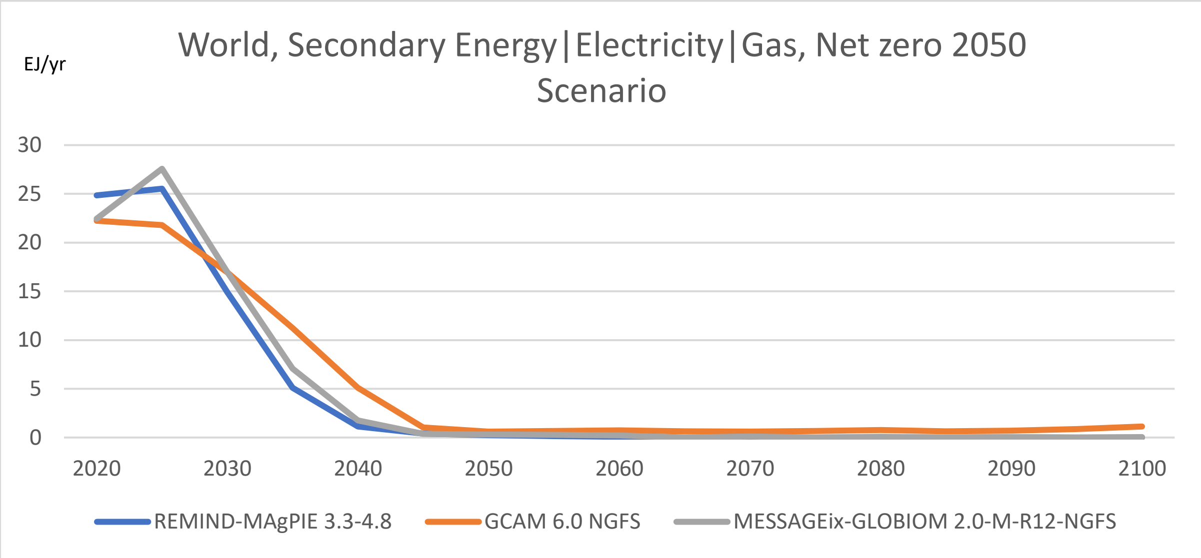


Figure 13: Gas-powered electricity production, net zero scenario.

Other mechanisms that would affect transition dynamics between the IAMs include negative emissions technologies like carbon capture and storage (CCS), which is incorporated in differing sectors depending on the IAM. As expected, the CCS option allows for a certain amount of fossil fuels to be burned even in a net zero scenario. For example, the prominence of CCS in MESSAGEix explains the high level of gas-powered electricity production in the net zero scenario shown in **Figure 13** (in combination with high energy demand and the role of gas power plants to balance the load of variable renewables). Generally, though, it is typically represented as a costly option. Other negative emissions technologies typically go through the land-use modules, including soil carbon management, direct ocean capture, and forest restoration. However, IAMs vary in which technologies they include.

In addition, there are various other ways through which energy technologies materially affect transition speed. For example, two IAMs model the intermittency and lack of flexibility inherent in some energy sources, particularly wind and solar, and require additional investment in energy storage capacity to bridge the gap. This is parametrized as a reliability factor in MESSAGE, while GCAM models the costs of intermittent and non-intermittent conversion technologies separately.

Emissions are calculated in separate modules and are typically a function of sectoral energy usage, technology choice and emissions mitigation, interacting with the land/water-use modules. This includes emissions from power generation, limestone production in cement, steel production, and other industrial CO_2 production. In all IAMs, these are then fed into separate climate modules that represent the global carbon cycle and atmospheric chemistry and produce estimates of atmospheric composition, radiative forcing, and mean global surface temperature. MAGICC performs the endogenous climate modelling in MESSAGEix-GLOBIOM and REMIND. HECTOR produces the endogenous estimates in GCAM. The IAMs also model other pollutants to some extent, such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3). The NGFS scenario database includes harmonized climate modelling results for all three models from the latest version of MAGICC (see **Box: MAGICC: A reduced complexity Earth system model)**

Table 4. Key model characteristics.

	REMIND-MAgPIE 3.3-4.8	MESSAGEix-GLOBIOM 1.1-M-R12	GCAM 6.0
Hosting Institution	PIK	IIASA	PNNL
Economic Equilibrium	Computable general equilibrium (CGE)	CGE	Partial equilibrium (PE)
Agriculture Sector Modelling	PE with recursive dynamic	CGE with intertemporal optimization	PE with recursive dynamic
Solution method	Inter-temporal optimization	Inter-temporal optimization	Recursive dynamic
Energy technology diffusion	Modelling of supply energy based on cost optimization	Modelling of supply energy based on cost optimization	Modelling considering choice function (cost plus penalty cost due to inconvenience)
Cross sectors	Primary energy supply, transformation, manufacturing, and end uses, including residential, commercial, transport, construction, agriculture, and forestry		
Model specific (singular) sectors			
Transport	Road, rail, air, and sea; breakdown by freight and passenger and type of vehicle	Aggregated	Road, rail, air, and sea; breakdown by freight and passenger and type of vehicle
Buildings	Residential and commercial floor space	Aggregated	Residential floor space and commercial floor space determine scale of demands for building services (e.g. heating, cooling, cooking)
Industry	Cement, chemicals and steel	Cement, chemicals (high value chemicals) non-ferrous metal and steel	Cement, chemicals (ammonia) non-ferrous metal and steel; breakdown by technology investment and type of fuel
Regions	12	12	32
Technological change	Endogenous	Exogenous	Exogenous
Behavioural change	No (only in Low Demand)	Yes	No (only in Low Demand)
Number of policy instruments	9	7	14
Demand side mitigation options	15	16	14

Supply side mitigation options	17	20	18
AFOLU options	7	8	8
Freight electrification	No	No	Yes
Technology substitution	high substitutability with increment cost	High substitutability with increment cost	Mixed high and low substitutability with growth constraints
Technology lifetime	Fixed lifetime and early retirement	Fixed lifetime and early retirement	Fixed lifetime and early retirement
CCS Technologies	Included in electricity technologies, bioenergy with CCS, afforestation, direct air capture and enhanced weathering	Included in electricity technologies, bioenergy with CCS, reforestation and afforestation	Included in electricity, refining, hydrogen production, and manufacturing technologies, bioenergy with CCS, reforestation and afforestation

One notable difference in approaches is in the level of foresight. As mentioned previously, GCAM assumes that investors have myopic foresight and assume that current prices, including for example, the price of carbon, will persist throughout the future life of the investment. Hence, costs for capacity installation are assumed to be relative to current prices and not expected future prices. In contrast, REMIND and MESSAGEix assume perfect foresight in that the full path of the carbon price is known to agents while investing. Ceteris paribus, one could expect a sharper reaction to a net zero announcement in the perfect foresight case. However, this is not immediately clear when looking at a between-IAM comparison due to other model differences.

In addition, the solution method differs between the IAMs, with MESSAGEix and REMIND being general equilibrium models. One of the consequences is that carbon revenues can be recycled back into the economy for MESSAGEix and REMIND, increasing production, while this is not feasible in GCAM. On the other hand, GCAM, clears all energy, agriculture, land, and water markets, but does not model other markets explicitly. However, GCAM is able to model over twice the number of regions and several more key sectors.

For a summary of high-level differences between the IAMs, see **Table 4**.

3.3 The NGFS IAMs – implications of differences and similarities.

While the previous section illustrates some of the key structural differences between IAMs, the conceptual underpinnings and goals of the models are broadly aligned. Indeed, most variables have an estimate from each IAM, with differences confined to small variations in sectoral and regional granularity. This means that variability observed between models can safely be interpreted as a measure of confidence. This is especially useful as the models otherwise are deterministic and do not have a concept of uncertainty. In addition, as time horizons are in the distant future, there is no possibility of direct validation. Hence, sensitivity and robustness analyses are even more central to ensuring model trust.

Suppose a model like MESSAGE, which relies strongly on low-level process-based modelling, agrees on a variable with a model like REMIND, which relies more on a nested CES structure. The convergence of these two methodologies would provide additional assurance on robustness for downstream users. On the other hand, if they disagree, one can pinpoint the methodological divergence that causes the difference, providing insights into potential areas of uncertainty.[23] A straightforward example is related to the CCS cost differences between models, which causes significant differences in fossil fuel electricity production in the net zero scenario. However, on many of the most critical metrics, the IAMs are closely aligned – **Figure 14** shows an overview for many of the main energy series.

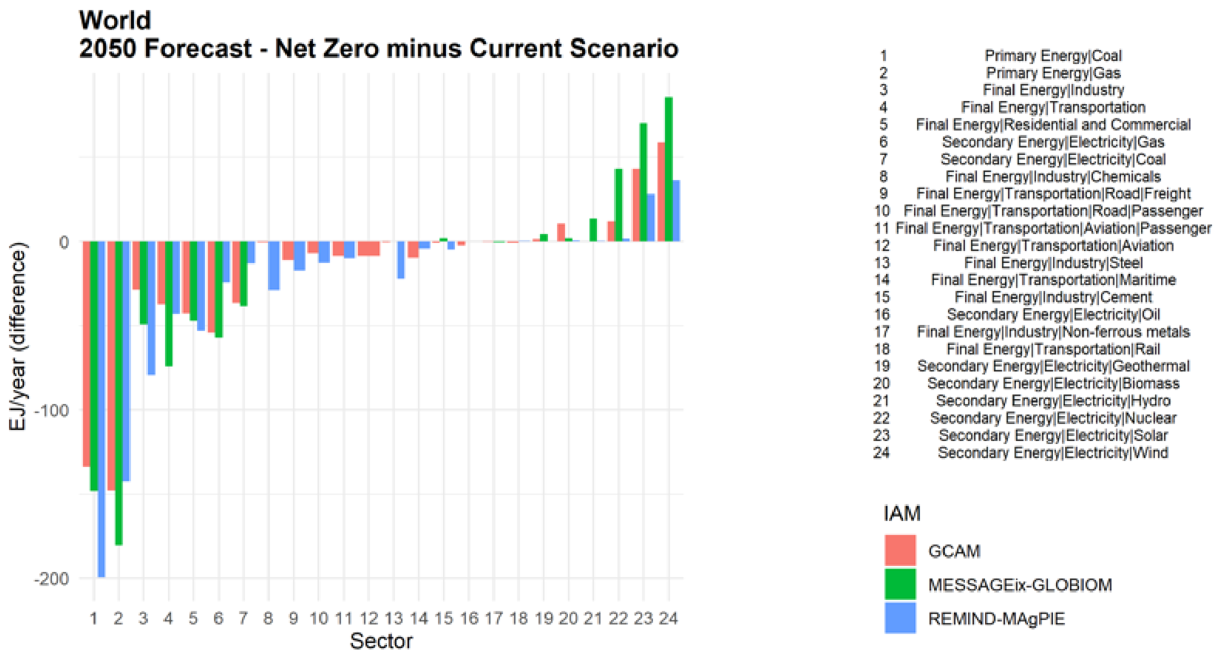


Figure 14 Energy series dynamics comparison between the IAMs. Metric shown is the absolute difference between the net zero and current scenario for the year 2050.

A final benefit to the suite-of-model method lies in the differing granularity of the estimates. By necessity, models with more complicated estimation routines must make trade-offs in terms of granularity. On one end, GCAM estimates significantly more regions and sectors while maintaining broadly consistent dynamics with the other IAMs. Conversely, MESSAGEix-GLOBIOM has a less granular representation of sectors and regions but is grounded in sophisticated process-based modelling at the low-level and conceptually sound macroeconomic modelling at the high level. REMIND-MAgPIE provides a middle ground in sectoral representation, highly reliant on a CES nesting structure, with a geographic representation like MESSAGE, but leveraging a partial equilibrium approach to interact with the agricultural module. This wide range of approaches leads to different coverage and provides a flexible menu of options for various potential use cases. However, this flexibility increases the importance that users deep-dive into the methodology of each model to understand which provides the best fitness for purpose for their specific area of analysis.

[23] Multi model analysis for climate and integrated assessment models is a common approach in the literature. See https://iopscience.iop.org/article/10.1088/1748-9326/aaf8f9/meta. This is also the approach taken for the climate models prepared for the IPCC, which resulted in the Coupled Model Intercomparison Project, currently in its sixth phase (CMIP6).

Box: MAGICC: A reduced complexity Earth system model

What is the MAGICC model?

MAGICC is a reduced complexity Earth system model that has been widely used in climate science for over three decades, most notably in multiple IPCC reports. It is most often used in a probabilistic setup, providing information not only about our best estimate of future climate change but also the uncertainty that arises from interactions between the Earth system's many components.

- MAGICC is used for evaluating the impacts of greenhouse gas emissions on global climate change. It combines climate science, atmospheric chemistry, and radiative forcing calculations to estimate the relationship between greenhouse gas emissions and changes in temperature, as well as other related climate variables under different emissions scenarios.
- MAGICC is also used as the climate component in multiple integrated assessment models (IAMs), including REMIND and MESSAGE[24]. The strength of MAGICC is that it is sufficiently flexible to closely emulate the large and complex climate models and sufficiently physically based to allow credible interpolations and indicative extrapolation near the calibration range.
- The key outputs of the climate model include climate feedbacks which are processes that amplify or dampen the initial response to greenhouse gas emissions, radiative forcing caused by greenhouse gases, aerosols, and other factors, and climate sensitivity, a crucial parameter in estimating the temperature response to greenhouse gas emissions.
- For the NGFS scenarios, MAGICC 7.5.3 is applied in a probabilistic setup as used in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC WG3 2022; Kikstra et al. 2022). This ensures comparability of the NGFS scenario climate outcomes with the latest IPCC report and assessment.

What are the key model inputs?

MAGICC's key input are anthropogenic emissions that impact the climate system, primarily greenhouse gases but also aerosol precursors and emissions that influence other gas cycles such as carbon monoxide. Based on these inputs, MAGICC provides projections of a number of key quantities, including atmospheric greenhouse gas concentrations, effective radiative forcing for different species, temperature change, Earth system heat uptake and sea-level rise. Global-mean quantities are the key output, but outputs at the hemispheric level can also be used in more specialized applications.

[24] See post-processing sections under the IAM chapters in Module 5: Chronic physical risks

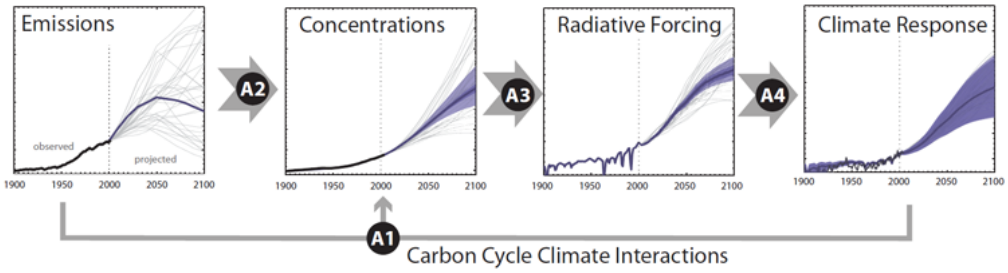


Figure 15. Schematic overview of MAGICC calculations showing the key steps from emissions to global and hemispheric climate responses.

MAGICC represents the Earth with four boxes: one for land and one for the ocean, in each hemisphere. The ocean component is an upwelling-diffusion model with multiple layers. The atmospheric component is based on the energy balance equation, modified to support MAGICC's four box structure. In addition to its core energy balance components, MAGICC includes models of the carbon cycle, methane cycle, impact of anthropogenic aerosol emissions and sea-level rise.

MAGICC's development is led by Prof. Malte Meinshausen at the University of Melbourne. A full description of MAGICC can be found in Meinshausen et al. (2011), with updates as described in Meinshausen et al. (2020) and Nicholls et al. (2021).

In Phase V, sulfur emissions have been harmonized in the benchmark year based on the latest 2024 CEDS (Community Emissions Data System) data. We switched off the harmonisation procedure for CO_2 emissions, leading to an improved fit between IAM results and climate outcomes. Two options are available for the harmonization of CO_2 emissions in the benchmark year using the latest 2024 CEDS data and its previous version.

3.4 Physical risk modelling approach

Physical risk modelling is split between chronic and acute risk. Chronic risk macro-economic impacts are calculated with a new damage function developed by Kotz et al. (2024) used to quantify the effect of a change in climate-related variables (temperature) on economic output. This approach has several advantages, including its easy implementation for a large range of countries, but it is still an area of research and most likely does not capture the full extent of climate change yet. The new damage function has been calibrated using the newest state-of-the-art climate datasets and models. Both climate data and economic data were used on a highly granular (sub-national) level for a period spanning between 1979 and 2019. In contrast to the previous damage function, the new one encompasses the effects of climate change extending beyond increases in mean temperature. The variables included in the model are average annual temperature, daily temperature variability, total annual precipitation, number of wet days, and extreme daily rainfall.

The third and potentially most important novelty of the new damage function is the inclusion of lagged effects of climate shocks on economic output. As such, this damage function captures the impact of climate shocks up to 10 years after the occurrence.

Acute risk is modelled instead focusing on specific climate risks, or hazards, and their potential increase for a given temperature pathway. This approach captures better countries idiosyncrasies and allows to better identify the channel through which climate risk might affect the economy. Probabilities of damages are estimated on the basis of various data sources (mentioned in the dedicated section) and macroeconomic impacts estimated via stochastic simulations (to also control for the uncertainty surrounding the estimates) in NiGEM on the basis of the relevant transmission channels. However, challenges are posed by the lack of reliable and complete datasets and improvements in modelling should be matched by an increasing effort in collecting data and observation.

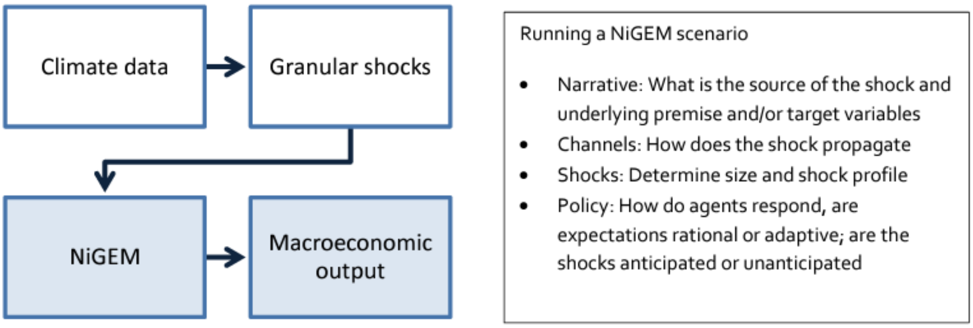


Figure 17. Implementation of climate shock in the NiGEM macreconomic model

Up until now, the NGFS considered the impacts from chronic and acute physical risk additively. With the implementation of the new damage function, there appears to be a higher risk of double counting if chronic and acute physical risks are summed. This is mainly driven by the correlation of additional climate variables with extreme weather events and by the higher overall loss projections displayed by the new damage function from Kotz et al. (2024). Therefore, the NGFS recommends to not perceive total physical risk as the simple sum of chronic and acute risks, but acknowledges that they can still have complementary uses in specific use cases. See the document ‘Damage functions in NGFS scenarios - an explanatory note’ for more details.

Module 2: IAM – REMIND-MAgPIE

1. Non-technical summary

What is the REMIND-MAgPIE model?

REMIND and **MAgPIE** are two models developed at the Potsdam Institute for Climate Impact Research (PIK) that were created over a decade ago (Leimbach *et al*., 2010a; Lotze-Campen *et al*., 2008) and are continually being improved to provide up-to-date scientific evidence.

REMIND (REgional Model of INvestment and Development) is a numerical model that generates projections for the future evolution of the world economies with a special focus on the development of the energy sector and the implications for our world climate. The goal of REMIND is to find the optimal mix of investments in the economy and the energy sectors of each of the 12 model regions given a set of population, technology, policy, and climate constraints. It also accounts for regional trade characteristics on goods, energy fuels, and emissions allowances. The most relevant greenhouse gas emissions due to human activities are represented in the model.

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global land use allocation model, which is in turn connected to the grid-based dynamic vegetation model LPJmL (Lund-Potsdam-Jena managed Land) to simulate the interactions between the land surface and the atmosphere as well as the impact of human activities on the environment. As a partial equilibrium model, the objective function of MAgPIE is the fulfilment of agricultural demand for each region at minimum global costs under consideration of biophysical and socioeconomic constraints. The MAgPIE results are consolidated to the 12 REMIND regions through a process called spatial aggregation or regional harmonization. This process involves grouping or merging the individual regions into larger and more manageable units for analysis and modelling purposes. The specific method of consolidation can vary depending on the specific requirements of the modelling framework and the research objectives. Common approaches include geographical proximity, economic similarities, administrative boundaries, and model requirements.

REMIND-MAgPIE aims to help policy and other decision makers to plan ahead by understanding the roles, synergies and trade-offs between various factors, including population, resources, technologies, policies and the environment. Using REMIND-MAgPIE, research and policy-relevant questions related to sustainability can be explored: Which technologies should we use in the future? What is the impact of policy proposals that are meant to prevent (mitigate) climate change? What are the consequences on economic development, air pollution, and land use? For some questions, REMIND is used in connection with other models to allow the analysis of other environmental impacts such as water demand, air pollution, health effects and climate impacts. (see four main components of the REMIND-MAgPIE framework in **Figure 42**). One such model is **MAGICC** (Model for the Assessment of Greenhouse Gas Induced Climate Change). This is a climate model, which accounts for changes in climate-related variables like global surface mean temperature. The linkage to MAGICC analyses the complex interactions between agriculture, land-use, greenhouse gas emissions, and climate change. More details on MAGICC are provided in a dedicated box (Module 1).

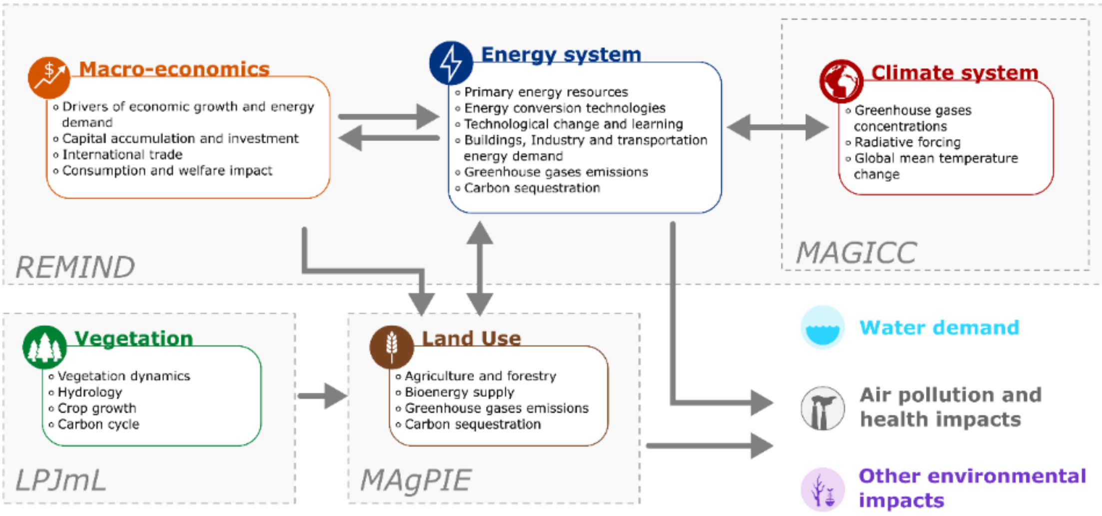


Figure 42. Overview of REMIND-MAgPIE framework

REMIND-MAgPIE is well equipped to capture the interactions between the energy transformation in response to climate policies and economic development. Full macroeconomic integration is particularly valuable for the assessment of effects of climate policies on the scarcity of energy carriers, demand response, structural changes, investments, macroeconomic costs, and their regional distribution. Changing crucial parameters in REMIND (such as the climate target or the availability of technologies or resources) can have significant impact on GHG prices and bioenergy demand. Therefore, we run REMIND and MAgPIE in an iterative soft-coupled mode, where REMIND updates MAgPIE's assumptions regarding bioenergy demand and GHG prices, and MAgPIE, in turn, updates REMIND's assumptions regarding bioenergy prices and land-use emissions and agricultural production costs. The iteration is continued until changes between iterations become negligible. The resulting scenarios are consistent regarding the price and quantity of bioenergy and GHG emissions.

The central strength of REMIND with its perfect foresight is its ability to calculate first-best mitigation strategies that provide benchmark development scenarios with detailed representation of the key dynamics related to the scale up of novel technologies and integration constraints in the power sector. These benchmark scenarios allow for comparison with mitigation scenarios under second-best policy settings (regional or sectoral fragmentation) or technology constraints. Within some numerical restrictions, the flexible spatial resolution of REMIND enables the exploration of transformation pathways of the energy-economic system for specific countries or global regions.

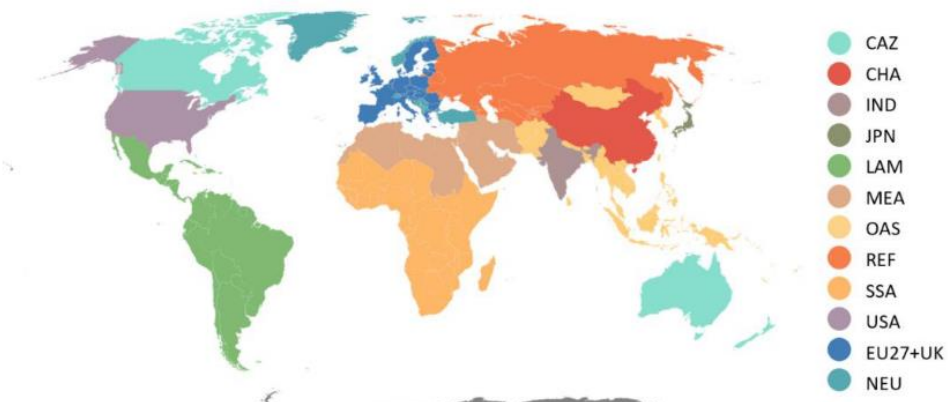


Figure 43. Regions in REMIND

What are the key model inputs?

Key model inputs are the available historical data, for example population, GDP, fossil resources, energy use, emissions, land-use and vegetation patterns, capital stocks, and investments. They come from both international organisations (World Bank, OECD, UN, IEA, ...) and the academic literature. Additionally, projections for future development are used, such as UN population projections, short-term IMF or World Bank GDP projections, long-run projections on technological parameters and prices, again drawing on academic literature. These datasets are used to calibrate the model to determine key model parameters.

What are the key model outputs?

The output of these models (with a given set of population, technology, policy and climate constraints) can help policymakers and other relevant stakeholders evaluate the effectiveness and efficiency of different policy interventions and identify optimal pathways for achieving sustainable development goals. It also accounts for regional trade characteristics on goods, energy fuels, and emissions allowances and all greenhouse gas emissions due to human activities.

What is new in the 2024 edition?

The REMIND-MAgPIE version 3.3-4.8 contains new datasets from UNFCCC, IEA WEO, UBA, IRENA, EDGAR7 and EEA to improve the quality of the calibration. GDP and Population projections were updated based on the SSP scenarios. The policy database for NDC and Net Zero targets was updated. Compared to Phase 4, the flexibility of the model to adapt its 2025 value was further reduced. A new industry implementation that keeps track of feedstocks was used. To reflect the energy crisis, import restrictions on fossil gas in Europe remain were implemented. We use a newly implemented damage function based on Kotz et al. (2024).

2. Overview of model scope and methods

REMIND[25] is a modular multiregional general equilibrium model linking a macro-economic growth model with a bottom-up engineering-based energy system model. It uses non-linear optimization to derive welfare-optimal regional transformation pathways of the energy-economic system subject to climate and sustainability constraints for the time horizon from 2005 to 2100. REMIND operates at a time resolution of 5 years until 2060, and 10 years thereafter to derive long-term projections. Using different scenario analysis techniques which cover a wide array of factors, simulations can explore a range of possible futures. The resulting solution corresponds to the decentralized market outcome under the assumptions of perfect foresight of economic agents. In the integrated damage runs, external effects from climate damages are internalized into the optimization function.

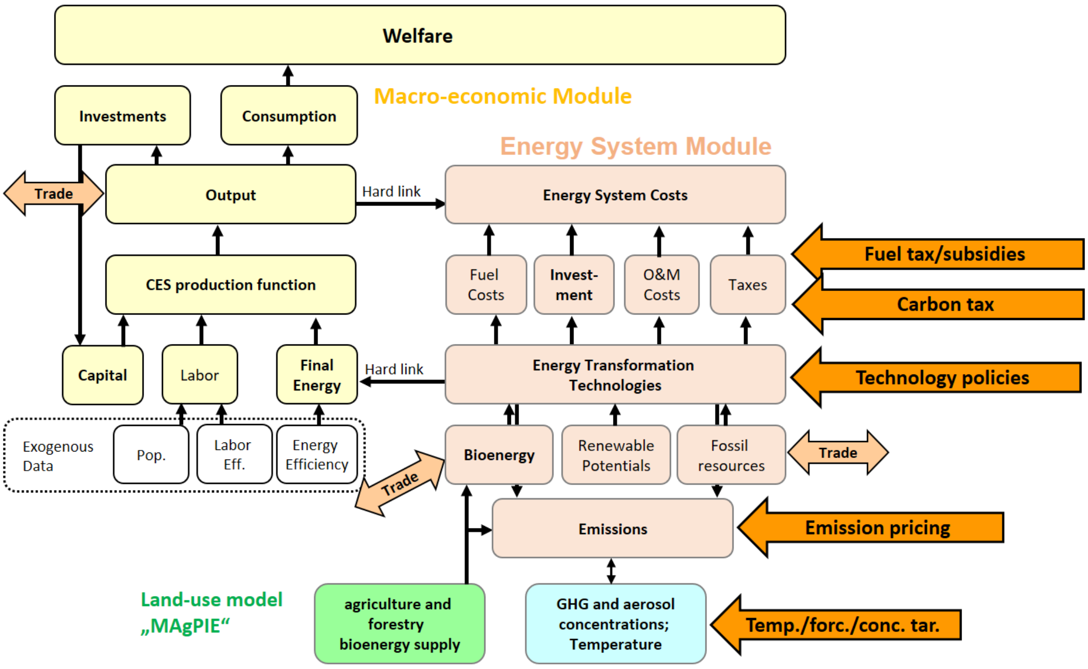


Figure 44: Structure of REMIND model

A Ramsey-type[26] growth model with perfect foresight serves as a macro-economic core projecting growth, savings and investments, factor incomes, energy, and material demand. The macroeconomic production factors are capital, labour, and final energy. A nested production function with constant elasticity of substitution (CES) determines the final energy demand. REMIND uses economic output for investments in the macro-economic capital stock as well as for consumption, trade, and energy system expenditures.

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25 Phase V NGFS scenarios have used version 3.3 of REMIND. The last release of the model is available at https://github.com/remindmodel/remind and https://zenodo.org/records/12104410. The REMIND Documentation is available at: https://rse.pik-potsdam.de/doc/remind/3.2.0/.

26 In the Ramsey growth model, the investment share of economic output is determined endogenously to maximize inter-temporal welfare. See Barro and Sala-i-Martin (2004) for an overview of these models.

The energy system representation differentiates between a variety of fossil, biogenic, nuclear, and renewable energy resources. More than 50 technologies are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy.

The macroeconomic core and the energy system part are hard linked via final or useful energy demand (input to the economy) and the costs incurred by the energy system (output of the economic part). Economic activity results in demand for energy in different sectors (transport, industry, and building sectors) and of different types (electric and non-electric). See **Figure 44**.

The model accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as adjustment costs for rapidly expanding technologies.

Tax revenues are redistributed as a lump sum; thus, net taxes converge to zero in the optimal solution. REMIND considers the trade of coal, gas, oil, biomass, uranium, the composite good (aggregated output of the macroeconomic system)... It assumes that renewable energy sources (other than biomass) and secondary energy carriers are non-tradable across regions.

The emissions of greenhouse gases (GHGs) and air pollutants are largely represented by source and linked to activities in the energy-economic system. Several energy sector policies are represented explicitly, including energy-sector fuel taxes and consumer subsidies. The model also represents trade in energy resources.

2.1 Macro-Economic Module

The macroeconomic core of REMIND (Leimbach *et al*., 2010b, a; Bauer *et al*., 2012b; Luderer *et al*., 2012) features a multiregional general equilibrium representation of the Ramsey growth model (i.e., the investment share of economic output is determined endogenously to maximize intertemporal welfare). This approach is well suited for describing patterns of long-term economic growth (Barro and Sala-i-Martin, 2004), which are key drivers of energy demand and, thus, emissions.

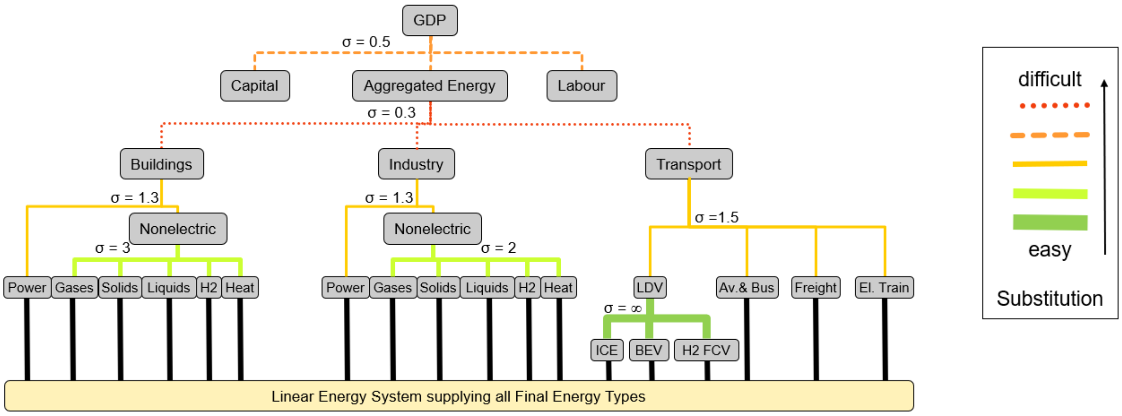
Physical capital is a major driver of economic growth, and related investments are endogenous in such models. In each period, the representative agent, endowed with perfect foresight, has to make the choice of using output for consumption or for investment, which can be used to produce consumption goods tomorrow. Perfect foresight is a standard assumption in economic models and widely used in IAMs (e.g., DICE/RICE, Nordhaus and Yang, 1996; MERGE, Manne *et al*., 1995; MESSAGE, Fricko *et al*., 2017; WITCH, Bosetti *et al*., 2007). While in the real-world agents rarely have perfect foresight, using this concept is a useful approximation in a context of models with long planning horizons. When using the perfect foresight assumption to formulate an intertemporal optimization problem, the model is completed by components (technically: side constraints) that help to reproduce real-world dynamics caused by imperfectly foresighted decision-making (e.g., adjustment costs for the increase of the macroeconomic capital stock). In REMIND, each region maximizes its welfare subject to a budget constraint.

The model explicitly represents trade in final composite good, primary energy carriers, and, if certain climate policies are enabled, emissions allowances. Thus, equilibrium refers to the balance in goods markets and international trade, such as the global oil market. It is a valid assumption for the decadal timescales considered in scenarios and, thus, does not compromise the validity of the model dynamics.

2.2 Production

The macroeconomic production factors are capital, labour, and final or useful energy. A nested production function with constant elasticity of substitution (CES) determines a region's gross domestic product (GDP) and its energy demand.

Generated economic output (GDP) is used for consumption, investments in the macroeconomic capital stock, and energy system expenditures, as well as trade, non-energy-related greenhouse gas abatement costs, and agricultural costs delivered by the land-use model MAgPIE (see **Figure 45**).



Abbreviations: *Heat: District heat & heat pumps, H2: Hydrogen, LDV: Light Duty Vehicle, ICE: Internal Combustion Engine, BEV: Battery Electric Vehicle, H2 FCV: Hydrogen Fuel Cell Vehicle, Av.& Bus: Aggregate of Aviation and Bus.*

Figure 45: Production function of REMIND model

Inputs at the upper layer of the production function include labour, capital, and energy services. Labour is represented by the population at working age (exogenous). Investments increase capital stocks which depreciate according to the depreciation rate and energy is produced at a cost. Energy services at the upper level are the output from a CES tree combining sectoral energy inputs from transportation, the building sector, and industry. In turn, the demand for specific energy carriers at the sectoral level is also depicted through individual CES nests. Each production factor in the various macroeconomic CES functions has an efficiency parameter. These three sectors present slightly different structures.

Transport demand composition is calculated for light-duty vehicles (LDVs), electric trains, and heavy-duty vehicles (HDVs), an aggregate category including passenger non-LDVs and freight modes (Pietzcker et al., 2014a). The three corresponding nodes in the CES transport branch represent aggregated transportation demands in terms of useful, i.e., motive, energy. The LDV node in the CES tree is supplied by either electricity, hydrogen, or liquid fuels with different conversion efficiencies, accounting for vehicles with internal combustion engines, fuel cell cars, or battery electric vehicles.

The final energy demand is determined for the aggregated **industry** sector and subdivided into four industry subsectors: cement production, chemicals production, iron, and steel production, as well as all remaining industry energy demand (denoted "other Industry") using region-specific shares that are kept constant at 2005 levels. Fuel switching (e.g., electrification) is enabled based on final energy prices and elasticities of substitution of the final energy carriers in the CES function.

In the "subsectors" realization, the energy demand from industry is modelled explicitly for the four subsectors (cement, chemicals, and iron and steel, and all remaining industry energy demand (denoted "other industry") in the nested CES production function. The iron and steel sector is subdivided into primary steel (from iron ore) and secondary steel (from scrap). The production of cement and steel as well as the value added from chemicals are derived via econometric regressions models based on per capita GDP at the country level. Steel demand is projected following the approach of Pauliuk *et al*. (2013). In all realizations of the industry module, three marginal abatement cost (MAC) curves have been derived from the literature for CCS in the cement, chemicals, and iron and steel sectors (Kuramochi *et al*., 2012).

The heterogeneity of the **building** demand is rendered through a nested CES function with a high degree of substitutability among non-electric fuels (e.g., heating oil and natural gas) and a low degree of substitutability between non-electric fuels and electric demand. The distinction between the non-electric and electric energy carriers is motivated by the different uses that can be made of these energy sources. While non-electric fuels are mostly used for heating purposes (e.g., space, water, and cooking), electricity consumption covers a wider range of purposes (e.g., lighting, appliances, and cooling).

2.3 Trade

REMIND considers the trade of coal, gas, oil, biomass, uranium, and the composite good (aggregated output of the macroeconomic system). It assumes that renewable energy sources (other than biomass) and secondary energy carriers are non-tradable across regions.

REMIND models regional trade via a common pool. While each region is an open system – meaning that it can import more than it exports – the global system is closed. The combination of regional budget constraints and balanced international flows ensures that the sum of regional consumption, investments, and energy-system expenditures cannot be greater than the global total output in each period. In line with the classical Heckscher–Ohlin and Ricardian models (Heckscher *et al*., 1991), trade between regions is induced by differences in factor endowments and technologies. REMIND also represents the additional possibility of intertemporal trade. This can be interpreted as capital trade or borrowing and lending. Capital trade is linked to the export and import of goods and energy and is accounted for in the inter-temporal trade balance. By directing the goods trade, the capital market implementation affects the consumption.

To reconcile modelled capital flows and currently observed patterns (Lucas paradox[27]; Lucas, 1990), REMIND represents capital market imperfections. The default setting includes limitations on the growth of debts and surpluses that each region can accumulate within a 5-year period. Alternative realizations with capital market imperfections are available (Leimbach and Bauer, 2021).

2.4 Taxes

REMIND includes different types of taxes (see **Table 5**), representing existing energy taxes, emulating climate policies via carbon prices or additional externalities for some technologies and processes. The overall tax revenue is the sum of various components.

[27] i.e. the fact that capital do not always flows from developed countries to developing countries despite the fact latter have lower levels of capital per worker.

Table 5: Types of taxes within REMIND, the reason for their inclusion, and the approach to their implementation.[28]

Tax type	Rationale	Implementation
Bioenergy tax	Represents negative externalities of bioenergy plantation on land	Determined as the tax rate (as multiple of bioenergy price) times primary energy use of purpose-grown biomass
Greenhouse gas tax	Main policy instrument for achieving mitigation targets	Calculated as the tax rate times GHG emissions
CCS (carbon capture and storage) tax	Represents performance difference of carbon stored in fuel vs. carbon in the form of CO_2 in geological storage	Calculated as the tax rate (defined as fraction of operation and maintenance, O&M, costs) times the amount of CO_2 sequestration
Net-negative emissions tax	Represents marginal damages of overshoot in emissions budget	Calculated as the tax rate (defined as fraction of carbon price) times net negative emissions
Final energy taxes in Transports	Status quo of fuel taxation, with different assumptions regarding convergence	Calculated as the effective tax rate (tax minus subsidy) times final energy (FE) use in transport
Final energy taxes in Buildings/Industry	Status quo of fuel taxation, with different assumptions regarding convergence	Calculated as the effective tax rate (tax minus subsidy) times FE use in the sector
Final energy taxes in the sectors with energy service representation	Status quo of fuel taxation, with different assumptions regarding convergence	Calculated as the effective tax rate (tax minus subsidy) times FE use in the sector

[28] The taxes displayed in this table are not modelled in the Remind version used to generate the NGFS Scenarios.

Resource extraction subsidies	Status quo of extraction subsidies	Calculated as the subsidy rate times fuel extraction
Primary to secondary energy technology taxes, specified by technology	Non-explicitly represented externalities of different technologies (water use, emissions of substances beyond SO_2 and CO_2)	Calculated as the effective tax rate (tax minus subsidy) times the SE output of technology
Export taxes	Represent export barriers	Calculated as the tax rate times the export volume
SO_2 tax	Represents air pollution externality	Calculated as the tax rate times emissions
High implicit discount rates in energy efficiency capital	Mirror the overvaluation of initial investments vs. runtime costs by customers	Calculated as the additional discount rate times the input of capital at different levels
Regional subsidy on learning technologies	Internalizes the positive externality of the learning spillovers to other regions so as to arrive at a globally optimal solution	Sum over the regional capitalized benefits of learning which corresponds to the shadow price of the equation that describes the capacity build-up of this technology.

2.5 Energy Module

The energy system module includes a detailed representation of energy supply and demand sectors and differentiates between a variety of fossil, biogenic, nuclear and renewable energy resources (Bauer *et al.*, 2012, 2016, 2017; Klein *et al.*, 2014, 2014; Pietzcker *et al.*, 2014). The model accounts for crucial drivers of energy

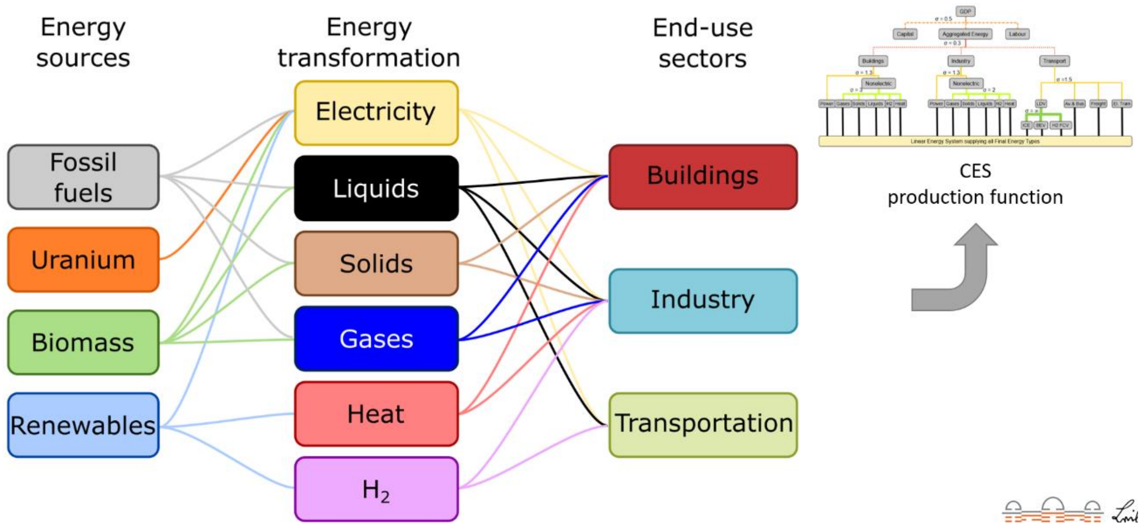


Figure 46: Energy module structure for REMIND

system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, and adjustment costs for rapidly expanding technologies. The learning of emergent new technologies is typically represented using learning or experience curves, which depict the relationship between cumulative production or deployment of a technology and its associated costs or performance. Costs for expanding technologies are adjusted to simulate the decreasing costs and improving performance of technologies as they are deployed and gain experience in the system) (Pietzcker *et al.*, 2017).

The core part of REMIND includes the representation of the energy system via the **conversion of primary energy into secondary energy carriers via specific energy conversion technologies**: The conversion chain is depicted in **Figure 46**. Around 50 different energy conversion technologies, including fossil fuel based, renewable energy, bioenergy, nuclear power, energy storage and carbon capture, are included in REMIND. For example, bioenergy, fossil gas, coal or oil can be transformed into secondary energy carriers such as liquids, solids, electricity, hydrogen, gas, or district heating. In general, technologies providing a certain secondary energy type compete linearly against each other, i.e., technology choice follows cost optimization based on investment costs, fixed and variable operation and maintenance costs, fuel costs, emission costs, efficiencies, lifetimes, and learning rates. REMIND assumes full substitutability between different technologies producing one energy type.

A few technologies convert secondary energy into another form of secondary energy, namely the conversion of electricity to hydrogen via electrolysis and the reconversion via hydrogen turbines, as well as the production of methanol and methane from hydrogen. In REMIND, technologies are represented as linear transformation processes that convert one or more inputs into one or more outputs. In- and outputs can be energy, materials, water, intermediate products or emissions, or labour inputs. The number of in- and outputs is not restricted, and technologies vary between in- and output characteristics. In the broader system context, technologies and their deployment interact via various budget constraints, which give rise to competition for resources as well as the potential to expand feasible production possibilities. A model solution provides a set of activities that is feasible with all constraints simultaneously. REMIND specifies each technology through several characteristic parameters:

- Specific overnight investment costs that are constant for most technologies and decrease due to learning-by-doing for some relatively new technologies
- Cost markups due to financing costs over the construction time
- Fixed yearly operating and maintenance costs in percent of investment costs
- Variable operating costs (per unit of output, excluding fuel costs)
- Conversion efficiency from input to output
- Capacity factor (maximum utilization time per year): this parameter also reflects maintenance periods and other technological limitations that prevent the continuous operation of the technology
- Average technical lifetime of the conversion technology in years
- If the technology experiences learning-by-doing: the initial learn rate, initial cumulative capacity, and floor costs that can only be approached asymptotically

REMIND represents all energy technologies as capacity stocks in gigawatt (GW) with full vintage tracking. As there are no hard constraints on the rate of change in investments, the possibility of investing in different capital stocks provides high flexibility for technological evolution. However, the model includes cost markups for the fast upscaling of investments into individual technologies; therefore, a more realistic phasing in and out of technologies is achieved. The model allows for premature retirement of capital stocks before the end of their technological lifetime, and the lifetimes differ between various types of technologies. Capital stocks can be phased out before they reach the end of their technical lifetime by the optimization if the value of their outputs is lower than the costs of variable inputs, reflecting a situation of asset stranding. This happens predominantly in "delayed" scenarios, where unanticipated policy changes change the cost or yield assumptions. Furthermore, capacities of conversion technologies age realistically from an engineering point of view: depreciation rates are very low in the first half of the lifetime and increase strongly thereafter.

REMIND characterizes the **exhaustible resources** (coal, oil, gas, and uranium) in terms of extraction cost curves. Fossil resources (e.g., oil, coal, and gas) are further defined by decline rates and adjustment costs (Bauer *et al.*, 2016b). Extraction costs increase as low-cost deposits become exhausted (Herfindahl, 1967; Rogner, 1997; Aguilera *et al.*, 2009; Bauer *et al.*, 2016a). In REMIND, region specific extraction cost curves relate the production cost increase to cumulative extraction (Bauer *et al.*, 2016a; Rogner *et al.*, 2012, p. 7). In the model, the fossil extraction cost input data (see Bauer *et al.*, 2016b for details) are approximated by piecewise linear functions that are employed for fossil resource extraction curves.

REMIND models resource potentials for non-biomass **renewables** (hydro, solar, wind, and geothermal) using region-specific potentials. For each renewable energy type, potentials are classified by different grades, specified by capacity factors. Superior grades have higher capacity factors, which correspond to more full-load hours per year. This implies higher energy production for a given installed capacity. Therefore, the grade structure represents optimal deployment of renewable energy, first using the best sites before turning to sites with worse conditions.

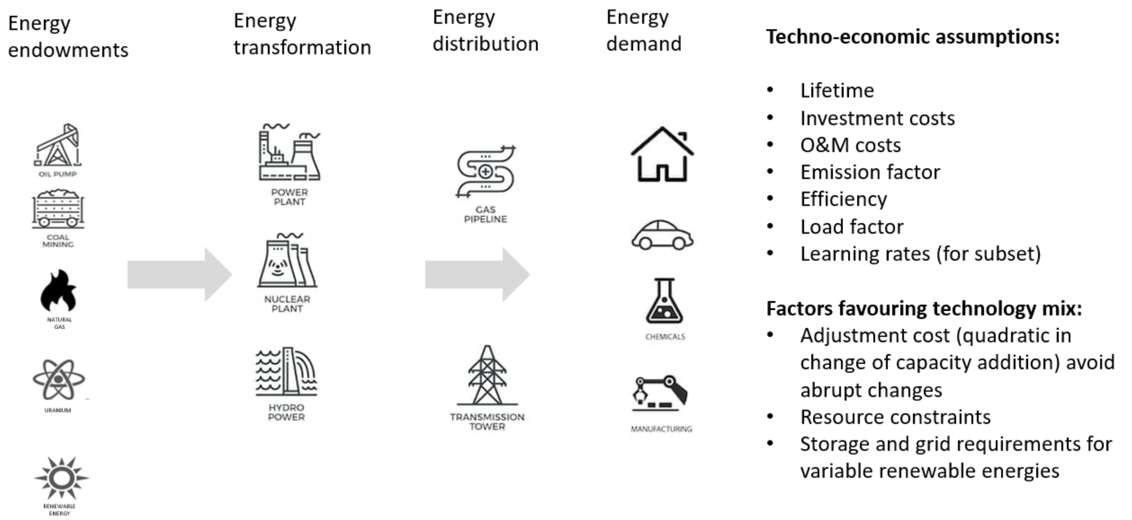


Figure 47: Energy module technologies of REMIND

The renewable energy potentials of REMIND[29] may appear higher than the potentials used in other models (Luderer *et al.*, 2014). However, these models typically limit potentials to specific locations that are currently competitive or close to becoming competitive. The grade structure of REMIND allows for the inclusion of sites that are less attractive but that may become competitive in the long-term as the costs of technologies and fuels change.

[29] That is, the physical limits of what could be installed disregarding economic considerations. See subsection 2.3 for details.

The model assumes a single electricity market balance that is complemented by equations that implicitly represent challenges and options related to the temporal and spatial variability of **wind and solar power**. The core approach (Pietzcker *et al.*, 2014b) is an aggregated representation of technology- and region-specific wind and solar PV (variable renewable energy, VRE) integration costs and curtailment rates (i.e., unused surplus share of VRE electricity generation), which, since 2017, are parameterized with the help of two detailed electricity production cost models (Scholz *et al.*, 2017; Ueckerdt et al., 2017). Integration costs consist of costs associated with short-term storage deployment (batteries), long-term hydrogen storage (electrolysis and hydrogen turbines), transmission and distribution grid expansion and reinforcement, and curtailment of surplus electricity. These variables are linked to the shares of VRE generation, with higher VRE shares resulting in higher requirements for storage and grid.

The **land-use sector** as modelled by the MAgPIE model (see next subsection) is particularly relevant for climate change mitigation because of its big share of global emissions and its ability to provide the renewable and comparatively low-emission resource biomass. In REMIND-MAgPIE, biomass is used to produce electricity, heat, ethanol, diesel, and hydrogen energy sources. Some of the conversion routes are equipped with CCS, which makes biomass an important source of negative emissions.

2.6 Land and vegetation system

From a climate protection perspective, two aspects of the land-use sector are of particular interest: the supply of biomass that can be used for energy production (possibly with carbon capture and storage, CCS) and the total emissions of the land-use sector. REMIND obtains its supply curves for purpose-grown biomass, its data for land-use emissions, and agricultural production costs from the MAgPIE land-use model. For the NGFS scenarios, REMIND and MAgPIE are run in an iterative soft-coupled mode (Klein, 2015; Bauer *et al.*, 2020), where a simultaneous equilibrium of bioenergy and emissions markets is established by an iteration of simulations in which REMIND provides emissions prices and bioenergy demand to MAgPIE and receives land use emissions and bioenergy prices from MAgPIE in return (see Figure 48).

The coupling approach between REMIND and MAgPIE is designed to derive scenarios with equilibrated bioenergy and emissions markets. In equilibrium, bio-energy demand patterns computed by REMIND are

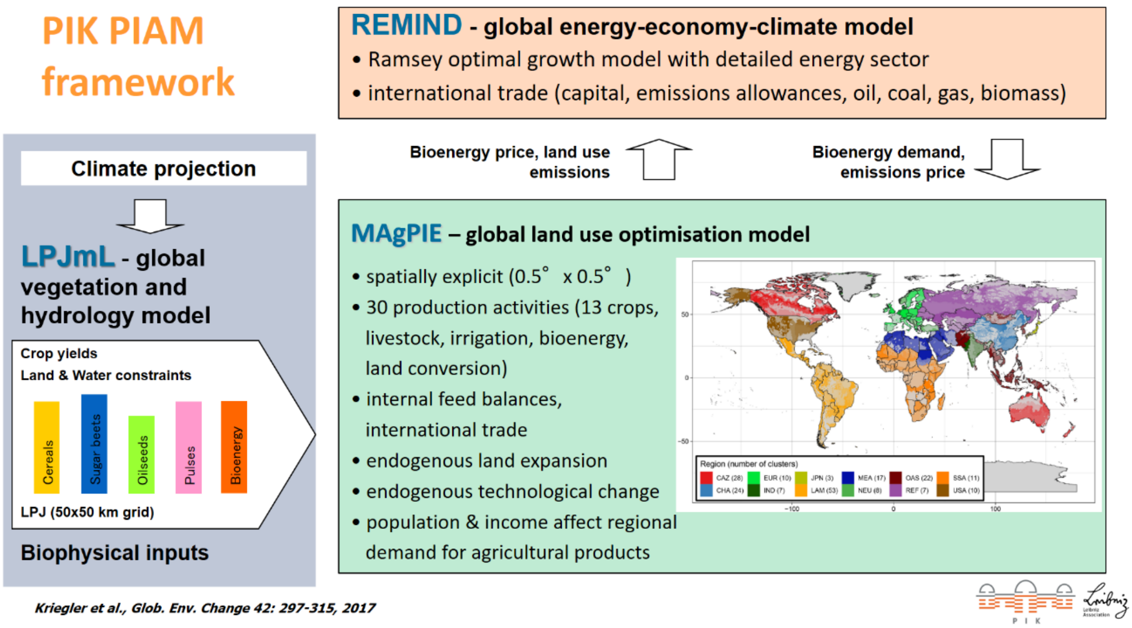


Figure 48. Integration of REMIND with MAgPIE

fulfilled in MAgPIE at the same bioenergy and emissions prices that the demand patterns were based on. Moreover, the emissions in REMIND emerging from pre-defined climate policy assumptions account for the greenhouse gas emissions from the land-use sector derived in MAgPIE under the emissions pricing and bioenergy use mandated by the same climate policy. The coupling approach with this iterative process at its core is explained in Bauer *et al.*, 2014.

MAgPIE[30] is a global land use allocation model, which is connected to the grid-based dynamic vegetation model LPJmL, with a spatial resolution of 0.5°x0.5°. It takes regional economic conditions such as demand for agricultural commodities, technological development, and production costs as well as spatially explicit data on biophysical inputs into account. Biophysical inputs, such as agricultural yields, carbon densities and water availability, are derived from LPJmL. Based on these, the model derives specific land use patterns, yields and total costs of agricultural production for each grid cell. The objective function of the land use model is to minimize total cost of production for a given amount of regional food and bioenergy demand under consideration of biophysical and socioeconomic constraints.

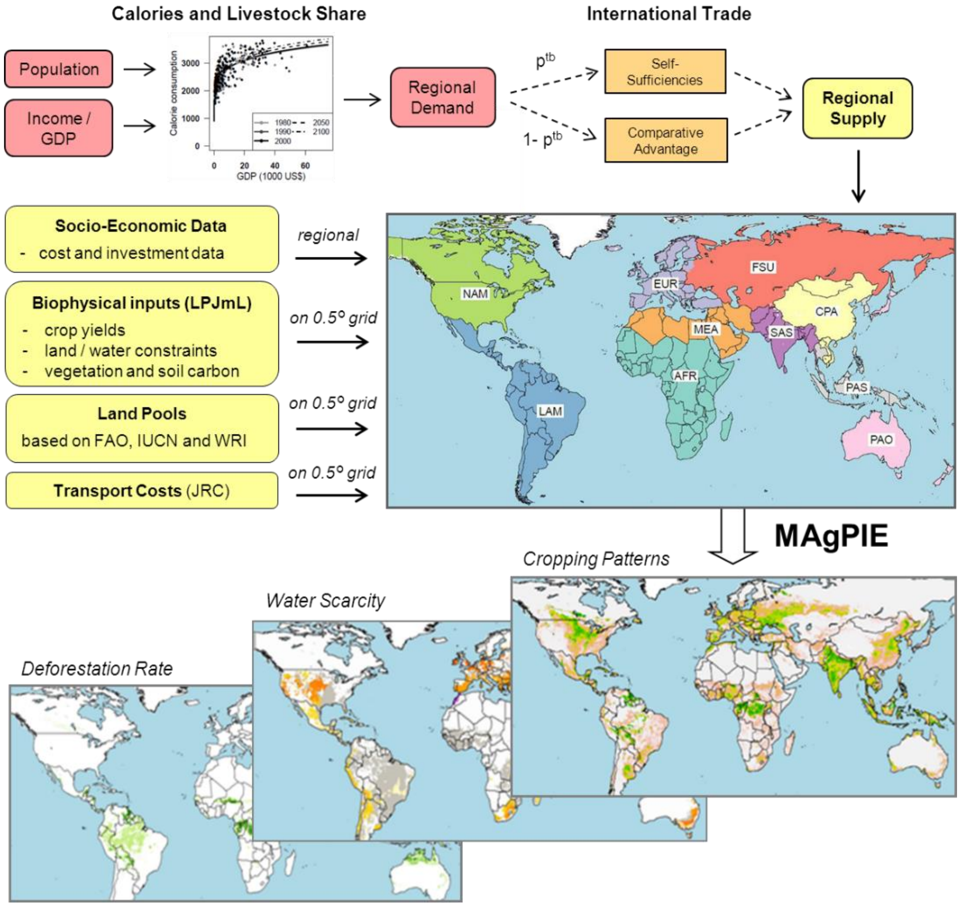


Figure 49. Simplified MAgPIE flowchart of key processes (demand and trade implementation, data inputs from LPJmL and spatially explicit water shadow prices).

Regional food energy demand is defined for an exogenously given population in 10 food energy categories, based on regional diets. Future trends in food demand are derived from a cross-country regression analysis, based on future scenarios on GDP and population growth. Food and feed energy for the demand categories can

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30 Phase V NGFS scenarios use version 4.8 of MAgPIE. See https://github.com/magpiemodel/magpie for the last version and documentation of the model.

be produced by 20 cropping activities and 3 livestock activities. Feed for livestock is produced as a mixture of crops, crop residuals, processing by-products, green fodder produced on crop land, and pasture. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about intensification of agricultural production, cropland expansion and production relocation (intra-regionally and inter-regionally through international trade), see Dietrich *et al*. (2014), Lotze-Campen *et al*. (2010) and Schmitz *et al*. (2012).

Variable inputs of production are labour, chemicals, and other capital (all measured in US$). Costs of production are derived from the Global Trade Analysis Project (GTAP) Database. The model can endogenously decide to acquire yield-increasing technological change at additional costs. The costs for technological change for each economic region are based on its level of agricultural development, measured as agricultural land-use intensity. These costs grow with further investment in technological change. The use of technological change is either triggered by a better cost-effectiveness compared to other investments or as a response to resource constraints, such as land scarcity.

The model **LPJmL**[31] is designed to simulate vegetation composition and distribution as well as stocks and land-atmosphere exchange flows of carbon and water, for both natural and agricultural ecosystems. Using a combination of plant physiological relations, generalised empirically established functions and plant trait parameters, it simulates processes such as photosynthesis, plant growth, maintenance and regeneration losses, fire disturbance, soil moisture, runoff, evapotranspiration, irrigation, and vegetation structure.

LPJmL is currently the only DGVM (Dynamic Global Vegetation Model) that has dynamic land use fully incorporated at the global scale and simulates the production of woody and herbaceous short-rotation bioenergy plantations and the terrestrial hydrology. It differs from other models in the wider field by computing carbon, nitrogen, and water flows explicitly: most other macro-hydrological models lack the important vegetation structural and physiological responses that influence the water cycle, while most other vegetation models lack the advanced consistent water balance of LPJmL or are not global in scale.

2.7 Emissions, abatement costs and Carbon dioxide removal

REMIND simulates emissions from long-lived GHGs (CO_2, CH_4, and N_2O), short-lived GHGs (CO, NO_x, and VOCs), and aerosols (SO_2, BC, and OC). REMIND accounts for these emissions with different levels of detail depending on the types and sources of emissions.

It calculates CO_2 emissions from fuel combustion and industrial processes, CH_4 emissions from fossil fuel extraction and residential energy use, and N_2O emissions from energy supply based on sources. Fluorinated gases (F-gases) and emissions from land-use change are included exogenously with different trajectories depending on the SSP and climate target.

There are mitigation options for CH_4, N_2O, and CO_2 from land-use change, fossil fuel extraction, cement production, and waste handling that are independent of energy consumption and are calculated in the core of REMIND. However, there are costs associated with these emission reductions. Therefore, REMIND derives the mitigation options from **marginal abatement cost** curves (MACC), which describe the percentage of abated emissions as a function of the costs (Lucas *et al*., 2007).

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[31] See https://github.com/PIK-LPJmL/LPJmL for the repository and documentation of the model.

In addition to CCS (carbon capture and storage) with fossil fuels and in the industry sector, four **carbon dioxide removal (**CDR) options are available: afforestation and reforestation, bioenergy with CCS (BECCS), direct air capture with CCS (DACCS), and enhanced weathering of rocks (EW). CO_2 emissions from afforestation and reforestation are derived from the land-use optimization model MAgPIE4. The trade-off between land expansion and yield increases is treated endogenously in the model. BECCS (bioenergy with carbon capture and storage) is the only CDR technology that provides sizable energy instead of consuming it. The idea of BECCS is to turn biomass grown on land carbon-negative by capturing the emissions arising during combustion or the refinery process. BECCS can be used for electricity, hydrogen, gas, or liquid-fuel production with different carbon capture rates. DACCS (direct air and carbon capture and storage) and enhanced weathering of rocks were switched off in REMIND for the NGFS scenarios.

2.8 Climate

To translate emissions into changes in atmospheric composition, radiative forcing, and temperature increase, REMIND is coupled with the MAGICC 7.5.3 climate model. Due to numerical complexity, the evaluation of climate change using MAGICC is performed after running REMIND. Iterative adjustment of emission constraints or carbon taxes allows for specific temperature or radiative forcing limits to be met in the case of temperature targets.

MAGICC is a reduced-complexity climate model that calculates atmospheric concentrations of greenhouse gases and other atmospheric climate drivers, radiative forcing, and global annual-mean surface air temperature. More details on this model are provided in the **Box: MAGICC: A reduced complexity Earth system model**, and in the corresponding sections of the IAMs modules, as it is also used in post-processing for the estimation of chronic physical damages.

3. Key model inputs

Description of key input variables (e.g., which series, years, sources) and main assumptions

REMIND-MAgPIE uses a range of exogenous data as input to ensure the consistency of scenarios with historic developments and realistic future projections. Historical data for the year 2005 are used to calibrate most of the free variables (e.g., primary energy mixes in 2005, secondary energy mixes in 2005, standing capacities in 2005, and trade in all traded goods for 2005). Additional bounds for a select few variables, primarily capacity (additions), up to 2023 ensure that the point of departure in current policy cases is proximal to actual developments.

Technology parameters are projected into the future, generally assuming a certain level of convergence across regions in the long term.

3.1 Population and GDP

All economic assumptions are taken from the Shared Socioeconomic Pathway 2 (SSP 2), designed to represent a "middle-of-the-road" future development. Population is a fully exogenous input assumption. Projections of coherent future demographic and economic developments offer population and labour trajectories from 2005 to 2100 (SSP trajectories; Dellink et al., 2017; KC and Lutz, 2017). The most recent version 3.0 of SSP trajectories is used (2024).

Gross Domestic Product[32] is a semi-endogenous output. The model takes the SSP2 GDP trajectories for calibrating assumptions on exogenous productivity improvement rates in a no-policy reference scenario (Current policies). GDP trajectories in other scenarios thus reflect the general equilibrium effects of constraints and distortions by policies (so changes in capital allocation and prices, but without taking potential damages from climate impacts into account).

3.2 Production function calibration

To align with gross domestic product (GDP) trajectories consistent with the population trajectories from 2005 to 2100, as well as final and useful energy trajectories, REMIND calibrates its production function.

The changes in efficiency parameters over time are tuned such that the baseline scenario meets exogenous economic growth pathways and final or useful energy pathways in line with the SSPs (O'Neill et al., 2013). The calibration has to fulfil two constraints: an economic and a technological constraint. The **technological constraint** requires the inputs of the CES (constant elasticity of substitution) production function to yield the desired output. At this stage, there is no economic consideration at all. During a REMIND run, however, the model will strive to find the most efficient solution in terms of costs. Therefore, the second constraint is an economic constraint. The derivatives of the CES function, i.e., the marginal increase in income from increasing the considered input by one unit, must equal the price of that input, i.e., the marginal cost. The **economic constraint** defines that the prices are equal to the derivatives. Following Euler's rule, the technological constraint determines that, for homogeneous functions of degree 1 (as is the case here), the output is equal to

[32] This series is provided in the NGFS database with the name GDP|PPP|counterfactual without damage and GDP|MER|counterfactual without damage

the sum of the derivatives times the quantity of inputs. Combining both constraints means that the output is equal to the sum of inputs valued at their price. Thus, the prices and quantities given exogenously, combined with the two constraints, are sufficient to determine all the quantities of the CES tree up to the last level with labour and capital.

3.3 Resource extraction costs and renewable maximum capacities

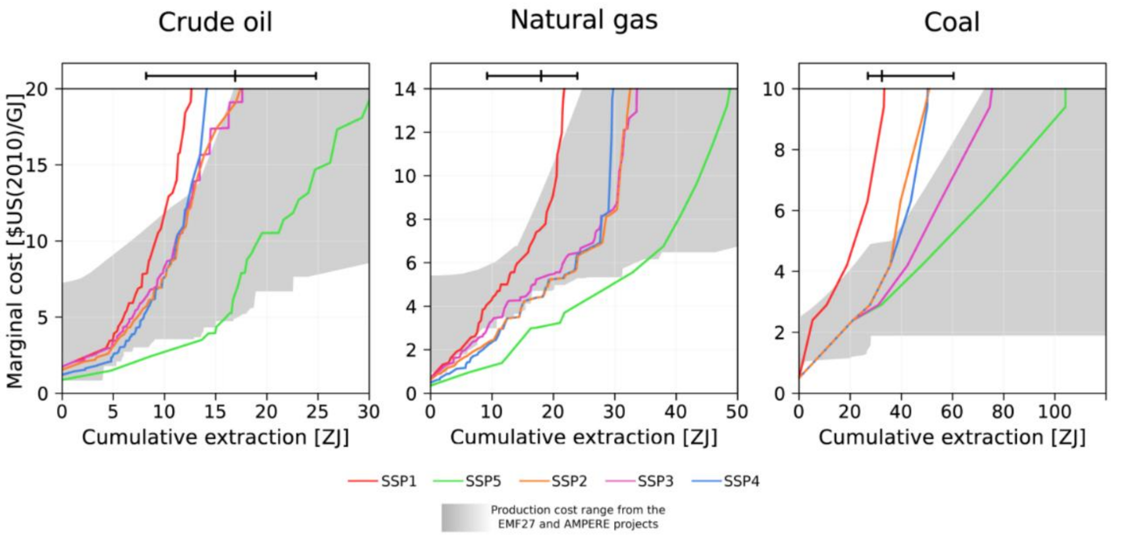

Figure 50. Extraction marginal costs by fossil resource. Bauer et al. (Energy, 2016)

While biomass resources are given by MAgPIE model, the extraction costs of fossil fuels need to be calibrated, see **Figure 50**. More details on the underlying data and method are presented in a separate paper (Bauer et al., 2016b). In the model, this fossil extraction cost input data is approximated by piecewise linear functions that are employed for fossil resource extraction curves. For uranium, extraction costs follow a third-order polynomial parameterization based on data of the Nuclear Energy Agency (NEA); see Bauer et al. (2012a) for details.

For renewables, maximum production capacity is calibrated by region, see **Figure 51**. The regionally aggregated potentials for solar photovoltaics (PV) and concentrated solar power (CSP) used in REMIND were developed in Pietzcker et al. (2014b) in cooperation with the German Aerospace Center (DLR). To account for the competition between PV and CSP for the same sites with good irradiation, an additional constraint for the combined deployment of PV and CSP was introduced in REMIND (Pietzcker et al., 2014b) to ensure that the model cannot use the available area twice to install both PV and CSP.

The regionally aggregated wind potentials were developed based on a number of studies (Hoogwijk, 2004; Brückl, 2005; Hoogwijk and Graus, 2008; EEA, 2009; Eurek et al., 2017). The technical potentials for combined on- and offshore wind power amount to 800 EJ/yr (half of this amount is at sites with more than 1900 full-load hours). The total value is approximately half the maximum extractable electric energy from wind over land area, as estimated in Miller and Kleidon (2016), and about one-fifth of the potential estimated in Lu et al. (2009). The global potentials of hydropower amount to 50 EJ/yr. These estimates are based on the technological potentials provided in the report from WGBU (2003) and the background paper produced for the report (Horlacher, 2003).

3.4 Emissions

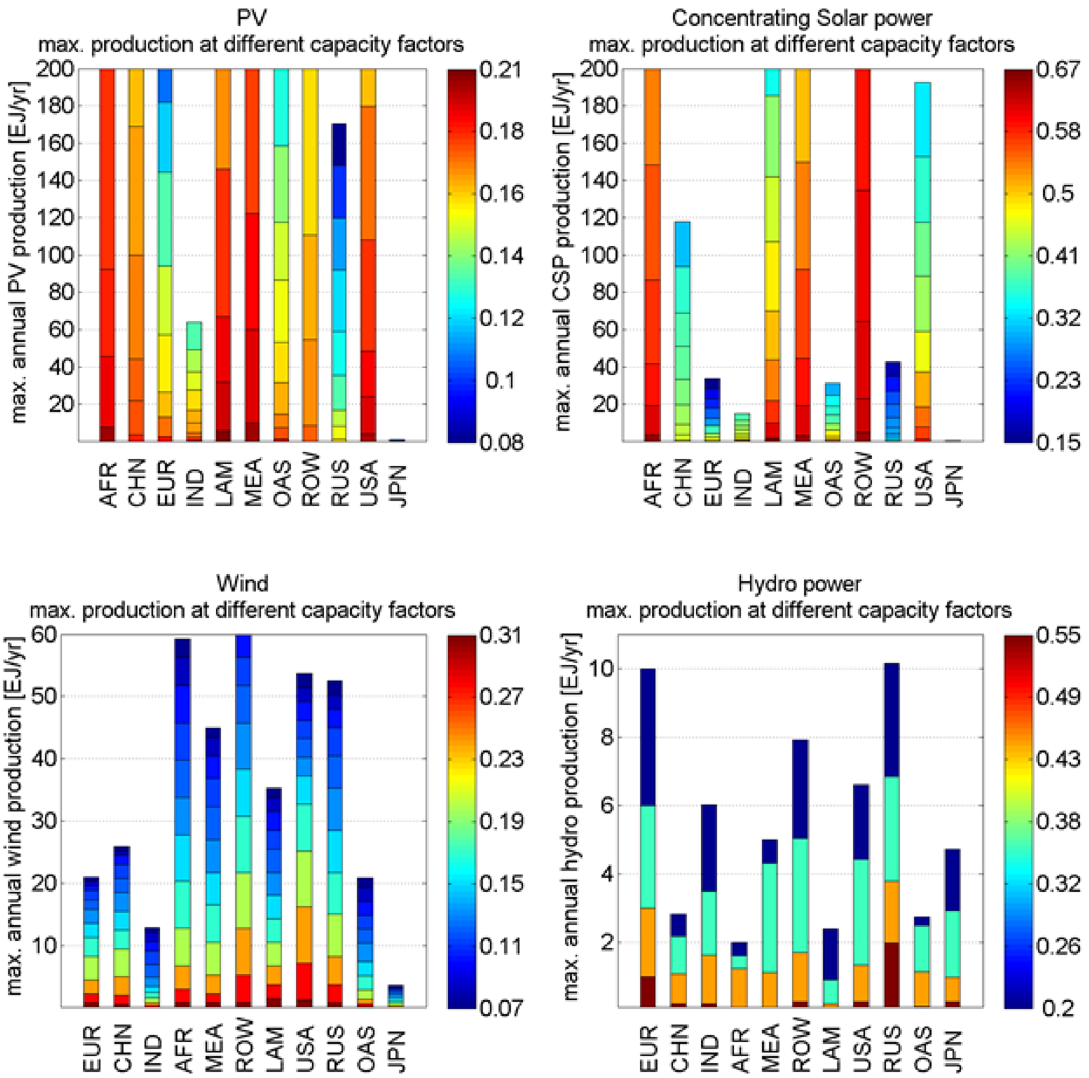

Figure 51. Renewables maximum production by regions. Pietzcker et al. (Applied Energy, 2014)

For each fuel, region, and technology, REMIND applies specific emissions factors, which are calibrated to match base year GHG inventories (Global Emissions EDGAR v4.2, 2013). Emission factors for CH_4 from the residential sector, and N_2O from energy supply are taken from Amous (2000).

Baseline emissions for CH_4 fugitive emissions from coal, oil, and gas extraction and processing, are calculated by source using region- and fuel-specific emission factors. The emission factors for CH_4 fugitive emissions are derived using the emissions inventory (Global Emissions EDGAR v4.2, 2013) and the amount of fossil fuel extracted in each region in REMIND in 2005.

REMIND uses an econometric estimate for CO_2 emissions from cement production as well as CH_4 and N_2O emissions from waste handling. In both cases, the driver of emissions depends on the development of population and GDP (as a proxy for waste production) or capital investment (as a proxy for cement production in infrastructure). REMIND uses exogenous baselines for N_2O emissions from transport and industry, and for CO_2, CH_4, and N_2O emissions from land-use and land-use change based on MAgPIE.

CH_4 and N_2O emissions from open burning are assumed to remain constant at their 2005 levels.

Emissions of other GHGs (e.g., F-gases and Montreal gases) are exogenous and are taken from the SSP scenario data set from the IMAGE model (van Vuuren et al., 2017).

For pollutant emissions of SO_2, BC, OC, NOx, CO, VOCs, and NH_3 related to the combustion of fossil fuels, REMIND considers time- and region-specific emissions factors coupled to model-endogenous activity data. BC and OC emissions in 2005 are calibrated to the GAINS model (Klimont et al., 2017; Amann et al., 2011). All other emissions from fuel combustion in 2005 are calibrated to Global Emissions EDGAR v4.2 (2013).

Emission factors for SO_2, BC, and OC are assumed to decline over time according to air pollution policies based on Klimont et al. (2021). Current near-term policies are enforced in high-income countries, with gradual strengthening of goals over time and gradual technology (research, development, demonstration, and deployment). Low-income countries do not fully implement near-term policies but gradually improve over the century. Emissions from international shipping and aviation and waste of all species are exogenous and are taken from Fujino et al. (2006). Further, REMIND uses land-use emissions from the MAgPIE model (see Sect. 2.4.1), which, in turn, are based on emission factors from van der Werf et al. (2010).

Module 3: IAM – MESSAGE-GLOBIOM

1. Non-technical summary

What is the MESSAGE-GLOBIOM model?

The MESSAGE-GLOBIOM model, or MESSAGE in short, is an Integrated Assessment Model (IAM) developed by the International Institute for Applied Systems Analysis (IIASA). It combines energy systems, environmental impacts, and economic analysis to evaluate the long-term implications of energy and climate policies. Although its name only refers to two of its components, the MESSAGE-GLOBIOM model consists of a combination of five different models or modules which complement each other and are specialised in different areas:

- the energy model **MESSAGE*ix*** [33] (**M**odel for **E**nergy **S**upply **S**trategy **A**lternatives and **G**eneral **E**nvironmental Impact),
- the land-use model **GLOBIOM** (**GL**obal **BIO**sphere **M**anagement),
- the air pollution and GHG model **GAINS** (**G**reenhouse gas – **A**ir pollution **In**teractions and **S**ynergies),
- the aggregated **macro**-economic model **MACRO**, and
- the simplified climate model **MAGICC** (**M**odel for the **A**ssessment of **G**reenhouse-gas **I**nduced **C**limate **C**hange).

All models and modules together build the **IIASA IAM framework**, also referred to as **MESSAGEix-GLOBIOM** since the energy model MESSAGE and the land use model GLOBIOM are its most important components. The five models provide input to and iterate between each other during a typical scenario development cycle.

The MESSAGEix-GLOBIOM model at its core is a technology-detailed energy-engineering optimization model used for energy planning. Through linkage to macro-economic, land-use and climate models it is capable of considering important feedback and limitations in these areas outside of the energy system.

What are the key model inputs?

Key model inputs, taken from external sources, relate to GDP and population pathways (taken from the Shared Socioeconomic Pathway SSP2), energy resource endowments, energy conversion rates, energy end-use, technological change, fuel blending, add-on technologies, energy demand, modelling policies, macroeconomic variables, land-use, and emissions.

What are the key model outputs?

Key model outputs comprise regional and country-level variables on emissions, land uses, prices, and quantities over different scenarios and over a pre-defined horizon common across scenarios.

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33 The "ix" stands for integrated assessment modelling with exogenous uncertainties. MESSAGEix is a versatile, dynamic systems-optimization modelling framework developed by the IIASA Energy, Climate, and Environment (ECE) Program 1 since the 1980s.

What is new in the 2024 edition?

The 2024 edition for Phase V does have several changes compared to the 2023 edition used for Phase IV. Some of the notable differences are:

1. Most recently updated socio-economic drivers of the SSPs
2. Calibration of energy system variables to the new baseyear of 2020 and fixed values across all scenarios for 2025 based on recent trends and implemented policies.
3. New projections of energy demand based on new sector-level modules (MESSAGEix-Buildings, -Materials, -Transport)
4. Updated calibration and projection method for techno-economic assumptions
5. Updated policy details for the Current Policies and NDC scenarios.

2. Overview of model scope and methods

The MESSAGE-GLOBIOM model[34] **was originally developed to represent global and regional energy systems**[35] **and can be used as an energy planning tool.** The name "MESSAGE" itself refers to the core of the IIASA IAM framework (see **Figure 52**) and its main task is to optimise the energy system so that it can satisfy specified energy demands at the lowest costs. The current version allows for a detailed representation of the technical-engineering, socioeconomic, and biophysical processes in energy and land-use systems. This is achieved by linking MESSAGE*ix* to four different models, which have also been developed by IIASA. These four models are the land-use model GLOBIOM (Global Biosphere Management Model), the air pollution and greenhouse gas (GHG) model GAINS (Greenhouse gas - Air pollution Interactions and Synergies model), the aggregated macro-economic model MACRO and the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change), which complement each other and are specialized in different areas. The IIASA IAM framework is also referred to as MESSAGE*ix*-GLOBIOM, since the energy model MESSAGE*ix* and the land-use model GLOBIOM are its central components. Key features of the model include:

- **energy system analysis**: production, conversion, and consumption across different sectors,
- **environmental impacts**: enabling the analysis of the environmental consequences of different energy pathways and policy interventions,
- **technological detail**: simulating the behaviour and evolution of different energy technologies over time,
- **economic analysis**: economic implications of different energy and climate policies, including the costs and benefits of different mitigation strategies, and
- **policy assessment**: analysing the impacts of policy measures such as carbon pricing, RE subsidies, and energy efficiency standards.

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[34] A comprehensive documentation of the model is available at these URLs: https://docs.messageix.org/en/stable/; https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_MESSAGE-GLOBIOM The source code of the model is open-source and available at this URL: https://github.com/iiasa/message_ix

[35] The energy system analytically traces the process of resource extraction, imports and exports, conversion, transport, and distribution, up to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. The energy system in MESSAGE*ix* is represented in *Figure 53*

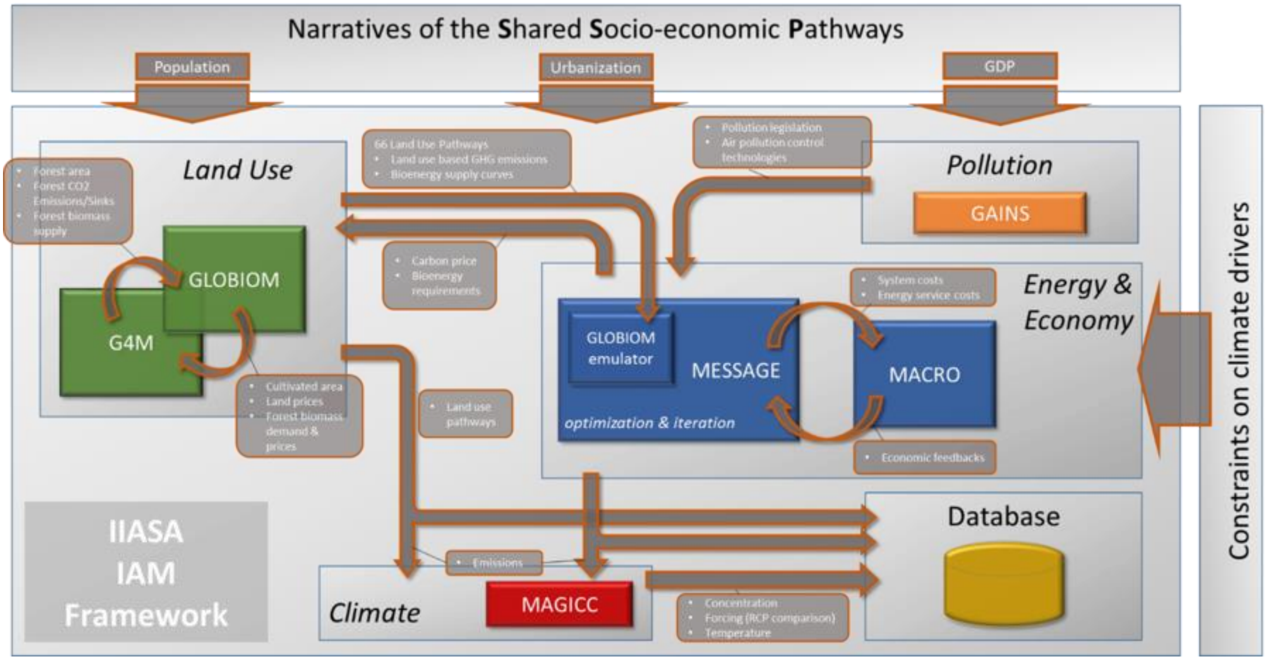

Figure 52. Overview of the IIASA IAM Framework. Coloured boxes represent respective specialized disciplinary models which are integrated for generating internally consistent scenarios. Figure from Riahi et al. (2016).

MESSAGE*ix*[36] represents the core of the IIASA IAM framework. Its main objective is to optimise the energy system (see Figure 53)**, i.e., to satisfy specified energy demands at the lowest costs.** This optimisation is carried out in an iterative setup with MACRO, a single sector macro-economic model, which provides estimates of the macro-economic energy demand response that results from energy system and services costs computed by MESSAGEix. For the six commercial end-use demand categories depicted in MESSAGE (see Energy demand), based on demand prices, MACRO will adjust useful energy demands, until the two models have reached equilibrium (see Macro-economy (MACRO)). This iteration reflects price-induced energy efficiency adjustments that can occur when energy prices change. MESSAGE can represent different energy- and climate-related policies.

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[36] Daniel Huppmann, Matthew Gidden, Oliver Fricko, Peter Kolp, Clara Orthofer, Michael Pimmer, Nikolay Kushin, Adriano Vinca, Alessio Mastrucci, Keywan Riahi, and Volker Krey. The messageix integrated assessment model and the ix modeling platform (ixmp): an open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Environmental Modelling & Software, 112:143–156, 2019. doi:10.1016/j.envsoft.2018.11.012.

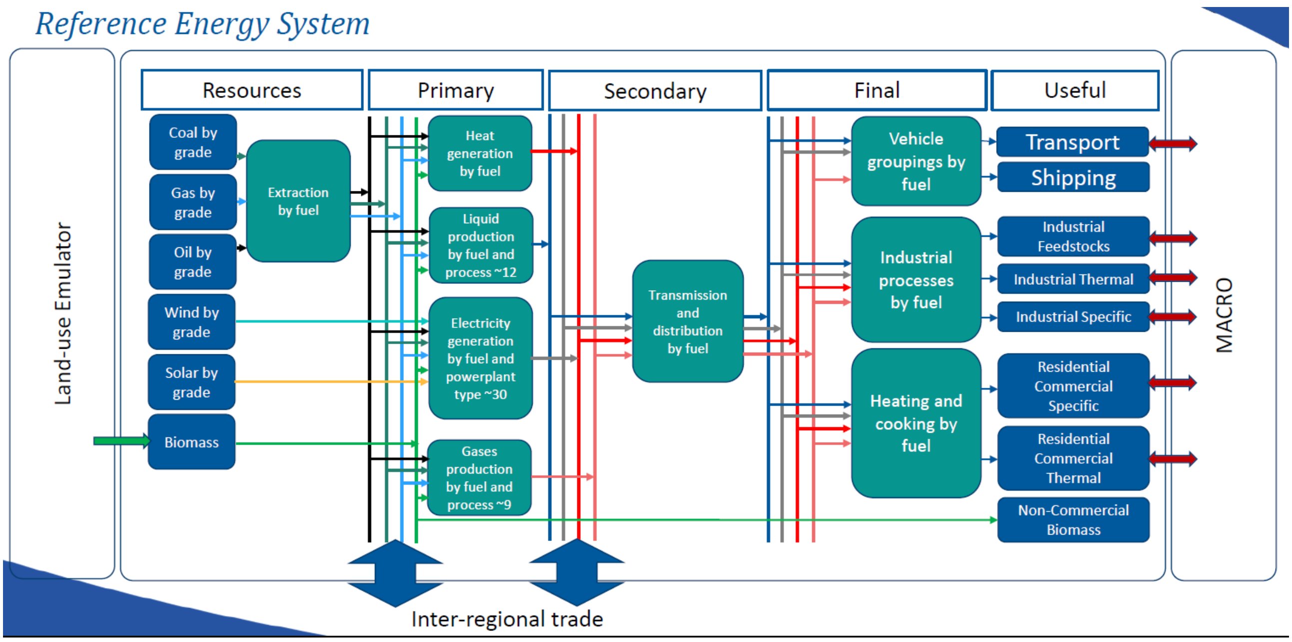

Figure 53. Reference Energy System in MESSAGEix

GLOBIOM is a partial-equilibrium model representing the mainland-use sectors, which include agriculture and forestry. The supply side of the model is built from the bottom-up (spatially explicit land cover, land use, management systems and economic cost information) combine with the top-down approaches on regional commodity markets, as illustrated in **Figure 54**. GLOBIOM provides MESSAGEix with information on land use and its implications, including the availability and cost of bioenergy, and availability and cost of emission mitigation in the AFOLU (Agriculture, Forestry and Other Land Use) sector. The link between MESSAGEix and GLOBIOM allows researchers to investigate how land-use changes and biomass supply influence the production of carbon emissions, which in turn affects energy demand, allowing for an integrated analysis of the energy system and GHG emissions linked to land use.

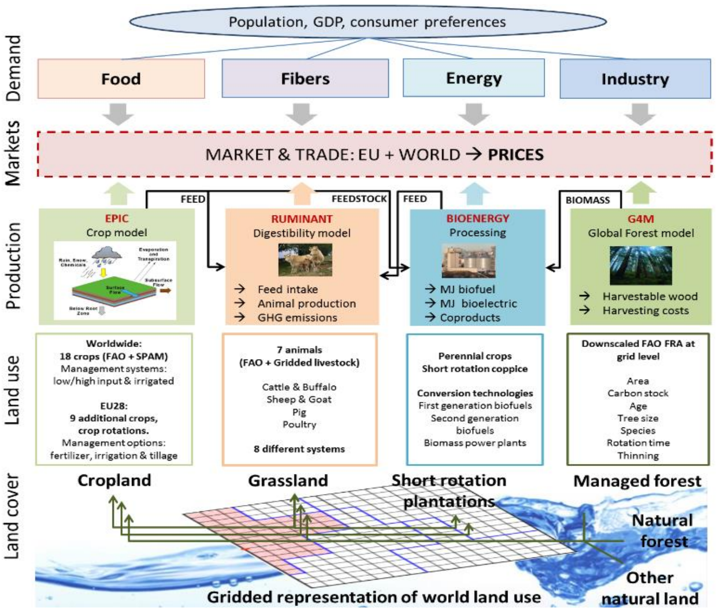

Figure 54. Overview of the GLOBIOM model

Air pollution implications of the energy system are accounted for in MESSAGEix by applying technology-specific air pollution coefficients derived from the GAINS model. The GAINS model is an analytical framework for assessing future potentials and costs for reducing air pollution impacts on human health and the environment while simultaneously mitigating climate change through reduced greenhouse gas emissions (**Figure 55**). It explores synergies and trade-offs in cost-effective emission control strategies to maximize benefits across multiple scales. GAINS is calibrated by estimating historic emissions of air pollutants and GHGs for each country based on data from international energy and industrial statistics, emission inventories and other data supplied by countries themselves. It assesses emissions over the medium-to-long term, with projections being specified in five-year intervals until 2050.

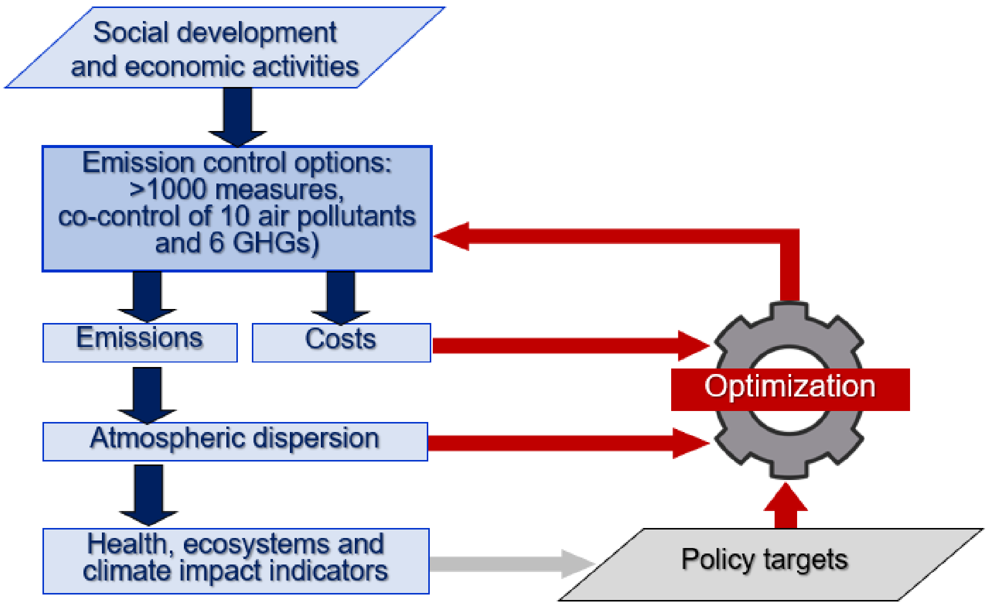

Figure 55. Overview of the GAINS model

In addition to these two large-scale models, two other key models are also closely related to the use of the MESSAGE model, namely MACRO and MAGICC. 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 labour, and energy inputs, which together determine the total output of an economy according to a nested constant elasticity of substitution (CES) production function. Thus, by linking the two models it is possible 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. A detailed description of MAGICC is provided separately in the Box: **MAGICC: A reduced complexity Earth system model**.

Relevant model assumptions for the interpretation of the NGFS scenarios include that the policy scenarios are a mix of internally consistent and externally imposed constraints on the model. Also, the GDP impacts produced by the native model, should be interpreted as long-run averages, contrary to the high-resolution data provided by NiGEM.

3. Key model inputs

This section describes key input variables to the MESSAGEix-GLOBIOM framework. In the following section, a distinction is made between input variables that are common across the models of the framework (i.e., MESSAGEix, GLOBIOM, MACRO, MAGICC and GAINS) and input variables that are specific to the different models. Temporally, the models operate in 5-year or, from 2060 onwards, 10-year steps.

Common input variables

Common input variables are those reflecting socio-economic developments over the projection horizons. More specifically, exogenous input variables include variables such as GDP and population. These variables are derived from other analyses and only used as input for the models. More precisely, the main source for socio-economic assumptions is the database on Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2015).[37] In particular, the SSPs reflect five different developments of the world that are characterised by varying levels of global challenges (see Riahi et al., 2017 for an overview). They include: a world of sustainability-focused growth and equality (SSP1); a "middle of the road" world where trends broadly follow their historical patterns (SSP2); a fragmented world of "resurgent nationalism" (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5). NGFS scenarios mainly use SSP2 as an input and have been updated to the latest release[38].

In the MESSAGEix scenarios for the NGFS, SSP2 projections of total population and GDP (at purchasing power parity exchange rates) are the primary drivers of future energy demand. In particular, GDP is common across scenarios for each region from 2005-2020 and differs depending on the scenarios afterwards. The SSP2 GDP trajectories are also used for calibrating assumptions on exogenous productivity improvement rates in the Current Policies scenario. GDP trajectories in other scenarios thus reflect the general equilibrium effects of constraints and distortions by policies. The other common variable from 2005-2100 is population, which is further split into rural and urban. Population paths are common across scenarios over the entire projection horizon, while they differ across regions.

Energy resource endowments (MESSAGEix)

Fossil fuel resources and renewable resource potentials: In MESSAGEix, assumptions on fossil fuel availability and the underlying extraction cost assumptions are derived from various sources, including global databases such as The Federal Institute for Geosciences and Natural Resources (BGR) and the U.S. Geological Survey (USGS), as well as market reports and outlooks provided by different energy institutes and agencies. The availability of fossil energy resources in different regions[39] is then aligned with the particular storyline of the chosen SSP, i.e.,

[37] These pathways cover the range of possible future development of anthropogenic drivers of climate change found in the literature. The SSP storylines served as the starting point for the development of the quantitative SSP elements. Each storyline provides a brief narrative of the main characteristics of the future development path of an SSP. The storylines were identified at the joint IAV and IAM workshop in Boulder, November 2011.

[38] https://data.ece.iiasa.ac.at/ssp/

[39] Conventional oil and gas are distributed unevenly throughout the world, with only a few regions dominating the reserves. Nearly half of the reserves of conventional oil is found in Middle East and North Africa, and close to 40% of conventional gas is found in Russia and the Former Soviet Union states. The situation is somewhat different for unconventional oil of which North and Latin America potentially possess significantly higher global shares. Unconventional gas in turn is distributed quite evenly throughout the world, with North America holding most (roughly 25% of global resources). The

SSP2 (Rogner, 1997; Riahi et al., 2012) for NGFS scenarios. Specifically, fossil fuel energy resources are aligned to technical and economic availability of overall resources underlying the SSP2 narrative/pathway. Key exogenous input variables to achieve this alignment are so called conversion technologies and technological change which differ across SSPs (e.g., technological change in fossil fuel extraction and conversion technologies is assumed to be slowest in SSP1). In particular, for SSP2 a continuation of recent trends is assumed, focusing more on developing extraction technologies for unconventional hydrocarbon resources, thereby leading to higher potential cumulative oil extraction than in the other SSPs.[40]

Nuclear resources: 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. The levels of uranium resources assumed available in the MESSAGE SSP scenarios are built upon earlier work developed in the Global Energy Assessment (see Riahi et al., 2012). In the SSP2 narrative, which underlies NGFS scenarios, we used the Uranium Resources, Production and Demand (Red Book 2022) for the nuclear potential and adopted a redistribution of its extraction costs.

Non-Biomass Renewable Resources: The resources considered are hydro, wind (on-/offshore), solar PV, concentrating solar power (CSP)[41] and geothermal. They are measured in terms of deployment potentials (EJ/yr.), i.e., in terms of the electricity or heat that can be produced by specific technologies (i.e., from a secondary energy perspective).[42] The estimates used in MESSAGEix are based on different sources, such as the U.S. National Renewable Energy Laboratory database as described in the Global Energy Assessment (Rogner et al., 2012). Moreover, resource potentials for solar photovoltaic (PV), concentrating solar power (CSP), and onshore/offshore wind are further downscaled by region and classified according to resource quality (annual capacity factor) based on Pietzcker et al. (2014) and Eurek et al. (2017). For Solar PV (utility scale), additional calibrations are introduced to account for more realisitic capacity factor allocation when doing optimisation runs.

Biomass Resources: Bioenergy includes both commercial and non-commercial use. Commercial refers to the use of bioenergy in, for example, power plants or biofuel refineries, while non-commercial refers to the use of bioenergy for residential heating and cooking, primarily in rural households of today's developing countries, and as such is typically not traded or sold. Bioenergy potentials are derived from the GLOBIOM model and differ across SSPs as a result of different levels of competition over land for food and fibre, but ultimately only vary

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distribution of coal reserves shows the highest geographical diversity. Russia and the former Soviet Union states, Pacific OECD, North America, and Centrally Planned Asia and China all possess more than 10 ZJ of reserves.

[40] For assumptions and references on global fossil fuel reserves and resources in the MESSAGE please refer to the tables at the following link: https://docs.messageix.org/projects/global/en/latest/energy/resource/fossilfuel.html

[41] Unlike CSP which uses the sun's energy, PV solar panels make use of the sun's light instead. In other words, photovoltaics is the direct conversion of light into electricity, while CSP systems produce electric power by converting the sun's energy into high-temperature heat using various mirror configurations and this concentrated energy is then used to drive a heat engine and drive an electric generator.

[42] This differs from the technical potentials which instead refer to the flows of energy that could become available as inputs for technology conversion. So, for example, the technical potential for wind is given as the kinetic energy available for wind power generation, whereas the deployment potential would only be the electricity that could be generated by the wind turbines.

to a limited degree. The drivers underlying this competition are different land-use developments in the SSPs, which are determined by agricultural productivity and global demand for food consumption. (Fricko et al., 2017). The biomass availability assessment used for the NGFS Phase V scenarios is an intermediate set of scenarios with limited changes in dietary change and limited restriction due to nature conservation.

Energy conversion (MESSAGEix)

Energy technologies are characterised 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 socio-political characteristics.[43] Model input data reflecting these parameters constrains the use of these technologies or, equivalently, determines their omission for some regions. The specific technologies represented in various parts of the energy conversion sector encompass "Electricity, Heat, Other conversion"[44] and "Grid, Infrastructure and System Reliability"[45,46]. Each energy conversion technology is characterized in MESSAGE by the following data:

- Energy inputs and outputs together with the respective conversion efficiencies.
- Specific investment costs (e.g., per kilowatt, kW) and time of construction as well as distribution of capital costs over construction time.
- Fixed operating and maintenance costs (per unit of capacity, e.g., per kW).
- Variable operating costs (per unit of output, e.g., per kilowatt-hour, kWh, excluding fuel costs).

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[43] An example for the socio-political 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).

[44] Other conversion includes liquid fuel production, gaseous fuel production and hydrogen production.

[45] Energy transport and distribution infrastructure is included in MESSAGE at a level relevant to represent the associated costs as well as transmission and distribution losses. Within individual model regions the capital stock of transmission and distribution infrastructure and its turnover is modelled for a number of energy carriers (electricity, district heat, natural gas and hydrogen). For all solid (coal, biomass) and liquid energy carriers (oil products, biofuels, fossil synfuels) a simpler approach is taken and only transmission and distribution losses and costs are taken into account. Inter-regional energy transmission infrastructure, such as natural gas pipelines and high voltage electricity grids, are also represented between geographically adjacent regions. Solid and liquid fuel trade is, similar to the transmission and distribution within regions, modeled by taking into account distribution losses and costs. A special case are gases that can be traded in liquified form, i.e., liquified natural gas (LNG) and liquid hydrogen, where liquefaction and re-gasification infrastructure is explicitly represented in addition to the actual transport process.

[46] The global MESSAGE model includes a single annual time period within each modelling year characterized by average annual load and 11 geographic regions. Seasonal and diurnal load curves and spatial issues such as transmission constraints or renewable resource heterogeneity are treated in a stylized way in the model.

- Plant availability or maximum utilisation time per year.[47]
- Technical lifetime of the conversion technology in years.
- Year of first commercial availability and last year of commercial availability of the technology.
- Consumption or production of certain materials (e.g., emissions of kg of CO_2 or SO_2 per produced kWh).
- Limitations on the (annual) activity and on the installed capacity of a technology.
- Constraints on the rate of growth or decrease of the annually new installed capacity and on the growth or decrease of the activity of a technology.
- Technical application constraints, e.g., maximum possible shares of wind or solar power in an electricity network without storage capabilities.
- Inventory upon start up and shutdown, e.g., initial nuclear core needed at the start-up of a nuclear power plant.
- Lag time between input and output of the technology.
- Minimum unit size, e.g., for nuclear power plants it does not make sense to build plants with a capacity of a few kilowatts power (optional, not used in current model version).
- Socio-political constraints, e.g., ban of nuclear power plants.
- Inconvenience costs which are specified only for end-use technologies (e.g., cook stoves)

Energy end-use (MESSAGEix)

MESSAGEix distinguishes three energy end-use sectors: transport, residential/commercial (also referred to as buildings sector), and industry.

Transport sector. The applied MESSAGEix transport sector representation is stylized and essentially includes fuel switching[48] –to account for a key option to reduce emissions; switching depends on fuel-specific relative

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[47] As an example, electric-sector flexibility in MESSAGE is represented as follows: each generating technology is assigned a coefficient between -1 and 1 representing (if positive) the fraction of generation from that technology that is considered to be flexible or (if negative) the additional flexible generation required for each unit of generation from that technology. Load also has a parameter (a negative one) representing the amount of flexible energy the system requires solely to meet changes and uncertainty in load.

[48] Limitations of switching to alternative fuels may occur, for example as a result of restricted infrastructure availability (e.g., rail network) or some energy carriers being unsuitable for certain transport modes (e.g., electrification of aviation). To reflect these limitations, share constraints of energy carriers (e.g., electricity) and energy carrier groups (e.g., liquid fuels) are used in the transport sector. In addition, the diffusion speed of alternative fuels is limited to mimic bottlenecks in the supply chains, not explicitly represented in MESSAGEix (e.g., non-energy related infrastructure). Both the share as well as

efficiencies - and price-elastic demands (via MACRO linkage) as the main responses to energy and climate policy. According to SSP2, the storyline underlying NGFS scenarios, the electrification rate within transport can amount up to 50 percent of total transport.[49] The following Figure 56 displays a schematic diagram of the stylized transport sector representation in MESSAGEix. For Phase V, the input projections of future energy demand into the aggregated MESSAGEix model described here, have been produced by a detailed bottom-up model for the transport sector, MESSAGEix-Transport, which includes dynamics of modal share and vehicle choice (McCollum et al., 2017).

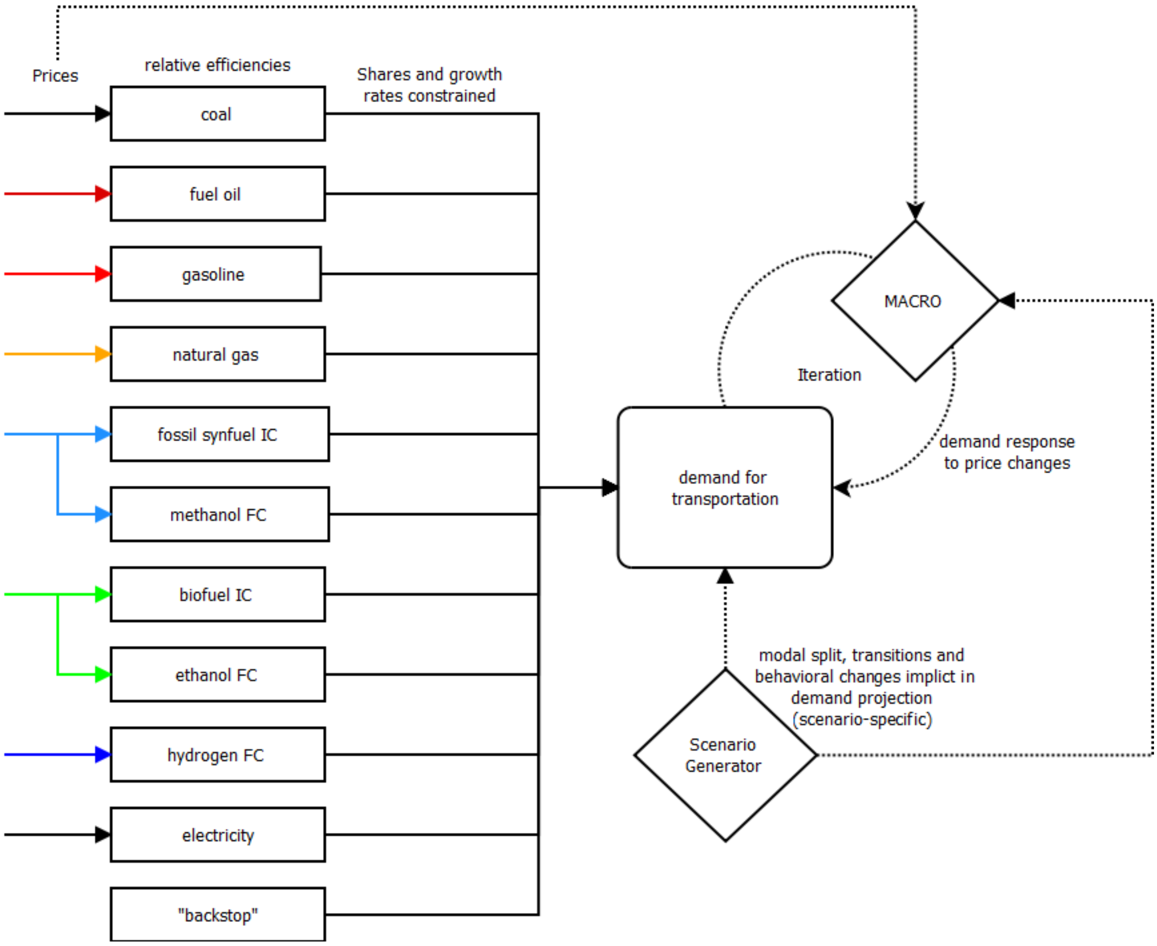

Figure 56 . Stylized transport sector representation in MESSAGEix

Residential and commercial sector. The residential and commercial sector in MESSAGEix distinguishes two demand categories: thermal and specific. *Thermal* demand, i.e., low temperature heat, can be supplied by a variety of different energy carriers, while *specific* demand requires electricity (or a decentralized technology to convert other energy carriers to electricity).

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the diffusion constraints are usually parametrized based on transport sector studies that analyse such developments and their feasibility in much greater detail.

[49] The quantitative translation of the storyline elements of SSP1, SSP2 and SSP3 in terms of electrification rate for transport can be found at https://docs.messageix.org/projects/global/en/latest/energy/enduse/transport.html (see also Fricko et al., 2017).

- The residential and commercial **thermal energy demand** includes fuel switching as the main option,[50] i.e., different choices about final energy forms to provide thermal energy. In addition to the alternative energy carriers that serve as input to these thermal energy supply options, their relative efficiencies also vary. For example, solid fuels such as coal have lower conversion efficiencies than natural gas, direct electric heating or electric heat pumps. Additional demand reduction in response to price increases in policy scenarios is included via the fuel switching option (due to the fuel-specific relative efficiencies) as well as via the linkage with the macro-economic model MACRO (see **Figure** 57 below).
- The residential and commercial **specific demand** (for electricity) can be satisfied either by electricity from the grid or with decentralized electricity generation options such as fuel cells and on-site combined heat and power (CHP).[51]

For Phase V, the input projections of future energy demand into the aggregated MESSAGEix model described here, have been produced by a detailed bottom-up model for the buildings sector, MESSAGEix-Buildings, which includes dynamics of stock turnover, building renovations, and fuel choice (Mastrucci et al., 2021).

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[50] To reflect limitations of switching to alternative fuels, as a result of limited infrastructure availability (e.g., district heating network) or some energy carriers being unsuitable for certain applications, share constraints of energy carriers (e.g., electricity), and energy carrier groups (e.g., liquid fuels) are used in the residential and commercial sector. In addition, as in the transport sector, the diffusion speed of alternative fuels is limited to mimic bottlenecks in the supply chains, not explicitly represented in MESSAGEix (e.g., non-energy related infrastructure).

[51] The quantitative translation of the storyline elements of SSP1, SSP2 and SSP3 in terms of electrification rate within the residential and commercial sectors can be found at https://docs.messageix.org/projects/global/en/latest/energy/enduse/transport.html (see also Fricko et al., 2017).

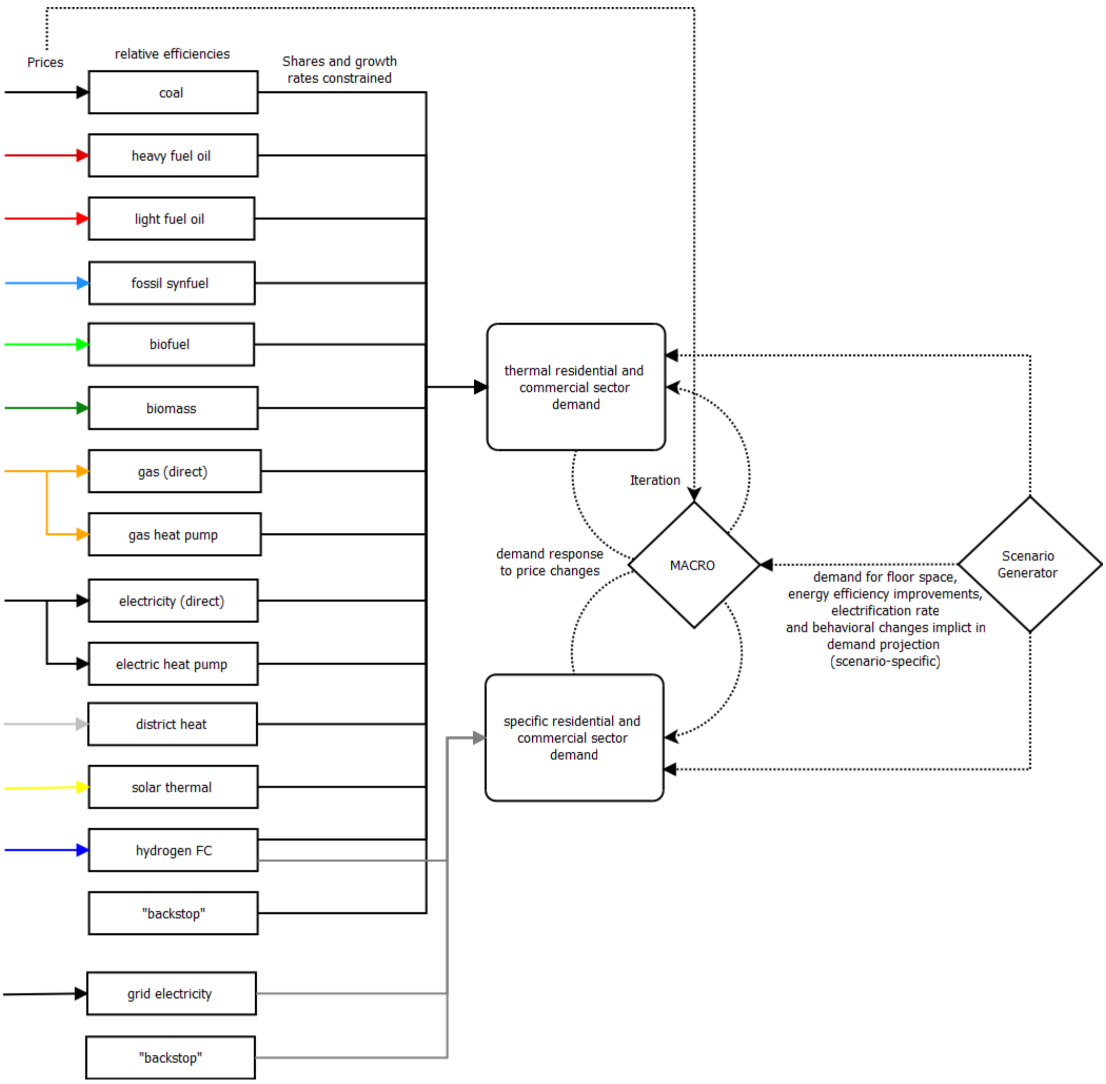

Figure 57 . Schematic diagram of the residential and commercial sector representation in MESSAGEix

Industrial sector (Materials). Differently from the two demand sectors above, the industrial sector in MESSAGEix used for the NGFS scenarios has more detailed representations of sub-sectors, which distinguish direct demands for industrial materials. We have representations for steel, cement, aluminium, petro-chemical (high-value chemicals, methanol, ammonia) industries. For the remaining industrial sub-sectors, MESSAGEix receives two energy demand categories: thermal and specific, linked to MACRO, similarly to the residential and commercial sectors. Figure 58 and Figure 59 provide schematic representations of the industrial sector in MESSAGEix. For a detailed documentation of the MESSAGEix-Materials model see Ünlü et al. (2024).

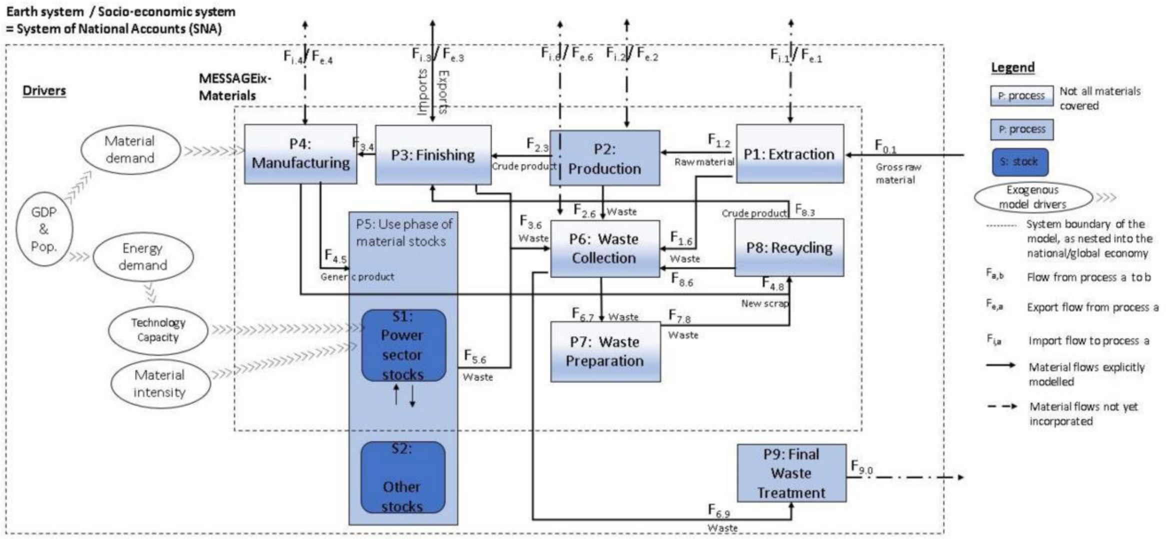

Figure 58 . Generic representation of an industry sector modelled in MESSAGEix

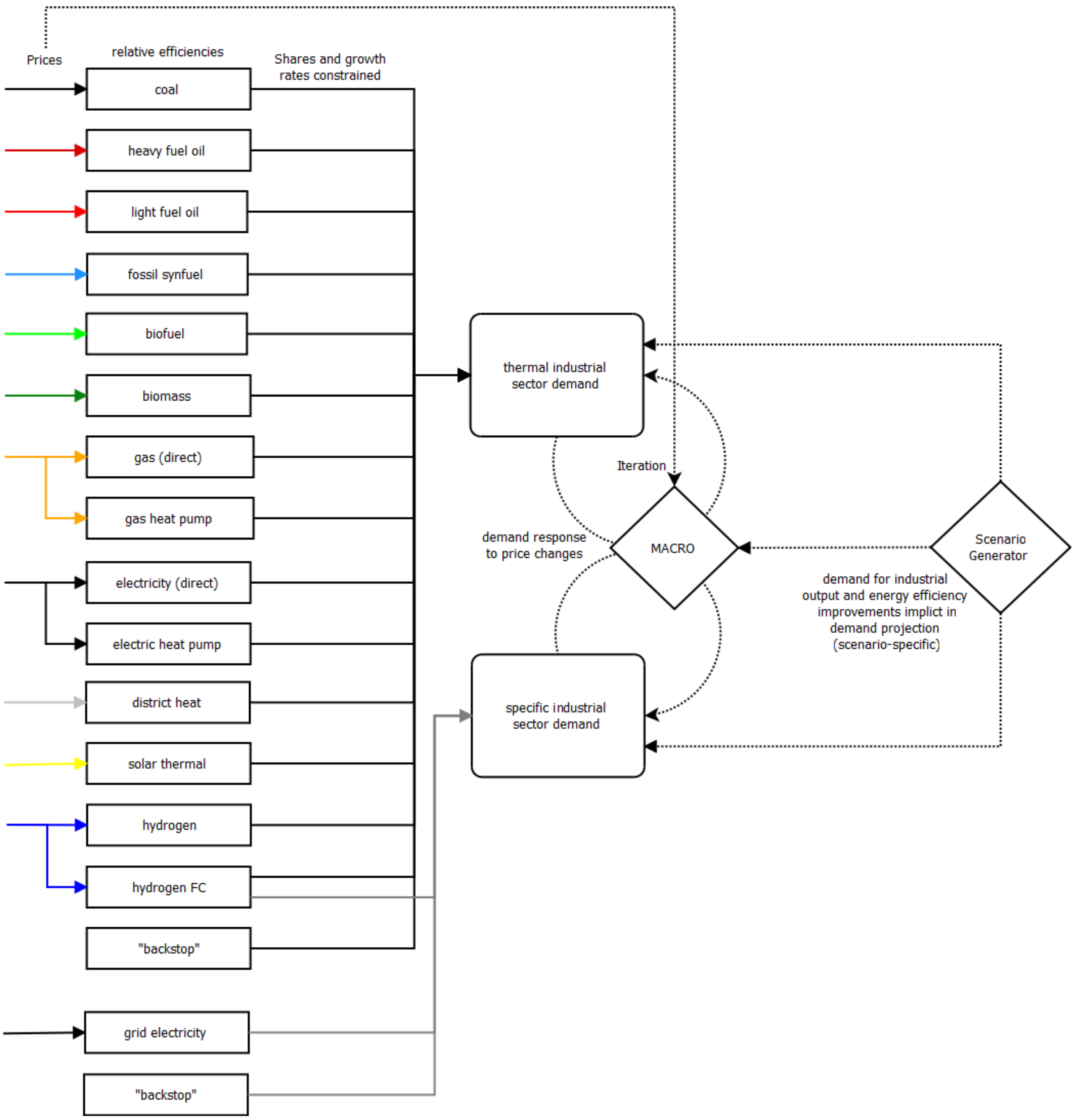

Figure 59 . Schematic diagram of the residual industrial sector representation in MESSAGEix

Technological change (MESSAGEix)

Technological change in MESSAGEix is generally treated exogenously.[52] The current cost and performance parameters, including conversion efficiencies and emission coefficients, are generally derived from the relevant engineering literature.

[52] However, some work endogenization of technological change has been introduced, e.g., the dependence of technology costs on market structure have been done with MESSAGEix (Leibowicz, 2015).

Technological costs vary regionally in all SSPs, reflecting marked differences in engineering and construction costs across countries observed in the real world.The regional differentiation of technology costs for the initial modelling periods are based on IEA WEO data (IEA, 2023) with convergence of costs assumed over time driven by economic development (GDP per capita).[53] Estimates for present-day technology costs are derived from the IEA World Energy Outlook (IEA, 2023), REN21 (2017), and IRENA (2019) . Fully learned-out technology costs are from the Global Energy Assessment (Riahi et al., 2012).

For technological diffusion, MESSAGEix tracks investments by vintage. In case of shocks (e.g., introduction of stringent climate policy), it is however possible to prematurely retire existing capital stock such as power plants or other energy conversion technologies and switch to more suitable alternatives.[54] Also, so called flexible or soft dynamic constraints have been introduced into MESSAGE (Keppo and Strubegger, 2010). These allow faster technology diffusion at additional costs and therefore generate additional model flexibility while still reducing the number of sudden policy reversals and penetration of technologies.[55]

Fuel blending (MESSAGEix):

Fuel blending is a common practice that allows the shared use of infrastructure by fuels with similar chemical attributes and thus their combined use at the secondary and final energy level, without requiring the consumer to adapt the power plant or end-use devices. Fuel blending in the global energy model is modelled for two distinct blending processes:[56] the blending of natural gas with other synthetic gases and. the blending of light oil with coal derived synthetic liquids.[57]

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[53] Generally, costs start out lower in the developing world and are assumed to converge to those of present-day industrialized countries as the former becomes richer throughout the century (thus, the cost projections consider both labour and capital components). This catch-up in costs is assumed to be fastest in SSP1 and slowest in SSP3 (where differences remain, even in 2100); SSP2 is in between.

[54] An important factor in this context that influences technology adoption in MESSAGEix are technology diffusion constraints. Technology diffusion in MESSAGEix is determined by dynamic constraints that relate the construction of a technology added or the activity (level of production) of a technology in a period t to construction or the activity in the previous period t-1 (Messner and Strubegger, 1995).

[55] More details on technological diffusion can be found at https://docs.messageix.org/projects/global/en/latest/energy/tech.html

[56] It is important to be able to track the use of blended fuels in the energy model for two reasons. Not all blended fuels can be used equally within all natural gas applications. For example, hydrogen mixed into the natural gas network is restricted to use in non-CCS applications only. Secondly, it is essential to keep track of where which of the blended fuels is being used in order to correctly report emissions and also to potentially restrict the degree to which fuels can be blended for individual applications. For example, natural gas end-use appliances may only be able to cope with a certain share of hydrogen while still guaranteeing their safety and longevity. Similarly, for policy analysis, it could be required that a certain minimum share of a synthetic gas is used sector specifically.

[57] For more details refer to https://docs.messageix.org/projects/global/en/latest/energy/fuel_blending.html

Add-on technologies (MESSAGEix):

Add-on technologies have a distinct formulation in MESSAGEix.[58] The formulation is used to represent two main types of technical extensions/options for technologies: a) additional modes of operation for a single or multiple technologies;[59] b) depicting emission mitigation options.[60] They are defined using the same parameters as any other technology. What makes a technology an add-on technology, is the fact that their activity is bound to the activity of one or more other technologies, the so-called parent technology. In particular, a single add-on technology can be coupled to the activity of multiple parent technologies. Furthermore, multiple add-on technologies can be linked to the activity of a single parent technology.

Energy demand (MESSAGEix):

Baseline energy service demands are provided exogenously to MESSAGEix, for the NGFS scenarios based on the latest SSP3 development. These baseline demands are adjusted endogenously based on energy price changes using the MESSAGEix-MACRO link. There are seven energy service demands that are provided to MESSAGEix, including:

1. Residential/commercial thermal
2. Residential/commercial specific
3. Industrial thermal
4. Industrial specific
5. Industrial feedstock (non-energy)
6. Transportation
7. Non-commercial biomass.

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[58] For more details please refer to https://docs.messageix.org/projects/global/en/latest/energy/fuel_blending.html

[59] For example, among the electricity generation technologies, a separate technology, known as a pass-out turbine, is considered an add-on technology. A pass out turbine allows select electricity generation technologies (i.e., parent technologies) the option to reduce their electricity output in favour of generating electricity and heat. The pass out turbine, which is a steam turbine in which a certain amount of the pressurized steam is passed out of the turbine for the purpose of heat production, is restricted to a share of the activity of the selected electricity generation technologies. Technically, this means that the electricity output of the electricity generation technologies remains unaltered, yet each unit of heat generated by the pass out turbine, requires a certain electricity input.

[60] For example, the possibility to retrofit existing fossil fuel-based energy generation technologies with CCS units. The separate CCS-retrofit unit is depicted in the model, constrained by the activity of the respective parent technologies. CCS-retrofits are available for: coal power plants including internal gasification combined cycle plants (IGCC), select gas power plants, biomass power plants, gas and coal fuel cells as well as for hydrogen and cement production. The share of the total emissions which can be reduced is limited to the technical feasibility and the combination of which mitigation technologies are employed.

For Phase V, these demands are derived from the separate sector-level modules (Building, Transportation) in the MESSAGE model. The Materials sector has been ran integrally with the supply side of the MESSAGE model. In general, the modeling of such sector-level demands can include both the top-down way (relating historical country-level GDP per capita to final energy and using projections of GDP and population to extrapolate demands into the future.[61, 62]) and the bottom-up part (bottom-up useful energy demands across higher-resolution regions).

Modelling policies (MESSAGEix):

MESSAGEix distinguishes between twelve global regions.[63] It can account for currently implemented and planned national policies - such as the nationally determined contributions (NDCs) as agreed upon in the Paris Agreement - at a lower geographical resolution[64], to be able to adequately account for future changes in the scenario development processes.[65] The targets formulated in national policies come in many different flavours. This applies to the sectors and gases covered by these policies, but it also applies to how the policies are defined and quantified. In MESSAGEix, four broad categories of policy types related to the different policies embedded in different scenarios are represented, each of which is translated into a set of constraints: (i) emission targets, (ii) energy shares, (iii) capacity or generation targets, (iv) macroeconomic targets such as energy-related taxes and subsidies.[66] As the year 2025 is rapidly approaching, the MESSAGE results for orderly 2C and 1.5C scenarios have been fixed to the NDC trajectory for the year 2025. More stringent mitigation can only happen after 2025 in these scenarios.

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[61] The sources for the historical and projected datasets are the following: Historical GDP (PPP) – World Bank (World Development Indicators, 2012); Historical Population – UN Population Division (World Population Projection, 2010); Historical Final Energy – International Energy Agency Energy Balances (IEA, 2012); Projected GDP (PPP) – Dellink et al. (2015), also see Shared Socio-Economic Pathways database (SSP scenarios); Projected Population – KC and Lutz (2014), also see Shared Socio-Economic Pathways database (SSP scenarios).

[62] More details on the techniques and variables used to compute energy demands at regional levels and convergence rates in final energy intensities across countries and sectors can be found at https://docs.messageix.org/projects/global/en/latest/energy/demand.html

[63] Regions in MESSAGEix-GLOBIOM are, in alphabetical order: China, Eastern Europe, Former Soviet Union, Latin America, Middle East and North Africa, North America, Other Pacific Asia, Pacific OECD, Rest Centrally Planned Asia, South Asia, South Asia, Sub-Saharan Africa, Western Europe.

[64] National-level NDCs and the detailed policy targets specified are. MESSAGE aggregates those national targets to the regional level and use it impose bounds in the scenario. Policies which cannot be directly applied as a constraint within a scenario can be reflected by adjusting MACRO related parameters to reflect improvements on the demand side.

[65] National-level NDCs and the detailed policy targets specified are taken into account. MESSAGE aggregates those national targets to the regional level and uses them to impose bounds within the scenario. Policies which cannot be directly applied as a constraint within a scenario can further be reflected by adjusting MACRO related parameters to reflect improvements on the demand side.

[66] A more detailed description of (i)-(vi) can be found under https://docs.messageix.org/projects/global/en/latest/energy/policy.html

Emission factors of air pollutants (GAINS):

The historical emissions of air pollutants and GHGs in the baseline are then calibrated by GAINS based on the data from international energy and industrial statistics, emission inventories, and other data supplied by individual countries.

Macroeconomic input variables (MACRO):

The main variables of the model are capital stock, available labour force (derived from population projections), and energy inputs, which together determine the total output of an economy according to a nested constant elasticity of substitution (CES) production function. The model's most important driving input variables are the projected growth rates of total labour, i.e., the combined effect of labour force and labour productivity growth, and the annual rates of reference energy intensity reduction, i.e., the so-called autonomous energy efficiency improvement (AEEI) coefficients. In the absence of price changes, energy demands grow at rates that are the approximate result of potential GDP growth rates, reduced by the rates of overall energy intensity reduction. The baseline GDP trajectory is calibrated to an externally provided GDP projection used in all IAMs for the NGFS scenarios, existing of a combination of IMF short term projections and longer-term SSP2 projections (Dellink et al., 2017). [67]

Land-use input variables (GLOBIOM):

Spatial resolution: In order to enable global bio-physical process modelling of agricultural and forest production, a comprehensive database has been built (Skalsky et al., 2008), which contains geo-spatial data on soil, climate/weather, topography, land cover/use, and crop management (e.g., fertilisation, irrigation). The data were compiled from various sources (FAO, ISRIC, USGS, NASA, CRU UEA, JRC, IFRPI, IFA, WISE, etc.) and significantly vary with respect to spatial, temporal, and attribute resolutions, thematic relevance, accuracy, and reliability. Data were harmonized into several common spatial resolution layers as well as country layers. At the global scale, five altitude classes, seven slope classes, and five soil classes have been included.[68]

Crop production: GLOBIOM directly represents production from three major land cover types: cropland, managed forest, and areas suitable for short rotation tree plantations. Crop production accounts for more than 30 of the globally most important crops. The average yield level for each crop in each country is taken from FAOSTAT.[69]

Livestock: GLOBIOM distinguishes between (i) livestock population, (ii) livestock products, (iii) livestock feed, (iv) grazing forage availability and (vi) livestock dynamics.[70]

Forestry: The forestry sector is represented in GLOBIOM with five categories of primary products (pulp logs, saw logs, biomass for energy, traditional fuel wood, and other industrial logs) which are consumed by industrial

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[67] Cfr. also for more details https://docs.messageix.org/projects/global/en/latest/macro.html

[68] For a more detailed description of how spatial resolution is modeled in GLOBIOM please refer to https://docs.messageix.org/projects/global/en/latest/land_use/spatial.html

[69] For more details on yield coefficients and crop management systems please refer to https://docs.messageix.org/projects/global/en/latest/land_use/crop.html

[70] A more detailed description of (i)-(vi) can be found under https://docs.messageix.org/projects/global/en/latest/land_use/livestock.html

energy, cooking fuel demand, or processed and sold on the market as final products (wood pulp and sawn wood). These products are supplied from managed forests and short rotation plantations.[71]

Land use change: Land cover types include cropland, grassland, short rotation plantations, managed forests, unmanaged forests, other natural land, other agricultural land, wetlands, and not relevant (bare areas, water bodies, snow and ice, and artificial surfaces). Economic activities are associated with the first four land cover types.[72]

Food demand: Food demand is endogenous in GLOBIOM and depends on population, gross domestic product (GDP) and own product price. Population and GDP are exogenous variables while prices are endogenous. The latter are computed via a simple demand system that uses as inputs population GDP per capita and income elasticities. It is further assumed that food demand in developed countries is more inelastic than in developing ones. In the latter the value of this elasticity is assumed to decrease with the level of GDP per capita to the price elasticity of the USA in 2000.[73]

Land-use emulator: The land-use emulator integrates a set of land-use scenarios into the MESSAGE*ix* energy system model (RES). Each land-use scenario represents a distinct land-use development pathway for a given biomass potential and carbon price. The biomass potentials for use in the energy sector are determined by the biomass price.[74] In addition, for each level of biomass potential, different carbon prices reflect the cost of mitigation for land-use related greenhouse gas (GHG) emissions. The combination of land-use pathways can therefore be depicted as a trade-off surface, illustrated for SSP2 (Fricko et al., 2017) in the figure below (**Figure 60**). The figure depicts global biomass potentials and respective GHG emissions at different carbon prices cumulated from 2010 to 2100.

[71] For further details on the estimation of harvesting costs and mean annual increments plese refer to https://docs.messageix.org/projects/global/en/latest/land_use/forest.html

[72] Cfr. also https://docs.messageix.org/projects/global/en/latest/land_use/land.html

[73] More details on data sources and the formulas used for computing price elasticities can be found under https://docs.messageix.org/projects/global/en/latest/land_use/food.html

[74] At lower biomass prices, biomass mainly stems from forest residues, for example from sawmills or logging residues. With increasing prices, land-use will be shifted to make room for fast-rotation tree plantations, purposely grown for use in energy production which may cause indirectly through increased competition with agricultural land deforestation of today's forest. At very high prices, roundwood will be harvested for energy production (for further details see Forestry) competing with material uses.

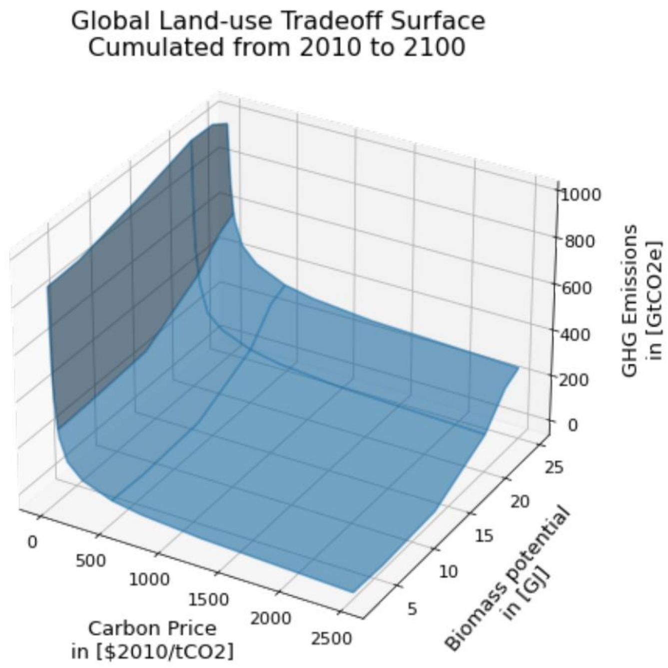

Figure 60. Land-Use Pathway Trade-Off Surface for SSP2

From this trade-off surface it possible to deduct that when climate policy scenarios are run in MESSAGE*ix*, the land-use pathways will be chosen such that the optimal balance between the land-use related emission and biomass use in the energy system is obtained.

Emissions input variables (MAGICC):

MAGICC receives its main inputs, GHG and aerosol emissions, from the MESSAGE*ix* energy system RES (i.e., CO_2 emissions, non-CO_2 GHGs, air pollution) and from GLOBIOM (crop sector emissions, livestock emissions, land use change emissions).

4. Key model outputs

Description of key output variables/sectors

Output variables are available for the World aggregate and for 12 regions (China, Eastern Europe, Former Soviet Union, Latin America and the Caribbean, Middle East and North Africa, North America, Other Pacific Asia, Pacific OECD, Rest Centrally Planned Asia, South Asia, Sub-Saharan Africa, Western Europe). Within these regions data are further downscaled at country-level. Data are provided in 5-year steps until 2060 and 10-year steps thereafter until 2110. The output variables available for MESSAGEix-GLOBIOM are denoted by “M” in the last column of the tables presented in Appendix.

5. What is new in the 2024 edition?

What is new in the 2024 edition?

- **New reference year**. The reference year in the MESSAGE model in this edition has been shifted to 2020 from 2015. We calibrated the model inputs in the year 2020 to IEA World Energy Balances v2022 and ran the model with the year 2025 as the first model year.

- **New socio-economic drivers.** The most recently updated drivers of the SSPs (GDP and population) are used in this phase to have the most up-to-date projection of future growth patterns across world regions. This ensures that our analysis is based on the latest available information, thereby enhancing the accuracy of the projection and the comparability with the other long-term scenario model teams. Correspondingly, the iterations between MESSAGE and its aggregated macro-economic model MACRO, result in nuanced variations in the growth patterns compared to the previous phase at both the sectoral level and regional level.

- **New demand projections**. Different from the last phase, where a temporary projection considering COVID impacts was utilized in the near-term energy demand and then an extrapolating projection approach was applied for the long-term energy demand, the energy demands in this phase are derived from the separated sector-level modules (MESSAGE Building, Materials, Transport).

  Building: MESSAGEix-Building applied a thorough mapping to feed the demand projection from ACCESS (providing the projection of cooking energy demand and appliance energy demand), STURM (providing the building stock turnover and building material demand projection), and CHILLED (the projection of cooling and heating energy demand; Mastrucci et al., 2021) across multiple building user types to MESSAGEix technologies.

  Materials: MESSAGEix-Materials (Ünlü et al., 2024) is integrated as the default model feature of MESSAGE in this phase. Its demand projections include both endogenous parts (power-sector-induced material demand, recyclable scrap/furnace slags, etc.) and exogenous parts (steel, cement, aluminum, etc. best-fitting curve driven by per-capita GDP). Other endogenized material demand projections include: Nitrogen fertilizer demand projection using inputs from GLOBIOM, bulk material demand projections using inputs from MESSAGEix-Buildings, and methanol demand partially determined by feedstock demand for methanol-to-olefins production route as well as synthesis of transport fuels (MTBE and biodiesel).

  *Transport***:** MESSAGE-transport applied an improved approach for the projection of passenger distance traveled in this phase (less sensitive to the small changes in the fixed_GDP) which directly affects the energy service demands in multiple transportation modes. Decisions on fuel choice are still taken in the main version of the MESSAGEix model.

- **More available options for techno-economic assumptions.** The techno-economic assumptions (extraction costs, investment costs, fixed costs, operation & maintenance costs, and overall potentials) for fossil fuels, nuclear, and renewable energies have been updated according to the SSP development processes. Also, we updated the storage and integration costs of renewables in the scenario assumption.

  Multiple approaches to represent cost reduction over time are available in this phase. The cost trajectories are projected by assuming costs decrease exponentially with multiple available options for a reference region, from a base year, by a convergence year, or with or without dynamic fix costs across vintage years.

- **Non-CO2 GHG emissions and land-use matrix.** The re-mapping and downscaling for the non-CO2 GHG emissions data inputs were conducted when linking GAINS and MESSAGE (emissions coefficients and MACs from MESSAGE SSP updates; pollutant emissions coefficients from GAINS).

  The land-use matrix (for each level of biomass supply potential, the model looks up different carbon prices in this matrix that reflect the cost of mitigation for land-use related GHG emissions) that links GLOBIOM and MESSAGE is also updated in the baseline scenario.

- **Updated policy assumptions.** Policy details and assumptions for the Current Policies and NDC scenarios are updated to include relevant information up to the cut-off date of March 2024.

- **Other protocol-specific updates.** Other updates for protocol-specific assumptions (e.g., the constraints on the BECCS availability by 2050, the constraints on international gas imports/exports in regions such as the EU and Russia) are also included. Additionally, we kept the regionally different carbon price reporting method based on regionally defined emission trajectories. The regional prices are produced consistent with mitigation at the regional level instead of being derived from the global targets.

Scenario implementation: differences from other NGFS models

- Net-zero targets
  - Translation of national net-zero targets (CO2 and GHG) to regional (R12) level
    - Countries *without* net-zero pledges can keep their emissions amount at the base year in the region.
    - Countries *with* net-zero pledges collectively set the regional emission bounds, which are constructed by linearly interpolating aggregated country-level target mitigations in different target years.
  - We applied a very low overshoot in the Net Zero 2050 scenario, as well as in its paired Low Demand scenario (where we applied the lower numbers of useful energy under the Low Demand assumption and the Net Zero 2050 assumption).
- NDC targets
  - The emission constraint in 2030 under the NDC scenario was relaxed to 883 TCE in Sub-saharan Africa and 1387 TCE in Latin America and the Caribbean to have feasible solutions.
- Model period interpretation
  - MESSAGEix model year represents the period between the given and the previous model year, e.g., 2050 is for 2046-2050 (with 5-year interval).
  - This also affects the interpretation of net-zero target years in MESSAGE scenarios (i.e., the reported 2050 value is often not yet fully zero, because it also includes the years 2046-2049 which had actual emissions).

Other notes

- Post-processing of investment variables

  The post-processing of investment variables from all participating models would require the infill of extraction investment data, which is not available in some models. We applied the average of all models for models with such missing values. Therefore, the patterns of overall investment level before and after processing may differ in the NGFS 2024 edition compared to the previous edition.

- Commodity prices

  The prices of primary energy commodities (e.g., coal, gas, oil, etc.) are the prices at a global level before processing with carbon prices, taxes, and transport to users.

Module 4: IAM – GCAM

1. Non-technical summary

The **G**lobal **C**hange **A**nalysis **M**odel (**GCAM**) is a global market equilibrium model, that combines economic, energy, land use, and climate systems to analyse the interactions between human activities and global environmental changes. It is designed to assess the impacts of various policy scenarios and technology options on energy use, land use change, greenhouse gas emissions and climate change. GCAM is an **I**ntegrated **A**ssessment **M**odel (**IAM**) applied to the NGFS phase V scenarios.

Key model inputs into GCAM's modules:

- Macroeconomy: population; labour productivity growth rate; labour force participation rate; base year GDP.
- Earth system: atmospheric CO_2 concentrations; radiative forcing of emissions; global mean temperature change; air-land carbon fluxes; air-sea carbon fluxes.
- Land use: historical land use and land cover; vegetation carbon density; soil carbon density.
- Water: crop, electricity, livestock, primary energy, and industry water coefficients; crop and electricity production; crop, electricity, livestock, and primary energy production; industry output.
- Emissions: emissions and activity data by sector; energy production and consumption; agricultural production; land use and land use change.
- Marketplace: supply of and demand for all energy commodities; supply of and demand for all agriculture and land-based commodities; supply of and demand for all water types.

Key model outputs of GCAM for each NGFS phase V scenario and horizon year:

- Emissions: emissions (CO_2 and non-CO_2); resource production emissions (CO_2 and non-CO_2); land use change emissions; CO_2 sequestration.
- Land use: land use and land cover; land use change emissions; change in above and below ground carbon.
- Prices: energy; agriculture and forestry; water; fish.
- Quantity: energy production and consumption; agriculture production and consumption; water withdrawals; consumption and supply.

Key updates: The 2024 edition of GCAM scenarios used for the NGFS Phase V are done with the same structural model version than the 2023 edition. While GCAM v6.0 used here included a number of updates: a new residential floorspace expansion model; bio-energy updates; reset of default hotelling rate for climate stabilization scenarios to 3%; splitting out six detailed industrial sectors from the aggregate industry sector; updated hydrogen production, distribution, and end-use technologies; a new protected lands definition; expanded crop commodities; HFC MAC curve fixes; new pollutant emissions controls, various input assumptions have been adjusted and listed in the next section.

2. What is new in the 2024 edition of scenarios?

1. GDP and population projections updated based on the new Share Socioeconomic Pathways (SSPs)
2. Constraied CCS overall, which led to considerably reduced fossil CCS use, and further slight reduction of bioenergy use with CCS
3. More realistic current policy representations for different regions (examples include the restart and planned growth of nuclear power in Japan, limiting addition of new nuclear and coal power generation and additional use in 'other industry' sectors in the USA and EU-15 regions, limits on coal power generation increases in South America_Southern, Africa_Southern & Southeast Asia, improvements in projection of concentrated solar power relative to photovoltaics etc.)
4. A revised marginal abatement cost curve and revised baseline projections for Methane emissions from the agriculture sector, as well as revised marginal abatement cost curves for methane emissions from fossil fuel production and use
5. A shift from use of traditional biomass to cleaner fuels in the residential buildings sector
6. Smoothing of land use change CO_2 emissions

3. Overview of model scope and methods

GCAM has been under development for over 40 years. Work began in 1980 with the work first documented in 1982 in working papers (Edmonds and Reilly, 1982a,b,c) and the first peer-reviewed publications in 1983 (Edmonds and Reilly, 1983a,b,c).

Throughout its lifetime, GCAM has evolved in response to the need to address an expanding set of science and assessment questions. The original question that the model was developed to address was the magnitude of mid-21st-century global emissions of fossil fuel CO_2. Over time GCAM has expanded its scope to include a wider set of energy producing, transforming, and using technologies, emissions of non-CO_2 greenhouse gases, agriculture and land use, water supplies and demands, and physical Earth systems. GCAM has been used to produce scenarios for national and international assessments ranging from the very first IPCC scenarios through the present Shared Socioeconomic Pathways(Calvin et al, 2017). GCAM is increasingly being used in multi-model, multi-scale analysis, in which it is either soft- or hard-coupled to other models with different focuses and often greater resolution in key sectors. For example, a range of downscaling tools have been developed for use with GCAM to be able to obtain land and water outputs at a grid resolution. Similarly, it has been coupled to a state-of-the-art Earth system model(Collins *et al*, 2015).

GCAM includes two major computational components: a data system to develop inputs and the GCAM core. GCAM takes in a set of assumptions and then processes those assumptions to create a full scenario of prices, energy and other transformations, and commodity and other flows across regions and into the future. The interactions between these different systems all take place within the GCAM core; that is, they are not modelled as independent modules, but as one integrated whole.

While the agents in the GCAM model are assumed to act to maximize their own self-interest, the model as a whole is not performing an optimization calculation. In fact, actors in GCAM can make decisions that "seemed like a good idea at the time", but which are not optimal from a larger social perspective and which the decision maker would not have made had the decision maker known what lay ahead in the future. For example, the model's actors do not know about future climate regulations and could install fossil fuel power in the years preceding the implementation of such policies.

Key scenario assumptions for the GCAM core:

- **Macroeconomy**: population, labour participation, and labour productivity.
- **Energy technology characteristics**: e.g., costs, performance, water requirements, GHG and other emissions coefficients.
- **Agricultural technology characteristics**: e.g., crop yields, costs, carbon contents, water requirements, fertiliser requirements.
- **Energy and other resources**: e.g., capital/extraction costs and availability of fossil fuel resources and reserves, wind, solar, uranium, groundwater.
- **Policies**: e.g., wide range of potential regulatory and fiscal policies including emissions constraints, coal phaseout, renewable portfolio standards, EV targets, fuel efficiency standards, etc.

Key scenario results from the GCAM core:

- **Energy system**: energy demands, flows, technology deployments, international trade, and prices throughout the energy system.
- **Agriculture and land use**: prices, supplies, and consumption of all agricultural and forest products, land use and land use change.
- **Water**: water demands and supplies for all agricultural, energy, and household uses.
- **Emissions**: 24 greenhouse gases and short-lived species: CO_2, CH_4, N_2O, halocarbons, carbonaceous aerosols, reactive gases, sulphur dioxide.

GCAM is an integrated, multi-sector model that explores both human and Earth system dynamics. The role of models like GCAM is to bring multiple human and physical Earth systems together in one place to shed light on system interactions and provide scientific insights that would not otherwise be available from the pursuit of traditional disciplinary scientific research alone. As shown in **Figure 61**, GCAM is constructed to explore these interactions in a single computational platform with a sufficiently low computational requirement to allow for broad explorations of scenarios and uncertainties. Components of GCAM are designed to capture the behavior of human and physical systems, but they do not necessarily include the most detailed process-scale representations of its constituent components. On the other hand, model components in principle provide a faithful representation of the best current scientific understanding of underlying behavior.

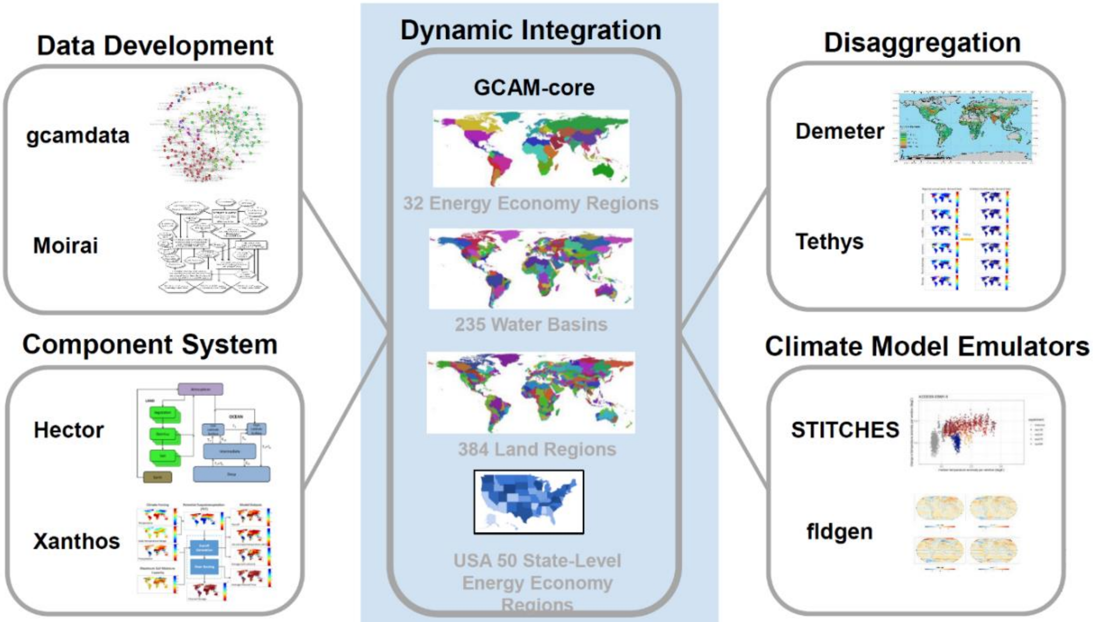

Figure 61. GCAM Model Integration

GCAM allows users[75] **to explore what-if scenarios, quantifying the implications of possible future conditions.** These outputs are conditional forecasts contingent on the validity of input assumptions; they are a way of analysing the potential impacts of different assumptions about future conditions **Figure 62** illustrates how GCAM reads in external "scenario assumptions" about key drivers (e.g., population, economic activity, technology, and policies) and then assesses the implications of these assumptions on key scientific or decision-relevant outcomes (e.g., commodity prices, energy use, land use, water use, emissions, and concentrations).

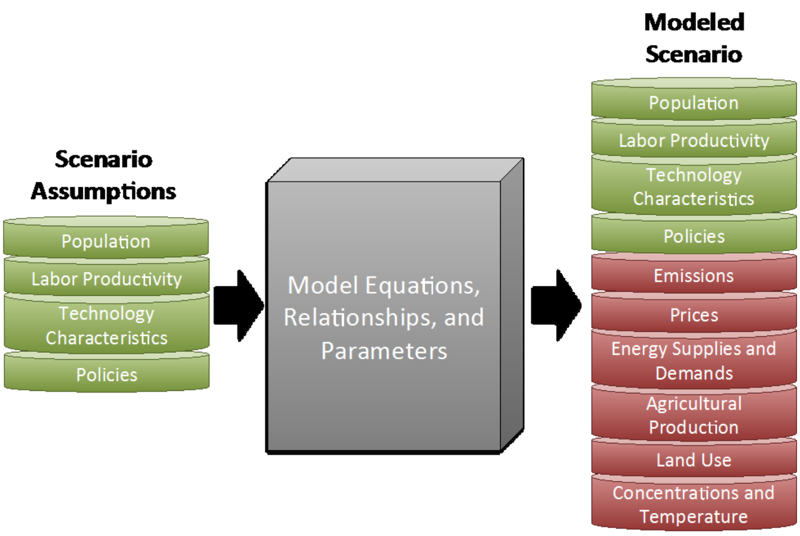

Figure 62. Use of scenario assumptions to produce fuller, modelled scenarios

The GCAM core is the component of the model in which economic decisions are made (e.g., land use and technology choices), and in which dynamics and interactions are modelled within and among different

75 In this context GCAM users are equivalent to GCAM-based NGFS climate policy scenario implementations whose outputs are provided by the NGFS Scenario Explorer.

human and Earth systems. **Supplied with input information from the GCAM data system, the GCAM core is the heart of the dynamic character of GCAM**. GCAM takes in a set of assumptions and then processes those assumptions to create a full scenario of prices, energy and other transformations, and commodity and other flows across regions and into the future. GCAM represents five different interacting and interconnected systems. The interactions between these different systems all take place within the GCAM core; that is, they are not modelled as independent modules, but as one integrated whole. The five systems in the GCAM core are as follows (see also Figure 63 for a schematic visualization):

- Macroeconomy: This module takes population and labor productivity assumptions as inputs and produces regional gross domestic product and regional populations as inputs for the other modules. The macroeconomy sets the scale of economic activity in GCAM.
- Energy systems: The energy system is a detailed representation of the sources of energy supply, modes of energy transformation, and energy service demands such as passenger and freight transport, industrial energy use across subsectors, and residential and commercial energy service demands. The module reports demand for, and supply of, energy forms, as well as emissions of greenhouse gases, aerosols, and other short-lived species. Energy systems demand bioenergy from agriculture and land systems and water from water systems.
- Agriculture and land systems: The agriculture and land systems provide information about land use, land cover, carbon stocks and net emissions, the production of bioenergy, food, fibre, and forest products. Demands are driven by the size of the population, their income levels, and commodity prices. The module reports demand for and supply of agricultural and other commodities, land and emissions of greenhouse gases, aerosols, and other short-lived species. The demand for bioenergy is a derived demand by the energy sector. Agriculture and land systems demand water from water systems.
- Water systems: The water module provides information about water withdrawals and water consumption for energy, agriculture, and municipal uses.
- Physical Earth system: The physical Earth system in GCAM is modelled using Hector, a physical Earth system emulator that provides information about the composition of the atmosphere based on emissions provided by the other modules, ocean acidity, and climate.

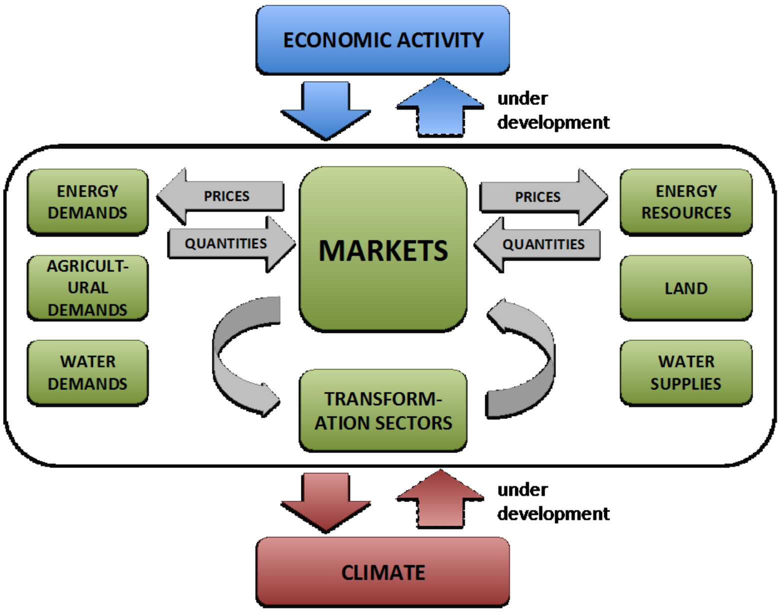

Figure 63. Conceptional schematic of GCAM core operation

The exact structure of the model explored in the GCAM core – for example, the number of regions and technologies – is data driven. In all cases, the GCAM core represents the entire world, but it is constructed with different levels of resolution for each of these different systems. In release version 6.0 of GCAM (which is used for the NGFS phase IV scenarios), the energy-economy system operates at **32 regions** globally, land is divided into **384 subregions**, and water is tracked for **235 basins** worldwide. The Earth system module operates at a global scale.

The core operating principle for GCAM is that of market equilibrium. Representative agents in GCAM use information on prices, as well as other information that might be relevant, and make decisions about the allocation of resources. These representative agents exist throughout the model, representing, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who must allocate land among competing crops within any given land region. Markets are how these representative agents interact with one another. Agents indicate their intended supply and/or demand for goods and services in the markets. GCAM solves for a set of market prices balanced supply and demand in all these markets across the model. The GCAM solution process is the process of iterating on market prices until this equilibrium is reached. Markets exist for physical flows such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

Explainer box 4

What is an example for the market equilibrium mechanism in GCAM?

- **In any single model period, GCAM derives a demand for natural gas starting with all the uses to which natural gas might be put,** such as passenger and freight transport, power generation, hydrogen production, heating, cooling, and cooking, fertilizer production, and other industrial energy uses.
- **Those demands depend on the external assumptions about,** for example, electricity generating technology efficiencies, but also on the price of all the commodities in the model. GCAM then calculates the amount of natural gas that suppliers would like to supply given their available technology for extracting resources and the market price. The model gathers this same information for all the commodities and then adjusts prices so that in every market during that period supplies of everything from rice to solar power match demands.

GCAM is a dynamic recursive model, meaning that decision-makers do not know the future when planning today. After it solves each period, the model then uses the resulting state of the world, including the consequences of decisions made in that period – such as resource depletion, capital stock retirements and installations, and changes to the landscape – and then moves to the next time step and performs the same exercise. For long-lived investments, decision-makers may account for future profit streams, but those estimates would be based on current prices.

4. Key model inputs

The macroeconomy component of GCAM 6.0 sets the scale of economic activity and associated demands for model simulations. Assumptions about population and per capita GDP growth for each of the 32 geopolitical regions together determine the gross domestic product (GDP). GDP and population both can drive the demands for a range of different demands within GCAM. Population and economic activity are used in GCAM through a one-way transfer of information to other GCAM components (see below **Key model outputs** on Key model outputs for explanation on the reported GDP for scenarios, which is different to the one described here used for the demand determination). For example, neither the price nor quantity of energy nor the quantity of energy services provided to the economy affect the calculation of the principal model output of the GCAM macroeconomic system, GDP (due to unidirectionality between the macro and energy modules). Changes in future per capita GDP and population will affect the final demand for energy, food, and forestry. For example, increases in population will increase regional consumption proportionally, while changes in per capita GDP affect consumption through income elasticities. Thus, different assumptions of future GDP and population growth across different socioeconomic scenarios may play key roles in determining an alternative future. In addition, regional heterogeneity in future GDP and population growth, leading to heterogeneous regional demand growth, is also a critical driver to future changes in regional supply, biophysical responses, and trade patterns. *Table 6* shows the inputs for the economic module.

Table 6. Inputs required by the economic module

Name	Resolution
Population	Region and year
Labour productivity growth rate	Region and year
Labour force participation rate	Region and year
Base year GDP	Region

The **Earth system model** (i.e., carbon-cycle climate module) Hector is the default climate model within GCAM (Hartin *et al*. ,2015). Users still have the option of running MAGICC in GCAM version 5.1, but this option is no longer supported beginning with version 6.0 of GCAM.[76] Hector (v2.5.0) runs essentially instantaneously while still representing the most critical global-scale earth system processes. This model has a three-part main carbon cycle: a one-pool atmosphere, three-pool land, and four-pool ocean. The model's terrestrial carbon cycle includes primary production and respiration fluxes, accommodating arbitrary geographic divisions into, e.g., ecological biomes or political units. Hector actively solves the inorganic carbon system in the surface ocean, directly calculating air-sea fluxes of carbon and ocean acidity. Hector reproduces the global historical trends of atmospheric CO_2, radiative forcing, and surface temperatures. The model simulates all four Representative Concentration Pathways (RCPs) with equivalent rates of change of key variables over time, consistent with compared to historical observations, MAGICC, and models from the Coupled Model Intercomparison Project (CMIP5). Currently the GCAM sectors interact with Hector via emissions. At every time step, emissions from GCAM are passed to Hector. Hector converts these emissions to concentrations when necessary, and calculates

[76] This contrasts with MESSAGE-GLOBIOM and REMIND-MAgPIE which use MAGICC as the climate model (see dedicated box in module 1).

the associated radiative forcing, as well as the response of the climate system and earth system (e.g., temperature, carbon-fluxes, etc.).

Economic land use decisions in GCAM are based on a probabilistic, logit model of land-allocation based on relative expected profitability of using land for competing purposes. In GCAM, there is a distribution of profit behind each competing land use within each of the 384 land-use regions. The share of land allocated to any given use is based on the probability that that use has the highest profit among the competing uses.

The way land types are nested in GCAM, in combination with the logit exponents[77] used, determines the substitutability of different land types in the model in future periods. **Figure 64** shows a nesting diagram of land with a subregion.

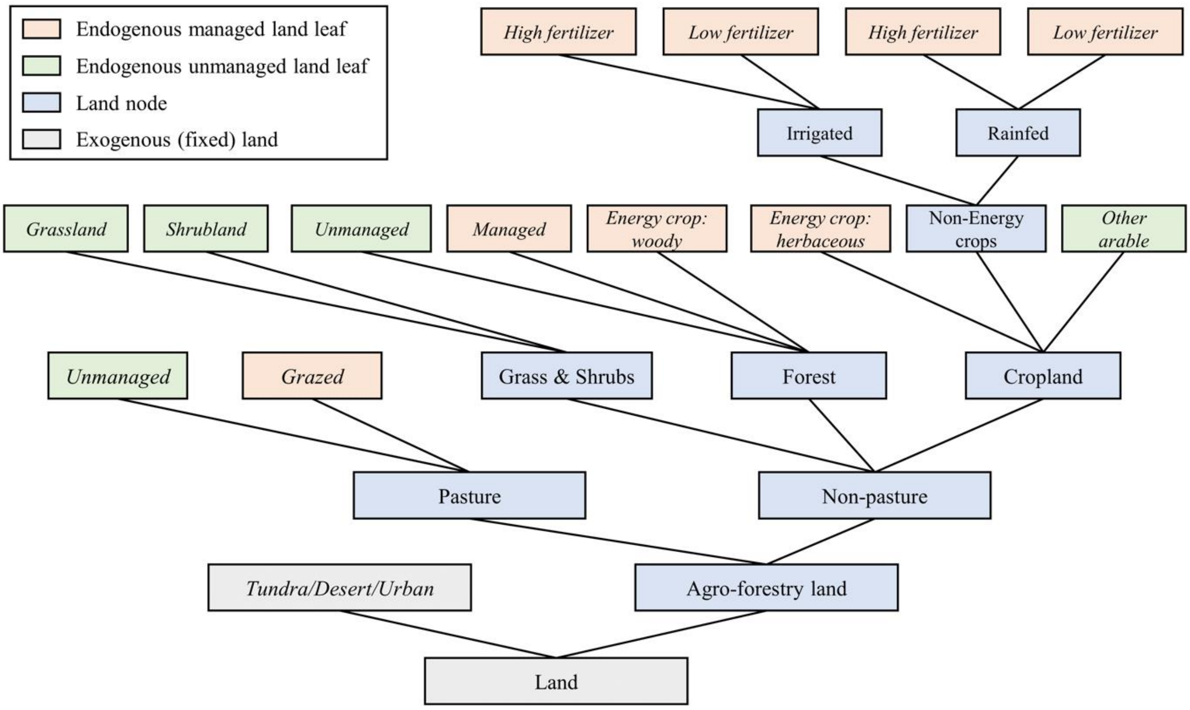

Figure 64. Agriculture and land use (AgLU) land nesting structure

The following **Table 7** shows the inputs relevant for the land-use module.

Table 7. Inputs required by the land allocation module[78]

Name	Resolution
Historical land use and land cover	By GLOBE Land Unit (GLU), land type, and year
Vegetation carbon density	By GLU and land type

[77] GCAM requires the user to specify the logit exponents that determine the substitutability between different leaves and nodes in the land model.

[78] Note that this table differs from **Table 33,** which lists all external inputs to the land module, including information passed from other modules. This table shows the variables used in the GCAM simulation after processing.

Name	Resolution
Soil carbon density	By GLU and land type
Mature age	By GLU and land type
Soil time scale	By geopolitical region and land type
Value of unmanaged land	By GLU
Profit rate of managed land	By GLU
Logit exponents	By GLU and land node

In the **water module**, three distinct sources of fresh water are modelled: renewable water, non-renewable groundwater, and desalinated water. Renewable water is water that is replenished naturally by surface runoff and subsurface infiltration and release (groundwater recharge). Non-renewable groundwater is water from aquifers whose recharge is sufficiently low as to be depletable on a human time scale and which have replenishment timescales greater than 100 years. Renewable water and non-renewable groundwater are separately modelled for each basin. Desalinated water of brackish groundwater and seawater is available as an additional source of freshwater within each basin and for municipal and industrial end-use demands for water.

Conveyance losses and improvements to water distribution efficiencies are included in the water distribution sectors. Conveyance losses for irrigated water use has been included and differentiated for each GCAM region. Conveyance losses/efficiencies for GCAM regions are derived from country level data (From Rohwer et al., 2007) and are the weighted mean of the original country level data weighted by irrigated harvested area. Water supplies and demands at each basin are balanced through a market mechanism in which prices for water (shadow price) are adjusted until water demands are constrained to available supply. The following Table 8 shows the inputs relevant for the water demand module.

Table 8. Inputs required by the water demand module

Name	Resolution
Crop water coefficients	GLU, GCAM commodity, water type (consumption, withdrawals, biophysical consumption) and year
Crop production	GLU, GCAM commodity, and year
Electricity water coefficients	GCAM region, technology, water type (consumption, withdrawals) and year
Electricity production	GCAM region, technology, and year
Livestock water coefficients	GCAM region, livestock type, water type (consumption, withdrawals, biophysical consumption) and year
Livestock production	GCAM region, livestock type, and year
Primary energy water coefficients	GCAM region, fuel, water type (consumption, withdrawals, biophysical consumption) and year
Primary energy production	GCAM region, fuel, and year
Industry water coefficients	GCAM region, water type (consumption, withdrawals, biophysical consumption) and year

Name	Resolution
Industry output	GCAM region and year
Income and price elasticity	By region, demand, and year
GDP per capita	By region and year
Population	By region and year

GCAM's Energy Module tracks production of primary energy forms, their transformation into end-use fuels and electricity, and the production of energy services such as heating, cooling, passenger and freight transport, and process heat. **Figure 65** gives an overview of the GCAM energy system.

GCAM models primary energy production for both depletable and renewable energy forms. GCAM models depletable resources (oil, unconventional oil, natural gas, coal, and uranium) using graded resource supply curves. Production of depletable resources occurs out of reserves. Resources are transformed to reserves based on the cost of finding and bringing resources into production. GCAM's renewable resources include onshore wind, offshore wind, solar, geothermal, hydropower, and biomass; some regions are also assigned a "traditional biomass" resource. In general, the costs of producing electricity from renewable energy forms consist of the sum of the resource costs, the technology costs[79], and in some cases, backup-related costs. In the energy transformation module, the competition between subsectors takes place according to a calibrated logit sharing function[80]. Broadly, the energy transformation sectors in GCAM consist of all supply sectors between the primary energy resources and the final energy demands (i.e., buildings, industry, and transportation).

The main **energy transformation** sectors are electricity, refining, gas processing, hydrogen production, and district services. Within the subsectors, there may be multiple competing technologies, where technologies typically represent either different efficiency levels, and/or the application of carbon dioxide capture and storage (CCS). Most of the economic activities represented in GCAM present a choice among several ways to produce the result of the activity. Examples of these choices include choosing between different fuels or feed stocks, between different technologies, and between transportation modes. In some cases, the choice is between different uses of a limited resource, such as when land area is allocated to different uses. Choice in GCAM is based on a single numerical value that orders the alternatives by preference (i.e., a choice indicator). In practice the choice indicator is either cost or profit rate, though other indicators are possible in principle. In cases where multiple factors influence a choice, such as passenger transportation (where faster modes are more desirable), the additional factors are converted into a cost penalty and added to the basic cost to produce a single indicator that incorporates all the relevant factors. More information in this GCAM technical document.

[79] The cost of a technology in any period depends on its exogenously specified non-energy cost, its endogenously calculated fuel cost, and any cost of emissions, as determined by the climate policy. The first term, non-energy cost, represents capital, fixed and variable operating and maintenance costs incurred over the lifetime of the equipment (except for fuel or electricity costs). For electricity technologies, GCAM reads in each of these terms and computes the levelized cost of energy within the model. For example, the non-energy cost of coal-fired power plant is calculated as the sum of overnight capital cost (amortized using a capital recovery factor and converted to dollars per unit of energy output by applying a capacity factor), fixed and variable operations and maintenance costs. The second term, fuel or electricity cost, depends on the specified efficiency of the technology, which determines the amount of fuel or electricity required to produce each unit of output, as well as the cost of the fuel or electricity.

[80] See the **Key model inputs**for explanations.

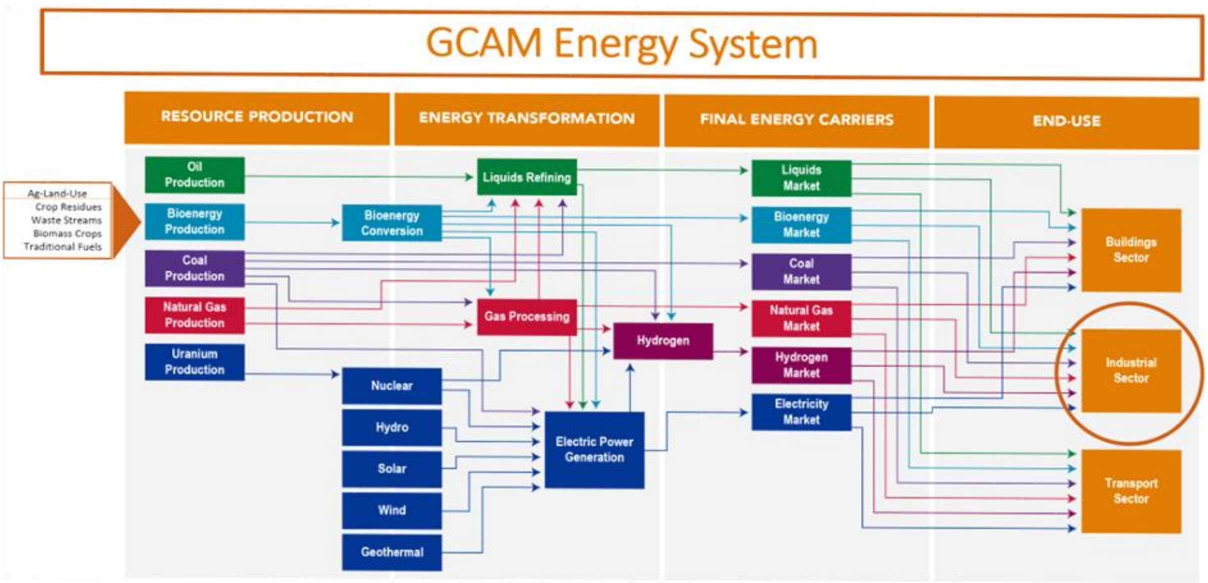

Figure 65. GCAM energy system

GCAM projects **emissions** of a suite of greenhouse gases (GHGs) and air pollutants: CO_2, CH_4, N_2O, CF_4, C_2F_6, SF_6, HFC23, HFC32, HFC43-10mee, HFC125, HFC134a, HFC143a, HFC152a, HFC227ea, HFC236fa, HFC245fa, HFC365mfc, SO_2, BC, OC, CO, VOCs, NO_x, NH_3. Future emissions are determined by the evolution of drivers (such as energy consumption, land use, and population), technology mix, and abatement measures. How this is represented in GCAM varies by emission type. The following **Table 9** shows the inputs relevant for the emissions module.

Table 9. Inputs to the emissions module

Name	Resolution
Emissions data by sector for non-CO2	Country, sector, fuel, gas, year
Activity data from GCAM by sector	By region, year, sector, fuel
Marginal abatement cost (MAC) assumptions	By region, sector, year
Energy production (for emissions driven by production)	By region, technology, year
Energy consumption (for emissions driven by consumption)	By region, technology, year
Agricultural production	By GLU, technology, year
Land use and land use change	By GLU, type, year

GCAM operates by determining a set of prices that ensure supply is equal to demand for all time steps. The **marketplace** collects the supplies and demands and uses solver algorithms to determine those prices. Given a carbon price, the resulting emissions will vary depending on other scenario drivers, such as population, GDP, resources, and technology. The following **Table 10** shows the inputs relevant for the marketplace module.

Table 10. Inputs required by the marketplace

Name	Resolution
Supply of all energy commodities	Region and year
Demand for all energy commodities	Region and year
Supply of all agriculture and land-based commodities	Region and year
Demand for all agriculture and land-based commodities	Region and year
Supply of all water types	Basin and year
Demand for water withdrawals and consumption	Basin and year

One of GCAM's uses is to explore the implications of different **future policies**. There are a number of types of policies that can be easily modelled in GCAM. There are three primary top-down policy approaches that can be applied in GCAM to reduce emissions of CO_2 or other greenhouse gases: carbon or GHG prices, emissions constraints, or climate constraints.[81] In all cases, GCAM implements the policy approach by placing a price on emissions. This price then filters down through all the systems in GCAM and alters production and demand. For example, a price on carbon would put a cost on emitting fossil fuels. This cost would then influence the cost of producing electricity from fossil-fired power plants that emit CO_2, which would then influence their relative cost compared to other electricity generating technologies and increase the price of electricity. The increased price of electricity would then make its way to consumers that use electricity, decreasing its competitiveness relative to other fuels and leading to a decrease in electricity demand. The three policy approaches are described below. For the NGFS scenarios, mostly emissions constraints are used, with the "Net Zero 2050" scenario using exogenously calculated GHG prices.

- **Carbon or GHG prices**: GCAM users can directly specify the price of carbon or GHGs. Given a carbon price, the resulting emissions will vary depending on other scenario drivers, such as population, GDP, resources, and technology.
- **Emissions constraints**: GCAM users can specify the total amount of emissions (CO_2 or GHG) as well. GCAM will then calculate the price of carbon needed to reach the constraint in each period of the constraint.
- **Climate constraints**: GCAM users can specify a climate variable (e.g., concentration or radiative forcing) target for a particular year. Users determine whether that target can be exceeded prior to the target year. GCAM will adjust carbon prices in order to find the least cost path to reaching the target.

In addition to the three primary top-down policy mechanisms that GCAM can model, GCAM can also model specific sectoral **regulatory policies** such as renewable portfolio standards, new source performance standards, and other regulatory policy instruments.

The cost of GHG emissions mitigation is a concept that is not uniquely defined. A wide range of measures are used in the literature. These include the price of carbon (or as appropriate given the policy) needed to achieve a desired emission mitigation goal, reduction in gross domestic product (GDP), consumption loss, deadweight loss (i.e., cost caused by market inefficiency), and equivalent variation. Beyond that is the concept of net cost, which includes the benefits of emissions mitigation as well as the resource cost of emissions reduction, while

[81] Besides emissions-related policies GCAM can also integrate energy production as well as land-use policies.

the social cost of carbon is also encountered. GCAM makes no attempt to calculate the benefits, and thus does not estimate net costs or benefits.

In addition to identifying policy prices as one measure of cost, GCAM employs the "deadweight loss" approach to measuring welfare loss from emissions mitigation efforts. GCAM employs the deadweight loss approach for several reasons. First, the deadweight loss approach is numerically straight forward to calculate in GCAM. Second, the deadweight loss approach provides a computationally tractable method to measuring the change in welfare, though it is only an approximation.[82] Third, the deadweight loss approach takes advantage of GCAM's detailed technological characterisation.

GCAM calculates the **cost of emissions mitigation** at each GCAM time step.[83] For example, in **Figure 66** below, the cost of moving from a reference path without a carbon tax (blue) to the emissions path with a carbon tax (green) in period T can be calculated simply. Successive scenarios with fixed carbon taxes in period T are run. The associated emissions are recorded for each carbon tax. The cost is calculated as the area of the purple triangle, which is the integral of each emissions mitigation step weighted by the carbon tax that was required to deliver the reduction. The final ton of carbon emissions is the most expensive ton because it is assumed that for a carbon tax, emissions mitigation occurs with the least expensive tons being reduced first. The final ton of carbon is simply the carbon tax rate itself. The tax revenue can be calculated as the tax rate times the remaining emissions, shown in red below.

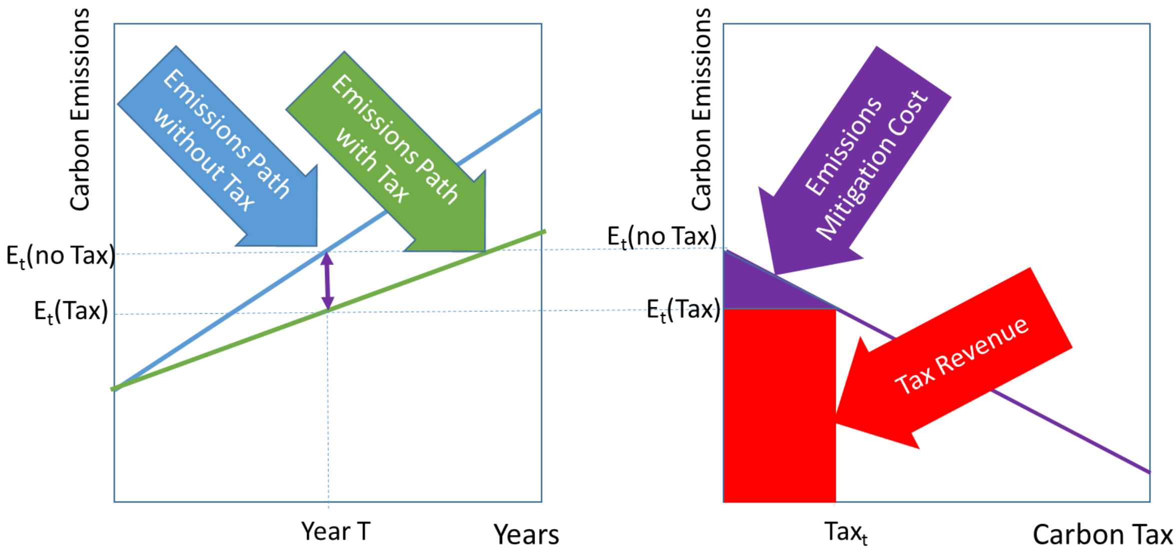

Figure 66. Carbon emissions paths, costs, and tax revenues

[82] In principle the equivalent variation is the right approach to measure an individual's loss in welfare. Equivalent variation measures the minimum amount of income that would be needed to leave consumers just as happy with the new price (e.g., carbon tax) as without. However, its calculation requires either knowledge of all of society's individual preference functions or the existence of a well-ordered set of social preferences, a requirement that Arrow (1950) demonstrated to be impossible under ordinary circumstances.

[83] Note that calculation of policy costs is currently only supported in GCAM for policies pegged to CO_2 prices.

Description of key input variables and main assumptions

GCAM's demand inputs include information on consumption and prices in the historical period to calibrate model parameters (see **Table 6, Table 7, Table 8**). Additional parameters related to income and price elasticities are needed for modeling future periods. GCAM requires demand data to be globally consistent with supply data for each of its historical model periods as it solves for market equilibrium in these years as it does for future years. These inputs are required for each region and historical year. GCAM's economic inputs include information on population and income (see **Table 9**). These inputs are required for each geopolitical region and historical year. GCAM's external land inputs include information on land, carbon, other emissions, and the value of unmanaged land in the historical period (see **Table 10**). These inputs are required for each global land unit and historical year. GCAM's supply inputs include information on production, prices, technology cost and performance, and other emissions in the historical period to calibrate model parameters (see **Table 30, Table 31, Table 32**). In addition, GCAM's supply modeling requires information on future technology cost and performance and emissions factors for future periods. GCAM requires that supply data is globally consistent with demand data for each of its historical model periods as it solves for market equilibrium in these years as it does for future years. These inputs are required for each region and historical year. GCAM subdivides the world into 32 geopolitical regions, representing countries or collections of countries (see **Table 33**).

5. Key model outputs

Description of key output variables/sector

The following tables comprise the general GCAM modular outputs and their respective units. The release version of GCAM is typically operated in five-year time steps with 2015 as the final calibration year and time horizon 2100. **Figure 67** shows a final overview of GCAM's model inputs and outputs.

Table 11. GCAM outputs from emissions modelling

Name	Resolution	Unit
Emissions (CO2)	Technology, region, and year	MtC/year
Emissions (non-CO2)	Technology, region, and year	Various
Resource production emissions (CO2)	Subresource, region, and year	MtC/year
Resource production emissions (non-CO2)	Subresource, region, and year	MtC/year
Land use change emissions	By GLU and land type	MtC/year
Change in above ground carbon	By GLU and land type	MtC/year
Change in below ground carbon	By GLU and land type	MtC/year
CO2 sequestration	Technology, region, and year	MtC/year

The units of non-CO_2 emissions vary. Fluorinated gas emissions are reported in Gg of the specific gas per year. All other emissions are reported in Tg of the specific gas per year (e.g., CH_4 emissions are reported in $TgCH_4$/yr.).

Table 12. GCAM outputs from the land model

Name	Resolution	Unit
Land use and land cover	By GLU, land leaf, and year	Thousand km^2
Land use change emissions	By GLU and land leaf	MtC/year
Change in above ground carbon	By GLU and land leaf	MtC/year
Change in below ground carbon	By GLU and land leaf	MtC/year
Above ground carbon stock	By GLU and land leaf	MtC
Profit rate	By GLU and land leaf	$_{1975}$\$/thousand km^2

Table 13. GCAM price outputs

Name	Resolution	Unit
Price	Market and year	Various
Food demand prices	Region, type and year	$_{2005}$\$/Mcal/day

The price units vary by market. In general, energy-related prices are reported in $1975/GJ, agricultural prices are in $1975/kg, forestry prices are in $1975/m³, and carbon prices are in $1990/tC.

Table 14.GCAM quantity outputs

Name	Resolution	Unit
Physical Output	Technology, region, vintage, and year	Various
Resource production	Region, resource and year	Various
Inputs	Technology, input, region, vintage, and year	Various
Supply	Market and year	Various
Demand	Market and year	Various

The quantity units vary. In general, energy-related outputs are reported in EJ/yr., agricultural outputs are in Mt/yr., forestry outputs are in million m^3/yr., and water outputs are in km^3/yr.

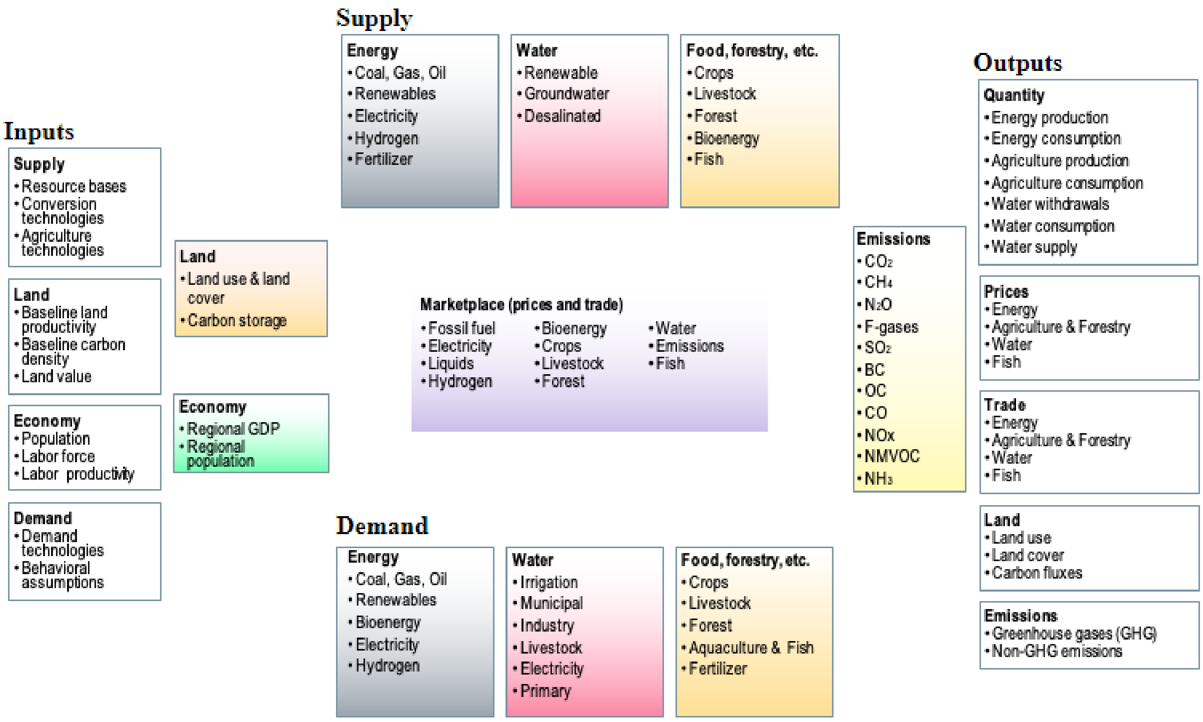

Figure 67. Overview of GCAM inputs and outputs

Table 34 shows a complete list of the sectoral GCAM variables with available output data for all 32 GCAM regions and implemented NGFS climate policy scenarios as provided by the NGFS Phase V Scenario Explorer (indicated as "G" in the IAM column). There, the main variables (variable groups) are also explained briefly.

Approach to computing GDP Losses

The version of GCAM used for the NGFS Phase V study employs utilizes a prescribed (exogenous) GDP trajectory. It currently does not employ an energy-GDP feedback mechanism. Since the NGFS scenario are representing an estimate of the full economic consequences of different scenarios, GDP values in non-reference scenarios (so all scenarios except Current Policies) were replaced with a modified GDP that uses the scenario carbon price and the relationship between the carbon price and GDP change from the REMIND-MAgPIE model to create a GDP path consistent with the REMIND-MAgPIE model response to emissions mitigation. However, since the GCAM energy, agriculture and land-use system produces its own unique carbon prices based on all of the information about energy-agriculture and land-use interactions, the GCAM GDP consistent with transformation pathways is different than the REMIND-MAgPIE GDP pathway.

The GCAM GDP for scenarios other than the reference scenario was calculated using the following formula:

$$GDP^{GCAM*}(t) = GDP^{GCAM}_{ref}(t)\left(1 + \left(\frac{\%\Delta GDP^{REMIND}_{ref}(t)}{P^{REMIND}_{CO2}(t)}\right) P^{GCAM}_{CO2}(t)\right)$$

Where, the reference scenario, ref, is the Current Policies scenario. GDP is measured in a common currency using purchasing power parity, PPP. The marginal cost of emissions mitigation is measured as the price of CO2 or PCO2. GCAM used the REMIND model's change in GDP to carbon price ratio, $\frac{\%\Delta GDP^{REMIND}_{ref}(t)}{P^{REMIND}_{CO2}(t)}$. We used the REMIND model's regional change in GDP to carbon price ratios, as these most closely resembled the macroeconomic effects observed in the GCAM-MACRO model version currently being developed for future use in the NGFS scenarios. Based on preliminary regional results of this model, the regional GDP loss ratio between any non-reference scenario and the Current Policy reference case was capped was capped to 10% for losses, and to 1% for gains.

The newly released version (GCAM v.7.1) which includes a Macroeconomic module that allows for endogenizing GDP responses[84], as well as more granular representation of residential sector consumers along with other updates will be used for future iterations of these NGFS scenarios.

Data access and availability

In addition to the NGFS Scenarios Portal, the output basex files for the NGFS Phase V scenarios using GCAM v.6.0 can be publicly accessed here[85]. They can be downloaded and viewed using the GCAM ModelInterface or the GLIMPSE tool developed by the US Environment Protection Agency (EPA).

[84] https://jgcri.github.io/gcam-doc/economy.html

[85] The raw output data provided here is produced by the Center for Global Sustainability (CGS) at the University of Maryland and is made available for external research purposes. However, CGS is not responsible for the use of the data beyond its own research settings. External researchers who use CGS' data for their own research in external settings should not make claims that results are validated by CGS or the University System of Maryland or its agents. If you wish to contact CGS regarding citations or use this data, write to bertram@umd.edu or georgemv@umd.edu.

Module 5: Chronic physical risks and damage function

1. Non-technical summary

Chronic physical risks are associated with long-term shifts in climate patterns, and include risks associated with long-term increases in temperature, changes in average precipitation patterns, rising sea levels, and ocean acidification. The impact of these can be reflected in reduced labor and land productivity, capital depreciation, scarcity of natural resources, forced migrations, increased adaptation costs, etc.[86]

The IAM models described in previous sections are capable of calculating policy costs associated with the goals of different scenarios. However, these models typically do not estimate the impact of the physical costs associated with climate change on the economy, including the impacts of chronic physical risks. To fill this gap, the NGFS scenarios include an ex-post (i.e., computed outside of IAMs) estimate of chronic physical risks. This also allows an estimation of the direct chronic physical risks without additional economic dynamic effects, allowing the use of these estimates in other economic models.

The approach used for the economic impact estimates from chronic physical risks in this year's edition of the NGFS scenarios has been updated to capture the latest scientific advances in the quantification of aggregate economic damages.

The basic methodology stays the same: macro-economic impacts are calculated using a damage function. Damage functions are relationships quantifying the effect of a change in climate-related variables (e.g., temperature) on economic output. There is a rapidly growing body of empirical research aimed at developing these functions, as well as other methods for estimating chronic physical risks, with different approaches generating a wide range of different results (**Figure 68**). This year the new damage function put forward by Kotz et al. (2024) is being used to calculate chronic physical risks for the NGFS scenarios. Compared to the damage function by Kalkuhl & Wenz (2020) used in previous years this includes the following key advances. First it includes climate drivers beyond annual mean temperature change, namely changing daily temperature variability, total annual precipitation, annual number of wet days and extreme daily rainfall. Second, persistence effects on economic output have been estimated for each of the climate drivers, allowing the new damage function to capture losses up to 10 years after the initial shock. This results in a significant increase in the damage estimates compared to previous years.

Explainer box 5

What is new in the 2024 edition of the NGFS Scenarios ?

- The approach used for the economic impact estimates from chronic physical risks has been updated to a new damage function, representing latest advances in estimating aggregate economic impacts from climate change.

[86] Note that not all of these impacts are explicitly captured in the NGFS estimates of chronic physical risk.

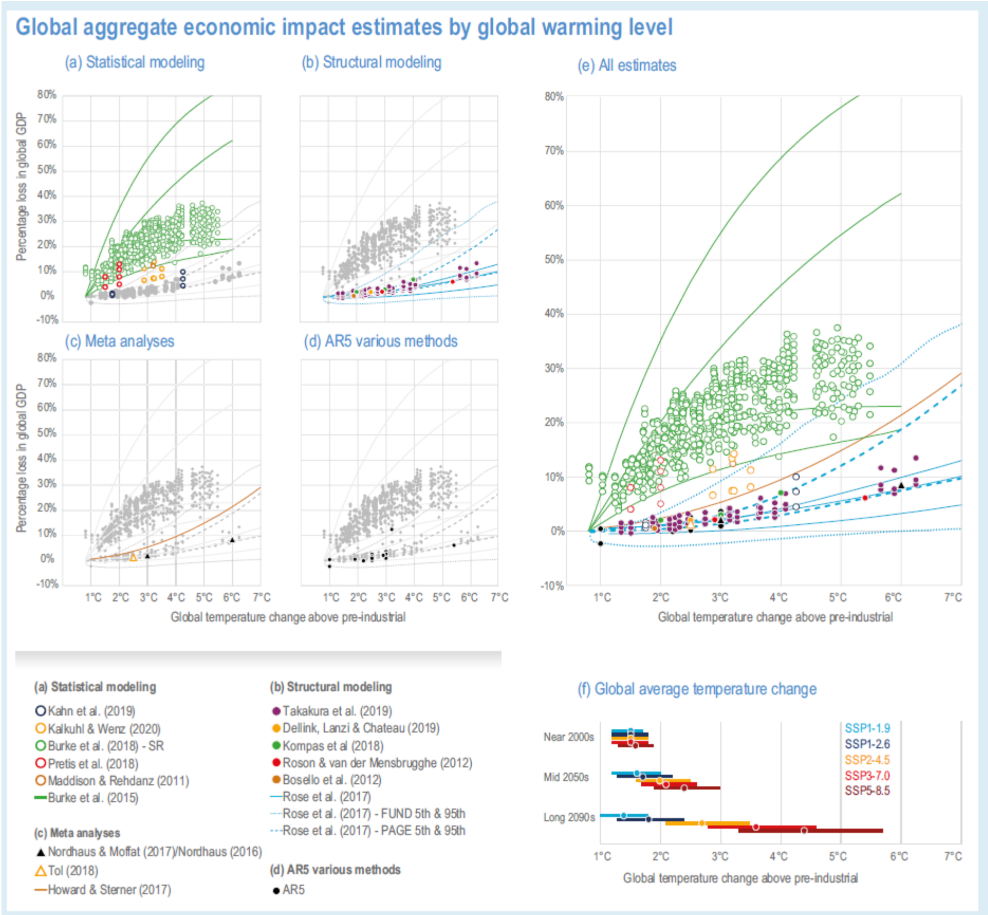

Figure 68. Global aggregate economic impact estimates by global warming level (annual % global GDP loss relative to GDP without additional climate change). Source: IPCC AR6 WGII Chapter 16, 2022.

NGFS scenarios account for three uncertainty dimensions related to the chronic risk estimation: (i) IAM emissions output; (ii) the temperature predicted by the climate module; and lastly (iii) the uncertainty layers of the damage function used. However, the scope of uncertainties on chronic damages is much wider as also illustrated in the figure above. Regarding the damage functions, for example, the degree of the persistence (i.e. how long the growth rate is affected) is still open. In addition, there are limitations in terms of what is captured by the damage functions used, with the approach not explicitly accounting for: (i) possible future impacts that are not reflected in historic relationships between the drivers used in the current damage function and GDP; (ii) damages from sea level rise, ocean acidification, and other chronic impacts beyond the drivers used in the damage function; and (iii) effects beyond impacts on labor and land productivity and capital depreciation, including conflict, violence and migration, and biodiversity and ecosystem impacts. Finally, the role of potential future adaptation is not taken up in these damage functions.

It is important to remark that, besides the limitations of the damage function methodology presented below, the estimates of chronic damages are not integrated in IAMs. This means that optimizing agents in these models are myopic with respect to physical costs and, therefore, the latter are not reflected in the savings decisions, investment, etc. This limitation contributes to underestimating chronic damages. To address this issue, an additional run of REMIND with endogenous chronic damages is presented in **Scenarios with integrated transition and physical risks.**

2. Macro-economic damage estimates

2.1.1 The damage function

For the NGFS scenarios, we use the results of a recent, state-of-the art econometric estimate by Kotz et al (2024) to calculate country-level macroeconomic losses. These estimates build on prior work by Kalkuhl & Wenz (2020) which was used in the previous round of the NGFS scenarios. The most important updates to these damage estimates which have been made can be broadly summarized as follows:

a. The incorporation of more recent data on sub-national economic output,
b. The inclusion of a number of additional climate conditions with known impacts on economic growth,
c. An improved constraint on the persistence with which climate conditions impact growth.

As in Kalkuhl & Wenz (2020), these estimates are built on an econometric assessment of the relationship between logarithmic growth rates, $g = \frac{dlnY}{dt}$, in aggregate economic output, Y, and climate conditions. As before, data on aggregate output is used at the sub-national regional level, r. Since the previous NGFS scenarios, further development of the underlying database means that an additional 15,000 observations are available, mostly from extending the data to cover more recent years (2015-2020). This underlying data is documented in Wenz et al. (2023).

Since the publication of Kalkuhl & Wenz (2020), a number of studies have demonstrated that other climate conditions drive impacts on aggregate economic output, in addition to impacts from annual mean temperature as captured by Kalkuhl & Wenz (2020). In particular, Kotz et al. (2021) demonstrated that increased variability of daily temperatures cause substantial negative impacts on growth which are larger at low-latitudes. Furthermore, Kotz et al. (2022) demonstrated that different aspects of the distribution of precipitation drive heterogenous impacts on growth, with increased total rainfall bringing benefits and increased rainfall extremes bringing negative impacts. Accounting for these additional climate components is an important step in capturing the broader set of conditions via which climate change can affect regional economies.

Furthermore, recent work by Kotz et al. (2024) has assessed the persistence with which these climate conditions impact economic growth rates – a key source of uncertainty between prior assessments of damages from future climate change. As shown by Kikstra et al. 2021, small changes in the extent of persistence can manifest as order of magnitude differences in the magnitude of damages. Kalkuhl & Wenz (2021) had used a framework in which climate variables are first-differenced, in order to describe a level-effect relationship in which only changes in climate conditions induce impacts on growth, corresponding to a scenario of no persistent impact of climate conditions on growth. By including one lag of the first-differenced annual mean temperature, Kalkuhl & Wenz (2021) had captured some extent of additional persistence. More recently in Kotz et al. (2024), a further exploration of persistence was undertaken using distributed lag models and Information Criteria. The framework for this analysis was supported by Monte-Carlo simulations which indicated that a sufficient number of lags was necessary to identify persistence when using first-differenced climate variables.

The empirical model used in Kotz et al. (2024) relates growth rates of subnational regions to a number of climate variables, using distributed lags of each climate variable in its first differenced form to identify persistent effects. The full model is outlined below:

$$g_{r,y} = \mu_r + \eta_y + k_r y + \sum_{L=0}^{N}(\alpha_{1,L}\Delta\bar{T}_{r,y-L} + \alpha_{2,L}\Delta\bar{T}_{r,y-L} \cdot \bar{T}_r) + \sum_{L=0}^{N}(\alpha_{3,L}\Delta\tilde{T}_{r,y-L} + \alpha_{4,L}\Delta\tilde{T}_{r,y-L} \cdot \hat{T}_r) + \sum_{L=0}^{M}(\alpha_{5,L}\Delta P_{r,y-L} + \alpha_{6,L}\Delta P_{r,y-L} \cdot P_r) + \sum_{L=0}^{M}\left(\alpha_{7,L}\Delta Pwd_{r,y-L} + \alpha_{8,L}\,\Delta Pwd_{r,y-L} \cdot Pwd_r\right) + \sum_{L=0}^{M}(\alpha_{9,L}\Delta Pext_{r,y-L} + \alpha_{10,L}\Delta Pext_{r,y-L} \cdot \bar{T}_r) + \epsilon_{r,y}.$$

μ_r and η_y constitute region and year fixed effects which respectively remove un-observed, time-invariant regional biases, and common yearly shocks across regions. $k_r y$ constitute region specific linear time trends which remove slow-moving trends in both growth and climate. Following this are distributed lag terms for each climate variable. Each climate variable is included in its first differenced form (Δ), and with a time-invariant interaction term. For annual mean temperature, $\bar{T}$, this interaction is with annual mean temperature (following prior work from Burke et al. (2015) and Kalkuhl & Wenz (2021) on the non-linearity of temperature impacts); for daily temperature variability, $\tilde{T}$, the interaction is with the seasonal temperature difference (defined as the difference between maximum and minimum monthly temperatures, as identified in Kotz et al. (2021)); for total annual rainfall, P, the interaction is with total annual rainfall; for the number of wet days Pwd ,the interaction is with the number of wet days; for extreme daily rainfall, $Pext$, the interaction is with annual mean temperature, with the latter three interactions as identified in Kotz et al. (2022).

Initial analyses used N=10 and M=10 lags of each climate variable to assess the persistence of impacts from each climate variable, by evaluating the significance of terms lagged $\alpha_{X,L}$. While precipitation variables were found to have impacts on growth for timescales of approximately only four years, temperature terms were found to have more persistent impacts which lasted up to ten years. The latter findings are consistent with evidence from national level data using low-pass filtering which demonstrated more highly persistent impacts of temperature on growth (Bastien-Olvera 2022). These persistence times were supported by the use of Information Crtieria to assess the trade-off between predictive power and overfitting, as well as Monte-Carlo simulations to demonstrate robustnenss to auto- and cross-correlations in the climatic conditions. The number of lags were therefore reduced to M=4 for precipitation variables, while including N=8-10 lags for temperature terms.

On the basis of these empirical models, Kotz et al. (2024) used CMIP-6 projections of future climate conditions to estimate the economic damage caused by future climate change. An ensemble of 21 climate models which have been bias-adjusted to accurately reflect the distribution of historical daily temperature and precipitation (Lange 2019) were used such that future projections matched the data on which historical impacts had been identified. Calculations of future reductions in economic growth rates were applied to baseline projections of GDP per capita from the Shared Socioeconomic Pathways (SSP) to derive percentage changes in future income per capita due to climate change, $\Delta Y_{r,y}$. Uncertainty in these estimates were obtained via a Monte-Carlo simulation procedure which sampled from both the physical climate models and from bootstrapped estimates of uncertainty in the econometric models.

NGFS uses scenarios of future climate change which do not correspond to the emission forcing scenarios from the SSPS used to drive the CMIP-6 simulations. Therefore it was necessary to derive aggregate damage functions which mapped global mean temperature (GMT) change to national level damages as projected by Kotz et al. (2024), such that these damages could be integrated into the NGFS senarios. Sub-national percentage reductions in future income were aggregated to the national level with a population weighting using down-scaled SSP population data. GMT change was then estimated for each climate model, and a functional relationship estimated between national damages and GMT using least squares regression. Linear, quadratic and cubic relationships were estimated without an intercept, reflecting the fact that no climate change implies no climate change damages. These damage functions were estimated for each of the 1000 Monte-Carlo samples of projection uncertainty provided by Kotz et al. (2024). While a quadratic function provided an improved fit compared to linear functions (average R2 of 0.93 compared to 0.88), cubic functions provided negligible increase in fit (average R2 of 0.94). Quadratic functions were therefore used, consistent with those typically applied in the wider literature on aggregate damage functions.

Although damage projections were estimated using a particular SSP baseline of economic development, the fact that impacts enter via the per-capita growth rate means that they are independent of projected income and population growth and hence consistent across the different SSP baselines. The fact that the damage functions are independent of the socioeconomic projections makes it appropriate to apply them to the scenarios used by NGFS. Damage functions were generated from the high emission forcing scenario RCP8.5 to provide coverage across the largest possible range of GMST change. Given that the first-differenced framework for climate impacts in Kotz et al. (2024) reflects that of a level-effect with delayed impacts (i.e. no long-term dependence of the growth rate on climatic conditions), the magnitude of damages depends on the level of climate change without a dependence on its rate. For this reason, the damage functions are highly consistent across RCPs, but we continue to use RCP8.5 as our main specification in order to provide maximum coverage across future GMT change.

2.1.2 Calculation of damages for the NGFS database

Damages are calculated in post-processing using the probabilistic global mean temperature change data. NGFS scenarios combine the transition pathways of IAMs, the MAGICC climate module[87] and the damage function by Kotz et al. (2024) as described in the previous section to provide estimates of chronic damages for each scenario on a country level. The way these pieces fit is shown in **Figure 69**. It starts with the output of the IAMs for a given scenario. In particular, the projection of emissions is fed into the MAGICC climate model, which translates this emissions pathway into a global temperature path with 90% confidence intervals, representing the first source of uncertainty. Then, these temperature series are used as input into the damage function, that calculates the impact on GDP. To reflect the uncertainty in the damages we use the median, 5^{th} and 95^{th} percentile of the damage distribution.

Note that this approach calculates damages compared to present-day conditions, i.e., it only captures temperature changes compared to the 2020 temperature level. It thereby assumes that GDP until 2020 already incorporates damages. Importantly, this has consequences for estimating damages for those scenarios with large temperature decreases towards the end of the century, in particular the low demand scenario, but in some instances also the 1.5° scenario. For the low end of the temperature distribution coming from the MAGICC model these temperature changes may drop below the level of 2020. In these cases, the damage function cannot be applied easily anymore, as this is outside of its range of applicability. Applying it would seemingly lead to benefits for hot countries above and losses for cool countries below their optimal temperature. However, these are only losses and benefits compared to the damage already incurred in 2020 which we presently cannot robustly quantify. To avoid confusion we set these damages to "NA" in the database.

Results are provided as annual, country-level output change in %, with losses reported as negative values (e.g. Diagnostics|GDP change|Kotz-Wenz ***th Percentile**|GMT AR6 climate diagnostics|Surface Temperature (GSAT)|MAGICCv7.5.3**|*.*th Percentile**), as well as net GDP values (e.g. net net GDP|PPP|**Kotz-Wenz *th Percentile**|GMT AR6 climate diagnostics|Surface Temperature (GSAT)|MAGICCv7.5.3**|*.*th Percentile**), where ***th Percentile** refers to the percentile of the temperature pathway or of the damage distribution used as input.

[87] MAGICC climate module is described in Box: MAGICC: A reduced complexity Earth system model

3. Chronic damages in post-processing and sources of uncertainty

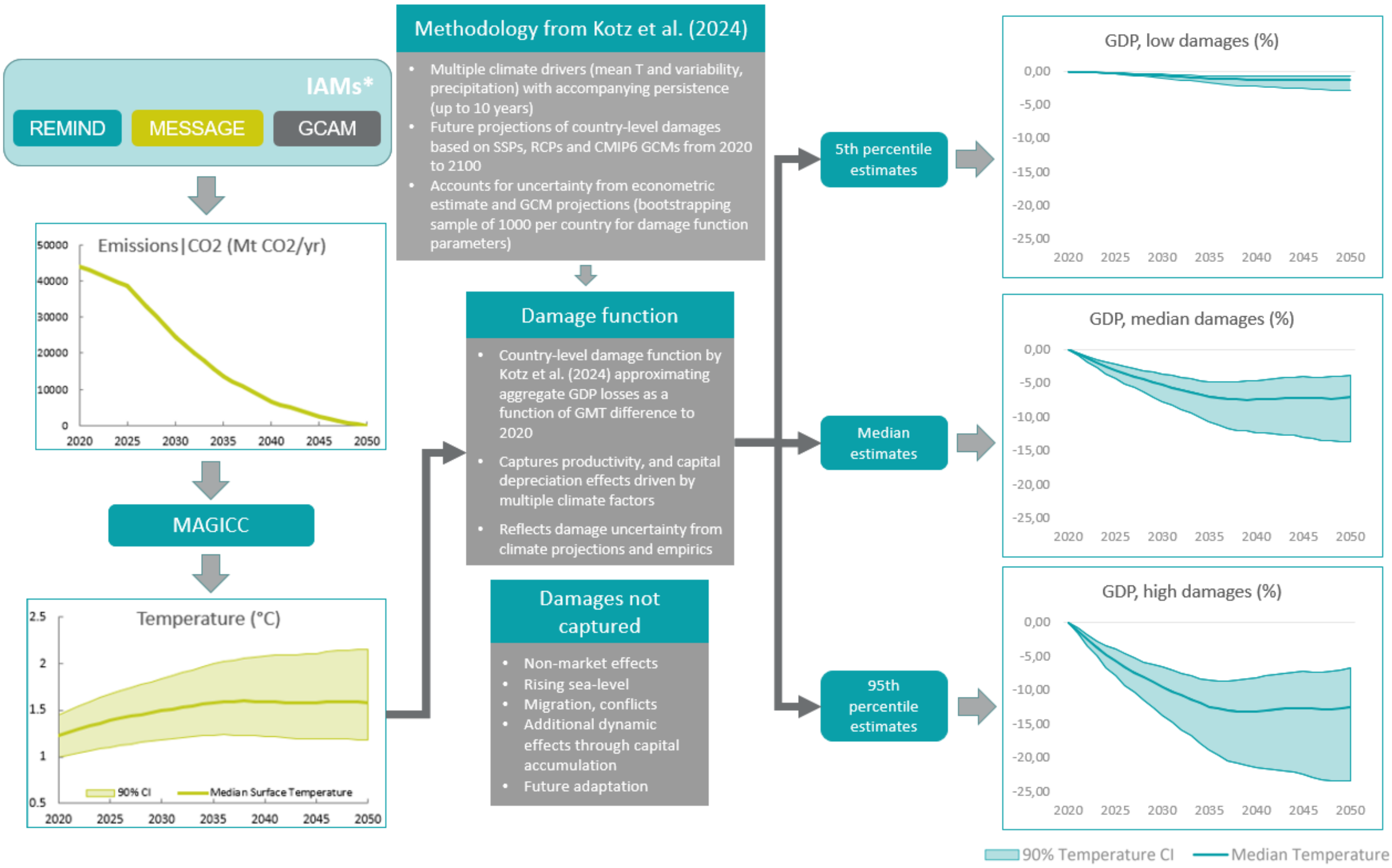

Figure 69. How post-processing chronic damages are calculated and sources of uncertainty.

4. Scenarios with integrated transition and physical risks

The methodology described in **Physical risk modelling approach** computes chronic damages outside the IAMs. This serves as a first approximation of these costs, as the agents in the models optimise policy and allocations in each scenario without internalising the costs of higher temperatures. Ideally, transition and physical risks should be modelled together in an integrated framework to capture feedback effects properly. Following the methodology by Schultes et al. (2021), we provide an additional set of such integrated scenarios for the NGFS framework. In a nutshell, this approach integrates chronic damages based on the empirical specification by Kotz et al. (2024) into the REMIND-MAgPIE model.

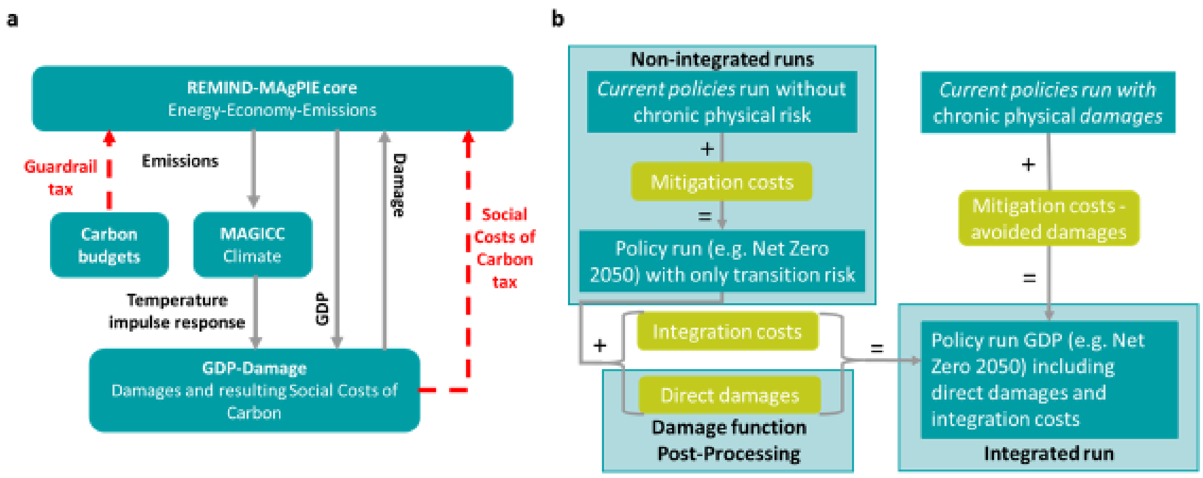

Figure 70. Conceptual framework of scenarios with integrated damages, and (b) comparison of GDP output (dark green) for non-integrated and integrated runs of REMIND

Overview of the integration

The approach is shown schematically in **Figure 70** (left panel). A module that calculates chronic damages based on Kotz et al. (2024) is coupled with the REMIND-MAgPIE core and MAGICC. This module is used to calculate an additional component in the carbon tax that captures the Social Cost of Carbon (SCC). The remaining component of the carbon tax is a *guardrail tax*, which adjusts to the carbon budget of each scenario. This way, the assumptions of the scenario are satisfied and the economic decisions of agents (savings, investments, etc.) do respond to physical damages, which are now included in the budget constraint and in turn on the temperature paths. In other words, with this approach, regions internalize the impact of own emissions on global temperature.

Iterative approach

The solution is obtained through an iterative approach. The level of the *guardrail tax*[88] is adjusted until the emissions budget of the scenario is reached and the emissions calculated in the REMIND model are passed to MAGICC for calculation of global mean temperature change.

Using the temperature pathways, the damage module calculates country-level damages based on the approach by Kotz et al. (2024), aggregates them to REMIND regions and computes the associated SCC tax, by solving a global planner problem with Negishi weights[89] that internalize the physical damages. The solution of this problem gives the socially optimal SCC tax given the output of REMIND. The resulting SSC tax is globally uniform.

[88] Which follows a a Hotelling form, i.e., rises exponentially with the interest rate. This is a common result for the carbon tax under a carbon budget.

[89] That is, welfare weights that equalize the marginal utility of consumption across regions. This is a common choice in the literature.

This social cost of carbon is internalized in the next iteration of the REMIND model as a component of the carbon tax, leading to additional mitigation. Damages reduce regional GDP which in turn affects emissions, capital accumulation and savings dynamics. This iteration continues until a fixed point is reached. [90]

Schultes et al. (2021) show that this iterative approach leads to results very close to the solution of the model with fully endogenous optimization of the SCC tax, which would be computationally very demanding.

Output

The Current Policy scenario with integrated physical risks captures the GDP effect of damages but does not internalize them for a policy response. The other scenarios combine social costs of carbon and guardrail taxes as outlined above, on the level of large world regions.

For the rest of scenarios, it is important to notice that the damages are not directly comparable to the ones reported in Post-Processing of non-integrated runs of REMIND, since the integration leads to additional dynamic responses. Therefore, the difference in final output between the integrated and the non-integrated policy runs can be separated into two components, the direct damages, comparable to the post-processed damages, and the integration costs, which include savings effects and changes in the mitigation strategy in response to the damages. Right panel in **Figure 70** provides a guide[91] of how to compare GDP counterfactuals across non-integrated and integrated runs. Notice that only GDP including both direct damages and integration costs is provided in the integrated run[92].

The damage function uncertainty is captured by taking percentiles from damages calculated with a set of 1000 parameter estimates for the damage function stemming from a boostrapping procedure combining uncertainty from climate model projections and empirial models. Only the combination of median climate and median damage estimates is provided in this year's NGFS release, indicated by the model name "REMIND-MAgPIE 3.0-4.4 IntegratedPhysicalDamages (median)". **Table 16** show the output variables provided by integrated REMIND runs.

Table 16. Output variables for integrated REMIND runs.

Output Variable	Description
GDP|MER|Counterfactual without damage	GDP net of mitigation costs
GDP|PPP|Counterfactual without damage	GDP net of mitigation costs
Macro-Economic Climate Damage|GDP Change	Direct and indirect chronic damages (MER)

[90] See supplementary material of Schultes et al. (2021) for details of the iterative approach.

[91] Yellow boxes indicate the differences between GDP series from different runs, represented by dark green boxes.

[92] Subtracting Post-processed damages from integrated output and comparing with non-integrated policy run without damages could serve as an approximation to estimate integration costs.

Policy Cost and Macro-Economic Climate Damage|GDP Change	Mitigation costs plus direct and indirect chronic damages
Policy Cost|GDP Loss	Mitigation costs (MER)
GDP|PPP|including chronic physical risk damage estimate	GDP net of mitigation costs and indirect chronic damages (MER, only downscaling)

Downscaling

To obtain country-level damages for integrated runs we use a pattern-scaling approach, distributing the regional direct GDP losses and the integration costs to countries using country damages from post-processed runs as weights. The GDP net of integrated policy costs and chronic physical risk damages is provided on country level. This is used for the downscaling of further variables (i.e., bringing variables from regional to country level) of the integrated damage runs. Figure 71 summarizes the differences between non-integrated and integrated runs in the variables they produced and the downscaling approach.

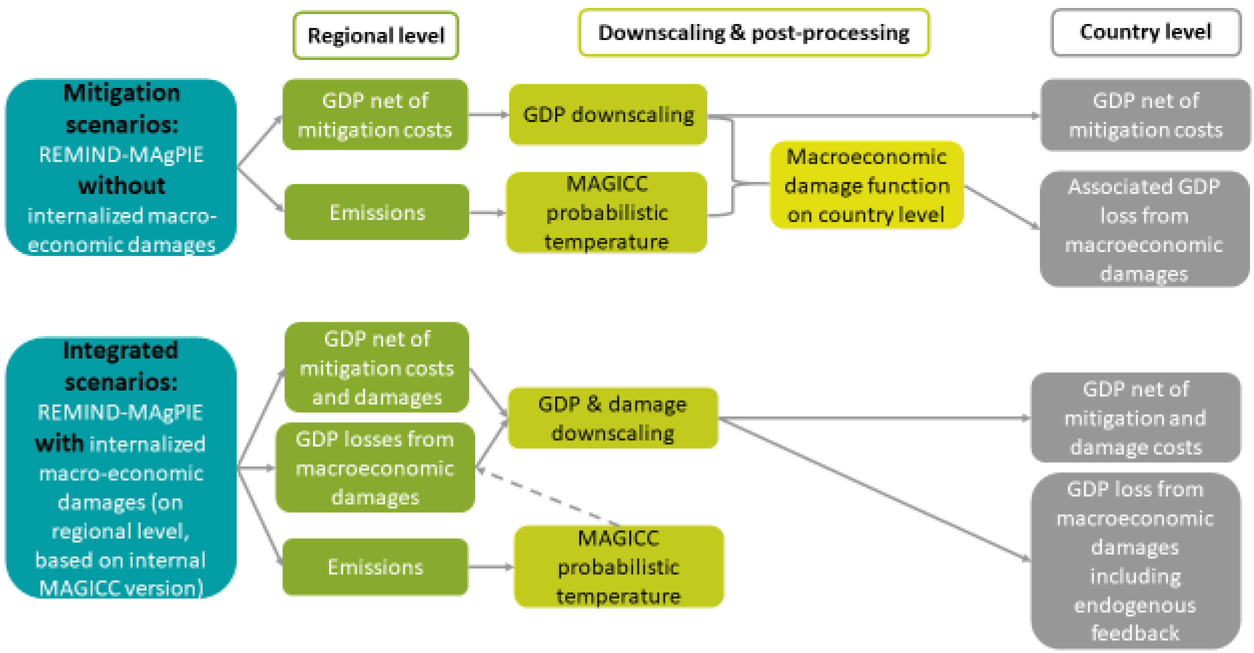

Figure 71. Non-Integrated REMIND runs vs Integrated REMIND runs

Module 6: Acute physical risks

1. Non-technical summary

Acute physical climate risk assessments estimate risk from extreme weather events like floods, heatwaves, tropical cyclones, and droughts.

Natural catastrophe models for acute risk are based on three main components: hazards or perils, i.e., the extreme events or physical variable causing the damage; exposure, i.e., a spatial map of the objects exposed to damage (e.g., assets, infrastructures etc.); and vulnerability, i.e., a function that allows assessing the degree of damage of the exposed objects. In the NGFS Phase III, acute physical risk was calculated for only two hazards and at aggregate (world) level only.

In Phase V, there are no changes to acute physical risk modelling compared to Phase IV. The same results continue to be reported.

The risk projection process generally follows three main steps: (1) estimation of distributions of country-level impacts, with impacts being in capital stock damages for floods and tropical cyclones, crop yield losses for droughts, and population impacted for heatwaves, using catastrophe modelling principles and grid level data across a range of projected temperatures values; (2) projection of these distributions in the future along temperature paths (expressed in Global Mean Temperature, or GMT in short); and (3) translation of these shocks into macroeconomic dynamics at country levels, by implementing them as supply and demand shocks in NiGEM.

2. Modelling of acute physical risk hazards

2.1 Drought: Yield Exposure to Severe Drought Conditions

Drought conditions, often defined as a long-term lack of precipitation and dry soils, are detrimental to ecosystems and societally relevant sectors in a variety of ways. For example, it can affect the energy sector through lack of cooling water and hydropower production, or impact crop yields. The aim of the provided metric is to estimate crop-land exposure to severe drought conditions under different levels of global warming and a first order assumption on how those might affect national yields. Several different drought definitions have been put forward, often related to their temporal evolution (flash drought, mega drought), the underlying physical or societal causes (meteorological drought, hydrological drought, agricultural drought, socioeconomic drought[93]). Out of the several possible indicators for detecting drought conditions, we selected the most suiting one.

We detect severe drought conditions using the standardized precipitation evaporation index (SPEI) over 12 months, which is a drought indicator based on relevant variables such as precipitation and evaporation. As evaporation is considered, this indicator is more sensitive to climatic changes compared to, e.g.,the

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93 https://www.ncei.noaa.gov/access/monitoring/dyk/drought-definition

Standardized Precipitation Index (SPI) (Touma et al. 2015). For a detailed description on how the SPEI is determined we refer to NCAR Climate guide [94]. World Bank's glossary indicates that when SPEI is calculated for a 12 month period, it may measure the potential impact of drought on ecosystems, crops, and water resources (like a precipitation deficit or a low remaining soil moisture[95]). The duration of a drought event is an important factor for determining its impact. In addition, the SPEI can be determined on different timescales. Hence, we use the SPEI-12, which in addition to the current month considers the conditions of eleven preceding months. Thus, this index considers long-lasting drought conditions on annual scales, which are particularly detrimental for local food security. Lastly, the SPEI calculation is based on Potential Evapotranspiration (PET) following the Thornthwaite method, which takes monthly mean temperature as input.

Detecting drought conditions

Drought conditions are determined on a monthly basis. A threshold of $SPEI12 = -3$ is used to define drought conditions for each grid point in a specific month[96]. A value of -3 indicates extreme precipitation and evapotranspiration conditions over an extended time, indicating an exceptionally severe drought, while a value of zero indicates no drought risk. The resolution is of 0.5 deg. x 0.5 deg. globally which refers to an area of scale of about 50km x 50km. Within a year the severity of the ruling drought conditions is determined by counting the total drought months detected within a year and dividing them by twelve. Thus, a grid-point is considered affected entirely if a drought is detected throughout all twelve months. Following this approach, if drought conditions of SPEI < -3 are found for one month only, the yields within a grid-point is considered to be affected by $1/12^{th}$.

Quantifying effects of drought conditions on national harvests.

Naturally, the impact of a drought on crop yields in a certain region scale with the intensity to which that particular region is used for agriculture. Therefore, we overlay the global output from the climate models with a global map that provides the percentage of harvested area per grid point at 0.5° resolution (***Figure 72***). The data is based on 2005 estimates from Ray et al. (2015). To determine the annual exposure of harvested area to drought conditions on a national level we multiply the drought severity determined by the number of affected months per year with the harvested area for each grid-point within national borders and aggregate all values for a year. Values are then normalised for each country, thus, yielding a value between zero or one for each year, where zero means no effect and one refers to a total exposure of drought conditions of the harvested area of one gridpoint:

$$\text{National annual yield in \% (SPEI)} = \sum_i^n \frac{(\#\text{of months SPEI} > -3)_i}{12} \cdot \text{harvested area share}_i \quad ,$$

where n is the total number of gridpoints within each country and $i \in \{1,2,3,\ldots,\text{n}\}$ the respective grid-point.

[94] https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-evapotranspiration-index-spei

[95] https://databank.worldbank.org/metadataglossary/environment-social-and-governance-(esg)-data/series/EN.CLC.SPEI.XD#:~:text=SPEI%20is%20used%20as%20a,negative%20values%20indicate%20dry%20conditions.

[96] The SPEI values range from -5 to 5. Smaller values indicate stronger degrees of drought, while the positive values indicate degree of moisture.

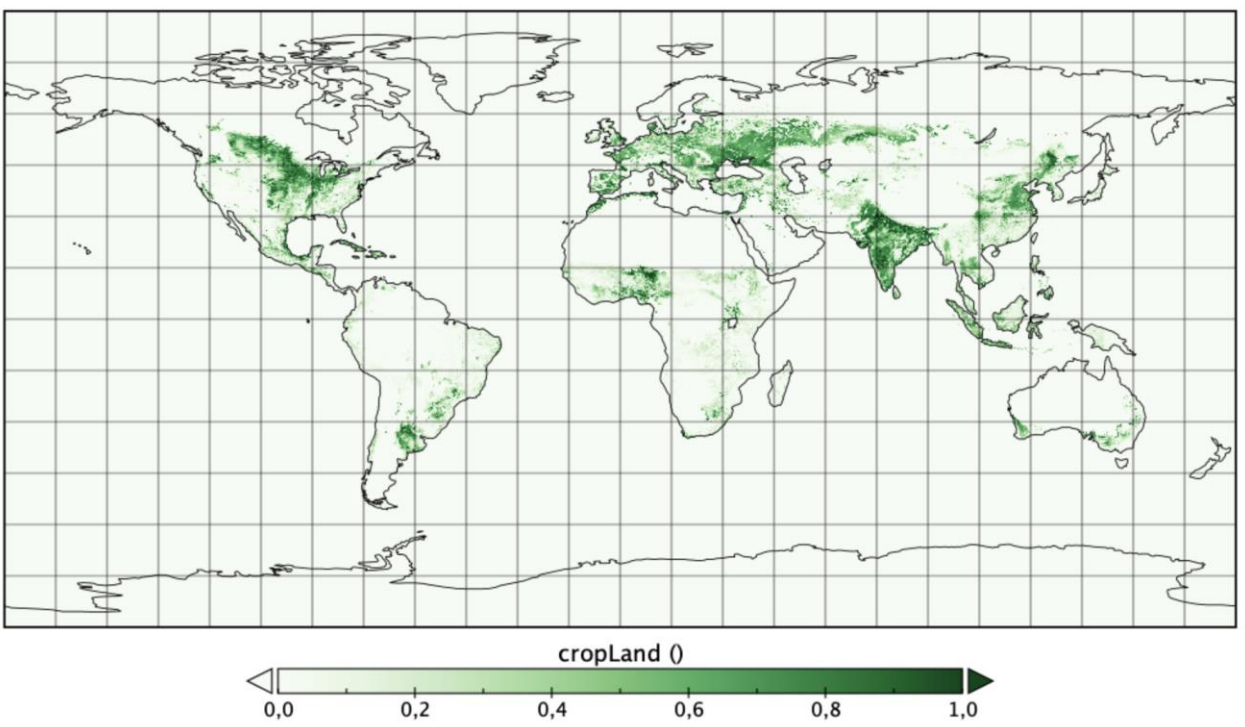

Figure 72. Intensity of agricultural activity as indicated by harvested area based on data provided by Ray et al 2015. Data is based on 2005 estimates.

Determining future drought conditions and projecting at different levels warming levels

We use the bias-adjusted and down-scaled output from four climate models of the fifth phase of the Coupled Model Intercomparison Project (CMIP5[97]): IPSL-CM5A-LR, GFDL-ESM2M, MIROC5, HadGEM2-ES. Following

Explainer box 6

What is CMIp 5 ?

- **The Coupled Model Intercomparison Project Phase 5 (CMIP5)**, managed by the World Climate Research Programme, **relies on climate models to analyse Earth's climate dynamics under different scenarios and current climate conditions.** These models integrate atmospheric, oceanic, terrestrial, and ice processes, giving insights into climate system responses to external factors like greenhouse gas emissions. They were a critical component of the 5th assessment report of the Intergovernmental Panel on Climate Change.

97 https://wcrp-cmip.org/cmip-phase-5-cmip5/

the approach used in other climate impact studies, four different models are employed to improve the sample size and provide a better range of possible climate futures.

Annual drought conditions are determined in four general circulation models in historic experiments and under a high emission scenario (RCP 8.5) to determine samples of exposed crop lands for global mean temperature (GMT) values between 1 degree to 3.6 degrees above preindustrial levels in 0.1-degree increments. First, we determine those years at which the 21-year running average GMT reaches a predefined value. For the respective year and the 20 years surrounding that particular year, drought intensity levels are quantified for each of the four climate models. Given that we are provided with 21 years per model, and we employ four different models, we receive a sample size of 84 years per GMT value respectively (***Figure 74***). The identified relationships between GMT and impacts allow for a mapping on to the temperature profiles of each NGFS scenario when running the micromodel (NiGEM). The process of collecting 84 observations around each GMT step allows us to generate distributions of drought risk per temperature level, rather than point estimates, to be used in the statistical trials of the macroeconomic model (NiGEM).

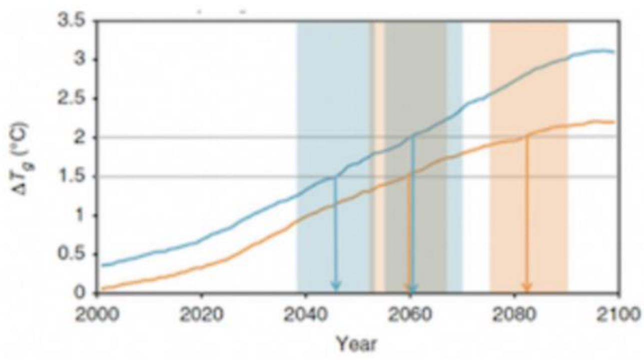

Figure 73. Illustration of how global mean Temperature levels are mapped to specific years, which are then used to analyse drought statistics.

Orange and blue line graphs refer to global mean temperature curves (y-axis) under two distinct scenarios from 2000 until 2100 (x-axis). The grey horizontal lines indicate specific GMT values (1.5 and 2 degrees). The crossing point of the horizontal lines and the temperature curves mark the year around which the 21 year period (blue and orange shaded area) are centred and are indicated by vertical arrows.

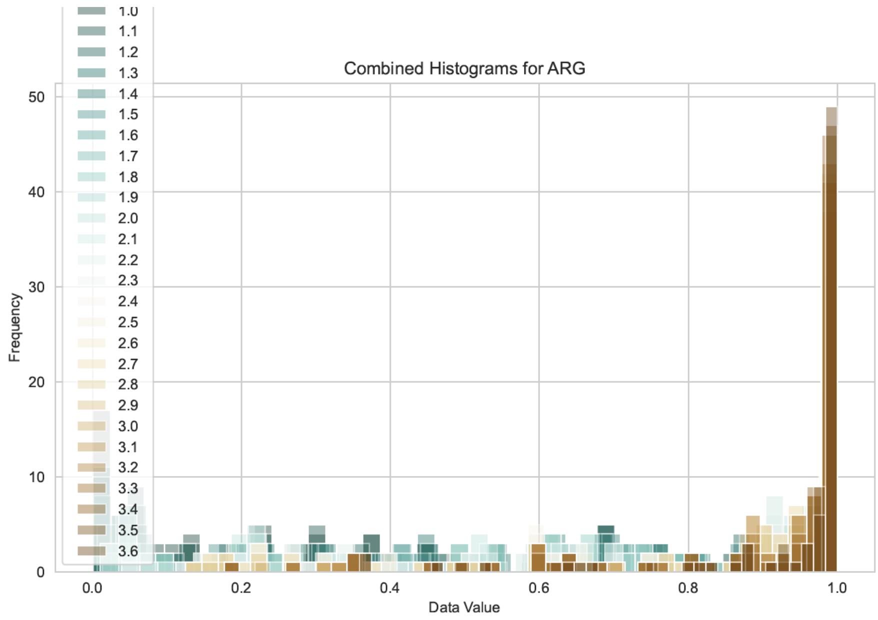

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Figure 74. Increased risk of yield losses from enhanced exposure to drought conditions under future warming levels.

Histograms of percentage of yield affected (x-axis) according to the equation "*National annual yield in % SPEI*" based on a sample size of 84 years per GMT value ranging from 1 to 3.6, here shown for Argentina. Colours of the bar plots refer to different levels of global warming, ranging from green (cool) to brown (warm), hence resulting in 84 observations (bars) per each colour. A level of one relates to a complete or 100% exposure to droughts according to the indicator of equation "*National annual yield in % SPEI*". Heatwaves are currently incorporated through population exposure to dangerous levels of humid heat which affect the economy through labour productivity and consumption. The exposure is measured at a grid-point level at which population and heatwave changes are quantified. For this reason, regions in which humid heat is projected to dramatically increase but are not as densely populated will be less impacted. This can be seen, for example, when comparing North America economies to Mediterranean or Southeast Asia (other direct or secondary Heatwave impacts e.g., on the energy sector, wildfire probability or on supply chains are not incorporated here).

Suggestions for future improvements

- Note that this indicator still requires further validation and approval from the scientific community through undergoing peer review processes.
- Drought conditions affect different crop types in different ways. A more accurate estimate of future crop losses to different warming levels would consider this by taking into account the regional mix of crop types planted.
- A 100% exposure to drought indicator is considered to lead to a 100% yield loss. However, this link would need to take in account additional factors of protection and adaptation. Other large and long-term effects, as for example on migration pressures, are not accounted for neither here, nor in the macroeconomic model (NiGEM).
- The chosen indicator affects non-irrigated crop areas most. A refined indicator would take into account differences and changes in local water management and irrigation.
- The impacts of drought conditions on yields have a seasonal dependency. The occurrence of a drought affects yields in a different way if it occurs, for instance, in the sowing season or in the harvesting season. A more accurate estimate of drought conditions would take into account the exact month in which it occurs.
- Here, we assume the impact of a drought on yields to scale linearly with the number of months within a year, however the damage function has likely a more complex character with a more nuanced

dependency based on drought intensity. Future estimates could use a linear dependency on drought intensity instead of using a threshold-based metric.

- Next to statistical relationships that take into account a single impact driver alone, crop modelling efforts as, for instance, done within the GGCMI initiative (Jägermeyr et al. 2021), could be used as a comprehensive source of estimates of crop yields under different emission scenarios.

2.2 Heatwaves: Calculating the nationally based exposure to Heat Stress on different warming levels

Heatwaves can affect the economic activity in various ways, e.g., they disrupt supply chains by damaging railways and roads, induce water scarcity and affect labour productivity. For national estimates of exposed population to dangerous levels of heat stress at different global warming levels we analyse wet bulb temperature – a measure of humid heat - which is particularly harmful for human health (Hall 2022). Humid heat affects the body's cooling capabilities which are based on evaporation of sweat. Once the surrounding air is saturated with humidity this mechanism stops working. When exposed to such conditions severe health risks could be the consequence, which can culminate in a total collapse from heatstroke. Wet bulb[98] temperatures of 35 degrees have been estimated to be fatal, while a value of 32 has been put forward for being fatal when doing physical labour (Veccellio et al 2020). Below these critical levels, the impacts of a humid heat can still be very significant but vary with the degree to which the local population is adapted to certain levels of heat stress characterising the local climatic conditions.

Detecting heat stress events.

Due to locally varying levels of heat stress adaptation, we apply a hybrid approach for detecting humid heat events for each grid-point. To identify heat stress, a relative threshold is provided by the 84th percentile calculated from annual maximum values for each grid-point. Assuming a gaussian distribution the 84th percentile corresponds to one standard deviation which can be considered a good estimate for extreme conditions. The climatology on which the percentiles are based corresponds to the distribution of humid heat days for years 1981- 2005 and is determined for each model separately. To that relative threshold, we add an absolute threshold value of 29.1 degrees, which is considered harmful for outdoor labour irrespective of the region (Saeed et al. 2021b, Kang et al 2019), we thus apply an upper limit to the quantile-based value and consider 29.1 degrees[99] as the local threshold wherever the local 84th percentile > 29.1 degrees. Threshold is hence the min (local 84th percentile, 29.1).

Thus, an event is detected for a grid point if i) a wet-bulb temperature of above the local 84th percentile is detected or ii) if a wet-bulb temperature is above 29.1 degrees.

[98] The wet-bulb temperature indicates the lowest level temperature that can be reached at a specific air (dry bulb) temperature thanks to the effect of water evaporation (i.e. until humidity saturation)

[99] This level is considered harmful (while 32 wet-bulb degrees is considered fatal for manual labour) and hence taken as threshold.

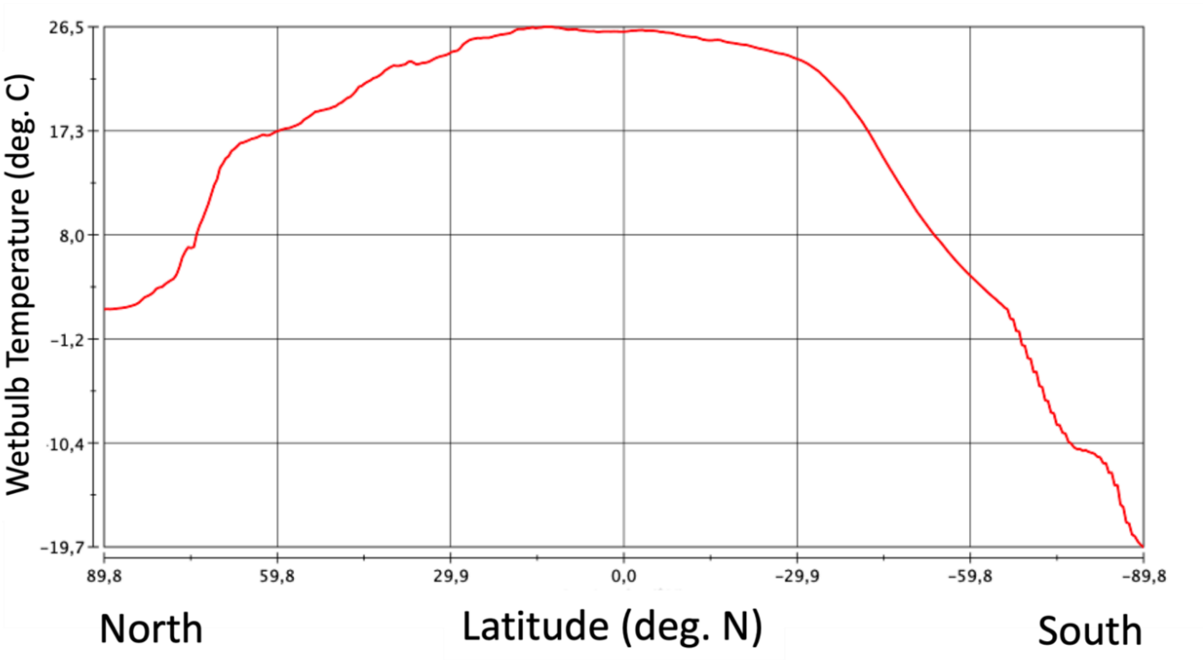


Figure 75. Latitudinal dependence of wet-bulb temperatures ranging from North pole (left) to South pole (right) determined by averaging the 84th percentile values over longitudes and years 1981 – 2019 including ocean and land areas. Highest wet bulb temperatures are occurring in the tropics around the equator (30°N – 30°S).

Quantifying effects of heat stress on aggregated exposed population

For determining the annually exposed population we use grid-cell based population data from the ISISMIP project[100] for the year 2005 at a resolution of 0.5. x 0.5 degrees, matching the resolution of the climate datasets. If for a given day the grid-point specific threshold is breached, the population within that specific grid-point is considered affected. For each year the affected population is then aggregated within national borders. Note that this approach considers that individuals can be affected multiple times per year as the population within a grid point is considered for each day within a year separately.

Determining future Heat Stress conditions and projecting heatwave distributions under different warming levels

We use the bias-adjusted and down-scaled output from four climate models of the fifth phase of the coupled model intercomparison project (CMIP5): IPSL-CM5A-LR, GFDL-ESM2M, MIROC5, HadGEM2-ES. Following the approach used in other climate impact studies four different models are employed to firstly improve the sample size and provide a better range of possible climate futures. These models provide relative humidity and temperature values on a 0.5x0.5-degree (approximately 50km x 50km) grid from which humid heat is calculated following the approach outlined in (Saeed et al. 2021a).

[100] https://www.isimip.org/gettingstarted/input-data-bias-adjustment/details/13/

We analyse data from four climate models at historic conditions (years 1981-2005) and under a high emission scenario until the end of the century (RCP. 8.5). This pathway was chosen as it provides the largest range of Global Mean Temperature (GMT) levels, which are then used to sample years with a time slicing approach.

Distribution of exposed population are determined for global mean temperature values between 1 degree to 3.6 degrees in 0.1 degree Celsius increments (compared to preindustrial temperatures). First, we determine those years at which the 21-year running average global mean temperature reaches a specific GMT value. For this year and the 20 years (21 in total) surrounding that particular year exposure levels are quantified for each of the four climate models (84 model-years in total).

This approach provides us with national population exposures for 84 modelled years: for each of the incremental GMT values we receive 21 years for each of the four models, which then are pooled into one sample. For each country and each warming level, aggregated population, quantified at the grid-point level, is fitted with a generalized extreme value distribution (Weibull), a distribution which is particularly well suited for capturing tails, to provide a continuous distribution (***Figure*** *73*) from which events can then be sampled for further analyses and used in the NiGEM macroeconomic model to estimate GDP losses. While this approach delivers reasonable results for most countries, geographical location and country size can lead to distributions with location factor close to zero (i.e., very small countries).

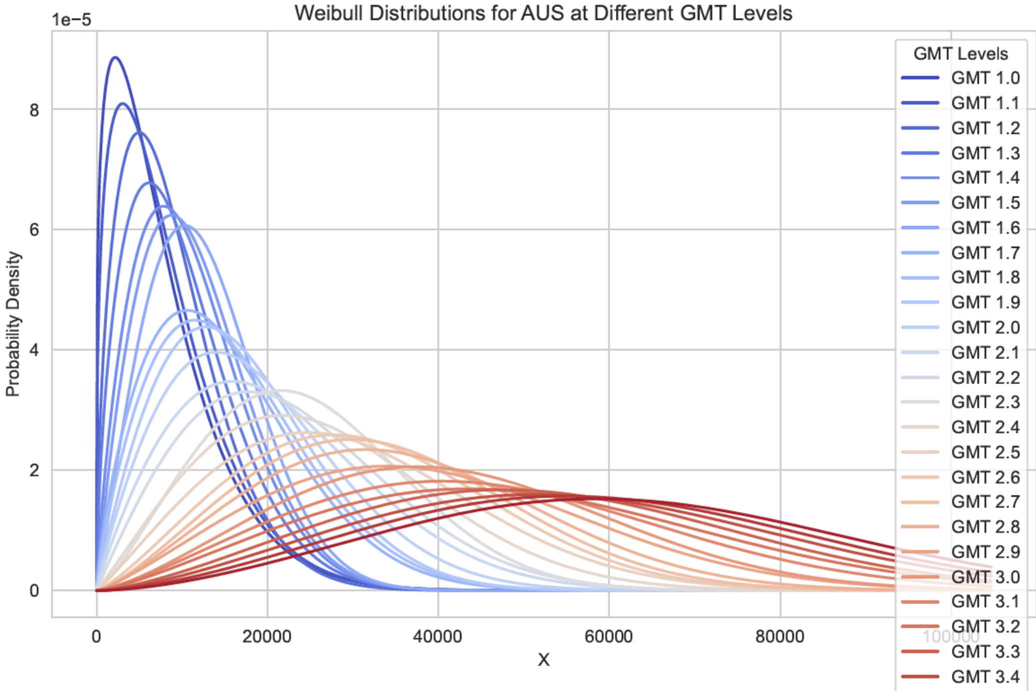


Figure 76. Increased Risk of heat stress exposure under higher global mean temperature levels.

Change in exposed population to dangerous levels of humid heat for in Australia (x-axis) in a given year. Curves show the Weibull distributions of exposed population to heat stress based on a sample size of 84 years sampled around the year that exhibits the respective warming level in RCP-8.5.

Suggestions for future improvements

- Note that this indicator still requires validation and approval from the scientific community through undergoing peer reviewed process.

- Impacts of extremes scale with their magnitude and duration. Here, the duration of a heat-stress event is considered only implicitly. By assuming that the population is affected each day anew, long duration events are increasing annual exposure levels each day they last. However, the chosen metric does not discriminate between days that breach the heatwave thresholds consecutively and those that are distributed independently within a year. Further, one could argue that a person can only be affected once. Here, allowing for double counting was chosen to account for the lasting effect of an affected individual to the labor market, which likely constitutes a simplification of real-world effects.
- Using globally gridded-population data, we do not account for population growth, changes in age structure or the number of employed citizens or the sectors they are employed in. Outdoor labourers, active in sectors such as construction or agricultural, are more exposed to the risks of high levels of heat stress, while the availability of air conditioning and other adaptation strategies might provide relief for heat stress locally. Differentiating the grid point specific labour structure and conditions within a country would yield more accurate estimates.
- The approach used delivers reasonable results for most countries but implies that only few events were captured when the country size is in the same scale as the resolution of the used climate models. In particular, Island states (e.g., Faroe Islands) exhibit distributions of questionable validity as the climate models likely don't resolve the physical mechanisms related to land cover with full accuracy. This likely leads to an underestimation of heat stress in these countries.
- The societal impacts of heat stress and heat extremes go beyond effects on human health and labor productivity. Recent heatwaves have severely impacted economies in numerous ways e.g., by favouring wild-fire conditions, by lowering gauge heights or rivers, thereby disrupting supply chains, destroying infrastructure such as tarmac roads, and disrupting energy supply (as water temperatures were too high as to be used for cooling some thermal power plants). Future initiatives within the NGFS network need to account for these effects to provide a more realistic estimate of future impacts on global warming on national economies.

2.3 Floods damage modelling

Global river flood simulations

Global annual flooded areas and flood depth used to quantify flood damages are derived from the ISIMIP2b[101] river flood simulations. The dataset is based on the experiments from the global water sector included in the ISIMIP2 protocol. For the entire time period we assume constant socio-economic conditions from 2005 regarding e.g., urbanisation patterns, river engineering and water withdrawal (2005soc). The climate forcing from four global circulation models (GCMs) for three RCP scenarios (RCP2.6, RCP6.0 and RCP8.5) was processed by a set of global hydrological models (GHMs)[102] and harmonized with regard to their underlying river routing scheme by means of the global hydrodynamic model CaMa-Flood (v. 3.6.2 Yamazaki et al., 2011), following the methodology employed in previous studies by Willner et al. (Willner et al., 2018; Willner, Otto and Levermann, 2018). This process results in daily fluvial discharge data at a resolution of 15' (~25 km × 25 km). For the analysis of the flood data, we use the annual maximum daily discharge. For each of the GCM/GHM model combinations and each grid cell on the 15' resolution, we fit a generalized extreme value distribution over the pre-industrial time series of the annual maximum discharge to derive L-moment estimators of the distribution parameters. This allows us to derive the return period of the annual maximum river discharge and to apply a model bias correction approach by Hirabayashi et al. (2013). Additionally, we account for current flood protection standards at the subnational scale using the FLOPROS database (FLOPROS database, Scussolini et.

[101] ISIMIP, Inter-Sectoral Impact Model Intercomparison Project; www.isimip.org; Database accessible under https://data.isimip.org/10.48364/ISIMIP.303619

[102] GCM's: GFDL-ESM2S, HADGEM-2-ES, IPSL-CM5A-LR, MIROC5
GHM's: CLM45,CLM50,CWATM,DBH,H08,JULES-W1,LPJML,MATSIRO,MPI-HM,PCR-GLOBWB,WATERGAP2

al, 2016). This database currently presents the best global-scale knowledge of the maximum return period of floods that an administrative region can prevent. In this modeling process, we use the "Merged layer" of the database. This layer combines empirical data concerning existing protection infrastructure ("Design layer"), information about protection standards and policy requirements ("Policy layer"), and model-generated outputs derived from an observed correlation between gross domestic product per capita and flood protection ("Model layer"). Here, we also apply a threshold procedure assuming that when the protection level is exceeded, the flood happens as if there was no protection in the first place (for example, dams break); below the threshold no flooding takes place. In case that the return period of the discharge exceeds the protection level, the surplus water (water amount that exceeds the capacity of the river channel) is distributed across the floodplain taking into account the topography (Yamazaki et al., 2011). This procedure allows for a spatially-explicit representation of the floodplain, providing flooded area and floodplain depth at a 0.3′ resolution corresponding to the resolution of the model internal Digital Elevation Model. For the final assessment, we reaggregate the high-resolution flood depth data from 0.3′; to a 2.5′ resolution (~5 km × 5 km) by retaining the maximum flood depth as well as the flooded area fraction, defined as the fraction of all underlying high-resolution grid cells where the flood depth was larger than zero. Further non-technical background information on the flood modeling chain can be found on [ISIpedia: the open climate-impacts encyclopedia] (Volkholz, 2021).

Quantifying flood damages

The damage modelling part closely follows the methodology of Sauer et al. (2021). To derive a local damage from the annual flood maps and exposure data. The continent-level residential flood depth-damage functions developed by Huizinga et al. (2017) are applied.

As asset (exposure) layer, a historical gridded Gross Domestic Product dataset (ISIMIP2) is used (Murakami et al., 2019) but with a fixed exposure set to 2005 and a conversion factor applied to transform the GDP to capital stock. The exposed assets on the grid level (150 arcmin) based on the flooded fraction obtained from the river flood model are determined. As a next step, the grid level damage is quantified by multiplying the exposed assets by the flood fraction and the flood-depth damage function (***Figure 72***). Then the estimated damage on the region/country level are calculated by aggregating over all grid cells within a respective region/ country.

Regional aggregation

In line with country level aggregation into regions used by the NIGEM model, the countries Australia, USA + Canada, China, India, Japan, and Russia are provided separately while all other countries are provided as regional aggregations according to **Table 17**.

Table 17. Regional aggregation of countries

Africa	Europe	Developing Europe	East Asia	Latin America	Middle East
Egypt	Iceland	Albania	Hong Kong	Argentina	Afghanistan
South Africa	Denmark	Belarus	Taiwan	Brazil	Algeria
Angola	Norway	Bosnia and Herzegovina	Indonesia	Chile	Armenia
Benin	Sweden	Cyprus	South Korea	Mexico	Azerbaijan

Botswana	Finland	Kosovo	Malaysia	Cuba	Bahrain
Burkina Faso	Switzerland	Luxembourg	New Zealand	Antigua and Barbuda	Djibouti
Burundi	United Kingdom	Malta	Singapore	Aruba	Georgia
Cameroon	Austria	Montenegro	Viet Nam	Bahamas	Iran
Cape Verde	Belgium	Serbia	Bangladesh	Barbados	Iraq
Central African Republic	France	Moldova	Bhutan	Belize	Israel
Chad	Germany	North Macedonia	Brunei Darussalam	Bolivia	Jordan
Comoros	Ireland	Ukraine	Cambodia	Colombia	Kazakhstan
Congo	Netherlands		Fiji	Costa Rica	Kuwait
Cote d'Ivoire	Croatia		Kiribati	Dominica	Kyrgyzstan
Democratic Republic of the Congo	Greece		Lao People's Dem. Rep.	Dominican Republic	Lebanon
Equatorial Guinea	Italy		Maldives	Ecuador	Libya
Eritrea	Portugal		Marshall Islands	El Salvador	Mauritania
Eswatini	Spain		Micronesia (Federated States of)	Grenada	Morocco
Ethiopia	Bulgaria		Mongolia	Guatemala	Oman
Gabon	Czech Republic		Myanmar	Guyana	Pakistan
Gambia	Hungary		Nauru	Haiti	Qatar
Ghana	Poland		Nepal	Honduras	Saudi Arabia
Guinea	Romania		Palau	Jamaica	Somalia

Guinea-Bissau	Turkey		Papua New Guinea	Nicaragua	Sudan
Kenya	Estonia		Philippines	Panama	Syria
Lesotho	Latvia		Samoa	Paraguay	Tajikistan
Liberia	Lithuania		Solomon Islands	Peru	Tunisia
Madagascar	Slovakia		Sri Lanka	Saint Kitts and Nevis	Turkmenistan
Malawi	Slovenia		Thailand	Saint Lucia	United Arab Emirates
Mali			Timor-Leste	Saint Vincent and the Grenadines	Uzbekistan
Mauritius			Tonga	Suriname	Yemen
Mozambique			Tuvalu	Trinidad and Tobago	Palestine
Namibia			Vanuatu	Uruguay	
Niger				Venezuela	
Nigeria					
Rwanda					
Sao Tome and Principe					
Senegal					
Seychelles					
Sierra Leone					
South Sudan					
Togo					
Uganda					

United Republic of Tanzania					
Zambia					
Zimbabwe					

Determining future Floods conditions and projections at different warming levels

To attribute economic losses to warming levels we follow the approach by James et al. 2017 which suggests that impact indicators can be seen as a function of the Global Mean Temperature (GMT) level. This leads to the assumption that a given GMT level will, on average, lead to the same change in that indicator even if it is reached at two different moments in time in two different emission scenarios. This assumption is generally well justified, and differences are small compared to the widespread changes projected by different models (Herger, Sanderson and Knutti, 2015).

In each GCM[103] simulation corresponding to each RCP scenario, we identify the year for which a certain GMT level (0.1°C incremented starting with 1°C) is reached. Having identified the year for which a specific GMT level is reached in a scenario-GCM combination, we average the projected values over a 21-year period centred over that year in the corresponding GCM (or IM scenario experiment). We then average over all available scenarios for each GCM (or GCM-IM) combination, before pooling the estimates obtained from all GCMs (or GCM-IM) combinations, from which we compute their median values for each 0.1°C GMT level increment.

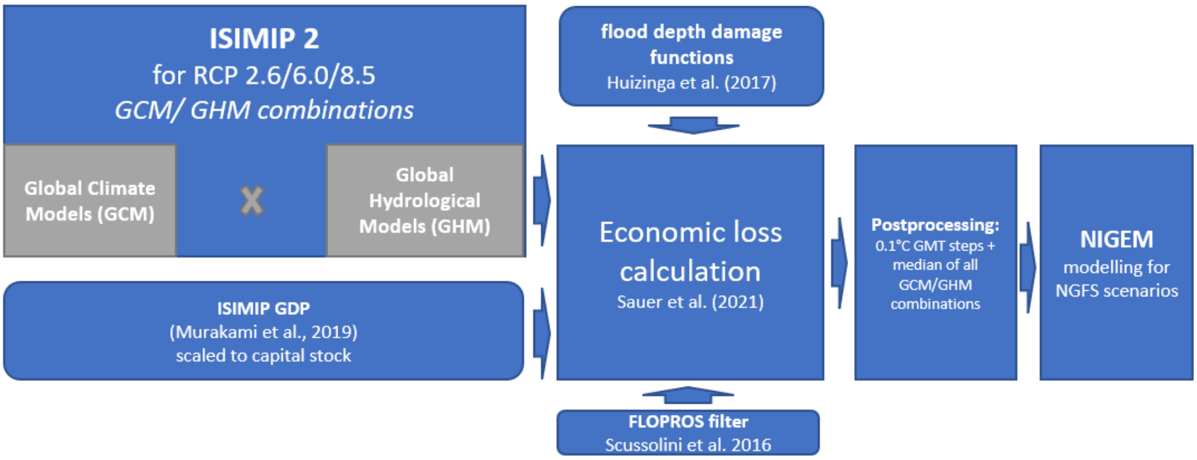
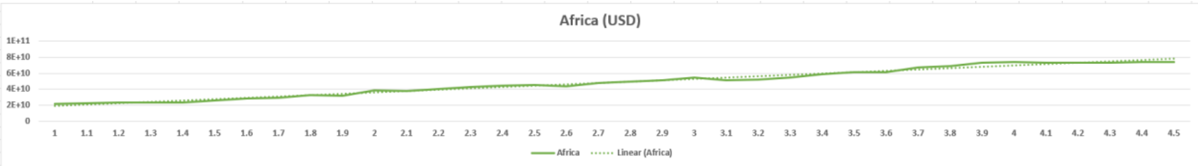


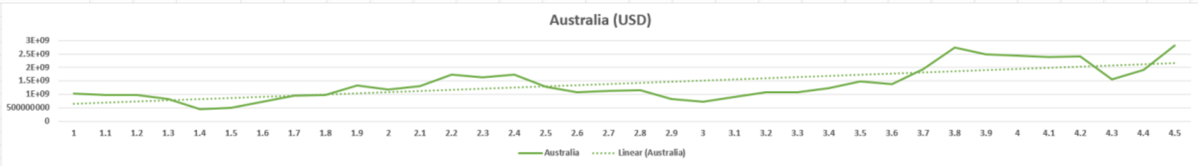
Figure 77. Modelling chain for flood per country/region losses based on ISIMIP2 data.

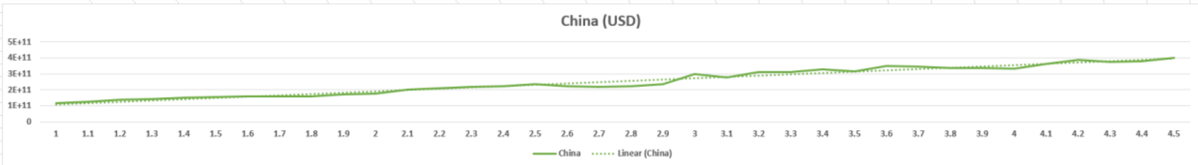
The data we are providing as 0.1°C step warming levels, can be used to analyse trends in some regions. While we see a clear trend towards more flood damage due to higher warming levels in Africa, India and China, there is an increase visible in Europa and the US + Canada but less significant. For Developing Europe (see **Table 17**), the trend shows a decrease that is also reported in other publications. Please note that these results were derived by aggregating a number of models with global coverage. For damage on a country level, local studies

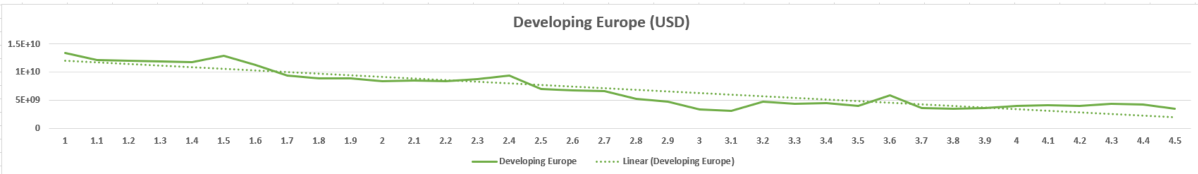
[103] Global Climate Models

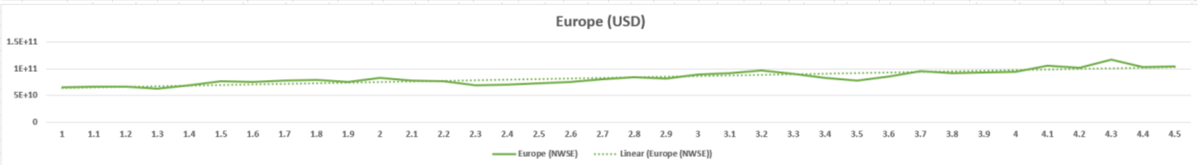
need to be considered. While Developing Europe show a downwards trend, it is still possible that one or multiple countries within this regional aggregation can have an upwards trend towards more flood loss with higher warming levels.

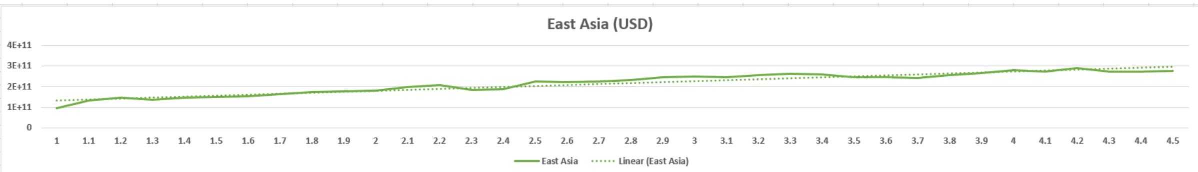


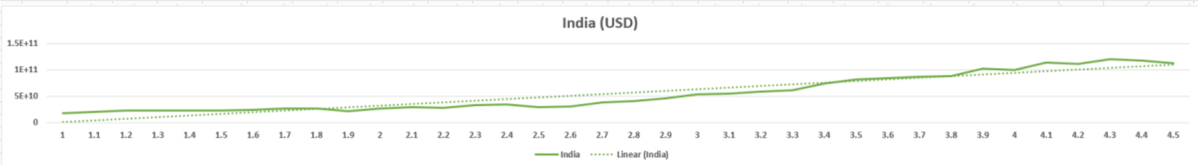


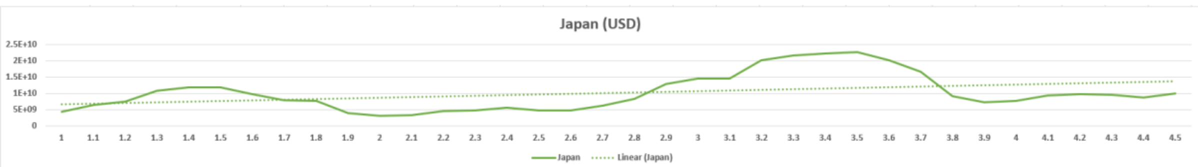


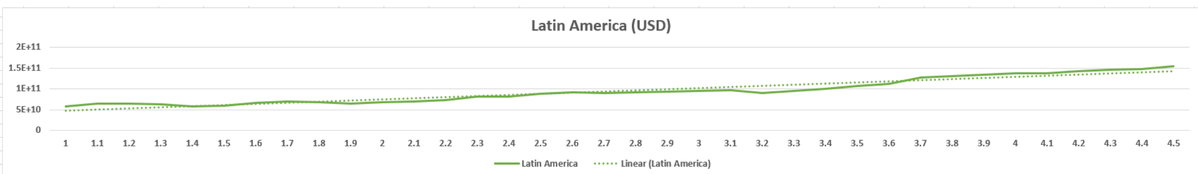












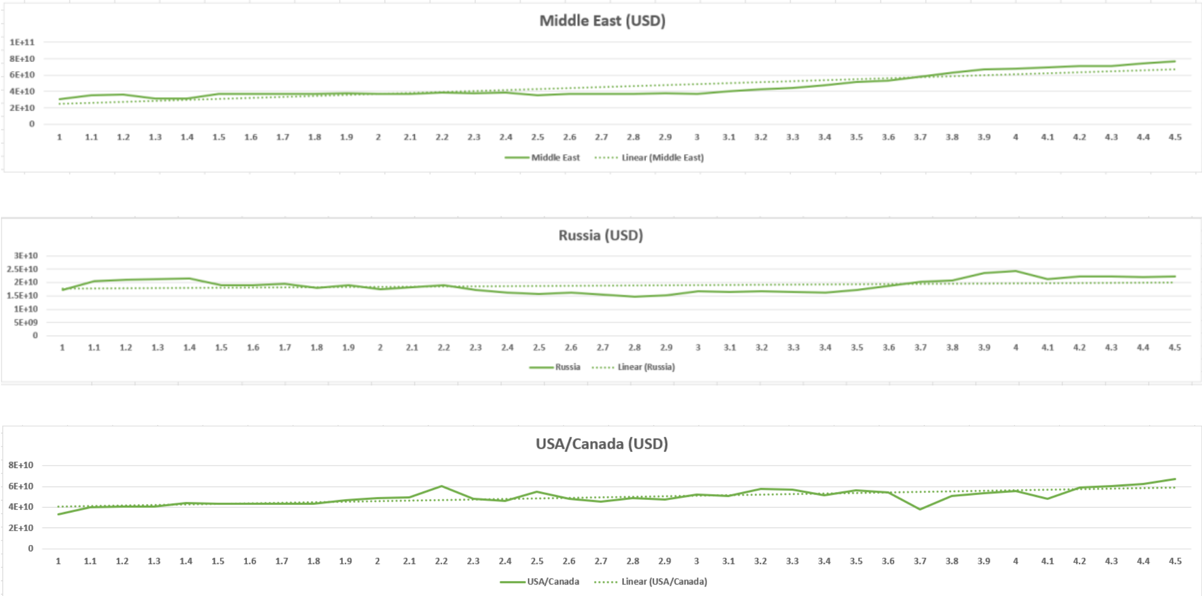


Figure 78. Flood loss (USD) for different warming levels for selected regions.

Suggestions for future improvements

- Provide flood damage estimates on a country level for a set of selected countries, where datasets can be considered most reliable.
- Compare between different data sources and projections to identify regional trends.
- Conduct research on these models and select the most suitable ones for loss estimation in a certain region, instead of using the full range of flood models provided within the ISIMIP project
- Separate into return frequencies (e.g., 5-year, 10-year, 100-year) for more detailed use by modelling teams of national banks. The loss data provided currently comes as annual average, and according to CIE user feedback, changing this would be very useful.
- Consider to also include coastal flooding, and potentially pluvial flooding. Currently only river floods are considered. Coastal flooding from storm surges compounded with sea level rise should be taken into account in the future as well (long-term strategy).
- Study the effect of the FLOPROS protection layer (with/without protection).

2.4 Tropical cyclones damage modelling

Observations and future conditions by warming levels

Among the costliest natural hazards are tropical cyclones (TCs). TCs, also known as typhoons or hurricanes, are highly destructive weather phenomena that form over warm tropical oceans, typically between 5° and 30° latitude North and South. TCs have a devastating impact on many coastal regions in the tropics and subtropics. For instance, the 2017 TCs Harvey, Irma, and Maria resulted in over 260 billion USD of damages to the United States (NOAA). Human-induced climate change might have diverse impacts on TCs, including heightened rainfall and wind speed and an increase in the frequency of extremely intense storms (Knutson et al., 2020). We estimate future TC risk globally under various Global Mean Temperature (GMT) increases using the CLIMADA natural catastrophe modelling platform (Aznar-Siguan & Bresch, 2019; Bresch & Aznar-Siguan, 2021). In the aftermath, we will describe in detail the chosen modelling set-up.

Hazard is given by a probabilistic set of future TC events. This is constructed in two steps. First, a probabilistic set of historical TCs is built and then, frequencies and intensities of such historic track sets are rescaled according to expected future changes. The historic track set is built starting from observed tracks given by the IBTrACS dataset (Knapp et al., 2010). A random walk algorithm is then used to expand such historic set and generate a larger number of events. This approach is designed to infer a probabilistic distribution of tracks from a single track and, in so doing, generates a set of probabilistic tracks. The method is described in detail in the supplementary material of Gettelman et al. (2018). For each of the generated tracks, a wind field map is estimated by using the parametric wind model proposed in Holland (2008). ***Figure 79*** shows an example of hazard footprint for tropical cyclone Maria. It is important to highlight that the hazard constructed only represents extreme winds. Storm surges and coastal flooding associated to TCs are not considered *explicitly* in this analysis. Yet, as the storm surge wave is created by the strong winds, they are included *implicitly*.

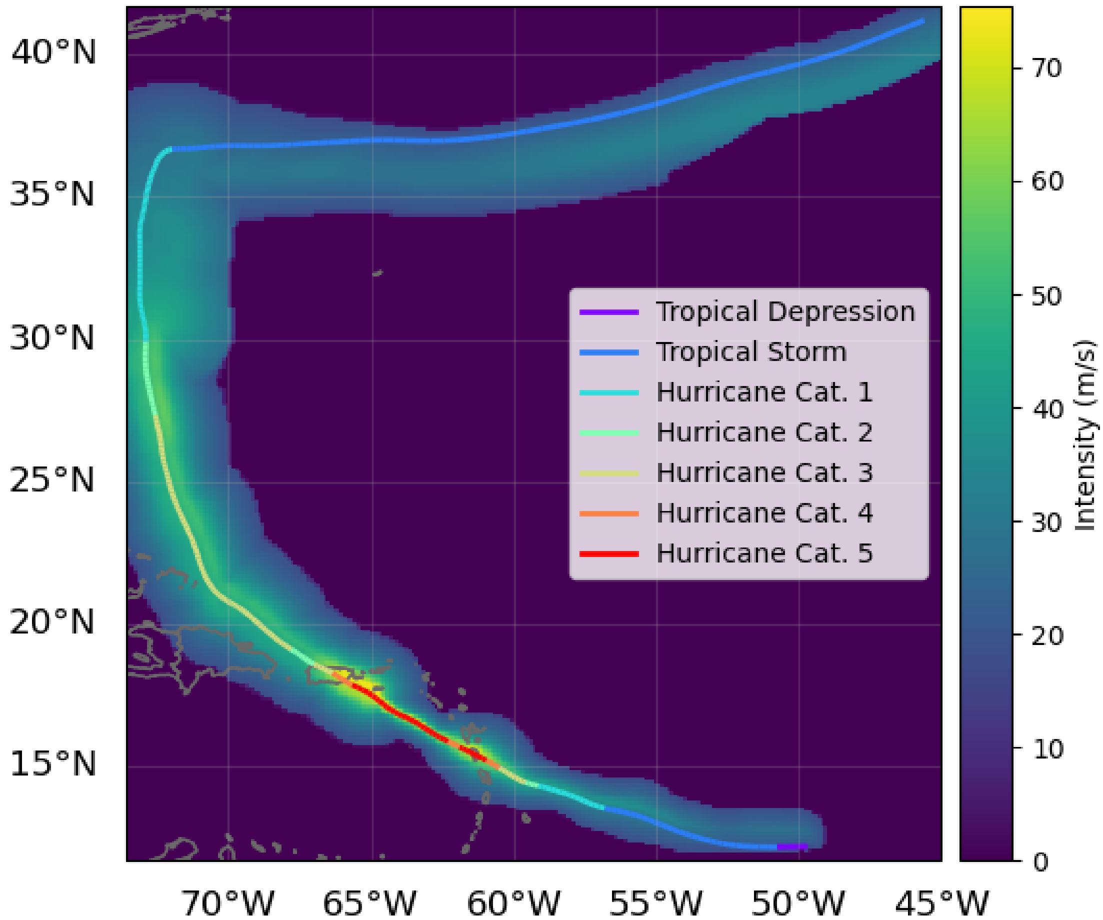


Figure 79 Track and wind field of tropical cyclone Maria (2017)

Finally, future probabilistic track sets are derived by rescaling the historic probabilistic wind fields with the information provided in Knutson et al. (2015). Therein, percentage changes of TCs' frequency and intensity until the end of the century (i.e., 2100) and under RCP4.5 are provided. Using linear interpolation, these scaling factors can be extrapolated for different RCPs, different years and, consequently, different Global Mean Temperature Levels (GMT). The chosen RCP is 6.0 and tracks are derived every 5 years from 2020 to 2100. The corresponding GMT levels are then derived by following Table 3 shown in the methodological section of the previous implementation phase[104].

Quantifying Tropical cyclones losses

Exposure is modelled globally at the country level via the LitPop approach proposed by Eberenz et al. (2020). LitPop disaggregates macro-economic data (e.g., GDP) proportionally to a combination of nightlight intensity and population data. Vulnerability is modelled using the damage functions provided by Eberenz et al. (2021). These functions were calibrated using EM-DAT loss data[105]. They are defined globally and are divided into 9 distinct regions. ***Figure 80*** shows the functions and regions.

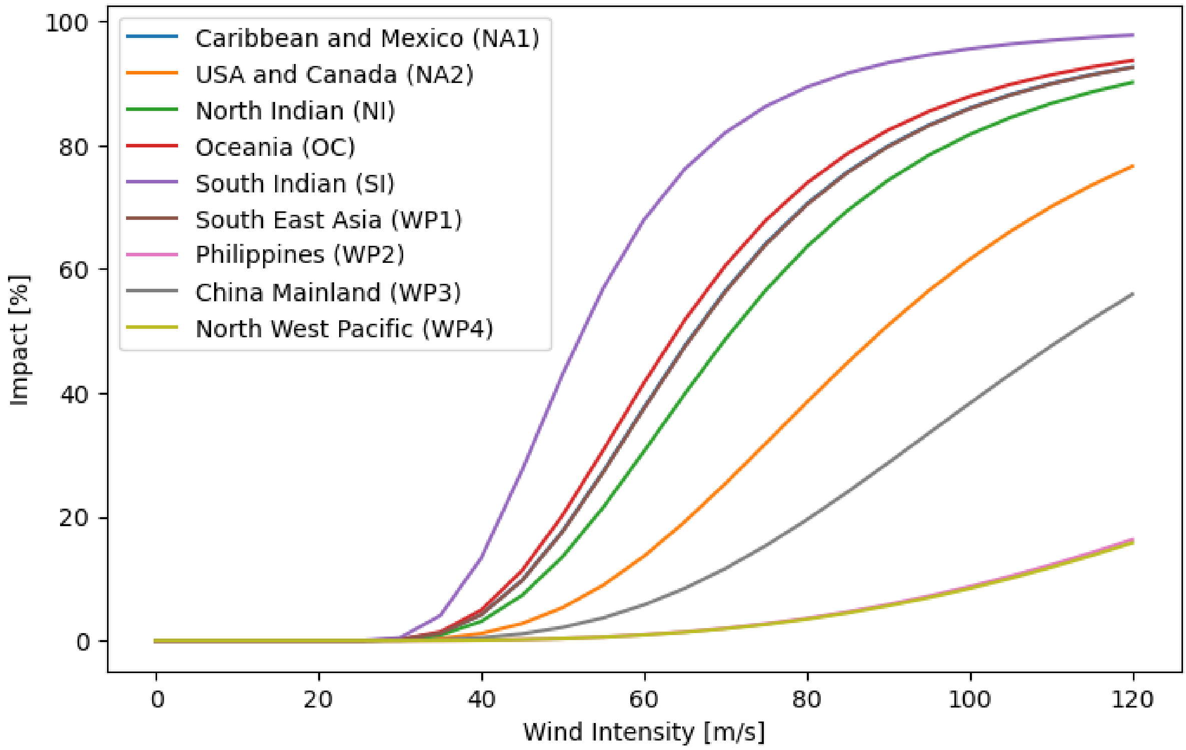


Figure 80. The calibrated impact functions as defined by Eberenz et al. (2021)

The probabilistic natural catastrophe model so defined allows generating a large set of synthetic losses. Since each of these losses have an associated occurrence frequency, output from this model defines the probability distribution of TC losses. Therefore, by running the model by country and at various time steps under a specific RCP, countries' loss distributions at various GMT levels are derived.

[104] https://climate-impact-explorer.climateanalytics.org/methodology/#one-methodology

[105] https://www.emdat.be/

Suggestions for future improvements and limitations

The analysis herein presented has several limitations. First, the analysis uses windspeed as a proxy for all losses and does include storm surge losses only implicitly. Second, due to the global scope of the analysis and the absence of global asset value datasets, exposure consists of proxy data and may therefore differ from actual asset values. Also, due to the lack of historical damage data, the same vulnerability functions are used for large – yet homogenous - geographical areas. While this provides a basic level of regional differentiations, it does not resolve single country vulnerabilities. More importantly, neither the exposures nor the vulnerabilities are evolving in time – as no reliable, spatially explicit projection of the sort exists to date at global scale – and thus we can only report impacts of future climate cyclones on current assets. In addition, the adopted scaling parameters to simulate TC changes in the future were defined on distinct historical datasets and only for the end of the century. Finally, in order to derive future tracks for increasing GMT a linear interpolation procedure is employed, even though future changes in tropical cyclones may not be linear.

3. Modelling of acute risk macroeconomic effects (NiGEM)

Overview

It is common to undertake policy analyses using models of the economy. These usually involve applying a single shock, such as an increase in energy prices, and evaluating its effects under different policy responses. Stochastic simulation techniques extend this approach where a variety of shocks are taken at random from a pre-determined distribution and are repeatedly applied to the model, producing a large variety of possible outcomes. From this large number of potential outcomes, the moments of the solution of the endogenous variables can be calculated and used to investigate the degree of uncertainty around projected data values (forecast or simulation) deriving from the range and distribution of the shocks applied.

Shocks can be estimated in several ways but essentially there are two categories. The first, and most popular in the past, is Monte Carlo based (MC), where the stochastic shocks are drawn from some assumed parametric distribution of the errors, usually the multivariate normal (where $\mu_i \sim (\underline{\mu}, \Sigma)$ with mean vector $\underline{\mu}$ and variance matrix Σ). The second method is the Residual Based (RB) approach, which consists of taking the actual sample period residuals as the stochastic shocks. In NiGEM, the standard stochastics analysis[106] uses the RB approach where the stochastic shocks are represented by historical NiGEM equation residuals, leading to a matrix of shocks of M*T where M is the number of equations in the model and T is the historical data range being used to run the model. This matrix of potential historical shocks is then drawn randomly from to provide future shocks. Brown and Mariano (1984) introduced this RB approach using historical residuals.

When analysing projections of acute weather impacts and their likely effects on the economy, we use both MC and a form of RB with historical equation residuals replaced with future climate projections from Climate Analytics.

[106] Barrell, Ray, Karen Dury and Ian Hurst (2000). 'International Monetary Policy Coordination: An Evaluation of Cooperative Strategies using a large Econometric Model.' National Institute of Economic and Social Research Discussion Paper 160.

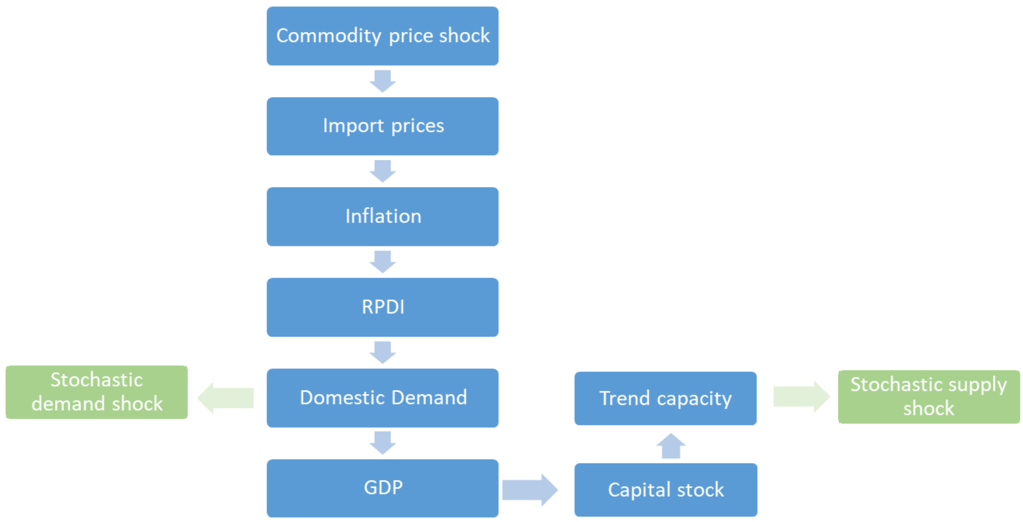
Trade and policy

One characteristic of NiGEM which needs to be addressed in the context of physical risk modelling is the inter-connected nature of the international economy represented in NiGEM. Via global linkages in NiGEM, if a country experiences an acute negative shock (of any type), other countries may experience an upswing in their economy. Only if a global shock of equivalent magnitude is applied would all countries experience a negative impact and even here, competitiveness, exchange rates etc. would mean the negative effects are not apportioned equally.

When considering future acute impacts, we are dealing with stochastic shocks of differing magnitudes and frequencies. To facilitate the assessment of the impact of acute climate events on individual countries, we isolated countries and only consider the impacts domestically which means that the stochastic trials[107] are executed with trade exogenous (i.e., turned off). This is the same approach followed for chronic physical risk. In addition, a neutral agent response (governments and central banks) is ensured by also exogenising monetary and fiscal policy.

Standard economic channels available for shocks in NiGEM require the model to be running with endogenous global links to correctly adjust to the economic impacts and find a stable solution. The loss of the trade and asset channels restrict the channels available to shock to only direct supply and demand shocks. To capture the equivalent impacts of the weather effects on GDP when using demand and supply shocks only, calibration scenarios were run. These provide the link between the actual economic channel used to model the acute weather impact (e.g., impact on crop yields) and their equivalent impact on demand and supply in the model, which is then used in the stochastic trial when trade and monetary policy are discounted.

Example – a commodity price is increased by 1 %. This shock is fed into the standard model providing delta impacts on both demand and supply. We use the ratio of 1/demand as the multiplier for the stochastic runs when converting the randomly determined acute impact to an equivalent demand shock in the model. This process is also used to determine the stochastic supply shock.



[107] A stochastic trial means the final output of n NiGEM simulations run with stochastic impacts where n is normally set in the region of 1000-5000. Each NiGEM simulation typically represents over 10 million calculations.

Figure 81.Example calibration shock process

Stochastic trial process

NiGEM is executed across all time-periods of the stochastic window (2023-2050) and the resulting output is saved. A NiGEM trial will contain around 1000 executions to ensure sufficient values are created to remove any bias in the random selection.

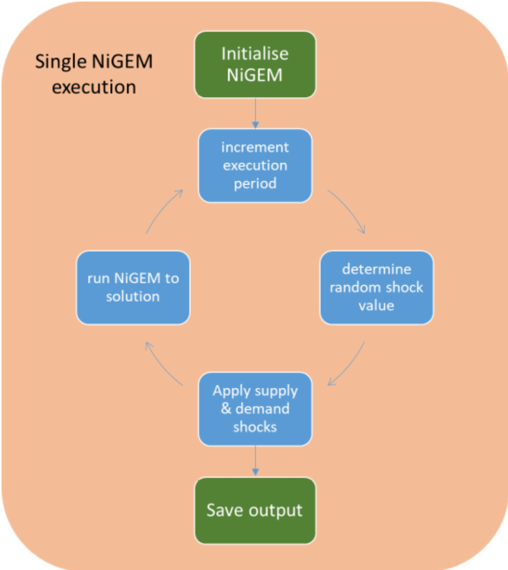


Figure 82. NiGEM stochastic execution

The random draw of the shock combines the Global Mean Temperature (GMT) with the climate impact data provided as input (see the second part of this chapter on hazard modelling) and uses a standard random number generator to create the resultant shocks. The GMT used is the temperature profile from one of the three scenarios below:

- Current policies (h_cpol)
- Delayed (d_delfrag)
- Net zero (o_1p5c)

Impact on country regions

NiGEM contains several regions (Africa, Asia, Developing Europe, Latin America & Middle East) that are made up of an aggregate of constituent countries. The impact in each constituent country is calculated separately (i.e., differing random shocks within the region) and the aggregate created by summing the constituents.

Model notes and possible refinements

Due to model constraints, the supply shock cannot exceed -70% because a reduction of the trend capacity by greater than 70% causes instability within NiGEM. This limit is applied to all stochastic trials. Further experimentation with individual countries could be undertaken to determine the country-specific limits for the shock size. Alternatively, shocks greater than the maximum could be incorporated into future years to provide a greater degree of shock persistence than currently considered. However, this approach would have to be ratified with CA for each acute impact.

The stochastic trials are run using 1000 individual NiGEM runs (approximates to 4e10 model calculations). Further investigation on the stability of the confidence bounds using increased trial sizes can be undertaken.

The data provided by CA for the stochastic trials is provided in 0.1 C intervals which in turn can produce step changes in the shocks applied to the model. Investigating into whether the shocks can be applied in a smoother fashion without affecting the academic integrity of the shocks themselves would remove these step changes. One possible option is if a weighted average of shocks would be appropriate. For example, currently if the shock is below GMT at a value of X, the shocks for GMT(X-0.1) are applied. If a reasonably linear progression can be assumed between the shocks at GMT(X-0.1) and GMT(X), a weighted ratio of the two shocks may be applicable.

There are two potential issues with regards to the demand and supply shocks used in the stochastic trials. The use of proxy demand and supply shocks in the stochastic trials, while providing accurate impacts for GDP, may not be sufficient to provide the correct size and profile of impacts for other economic variables. Further investigation on using the resultant GDP from the stochastic trials to create a calibrated shock in the standard model, which maintains trade and applies the shock to the correct channel, would prove useful here.

Currently, the demand and supply shocks are created, by necessity, with global linkages "On" in the model. The premise used is that as the shocks are applied equally and globally, the impact of global spillovers is minimised. However, NiGEM does allow individual country/regional models to be run in isolation (in which there is an exogenous 'rest of the world'). Therefore, an investigation on how much trade impacts the size of the demand and supply shocks, could be conducted for those shocks which can function correctly within this isolated framework.

Acute weather data

The impact data for four acute weather effects, used as input in the NiGEM runs, are provided as described in the second section of this chapter

Acute weather event	Hazard projection data
Heatwaves	Country level parameters for Weibull distribution for all countries and a range of GMT. The Weibull distribution represents the number of people affected by the heatwave
Cyclones	Capital stock damage values in Mn $US, 2017 based on GMT for a range of output samples along with the probability of that damage occurring in a country.
Floods	Annual average capital stock damage values for varying values of GMT for each country/region.
Drought	Projections the loss (%) of agricultural yield due caused by drought for each country across a range of GMT.

4. Stochastic Implementation

4.1 Cyclones

Cyclones' impact on the economy is assessed via the channel of asset damages (i.e., capital shock), derived from the disruptions caused by these type of events.

While capital stock is available for a sub-set of countries in NiGEM, it is primarily used for forecasting and direct shocks to capital stock can have non-intuitive effects in the simulations. Instead, the more generic investment premia variables (IPREM) are used by NiGEM to impact housing and business (as well as prices) and can be used to introduce a capital shock. The shock to IPREM will directly relate % damage on assets (from random sample) to an equivalent premia shock.

1. 1% investment premia (IPREM) shock applied in NiGEM 2023-2050
2. Resultant average productivity, investment (or domestic demand) and employment shock values used to create equivalent capital stock multipliers.

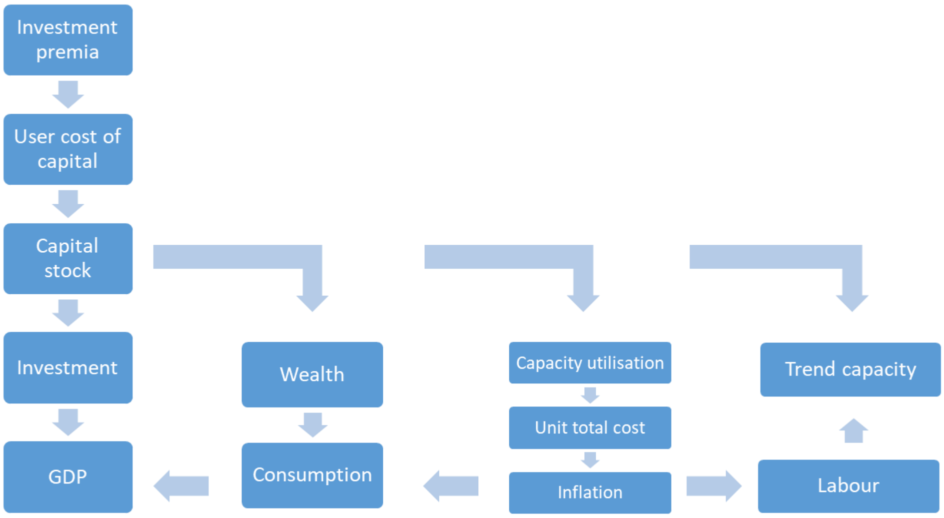


Figure 83. IPREM shock channels

For the stochastic implementation, the capital stock damage in any timestep is randomly drawn from the range of data provided for each country for the current scenario GMT. This is then used to create the relevant demand and supply shocks.

4.2 Floods

Input data

Different from all other acute risks modelled in the NGFS scenarios, flood data are the projected average yearly damages for all time-periods across a range of GMT. This means that a single shock is required to impact NiGEM rather than a stochastic trial. Again, absolute damages are transformed into equivalent percentage damages.

Shock implementation

Both flood and cyclone data represent capital stock damages, allowing the use of the same economic channels (IPREM) as used for Cyclones to implement flood damages. The capital stock percentage damage represents the flood data provided with the modelling approach described in the previous sections.

4.3 Droughts

Droughts have several channels of impact:

1. Productivity: This is a direct shock to supply based on the % damage to agricultural production.
2. Exports: this links the fall in agricultural production to a country-level fall in total export volumes. The share of agriculture in an economy is based on UN trade figures.
3. Prices: A fall in supply generates an increase in prices leading to a fall in demand.

Note:

- Domestic country level economic impact is the actual % drought shock scaled by UN data relating to agricultural Gross Value Added (GVA) to total GVA for that country.
- World prices: to overcome the limitation derived from ending trade, country level share of world agriculture, estimated as part of the physical risk modelling (see previous sections), is used to determine price increases as a result of droughts. A one-to-one correlation is imposed (e.g., 10% drought in Africa equals a 10% increase in prices scaled by Africa's proportion of total agriculture)

Calibration simulations

All three shock channels are again linked to demand and supply shocks, while aggregate drought to supply/demand shock multipliers are used in the stochastic trial.

1. Productivity: 1% shock to trend capacity (YCAP). Shock provides an equivalent demand multiplier.

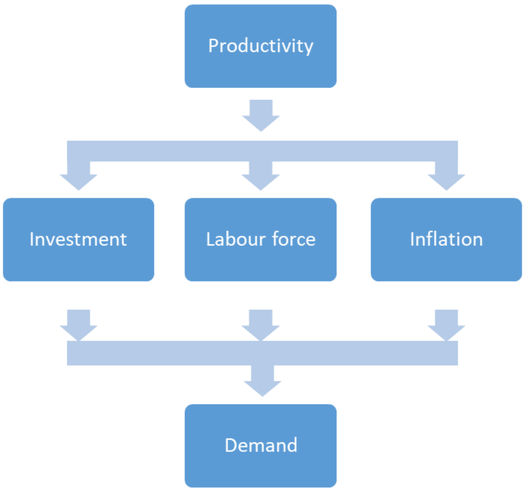


Figure 84. Productivity -- demand channels

2. Exports: 1% shock to exports, supply and demand exogenised so all GDP effects come through net trade impact. The GDP delta is then used as the exogenous impact on demand in the stochastic trial.

Figure 85. Imports adjust to exports and directly impact GDP

3. Prices: 1% shock to world prices of food, beverages, and agriculture to review resultant supply and demand impacts.

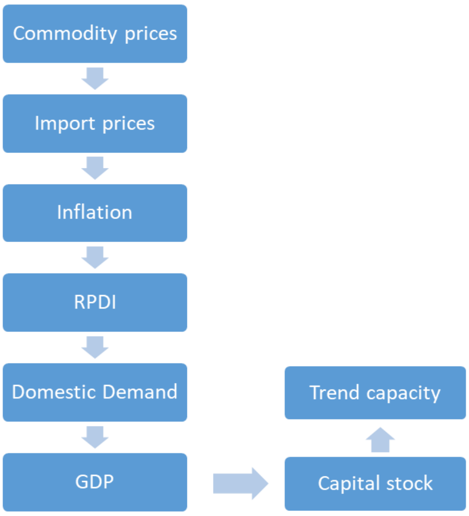


Figure 86. Prices transmission channel

To account for differing country-speed of adjustment, a three-year average is used to create the shock multipliers for productivity and export scenarios. With prices, an average of all periods in the simulation is used due to greater volatility (for example the positive impact on commodity exporters in the initial periods of the scenario, followed by overshoot as trade effects dominate).

Stochastic implementation

The percentage agricultural damage for each timestep is randomly drawn from the range of data available for the current GMT. This is then converted into equivalent price, demand, and supply shocks.

4.4 Heatwaves

The Weibull distribution explained in the dedicated section represents the size of population affected by a heatwave. The calibration shock will need to link population changes directly to supply and demand shocks in NiGEM.

1. 1% population shock applied in NiGEM for one year (2023)
2. Resultant average productivity and demand shock values reviewed[108].
    a. Supply impact uses the delta for trend capacity (YCAP).
    b. Demand impact uses either consumption (C) or domestic demand (DD)
3. Calibration multipliers calculated for each country to provide the link for a 1% population shock converted to equivalent YCAP & C/DD shocks

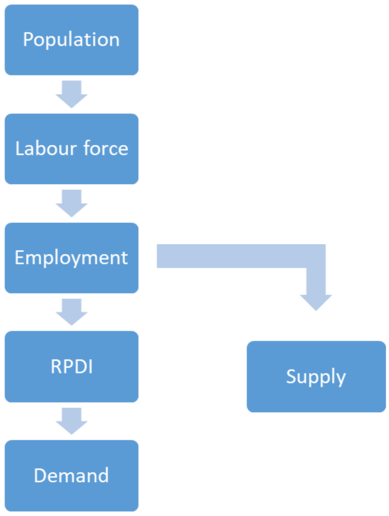


Figure 87. Population shock channels

Weibull parameters for each country are selected based on the GMT indicated by the scenario at each timestep. The parameters are then used (inverse transform) to generate the Weibull distribution value.

$$X = \lambda\left(-ln(U)\right)^{1/a}$$

Where X represents the absolute number of people affected by the heatwave. Scale (λ) and shape (a) parameters are provided by the models described in the previous section and U is a random number (0<=U<=1)

The value of X is then compared against the average population 1985-2005 to provide the percentage population shock to be used in NiGEM.

[108] Applying directly a population shock would require endogenous supply and demand, which is not possible with Trade set to OFF

Module 7: Country-level downscaling

1. Non-technical summary

What is country-level downscaling?

Downscaling here refers to the process of converting the world-region-level outputs from global integrated assessment models to the national level. Global IAMs provide projections at the level of world regions, which may not capture the finer resolution required for regional or local analysis. For the NGFS climate scenarios, downscaling involves refining the results of global climate models to provide more granular information about how climate mitigation impacts specific regions, industries, or economic sectors.

Why do we need country-level downscaling?

The goal of the Paris Agreement is to limit long-term global temperature change to well-below 2°C and pursuing efforts to limit it to 1.5°C. However, as energy and climate policies are not set at the global level, but by individual countries, these countries have developed and submitted their own plans formulated in Nationally Determined Contributions (NDCs) and mid-century net zero emissions strategies. Assessments of future emissions and the effectiveness of climate policies are usually performed with Integrated Assessment Models (IAMs) at the global and world-region level. However, bringing together insights from IAMs with information at the country level has remained difficult, as global models usually provide results for a limited number of world regions.

Several strategies have been developed to overcome these limitations. IAMs have increased regional resolution and added individual countries as native regions to their models. However, this strategy remains difficult due to the complexity of the IAMs, catering simultaneously for different modules including energy, economy, and climate change. Modelling teams such as REMIND (Dietrich *et al.* , 2023) and MESSAGE (Huppmann *et al.* , 2019)are tackling this issue by increasing the spatial heterogeneity. However, running these models for all countries in the world is still problematic. To solve this issue, downscaling approaches can be used to provide country-level results. One of the main advantages of applying downscaling techniques is that they do not require extensive computational time, since they do not increase the spatial resolution of the IAMs themselves.

How does country-level downscaling help to produce NGFS scenarios?

The NGFS Consortium has developed a downscaling methodology that can be used to assess the potential implications of the NGFS scenarios for 184 countries. To allow for country-level analysis, a subset of key energy-system-related variables like emissions, primary energy and final energy have been downscaled to country-level. However, there are also important limitations to consider:

- The country level results are derived from and primarily consistent with the regional IAM outputs. If the IAM scenario does not represent the region well, this will translate into the country level outputs.
- As the country-level results are derived from a standardised methodology that is applied across all countries, they currently do not incorporate specific policies on a country-by-country or sector-by-sector basis.
- The downscaling algorithm does not consider technology capacity evolution or investments required in the electricity grid infrastructure nor backup capacity. Users may need to cross-check these results with other specific factors and data to ensure the pathway is representative.

2. Overview of method

According to the literature, downscaling approaches should provide results in line with local scale (historical country-level) data and consistent with the original IAMs results (Van Vuuren *et al.* , 2010). Criteria used for the downscaling should be scenario specific, and leading to plausible results, avoiding violation of physical boundaries (Grubler *et al.* , 2007). As illustrated in **FiFigure 88**, the downscaling tool generates two pathways to provide results that are both consistent with historical data and IAMs results:[109]

- Short-term projections that are consistent with both countries historical data and regional IAMs results.
- Long-term projections that converge to regional IAMs results.

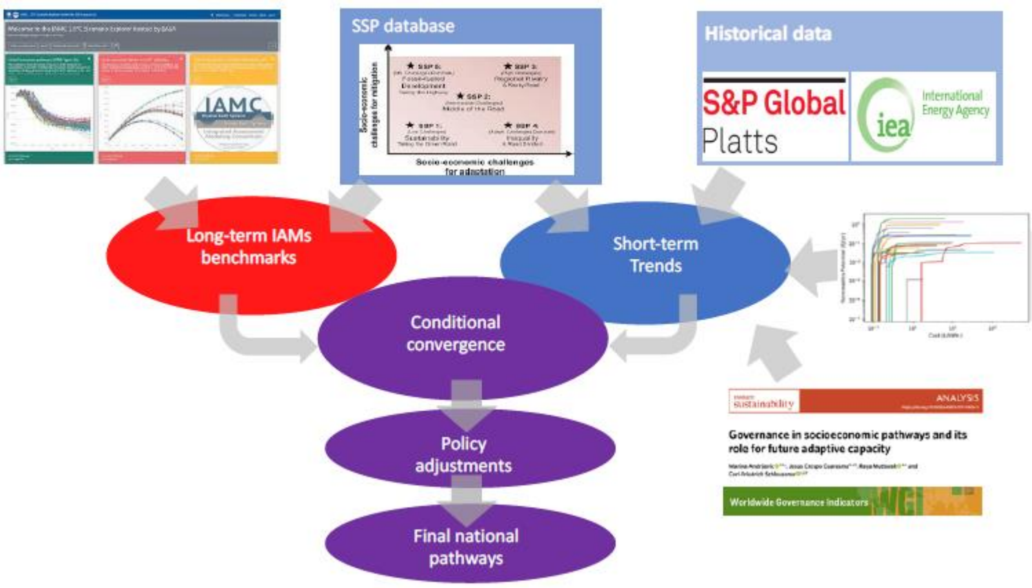


Figure 88. Conceptual framework for downscaling variables to the country level

[109] The downscaling methodology described in this section was developed by IIASA (International Institute for Applied Systems Analysis).

Both pathways are harmonized so that the sum of country level results within a region coincides with the regional IAM results, where large countries will undertake the biggest adjustments required to match the regional data. Then a linear interpolation is created to converge from the "short-term" pathway to the "long-term" pathway between the base year (e.g., 2010) and a future "time of convergence". The base year is the year after which model scenarios can start to diverge from historical data. However, historical data information can be used until more recent available years (hence beyond the base year) as is done for estimating the final energy demand. Different times of convergence between the short-term to long-term projections are assumed, based on the type of NGFS policy scenario, to better reflect the underlying scenario storyline. For scenarios compatible with 1.5°C, a faster convergence is assumed, while convergence is slower for scenarios in line with current policies or NDCs. Depending on the assumptions on convergence, the downscaling algorithm will provide a range of energy pathways at the country level.

Table 18. Timing of convergence and SSP storyline

NGFS Scenario	Convergence	SSP[110]
Delayed transition	Slow	SSP2
Divergent Net Zero	Fast	SSP2
Fragmented World	Slow	SSP2
Low Energy Demand	Fast	SSP2
Net Zero 2050	Fast	SSP2
Current policies	Medium	SSP2
NDCs	Medium	SSP2
Below 2°C	Medium	SSP2

The definition of slow, medium and fast convergence in terms of the "year of full convergence", differs depending on the type of variables, as summarized in **Table 19** below. The choice of these years is derived from experiments with the downscaling method and allows for strong influence of country-level characteristics in the next few decades across all variations.

Table 19. Timing of convergence

Timing of convergence	Final energy variables	Primary and secondary energy variables
Slow	2200	2300
Medium	2150	2250
Fast	2100	2200

[110] Shared socioeconomic pathway.

Short- and long-term projections are then combined, considering convergence time. Pathways are provided at the country level *c* (at time t) by using, e.g., for energy $EN_{c,t}$, a weighted average of these projections (without violating consistency with the IAMs results), where weights φ are linearly increasing for the long-term projections.

$$EN_{c,t} = \varphi_t \, ENLong_{c,t} + (1 - \varphi_t) \, ENShort_{c,t} \quad (1)$$

Weights will gradually change over time based on the assumption on the timing of convergence *tc*:

$$\varphi_t = \frac{t - tc}{2010 - tc} \quad (2)$$

The downscaling algorithm focuses on energy variables such as final energy, secondary energy and primary energy, and derives the energy-related CO_2 emissions from the downscaled energy system characteristics.

3. Key inputs

To downscale these variables, **regional input data** from IAMs are used. Here, the described downscaling algorithm uses GDP and population data from baseline scenarios (absent of climate policies) as they are available in the SSP online database.[111] Besides, historical data are used to initialize the country-level variables at the base year. The IEA Energy Balances 2022 provides energy-related historical data for 183 countries and regional aggregates (IEA, 2022). In addition, for the electricity sector, power plants information (regarding remaining economic lifetime of certain power plants and planned capacity additions) around the world are obtained from the PLATTS database (Platts, 2019). For emissions, PRIMAP is used as historical data source (Gütschow *et al.* ,2021). Also, governance indicators at the country level as well as supply-cost curves based on the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) for the renewables energy potential availability are included.

The downscaling tool provides country-level data for final, secondary, and primary energy variables as well as energy-related CO_2 emissions. Final energy variables include energy demand by energy carrier (i.e., electricity, liquids, gases, solids, heat, hydrogen) and sectors (i.e., transportation, residential and commercial, and industry). Secondary energy variables include information regarding the fuel mix (e.g., coal, natural gas, oil, renewables etc.) associated to each energy carrier (e.g., liquids, solids, gases etc.). Primary energy variables provide information regarding the overall energy mix (including energy transformation losses) by also differentiating technologies both with and without Carbon Capture and Storage (CCS). For an overview of the IAM downscaling output variables see **Table 38**.

Final energy demand can be decomposed into contributing factors by using a Kaya identity approach (Nakicenovic and Swart, 2000). Final energy consumption (*FEN*) is decomposed into three contributing

[111] https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome

elements: energy intensity (final energy consumption divided by GDP), GDP per capita, and population (*POP*) as shown in equation (3).

$$FEN_{c,t} = \frac{FEN_{c,t}}{GDP_{c,t}} \times \frac{GDP_{c,t}}{POP_{c,t}} \times POP_{c,t} \quad (3)$$

GDP and population projections are used as input to the downscaling tool, as they have been already downscaled at the country level as part of the SSP framework. As a result, to calculate total final energy demand, some reasonable assumptions are made about the evolution of the energy intensity over time. Energy intensity is a metric that allows for comparing how energy is used to produce services and final goods (hence, GDP) across countries (GEA, 2012). Historical data show that the energy intensity tends to increase in the early phases of industrialization as traditional (non-commercial) forms of energy are replaced by commercial (and more efficient) energy. Then, the energy intensity starts to decline again as soon as this transition to commercial energy is completed – a pattern known as the *hill of energy intensity* (Grubler et al. ,2012). Apart from this "peak", the historical energy intensity is dominated by a general downward trend associated to increasing income per capita that strengthens improvements in energy efficiency. Although energy intensities trajectories might differ across individual countries, historical data from 1972-2017 suggest an inverse relationship between the level of the final energy intensity (defined as final energy consumption divided by the GDP) and GDP per capita (***Figure 89***).

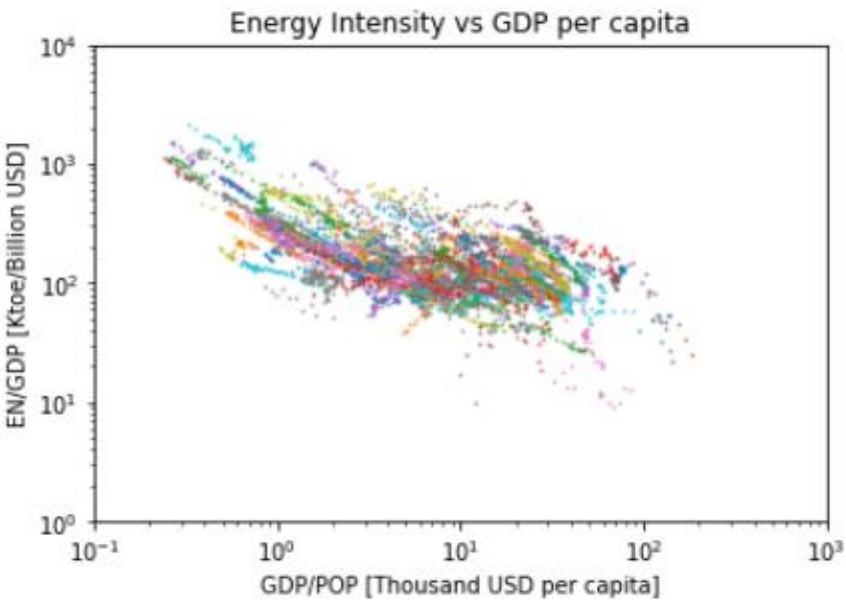


Figure 89. Historical energy intensities over GDP per capita across countries, from 1972 to 2017

The literature suggests that energy intensity can still improve by a factor 10 or more in the very long term 'Ayres (1989), Gilli *et al*. (1990), Nakicenovic (1993, 1998), Wall (2006), GEA (2012)). Hence, it is assumed that this relationship between energy intensity and income per capita will continue in future long-term scenarios, by using a log-log model, in which the linear regression coefficients are derived after taking the logarithm of both energy intensity (final energy per unit of GDP) and economic activity (GDP per capita):

$$\log\left(\frac{FEN_{c,t}}{GDP_{c,t}}\right) = \beta_c \log\left(\frac{GDP_{c,t}}{POP_{c,t}}\right) + \alpha_c \tag{4}$$

In the above equation, the parameters of the functional form (*α* and *β*) are estimated based on:

- Historical data at the country level (historical trend extrapolations for each country).[112]
- Future regional energy intensity based on IAM results (in this latter case *α* and *β* would be the same for all the countries *c*).

Long term IAMs projections are based on regionally aggregated IAM results, whereas the short-term projections $ENShort_{s,c,t}$ in each sector *s* are calculated based on historical trends extrapolations of the energy intensities at the country level. Short-term projections are finally also harmonised to match regional IAMs results.

For long term projections, it is assumed that the energy intensity path (over GDP per capita) will be the same across all countries within the same region. Therefore, a relationship between energy intensity $EILong$ and GDP per capita is estimated via regression, based on regional IAMs results.

$$\widehat{EILong}_{s,c,t} = exp\left[\alpha_c + \beta_c \log\left(\frac{GDP_{c,t}}{POP_{c,t}}\right)\right] \tag{5}$$

Then, the final energy demand (*EN*) at the country level is calculated by multiplying the energy intensity (*EI*) by the GDP projections (available at the country level).

$$\widehat{ENLong}_{s,c,t} = \widehat{EILong}_{s,c,t} \times GDP_{s,c,t} \tag{6}$$

Based on those calculations, countries with the same level of income per capita will have the same level of energy intensity in a given year. Then, the long-term projections are harmonised to ensure that the sum of country-level results coincides with the regional IAMs data $EN_{s,R,t}$ in a proportional manner.

$$ENLong_{s,c,t} = {EN_{s,R,t}}\Big/{\sum_{c\epsilon R}\widehat{ENLong}_{s,c,t}} \times \widehat{ENLong}_{s,c,t} \tag{7}$$

Using different assumptions on conditional convergence, the downscaling algorithm in principle provides a range of energy demand pathways at the country level. However, for the NGFS scenarios a mapping of conditional convergence to each scenario is used (see **Table 18**), leading to a single projection for each scenario.

[112] However, it is also important to evaluate historical data in the context of IAMs results and the future scenario storylines. IAMs scenarios or SSPs storylines usually envisage increasing GDP per capita over time, whereas historical data show that in several countries GDP per capita has declined during the period 1980-2010 (including for example Saudi Arabia, Brunei, Haiti, Venezuela, Zimbabwe etc.). In this case, it might not be entirely appropriate to rely only on historical trend extrapolations (as future income per capita growth might largely differ from the developments observed in the past). For this reason (only for countries with declining GDP per capita), an additional data point (with *t*=2100) is added to the historical data series, based on long term projections. By doing so, the historical data information (until the most recent available year) is combined with the energy intensity projections (based on regional IAMs long-term trajectory) in 2100.

The same approach as described here for final energy demand in general is used to downscale final energy results for individual subsectors (such as electricity, solids, liquids, gas, transportation, industry, residential and commercial). For example, the subsector electricity of sector final energy is downscaled by considering the relationship between the share of electricity on total final energy and GDP per capita.

The downscaled results need to be internally consistent. This means that the sum of sub-sectors (such as industry, transportation, and residential and commercial) needs to be in line with total final energy in each country. Hence, some adjustments are introduced by using an iterative process: first, the energy carriers are adjusted in a proportional manner, so that:

- The sum of subsectors coincides with total final energy demand,
- The sum across countries coincides with the regional IAMs results.

These two steps are iterated to obtain results that are in line with the IAMs results and consistent at the sector level. Note that these adjustments are applied only for short-term projections, which are based on historical country-level data. Conversely, long-term projections do not need further adjustments as they are entirely based on regional IAMs results. Finally, the range of projections is calculated based on assumptions on the timing of conditional convergence.

Secondary energy is downscaled by fuel (coal, oil, gas, biomass, nuclear, solar, wind and geothermal energy) for each energy carrier (e.g., liquids, solids, gases, electricity). For short-term projections, the fuel mix of solids, liquids and gases is calculated based on historical data at the base year (*t=tb*).

$$ENShort_{e,c,t,f} = EN_{e,R,t,f} \times \frac{EN_{e,c,t=tb,f}}{EN_{e,R,t=tb,f}} \quad (8)$$

For the long-term projections the fuel composition f in all countries within a given region R is derived from the IAM, based on regional IAMs results $EN_{e,R,t,f}$ for each energy carrier *e*, i.e., by the time of the conditional convergence year (see **Table 19**), all countries within a region will have the same fuel mix:

$$ENLong_{e,c,t,f} = ENLong_{e,c,t} \times \frac{EN_{e,R,t,f}}{\sum_f EN_{e,R,t,f}} \quad (9)$$

$ENShort_{e,c,t,f} = EN_{e,R,t,f} \times \frac{EN_{e,c,t=tb,f}}{EN_{e,R,t=tb,f}}$ For downscaling the electricity mix *EL*, a variety of criteria is used to calculate the short-term projections (historical data, remaining economic lifetime and planned capacities, governance, supply cost curves). To this end, a weight for each criterion *i* is assumed, and the short-term projections are calculated as a weighted average (where the sum of the criterion weights must equal 1).

$$\widehat{ENShort}_{e=EL,c,t,f} = \sum_i w_{i,f,t} \times ENShort_{e=EL,c,t,f,i} \quad (10)$$

At the base year, electricity generation is initialized by using historical data criteria, and for all other periods, specific weights are assumed for each fuel. The next steps are as follows:

- Harmonising the results proportionally to match regional IAMs data for each fuel.
- Updating the results dynamically over time to account for path dependencies, starting from the results at the base year, and computing the difference in IAM results.
- Allocating this difference to the country level (based on a range of criteria).
- Adjusting the results to match regional IAMs as well as calculating the projections based on the assumptions on conditional convergence.

The **primary energy** mix at the country level is calculated by multiplying secondary energy results by using the same conversion rates used in IAMs.

$$Primary_{e,c,t,f,tc} = Secondary_{e,c,t,f,tc} \times Conv_{e,R,t,f} \quad (11)$$

Regarding technologies with CCS the same share of CCS versus non-CCS technologies as in regional IAMs results is applied to the country level.

$$Primary\_CCS_{c,t,f,tc} = Primary_{c,t,f,tc} \times \frac{Primary\_CCS_{R,t,f,tc}}{Primary_{R,t,f,tc}} \quad (12)$$

$$Primary\_wo\_CCS_{c,t,f,tc} = Primary_{c,t,f,tc} \times \frac{Primary\_wo\_CCS_{R,t,f,tc}}{Primary_{R,t,f,tc}} \quad (13)$$

For calculating CCS sequestration from biomass, the same emission factor is applied as used by the various IAMs. The CCS sequestration from fossils is calculated by using adequate emission factors for oil, gas, and coal. Finally, total emissions from energy and CCS emissions are harmonised so that the sum of country level results matches the regional IAMs data.[113]

The change in land use emissions over time is distributed from regional IAM results to the country level the equation below:

$$LUD_{t,c} = \frac{\sigma c}{\sigma R}(LUDiam_{t,R} - LUDiam_{t-1,R}) + LUD_{t-1,c} \quad (14)$$

We allocate the change in direct land use emissions over time from IAMs (LUDiam) at the country level based on the historical standard deviation (σ) of the last 10 years. We use the standard deviation, as it captures both the size of emissions (in absolute terms) and the volatility in each country. As a result, changes in direct land use emissions from IAMs will be mostly allocated to countries with larger emissions and higher volatility within the region.

However, IAMs do not account for **indirect land use** emissions, further contributing to around 5.5 $GtCO_2$ of carbon sinks globally. Considering the volatile nature of land use, the indirect emissions data are initialized

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[113] For downscaling non-CO_2 emissions, regional IAMs results are linked with the GAINS (Greenhouse Gas – Air Pollution Interactions and Synergies) country-level results (Höglund-Isaksson *et al.*, 2020, Winiwarter *et al.*, 2018, Purohit *et al.*, 2020). The GAINS model focuses on cost-effective strategies for greenhouse gas emissions control, emphasizing improvements in air quality. It provides non-CO_2 emissions pathways for baseline and maximum technical abatement potential scenarios across 96 countries.

based on the average values from 2010-2020. The growth rates of the regional adjustment values estimated by the IMAGE/LPJmL model are then applied to each country belonging to the same region. As these growth rates are influenced by global mean temperature, a scenario mapping is utilised that aligns the NGFS scenario with the RCP emissions trajectory reported by Grassi *et al*. (2021).

Table 20. Mapping NGFS scenarios with RCP emissions trajectories

SSP RCP scenarios	NGFS scenarios
SSP2 RCP 1.9	Net Zero 2020, Low Energy Demand, Divergent Net Zero
SSP2 RCP 2.6	Delayed transition, Below 2°C
SSP2 RCP 3.4	Fragmented World, NDCs
SSP2 RCP 4.5	Current policies

Scenarios have been mapped based on the global temperature peak, as well as 2100 temperature values from the NGFS scenarios, in alignment with the SSP/RCP scenarios. Finally, total land use emissions are calculated as the sum of direct and indirect emissions and harmonised to match the observed historical emisssions from PRIMAP v2.5.1 (Gütschow *et al*., 2021, 2023) until 2020.

The downscaling method as described so far, does not yet account for policies at the country level that could influence a country's emissions. Ideally, in the Current policies and NDC scenarios, the energy system policies (such as renewable energy targets, or efficiency policies) would be explicitly taken into account in the downscaling. However, this labour-intensive development is left for future projects. Currently, **country-level policies** are incorporated in the downscaling algorithm by introducing an assessment of the NDC emissions targets at the country level, in order to enhance realism of country-level pathways. Those targets are applied to total GHG emissions and are introduced as soft constraints, as country-level policies might not be fully consistent with underlying IAMs results, depending on scenario/storylines considered. In other words, it is assumed that countries will try to reach their domestic targets, although these might be only partially achieved (depending on regional policies considered by a given model/scenario). Domestic targets for 2030 are introduced for all scenarios. The mid-century (2050) strategies are introduced only for the Net Zero 2050, Low Energy Demand, Fragmented World and Delayed transition scenarios. As described below, policies are introduced in three steps:

- First, total GHG emissions are computed as the sum of total CO_2 emissions, LULUCF (land use, land-use change and forestry) emissions and total non-CO_2 gases based on IPCC AR4 (IPCC 4th Assessment Report) Global Warming Potentials.
- Second, the gap between current total GHG emissions (without policies) and the emissions targets is calculated. Then those emissions targets (for 2030 and 2050) are distributed to yearly emissions targets for all time periods (starting from 2015), assuming that they will gradually tighten over time, based on a linear interpolation.
- Third, it is assumed that countries will fill the emissions gap by either increasing BECCS (biomass with CCS) or by replacing fossil fuels with renewables. Here, the assumption is that countries will try to fill

50% of the emissions gap by increasing BECCS. However, the amount of BECCS largely depends on the type of policy scenario (e.g., BECCS technologies are usually not deployed under a current policy scenario) and by biomass availability. As a result, it might not be possible to meet 50% of the emission gap by increasing BECCS. Therefore, it is further assumed that the remaining emission gap (50% or more) will be met by replacing fossil fuels with renewables.

This approach allows for generating pathways as consistent as possible with country-level NDCs targets and mid-century net zero strategies. A caveat of this methodology is that final energy is not adjusted to meet the domestic targets (the downscaling algorithm adjusts all the primary and secondary energy variables, but does not update the final energy variables), which might create inconsistencies if large adjustments are needed to achieve those targets.

4. Key outputs

After the methodological part, downscaling **results and available outputs** across the IAMs applied to the NGFS policy scenarios (i.e., GCAM, MESSAGE-GLOBIOM and REMIND-MAgPIE) are compared. For example, IAM results were downscaled to the country level and then re-aggregated to the EU27 level for each IAM. The graph in ***Figure 90*** below compares energy related CO_2 emissions for the EU27 regions across different NGFS climate policy scenarios for all the three models.

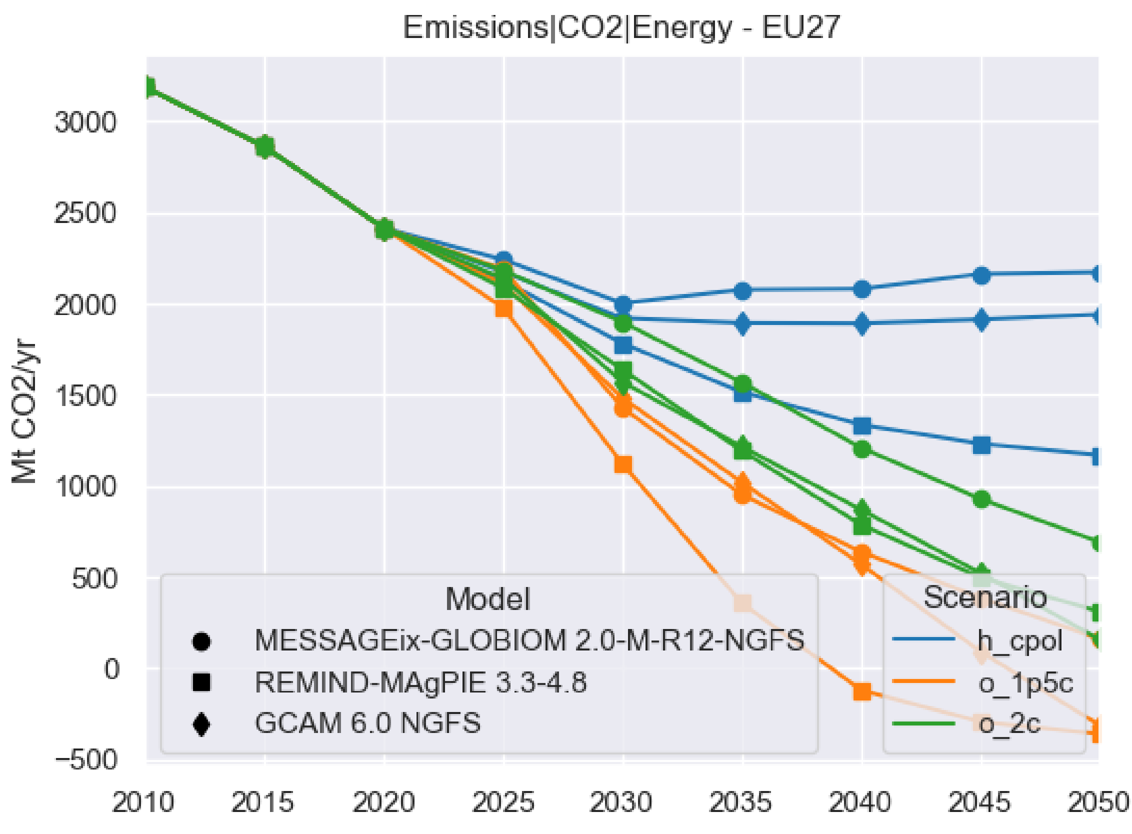


Figure 90. Energy related CO2 emissions in the EU27 region across models and scenarios

The graph above shows that projected energy related CO_2 emissions depend on the type of model chosen. For example, under the Current policies scenario, REMIND envisions a faster emissions reduction in the EU27, compared to MESSAGE and GCAM (results on individual country level might also largely differ). This pattern is affected by the development of final energy demand, as shown in ***Figure 91*** .

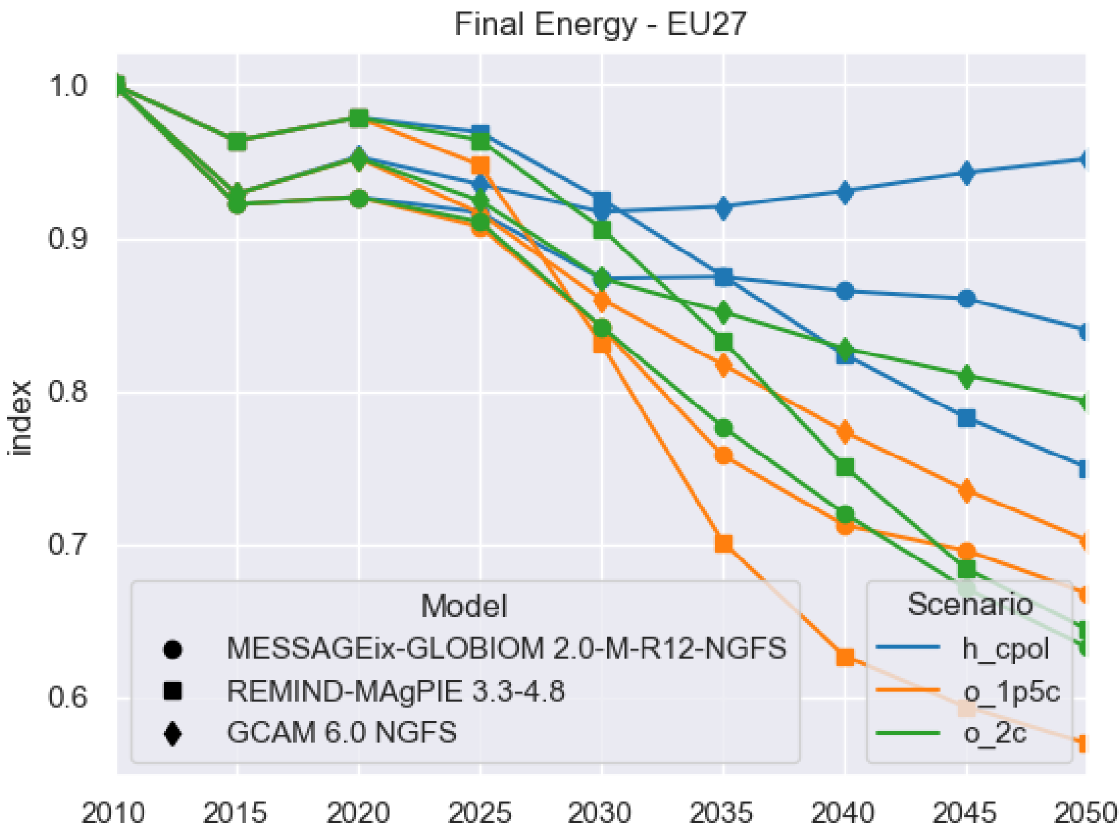


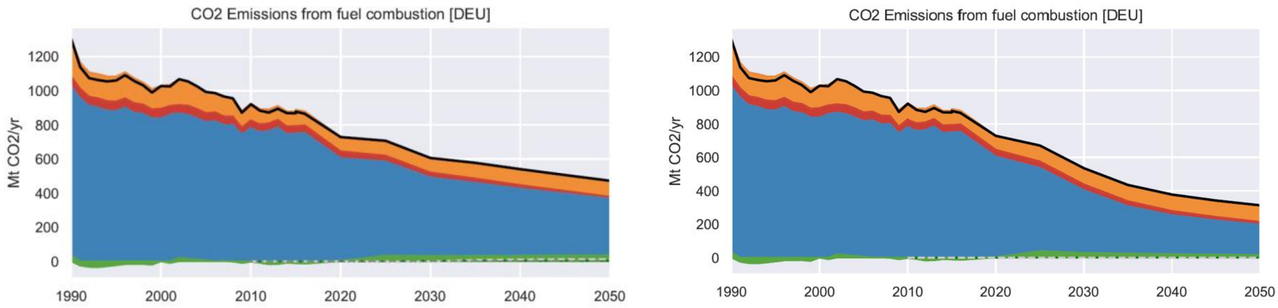
Figure 91. Final energy in the EU27 region across models and scenarios (indexed results, with 2010=1)

In **Table 38**, the list of output variables that are made available by the downscaling algorithm in the NGFS Phase V Scenario Explorer for all individual countries[114] is provided. For convenience, subsectors are named up to a specific level. For the full trees of IAM- and input-dependent disposable variables see **Table 34**.

EU27 results have been aggregated based on downscaled results from individual EU countries. For example, the ***Figure 92*** and ***Figure 93*** below show the results for Germany under a Current policies scenario from the three IAMs:

GCAM **REMIND**

[114] For some additional variables, downscaled outputs are available just for specific countries (based on input data).



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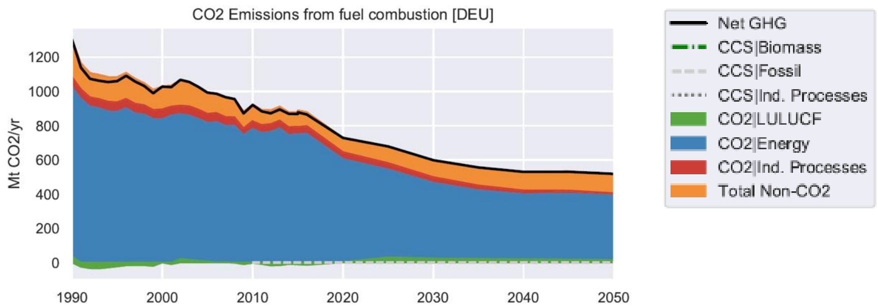

Figure 92. Germany's downscaled GHG emissions in the Current policies scenario across the three IAMs

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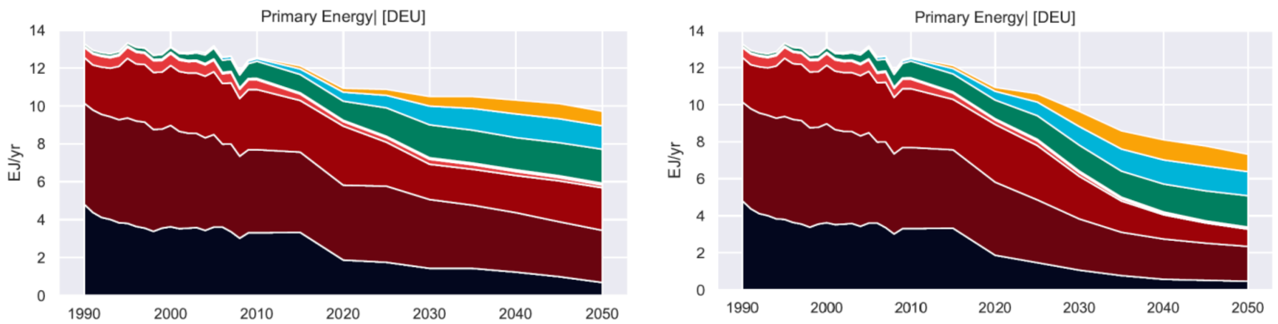

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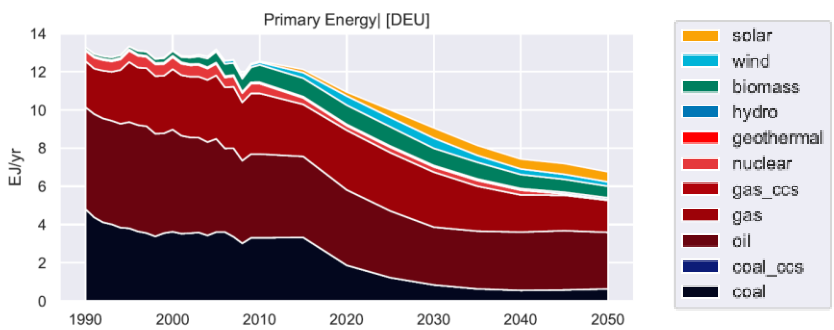

Figure 93. Germany's downscaled primary energy mix in the Current policies scenario across the three IAMs

5. What is new in the 2024 edition?

- **Sectorial CO2 emissions:** In this 2024 edition we add sectoral CO2 emissions from Transportation, Industry and Residential & Commercial. In order to breakdown total CO2 emissions to the individual sectors, we use the previously downscaled final energy demand by sector (transport/industry/residential and commercial) and by energy carrier (solids/liquids/gases) – by applying a different emissions factor for each of the energy carrier.

- **Trade variables:** In this 2024 edition, we better align the trade of primary energy variables, based on the observed trade status of countries. Our goal is to enhance the realism of the downscaled country results, by making more difficult to swap their trade status (e.g. from importing to exporting country) in the near future (e.g. up to 2025 or 2030).

- **Benchmarking of variables to historic data is extended until 2020:** secondary, primary energy and emissions results are harmonised to match the most recent historical data. This is done by using either offset or ratio methods, which utilise the difference (ratio) of unharmonised and harmonised results, combined with convergence methods, and converge to the long-term original results at a given point in time (Gidden *et al.*, 2018). In the NGFS 2024 edition, the historical data harmonisation is extended until 2020. In terms of the data series, the IEA energy statistics (2022) are used for primary and secondary energy variables, and PRIMAP v2.5.1 (Gütschow *et al.*, 2021, 2023) for emissions. We harmonize emissions using the HISTCR scenario of PRIMAP, prioritising country-reported data (CRF, BUR, UNFCCC) over third-party sources (CDIAC, FAO, Andrew, EDGAR, BP). Total CO2 and Kyoto emissions account for LULUCF (land use, land-use change and forestry), including both direct emissions (from human-induced land-use changes), and indirect emissions (from the natural response of land to environmental changes) (Grassi et al 2021, Gidden et al 2023).

Module 8: NiGEM

1. Non-technical summary

The National Institute Global Econometric Model (NiGEM) is a peer-reviewed global econometric model developed since 1987. NiGEM represents a closed world, where outflows from one country or region are matched by inflows into other countries and regions. NiGEM consists of individual country models for the major economies built around the national income identity, and contains the determinants of domestic demand, trade volumes, prices, current accounts, and asset holdings. Other countries are modelled through regional blocks (Africa, Middle East, Latin America, Developing Europe, and East Asia), so that the model is fully global in scope.

The NiGEM model is used for economic forecasting, scenario analysis and stress testing and has been in continuous development for over 30 years to remain relevant as economic behaviours, structures and theories have evolved.

The NiGEM climate model is an expanded version of the standard model that introduces channels to model climate policy instruments through the implementation of energy transition and physical climate shocks.

Further technical details of the NiGEM model are available here and the climate module manual can be accessed here

What are the key model inputs?

For the calibration of climate scenarios, NiGEM takes input from different modules of the NGFS modelling framework. The Integrated Assessment Models (IAMs) provide data for a new baseline forecast and climate transition risk scenarios. GDP damages due to chronic physical risk are provided by the Potsdam Institute (PIK) and the impact of acute physical risks are provided by Climate Analytics. The combination of transition, chronic and physical risk shocks, when executed as NiGEM scenarios, provide the output for the NGFS macro-economic variables.

What are the key model outputs?

NiGEM outputs provide the macroeconomic and financial information of the NGFS Scenarios, including transition, chronic and acute physical risks. Outputs include major macroeconomic and financial variables, like GDP, Inflation, Unemployment, Consumption, Investment, Exports, Imports, Interest rates.

What is new in the 2024 edition?

Malaysia expanded from a reduced country model to a full country model. Several countries have re-based their national account years since 2023 along with general model maintenance.

2. Introduction to NiGEM

The National Institute of Economic & Social Research (NIESR) has provided policy makers and private sector organisations around the world with a peer-reviewed global econometric model, the National Institute Global Econometric Model (NiGEM), since 1987. The model is used for economic forecasting, scenario analysis and stress testing and has been in continuous development for over 35 years to remain relevant as economic behaviours, structures and theories have evolved.

NiGEM represents a closed world, where outflows from one country or region are matched by inflows into other countries and regions. NiGEM is an *Econometric* model, in that key behavioural equations are econometrically estimated using historical data. This ensures that the dynamics and key elasticities of the model fit the main characteristics of individual country data.

The NiGEM climate model is an expanded version of the standard model that introduces channels to model climate policy instruments through the implementation of energy transition and physical climate shocks. NIESR started developing its climate module in 2018, with an aim of understanding the interactions between the macroeconomy and climate-related shocks and climate-related policy. Some of this early work was carried out in collaboration with the Dutch National Bank (Vermeulen et al, 2018)[115]. In 2021, NIESR joined the academic consortium of the Network for Greening the Financial System (NGFS), to contribute to the NGFS Climate Scenarios (NGFS, 2021)[116].

NiGEM v1.24-2 currently forms part of the NGFS Phase V suite of models, providing the macro-economic impacts of climate implied by both the IAM transition risks as well as acute and chronic physical risks.

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[115] Vermeulen, R., Schets, E., Lohuis, M., Kolbl, B., Jansen, D. J., & Heeringa, W. (2018). An energy transition risk stress test for the financial system of the Netherlands (No. 1607). Netherlands Central Bank, Research Department

[116] NGFS (2021). NGFS Climate Scenarios for central banks and supervisors. Available at: ngfs.net/sites/default/files/media/2021/08/27/ngfs_climate_scenarios_phase2_ june2021.pdf

2.1 Country model specification in NIGEM

NiGEM consists of individual country models for the major economies built around the national income identity, and contains the determinants of domestic demand, trade volumes, prices, current accounts, and asset holdings. These models also incorporate a well-specified supply-side, which underpins the sustainable growth rate of each economy in the medium term. Individual country models are linked together through trade in goods and services and integrated capital markets. So, in NiGEM, a slowdown in a given country, associated with lower imports, would impact other countries through the effect of lower exports to that economy and associated shift in asset prices. The overall impact would depend on both the underlying source of the shock and the policy responses (both in a country where the shock originates and other economies).

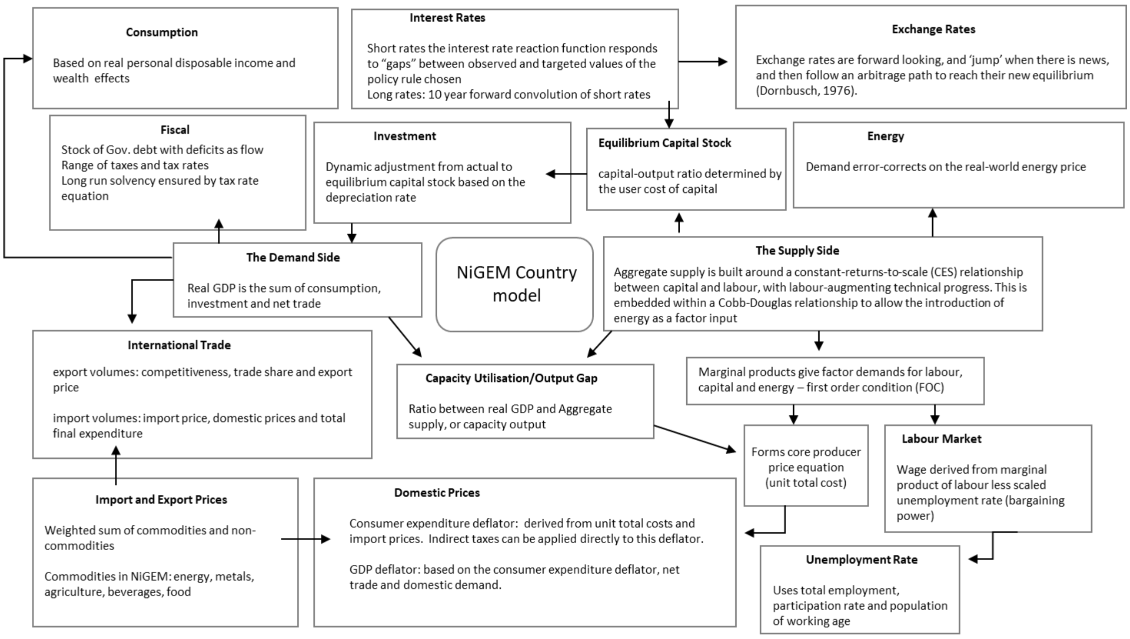


Figure 94. NiGEM country model structure

Full country models have a more disaggregated description of domestic demand than reduced country models and incorporate greater detail on the labour market and the government sector. See 5.1 for country classification.

2.2 Country coverage

Individual country models are in place for almost all OECD countries. There are also separate models of Argentina, Brazil, Bulgaria, China, Egypt, Hong Kong, Indonesia, India, Malaysia, Romania, Russian Federation, South Africa, Singapore, Taiwan and Vietnam. The rest of the world is modelled through regional blocks of Africa, Middle East, Latin America, Developing Europe, and East Asia, so that the model is fully global in scope. This ensures that there are no "black holes" in international transactions, as outflows from one country must be matched by inflows into other countries.

Country models are linked together through trade in goods and services, the influence of trade prices on domestic inflation, the impacts of exchange rates, and the patterns of asset holdings and associated income flows.

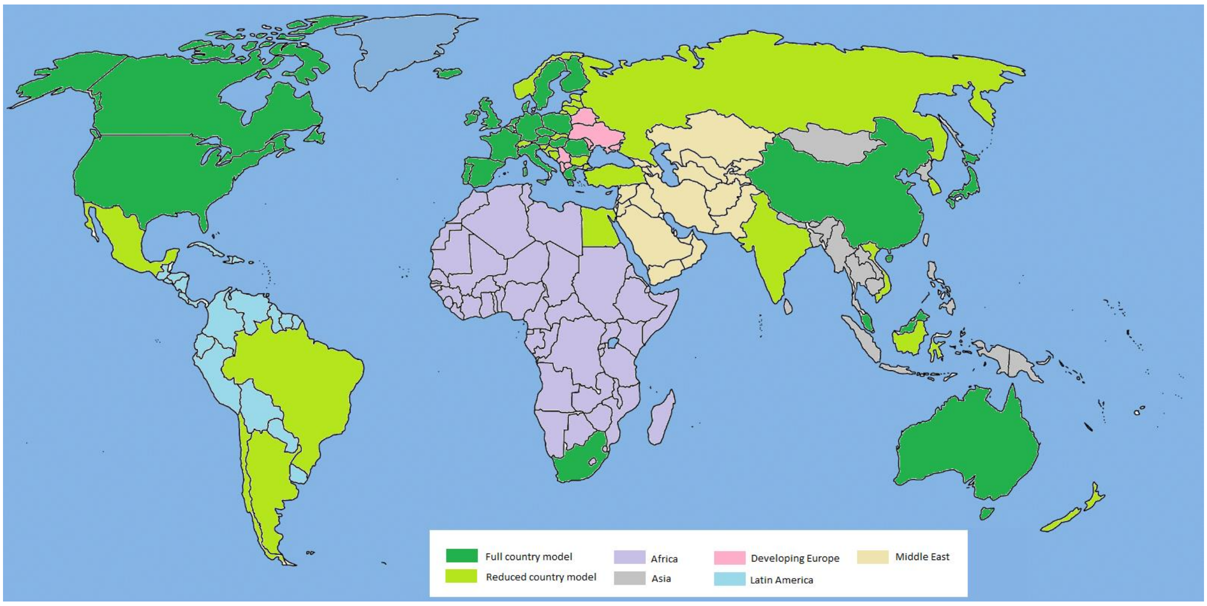


Figure 95. NiGEM coverage

2.3 Policy environment and key applications

The scenario space in NiGEM, including policy regimes, expectation formation by consumers, firms, wage setters or financial markets, and other assumptions and judgements can be set by the model user. In standard simulations, financial markets are normally assumed to look forward and consumers are normally assumed to be myopic but react to changes in their (forward looking) financial wealth. Monetary policy is set according to rules, with default parameters calibrated for individual countries. Key applications of NiGEM include:

- The *production of economic forecasts* for the world economy. NIESR publishes quarterly forecasts produced with NiGEM, along with a discussion of alternative scenarios around the central forecast and short notes based on recent model-based research.
- S*imulation and analysis tool*. Typical simulations involve analysing the effects of changes in monetary or fiscal policy, or changes in commodity prices such as an oil price shock. The model has a considerable degree of built-in flexibility, with key assumptions, such as the form of expectation formation in different markets and the policy rules followed by monetary and fiscal authorities able to be modified.
- The *stochastic mode* of NiGEM is used to construct error bounds around the central forecast baseline. The fan charts are based on stochastic shocks drawn from the historical errors on all the key model equations. Although this mode is not available for the NGFS scenarios, the stochastic work has been extended within the NGFS to investigate acute damages based on climate damage data provided by Climate Analytics.

2.4 Running a NiGEM simulation

An economic forecast normally represents the "most likely" future projections of the macro-economic variables being considered; in NiGEM this can be viewed as a central baseline scenario. This baseline is conditional on historical data, economic environment, and forecaster judgement. Conditional assumptions will include monetary and fiscal policy assumptions, and settings on other key variables such as the oil price and the pace of technological change.

What we refer to as a "simulation" in NiGEM is an alternative scenario that is assessed relative to a baseline forecast. The simulation includes one or more changes to the conditional assumptions of the baseline forecast, within a user-defined policy environment.

Simulation process

- Narrative: What is the source of the shock and your underlying premise for the scenario?
- Channels: How do the shocks propagate within the model and how will they be applied?
- Shocks: Determine the size and profile of the shock, for example is it permanent or temporary?
- Policy: How do agents such as central banks and governments respond, are the shocks anticipated or unanticipated?

3. NiGEM integration into the NGFS scenarios

For the calibration of climate scenarios, NiGEM takes input from different modules of the NGFS modelling framework. The Integrated Assessment Models (IAMs) provide data for a new baseline forecast and climate transition risk scenarios. GDP damages due to chronic physical risk are provided by the Potsdam Institute (PIK) and the impact of acute physical risks are provided by Climate Analytics The combination of transition, chronic and physical risk shocks, when executed as NiGEM scenarios, provide the output for the NGFS macro-economic variables. The various climate scenarios often use the same economic channels in the model, and therefore, cannot be imposed as a singular shock. Instead, individual scenarios are run as a "stacked" series, which ensures the output of the stack provides the same output as though all shocks being considered were run simultaneously. The chart below shows the data links between NiGEM and external NGFS inputs.

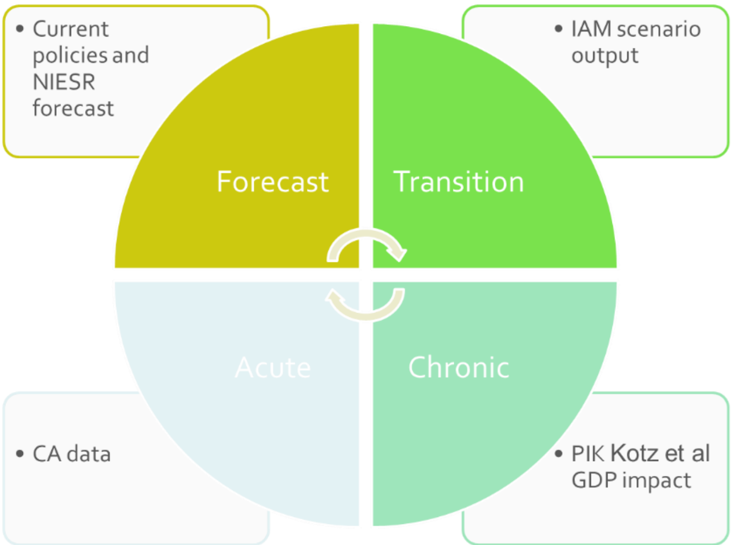


Figure 96. External data links with NiGEM

3.1 Climate neutral forecast

To ensure NiGEM and the IAMs are using an equivalent starting point for their investigations into climate risk, particularly in the energy sector, we use a combination of the NIESR v1.24-2 forecast coupled with IAM data from the NGFS current policies scenario to create a climate neutral forecast base. Climate neutral refers to the fact that projected data values do not reflect any climate transition or physical risks.

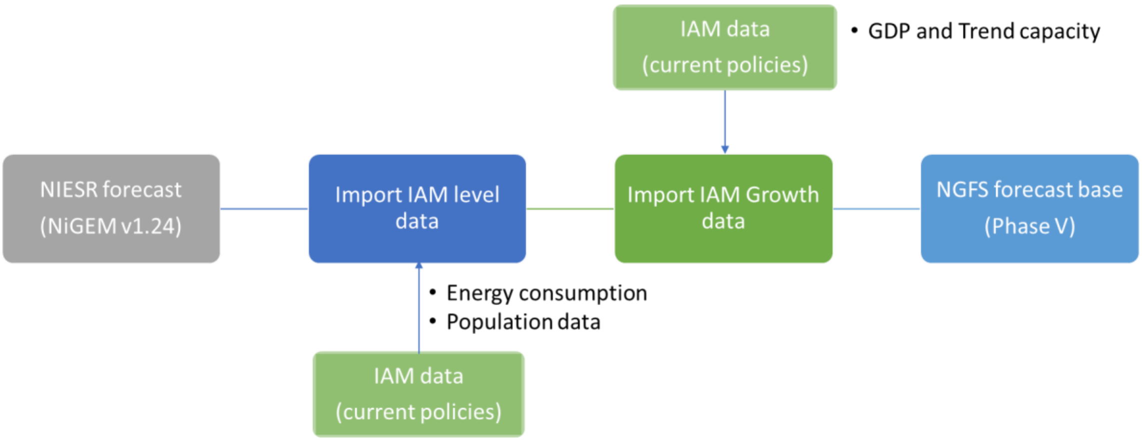


Figure 97. Creating the climate neutral forecast.

3.2 Transition scenarios

The transition scenarios represent two distinct NiGEM simulations : (i) carbon price shock and effects on energy use, and (ii) carbon revenue recycing.

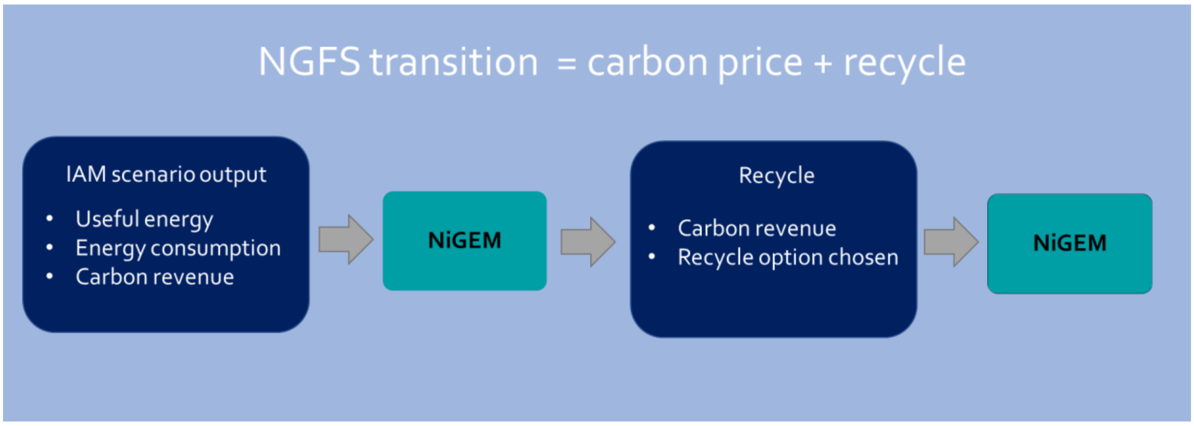


Figure 98. NiGEM transition risk scenario

The figure below disaggregates for each IAM input and displays the channel pass-through into NiGEM in more detail.

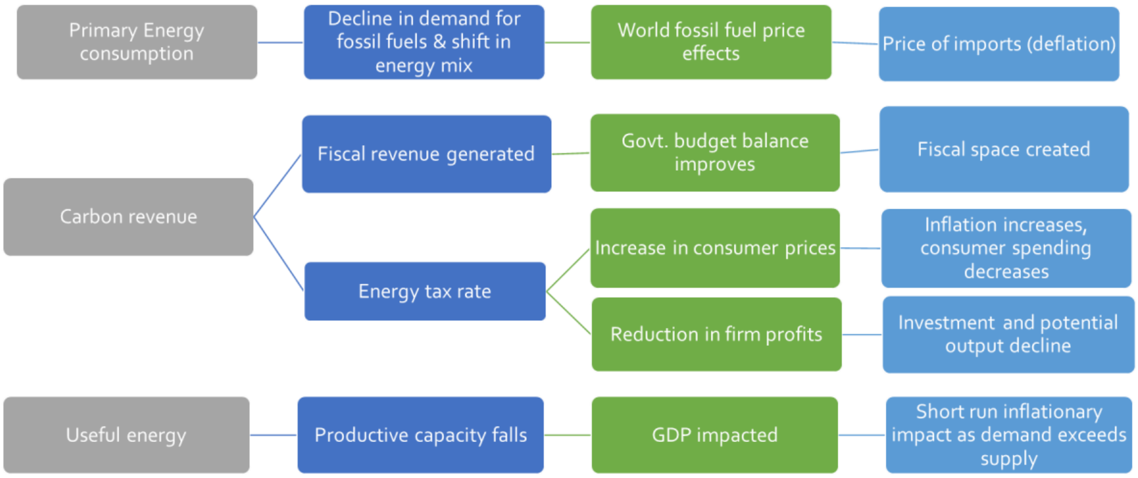


Figure 99. Transition risk channels from IAM inputs

The transition shock uses a combination of energy consumption, carbon tax revenue and useful energy[117] from the IAM scenario output to create the transition risk simulation connected to the application of a carbon tax. The carbon tax revenue is also used to reflect the budgetary impacts of recycling this revenue into the economy.

The recycling scenarios use the IAM carbon tax revenue as the basis for the size and profile of the shock to apply. Orderly scenarios use a recycling option where 50% of the revenue is used for government investment

[117] The portion of final energy which is actually available after final conversion to the consumer for the respective use. In final conversion, electricity becomes for instance light, mechanical energy or heat. The calculation of useful energy from sectoral final energy components is documented in the 2022 version of the Technical documentation, in the section containing table 4

while the remaining 50% is used to pay off government debt. All other scenarios recycle all revenue through taxes. The recycling simulations also turn the energy sector in NiGEM off. This is to ensure all energy movements, including world price of fossil fuels etc., are directly related to the IAM transition shock rather than because of fiscal stimulus.

The final impacts from transition scenarios are determined by a combination of competing factors across the two scenarios, as illustrated by the ***Figure 100*** below.

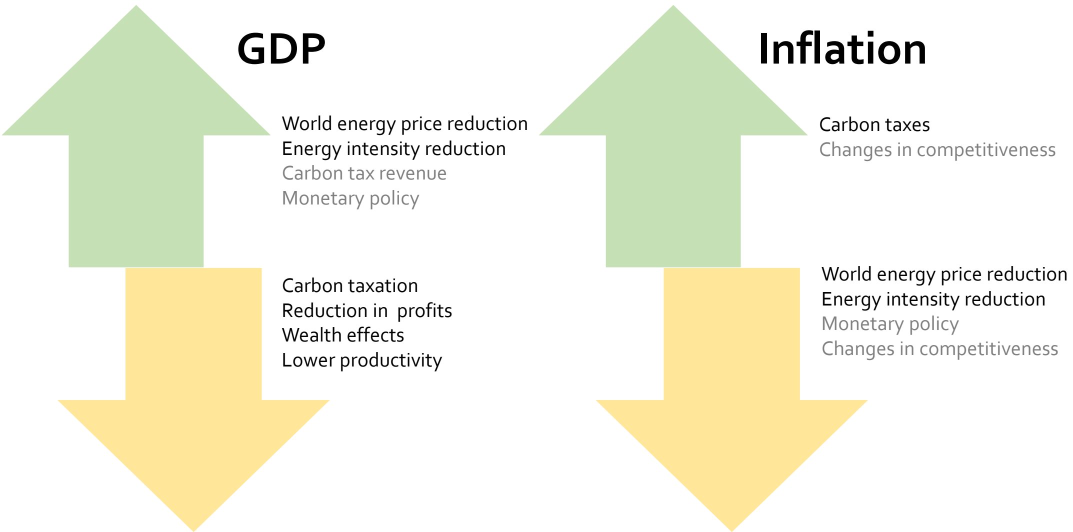
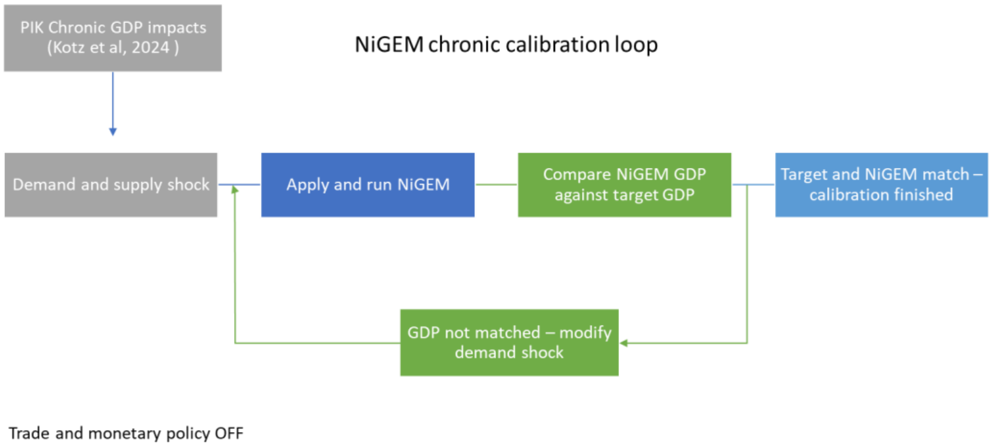


Figure 100.Factors affecting GDP and inflation.

3.3 Chronic physical impacts

The GDP percentage country damages for each scenario are provided directly by the Kotz et al (2024) damage function, as described in **section 5.2**.

Supply and demand shocks of the same magnitude as the Kotz et al GDP damage indicated are applied within NiGEM. The demand shocks are then modified and NiGEM re-run until the NiGEM GDP damage matches the Kotz et al damage. NiGEM is run with both trade and monetary policy ecxogenous (off).



Acute physical impacts

Building on the process used for chronic impacts, acute physical impacts use data provided by Climate Analytics to determine GDP impacts of four differing acute weather events. For acute risk, different channels of transmissions are assessed depening on the relevant hazard (see below). The different channels of transmission, e.g. labour force, crops productivity or asset damages, need to be adequately represented in NiGEM for the macroeconomic impacts to be correctly estimated. The hazard specific approaches are explained in Stochastic Implementation.

- Heatwaves (labour force impact)
- Cyclones (capital stock damages)
- Floods (capital stock impact)
- Drought (productivity, commodity price and export impact)

4. NiGEM NGFS output

NiGEM forecast data is in line with National accounts, so forecast values reference a country's domestic currency and base year[118].

$$\%\ difference = \left(\frac{x_{time=t}^{scenario}}{x_{time=t}^{base}} - 1.\right) * 100. \quad Abs\ difference = x_{time=t}^{scenario} - x_{time=t}^{base}$$

Database reference	Unit	NiGEM description
NiGEM|Gross Domestic Product (GDP)	% difference, country base year; local currency	Gross Domestic Product (GDP), country base year
NiGEM|Consumption (private)	% difference, country base year; local currency	Consumption (private), country base year
NiGEM|Investment (private sector)	% difference, country base year; local currency	Investment (private sector), country base year
NiGEM|Gov. consumption	% difference, country base year; local currency	Gov. consumption, country base year
NiGEM|Investment (gov.)	% difference, country base year; local currency	Investment (gov.), country base year
NiGEM|Domestic demand	% difference, country base year; local currency	Domestic demand, country base year
NiGEM|Exports (goods and services)	% difference, country base year; local currency	Exports (goods and services), country base year
NiGEM|Imports (goods and services)	% difference, country base year; local currency	Imports (goods and services), country base year

[118] A base year refers to the base point in time of a time series such as with a GDP deflator to convert GDP at current market prices into GDP at constant prices.

NiGEM|Productivity (output per hour worked); local currency	% difference	Productivity (output per hour worked)
NiGEM|Unemployment rate; %	Abs. difference	Unemployment rate
NiGEM|Gross operating surplus	% difference, pte corporations; local currency	Gross operating surplus, pte corporations
NiGEM|Real personal disposable income	% difference, country base year; local currency	Real personal disposable income, country base year
NiGEM|House prices (residential)	% difference, index; country base year=100	House prices (residential), index
NiGEM|Inflation rate; %	Abs. difference	Inflation rate
NiGEM|Central bank Intervention rate (policy interest rate); %	Abs. difference	Central bank Intervention rate (policy interest rate)
NiGEM|Long term interest rate; %	Abs. difference	Long term interest rate
NiGEM|Long term real interest rate; %	Abs. difference	Long term real interest rate
NiGEM|Nominal exchange rate	% difference	Exchange rate; local currency per US$
NiGEM|Effective exchange rate	% difference, index; 2019=100	Effective exchange rate, index
NiGEM|Equity prices	% difference, index; 2019=100	Equity prices, index – composite or benchmark for each country e.g. USA - NYSE COMPOSITE
NiGEM|Energy consumption (total); MnToe	% difference	Energy consumption (total)
NiGEM|Quarterly consumption of oil; MnToe	% difference	Quarterly consumption of oil
NiGEM|Quarterly consumption of gas; MnToe	% difference	Quarterly consumption of gas
NiGEM|Quarterly consumption of coal; MnToe	% difference	Quarterly consumption of coal
NiGEM|Quarterly consumption of non-carbon; MnToe	% difference	Quarterly consumption of non-carbon
NiGEM|Gross domestic income; local currency	% difference	Gross domestic income
NiGEM|Trend output for capacity utilisation	% difference, country base year; local currency	Trend output for capacity utilisation, country base year
NiGEM|Oil price; US$ per barrel	% difference	Oil price
NiGEM|Gas price; US$ per barrel(equiv)	% difference	Gas price
NiGEM|Coal price ; US$ per barrel(equiv)	% difference	Coal price

Additional notes

- Short-term interest rates: 3-month rates
- Long-term interest rates: a 40 period (10 year) look-ahead average of short-term interest rates
- Inflation: annual rate of change of the consumer expenditure deflator (CED) (YoY growth)
- Nominal exchange rate: country exchange rates are defined in terms of US$ in NIGEM, so positive delta (change) shows a depreciation, negative delta (change) an appreciation.
- Effective exchange rate: weighted sum of nominal exchange rates, positive delta shows an appreciation.
- Output variable nomenclature – combined, combined (no bus), transition, physical. E.g. GDP
    - Gross Domestic Product (GDP)(combined):
        - Disorderly scenarios (delayed, fragmented): combined impact of transition, chronic physical and business confidence shocks
        - Ordely scenarios: combined impact of transition and chronic physical shocks
    - Gross Domestic Product (GDP)(combined(no bus)): disorderly only, combined impact of transition and chronic physical shocks (no business confidence shock)
    - Gross Domestic Product (GDP)(transition): impact of carbon price shock and recycling
    - Gross Domestic Product (GDP)(physical): chronic physical impact

5. NiGEM Technical references

5.1 Country classification

Full country models		Reduced country models	
Australia	Poland[a]	Africa block	Malaysia
Austria	Portugal	Argentina	Mexico
Belgium	Romania	Brazil	Middle East block
Canada	South Africa	Bulgaria[b]	New Zealand
China	Spain	Chile	Norway
Czechia[a]	Sweden	Croatia	Rep. of Korea
Denmark	U.K.	Developing Europe	Romania[b]
Finland	USA	East Asia block	Russian Federation
France		Egypt	Singapore
Germany		Estonia[b]	Slovakia[b]
Greece		Hong Kong	Slovenia[b]
Hungary[a]		India	South Africa
Ireland		Indonesia	Switzerland
Italy		Latin America block	Taiwan
Japan		Latvia[b]	Turkey
Netherlands		Lithuania[b]	Viet Nam[b]

5.2 Regional country constituents

Africa block	Based on the IMF's group ***Sub-Saharan Africa***. From this we exclude the countries modelled individually on NiGEM (South Africa). This group includes: Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Republic of Congo, Côte d'Ivoire, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, South Sudan, Tanzania, Togo, Uganda, Zambia, and Zimbabwe.
Developing Europe block	Based on the IMF's group ***Emerging and Developing Europe***. From this we exclude the countries modelled individually on NiGEM (Bulgaria, Hungary, Poland, Romania, Russia and Turkey) and we add the advanced European economies that are not modelled separately on NiGEM (Iceland, Luxembourg, Malta and Cyprus). This group includes: Albania, Belarus, Bosnia and Herzegovina, Cyprus, Kosovo, Iceland, Luxembourg, Malta, Moldova, Montenegro, North Macedonia, Serbia, Ukraine.

East Asia block	Based on the IMF's group ***Emerging and Developing Asia***. From this we exclude the countries modelled individually on NiGEM (China, India, Indonesia, and Viet Nam). This group includes: Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Fiji, Kiribati, Lao P.D.R., Maldives, Marshall Islands, Micronesia, Mongolia, Myanmar, Nauru, Nepal, Palau, Papua New Guinea, Philippines, Samoa, Solomon Islands, Sri Lanka, Thailand, Timor-Leste, Tonga, Tuvalu, Vanuatu.
Latin America block	Based on the IMF's group ***Latin America and the Caribbean***. From this we exclude the countries modelled individually on NiGEM (Argentina, Brazil, Chile, and Mexico). This group includes: Antigua and Barbuda, Aruba, The Bahamas, Barbados, Belize, Bolivia, Colombia, Costa Rica, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, and Venezuela.
Middle East block	Based on the IMF's group ***Middle East and Central Asia***. To this we add the advanced Middle East economies that are not modelled separately on NiGEM (Israel). This group includes: Afghanistan, Algeria, Armenia, Azerbaijan, Bahrain, Djibouti, Georgia, Iran, Iraq, Israel, Jordan, Kazakhstan, Kuwait, Kyrgyz Republic, Lebanon, Libya, Mauritania, Morocco, Oman, Pakistan, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tajikistan, Tunisia, Turkmenistan, United Arab Emirates, Uzbekistan, West Bank and Gaza, and Yemen.

5.3 Theoretical foundation

NiGEM is based on a broadly New Keynesian structure with many of the characteristics of dynamic stochastic general equilibrium (DSGE) models, individual country models are grounded in textbook macroeconomic foundations, with features such as sticky prices, rational or model-consistent expectations, endogenous monetary policy based on a Taylor rule or other standard specifications, and long-run fiscal solvency. The structure of NiGEM is designed to correspond to macroeconomic policy needs.

From a theoretical perspective, NiGEM can be classed among global general equilibrium macroeconomic models, which are fundamentally grounded in Walrasian general equilibrium theory. It therefore strikes a balance between theoretical underpinnings that guide economies towards long-run market clearing equilibria, and data-driven individual country characteristics that fit the main characteristics of real-world data outturns.

5.4 Where does NiGEM sit within the spectrum of macroeconomic models?

Blanchard (2018) distinguishes five different classes of general equilibrium macroeconomic models: foundational models, dynamic stochastic general equilibrium (DSGE) models, policy models, toy models and forecasting models. Blanchard posits that each class of model is best suited to a specific purpose: foundation models are designed to make a deep theoretical point; DSGE models are designed to explore the macro implications of distortions; policy models are best suited to study the dynamic effects of specific shocks; toy models present the essence of an answer from a more complicated model; and forecasting models are designed for short-term forecasting. Under this framework, NiGEM best falls into the category of policy models, as it is: "aimed at analysing actual macroeconomic policy issues". Models in this class should fit the main characteristics of the data, including dynamics, and allow for policy analysis and counterfactuals. In terms of general methodological approach, it can be described as incorporating micro-founded long-run relationships – sharing some properties of standard DSGE models – but with more flexible lag structures that are fitted to the data. This combination ensures that NiGEM is useful for both policy analysis and forecasting.

5.5 Model usage

A key feature of the model is its flexibility, which allows users to define the scenario space, including policy regimes, expectation formation by consumers, firms, wage setters or financial markets, and other assumptions and judgements. Financial markets are normally assumed to look forward and consumers are normally assumed to be myopic but react to changes in their (forward looking) financial wealth. However, both of these default settings can be modified. Monetary policy is set according to rules, with default parameters calibrated for individual countries. However, these feedback rules can also be changed, and their parameters adjusted. Hence, to describe the results of a given scenario, rather than using a phrase such as 'the NiGEM simulation results suggest…' a better description would be 'under these assumptions, the NiGEM simulation results suggest…'. This is different from many other models, and it explains the widespread use of the NiGEM for policy analysis.

6. IAM variables input into NiGEM

6.1 Climate neutral forecast baseline

Table 21. IAM inputs for NiGEM baseline

IAM variables input into NiGEM	Variable Description	Units	NiGEM Suffix	Processing for use in NiGEM
Primary Energy|Coal	Energy consumption	EJ/yr	COLC	Level import • Exajoules to Million tonnes of oil equivalent • Annual to quarterly
Primary Energy|Gas	Energy consumption	EJ/yr	GASC	Level import • Exajoules to Million tonnes of oil equivalent • Annual to quarterly
Primary Energy|Oil	Energy consumption	EJ/yr	OILC	Level import • Exajoules to Million tonnes of oil equivalent • Annual to quarterly
Primary Energy|Biomass Primary Energy|Geothermal Primary Energy|Hydro Primary Energy|Solar Primary Energy|Wind Primary Energy|Nuclear	Energy consumption	EJ/yr	RNWC	Level import • Exajoules to Million tonnes of oil equivalent • Non-carbon = summation • Annual to quarterly
GDP|PPP/Trend capacity	GDP/YCAP	billion US$2010/yr	Y	Growth rate import • Annual to quarterly To prevent additional inflationary impacts from supply/demand imbalances, growth rates set equal to IAM GDP
Population	Population	million	POPT	Level import • Millions to 1000's

6.2 Carbon price

Table 22. IAM carbon tax inputs

IAM variables input into NiGEM	Variable Description	Units	NiGEM suffix	Processing for use in NiGEM
Primary Energy|Coal	Energy consumption	EJ/yr	COLC	Level import: • Exajoules to Million tonnes of oil equivalent • Annual to quarterly
Primary Energy|Gas	Energy consumption	EJ/yr	GASC	Level import: • Exajoules to Million tonnes of oil equivalent • Annual to quarterly
Primary Energy|Oil	Energy consumption	EJ/yr	OILC	Level import: • Exajoules to Million tonnes of oil equivalent • Annual to quarterly
Primary Energy|Biomass Primary Energy|Geothermal Primary Energy|Hydro Primary Energy|Solar Primary Energy|Wind Primary Energy|Nuclear	Energy consumption	EJ/yr	RNWC	Level import: • Exajoules to Million tonnes of oil equivalent • Annual to quarterly • Non-carbon = summation

Price|Carbon	Carbon price	US$2010/t CO2	CBTAX	Level import • Constant to current prices using NiGEM US GDP deflator (NIESR). *Deprecated since phase iii as the carbon revenue is now provided directly from the IAMs to account for CDR & CSS*
Useful Energy|Industry Useful Energy|Residential and Commercial Useful Energy|Transportation Electricity Gases Heat Hydrogen Liquids Solids	Useful Energy	EJ/yr	OIVOL	Multiplicative residual import • Delta calculated (w.r.t. current policies) • Annual to quarterly
Revenue|Government|Tax|Carbon	Carbon Revenue	billion US$2010/yr	ETAX	Level import • Constant to current prices using NiGEM US GDP deflator. • PPP (2019) used to convert to local currency • Annual to quarterly

6.3 Revenue recycling

Table 23.IAM recycling input

IAM variables input into NiGEM	Variable Description	Units	NiGEM Suffix	Processing for use in NiGEM
Revenue|Government|Tax|Carbon	Carbon Revenue	billion S$2010/yr	ETAX	Automated in NiGEM using NiGEM c-tax output file

6.4 Chronic physical damage

Table 24. Damage function input for chronic physical risk

IAM variables input into NiGEM	Variable Description	Units	NiGEM Suffix	Processing for use in NiGEM
Diagnostics | high GDP change | KW panel population-weighted	GDP Chronic damage (%)	billion US$2010/yr	YDMG	Level import • Annual to quarterly • 95th percentile for Current policies and NDCs • 50th percentile for all other scenarios

Appendix

NGFS Scenarios - Variables Metadata

Global and regional IAM output variables

Table 25 . NGFS Phase V Scenario Explorer IAM sector output

Database reference	unit	description	IAM		
Agricultural Demand	million t DM/yr	total demand for food, non-food and feed products (crops and livestock) and bioenergy crops (1st and 2nd generation).	G	M	R
Agricultural Demand|Crops	million t DM/yr	total demand for food, non-food and feed crops and bioenergy crops (1st and 2nd generation).	G		R
Agricultural Demand|Crops|Energy	million t DM/yr	demand for modern primary energy crops (1st and 2nd generation).	G		R
Agricultural Demand|Crops|Energy|1st generation	million t DM/yr	Demand for modern primary 1st generation energy crops.			R
Agricultural Demand|Crops|Energy|2nd generation	million t DM/yr	Demand for modern primary 2nd generation energy crops.			R
Agricultural Demand|Crops|Feed	million t DM/yr	total demand for feed crops.	G		R
Agricultural Demand|Crops|Food	million t DM/yr	total demand for food crops.	G	M	R
Agricultural Demand|Crops|Other	million t DM/yr	total demand for other crops.	G		R
Agricultural Demand|Livestock	million t DM/yr	total demand for livestock.	G		R
Agricultural Demand|Livestock|Food	million t DM/yr	total demand for food livestock.		M	R
Agricultural Demand|Livestock|Other	million t DM/yr	total demand for other livestock.			R
Agricultural Production	million t DM/yr	total production of food, non-food and feed products (crops and livestock) and bioenergy crops (1st and 2nd generation).		M	R
Agricultural Production|Energy	million t DM/yr	total bioenergy-related agricultural production (including waste and residues).		M	R
Agricultural Production|Energy|Crops	million t DM/yr	production for modern primary energy crops (1st and 2nd generation).		M	R
Agricultural Production|Energy|Residues	million t DM/yr	production of agricultural residues for modern bioenergy production.			R
Agricultural Production|Non-Energy	million t DM/yr	total production for food, non-food and feed products (crops and livestock).		M	R
Agricultural Production|Non-Energy|Crops	million t DM/yr	total production for food, non-food and feed products (crops).		M	R
Agricultural Production|Non-Energy|Livestock	million t DM/yr	total production for livestock products.		M	R
Capacity Additions|Electricity|Biomass	GW/yr	Capacity additions of all biomass power plants (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Biomass|w/ CCS	GW/yr	Capacity additions of biomass power plants with CCS (yearly average additions between previous and current model time step).	G	M	R

Capacity Additions|Electricity|Biomass|w/o CCS	GW/yr	Capacity additions of biomass power plants without CCS (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Coal	GW/yr	Capacity additions of all coal power plants (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Coal|w/ CCS	GW/yr	Capacity additions of coal power plants with CCS (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Coal|w/o CCS	GW/yr	Capacity additions of coal power plants without CCS (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Gas	GW/yr	Capacity additions of all gas power plants (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Gas|w/ CCS	GW/yr	Capacity additions of gas power plants with CCS (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Gas|w/o CCS	GW/yr	Capacity additions of gas power plants without CCS (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Geothermal	GW/yr	Capacity additions of geothermal power plants (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Hydro	GW/yr	capacity additions of hydropower plants (yearly average additions between previous and current model time step).		M	R
Capacity Additions|Electricity|Nuclear	GW/yr	Capacity additions of nuclear power plants (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Oil	GW/yr	Capacity additions of all oil power plants (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Oil|w/ CCS	GW/yr	Capacity additions of oil power plants with CCS (yearly average additions between previous and current model time step).		M	
Capacity Additions|Electricity|Oil|w/o CCS	GW/yr	Capacity additions of oil power plants without CCS (yearly average additions between previous and current model time step).	G	M	
Capacity Additions|Electricity|Solar	GW/yr	Capacity additions of solar power plants (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Solar|CSP	GW/yr	Capacity additions of concentrated solar power plants (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Solar|PV	GW/yr	Capacity additions of solar PV (yearly average additions between previous and current model time step).	G	M	R

Capacity Additions|Electricity|Storage Capacity	GWh/yr	capacity additions of electricity storage capacity (yearly average additions between previous and current model time step).		M	R
Capacity Additions|Electricity|Wind	GW/yr	Capacity additions of wind power plants (onshore and offshore) (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Wind|Offshore	GW/yr	Capacity additions of wind power plants (ooffshore) (yearly average additions between previous and current model time step).	G	M	R
Capacity Additions|Electricity|Wind|Onshore	GW/yr	Capacity additions of wind power plants (onshore) (yearly average additions between previous and current model time step).	G	M	R
Capacity|Electricity	GW	total installed electricity generation capacity.	G	M	R
Capacity|Electricity|Biomass	GW	total installed electricity generation capacity of biomass power plants.	G	M	R
Capacity|Electricity|Biomass|w/ CCS	GW	total installed electricity generation capacity of biomass power plants with CCS.	G	M	R
Capacity|Electricity|Biomass|w/o CCS	GW	total installed electricity generation capacity of biomass power plants w/o CCS.	G	M	R
Capacity|Electricity|Coal	GW	total installed electricity generation capacity of coal power plants.	G	M	R
Capacity|Electricity|Coal|w/ CCS	GW	total installed electricity generation capacity of coal power plants with CCS.	G	M	R
Capacity|Electricity|Coal|w/o CCS	GW	total installed electricity generation capacity of coal power plants w/o CCS.	G	M	R
Capacity|Electricity|Gas	GW	total installed electricity generation capacity of gas power plants.	G	M	R
Capacity|Electricity|Gas|w/ CCS	GW	total installed electricity generation capacity of gas power plants with CCS.	G	M	R
Capacity|Electricity|Gas|w/o CCS	GW	total installed electricity generation capacity of gas power plants w/o CCS.	G	M	R
Capacity|Electricity|Geothermal	GW	total installed electricity generation capacity of geothermal power plants.	G	M	R
Capacity|Electricity|Hydro	GW	total installed electricity generation capacity of hydro power plants.	G	M	R
Capacity|Electricity|Nuclear	GW	total installed electricity generation capacity of nuclear power plants.	G	M	R
Capacity|Electricity|Oil	GW	total installed electricity generation capacity of oil power plants.	G	M	R
Capacity|Electricity|Oil|w/ CCS	GW	total installed electricity generation capacity of oil power plants with CCS.		M	
Capacity|Electricity|Oil|w/o CCS	GW	total installed electricity generation capacity of oil power plants w/o CCS.	G	M	R
Capacity|Electricity|Other	GW	total installed electricity generation capacity of unclassified technologies.			R
Capacity|Electricity|Solar	GW	total installed electricity generation capacity of solar power installations.	G	M	R
Capacity|Electricity|Solar|CSP	GW	total installed electricity generation capacity of CSP plants.	G	M	R
Capacity|Electricity|Solar|PV	GW	total installed electricity generation capacity of PV installations.	G	M	R

Capacity|Electricity|Storage	GW	total installed (available) capacity of operating electricity storage.		M	R
Capacity|Electricity|Wind	GW	total installed electricity generation capacity of wind power installations.	G	M	R
Capacity|Electricity|Wind|Offshore	GW	total installed electricity generation capacity of offshore wind power installations.	G	M	R
Capacity|Electricity|Wind|Onshore	GW	total installed electricity generation capacity of onshore wind power installations.	G	M	R
Capacity|Gases	GW	total installed (available) capacity of gas plants.		M	R
Capacity|Gases|Biomass	GW	total installed (available) capacity of biomass to gas plants.		M	R
Capacity|Gases|Biomass|w/o CCS	GW	total installed (available) capacity of biomass to gas plants without CCS.		M	
Capacity|Gases|Coal	GW	total installed (available) capacity of coal to gas plants.		M	R
Capacity|Gases|Coal|w/o CCS	GW	total installed (available) capacity of coal to gas plants without CCS.		M	
Capacity|Hydrogen	GW	total installed (available) capacity of hydrogen plants.		M	R
Capacity|Hydrogen|Biomass	GW	total installed (available) capacity of biomass to hydrogen plants.		M	R
Capacity|Hydrogen|Biomass|w/ CCS	GW	total installed (available) capacity of biomass to hydrogen plants with CCS.		M	R
Capacity|Hydrogen|Biomass|w/o CCS	GW	total installed (available) capacity of biomass to hydrogen plants without CCS.		M	R
Capacity|Hydrogen|Coal	GW	total installed (available) capacity of coal to hydrogen plants.		M	R
Capacity|Hydrogen|Coal|w/ CCS	GW	total installed (available) capacity of coal to hydrogen plants with CCS.		M	R
Capacity|Hydrogen|Coal|w/o CCS	GW	total installed (available) capacity of coal to hydrogen plants without CCS.		M	R
Capacity|Hydrogen|Electricity	GW	total installed (available) capacity of hydrogen-by-electrolysis plants.		M	R
Capacity|Hydrogen|Gas	GW	total installed (available) capacity of gas to hydrogen plants.		M	R
Capacity|Hydrogen|Gas|w/ CCS	GW	total installed (available) capacity of gas to hydrogen plants with CCS.		M	R
Capacity|Hydrogen|Gas|w/o CCS	GW	total installed (available) capacity of gas to hydrogen plants without CCS.		M	R
Capacity|Liquids	GW	total installed (available) capacity of biomass to liquids plants.		M	R
Capacity|Liquids|Biomass	GW	total installed (available) capacity of biomass to liquids plants.		M	R
Capacity|Liquids|Biomass|w/ CCS	GW	total installed (available) capacity of biomass to liquids plants with CCS.		M	
Capacity|Liquids|Biomass|w/o CCS	GW	total installed (available) capacity of biomass to liquids plants without CCS.		M	
Capacity|Liquids|Coal	GW	total installed (available) capacity of coal to liquids plants.		M	R
Capacity|Liquids|Coal|w/ CCS	GW	total installed (available) capacity of coal to liquids plants with CCS.		M	
Capacity|Liquids|Coal|w/o CCS	GW	total installed (available) capacity of coal to liquids plants without CCS.		M	

Capacity|Liquids|Gas	GW	total installed (available) capacity of gas to liquids plants.		M	
Capacity|Liquids|Gas|w/ CCS	GW	total installed (available) capacity of gas to liquids plants with CCS.		M	
Capacity|Liquids|Gas|w/o CCS	GW	total installed (available) capacity of gas to liquids plants without CCS.		M	
Capacity|Liquids|Oil	GW	total installed (available) capacity of oil refining plants.		M	R
Capital Cost|Electricity|Biomass|w/ CCS	US$2010/kW	capital cost of a new biomass power plant with CCS.	G		R
Capital Cost|Electricity|Biomass|w/o CCS	US$2010/kW	capital cost of a new biomass power plant w/o CCS.	G		R
Capital Cost|Electricity|Coal|w/ CCS	US$2010/kW	capital cost of a new coal power plant with CCS.	G		R
Capital Cost|Electricity|Coal|w/o CCS	US$2010/kW	capital cost of a new coal power plant w/o CCS.	G		R
Capital Cost|Electricity|Gas|w/ CCS	US$2010/kW	capital cost of a new gas power plant with CCS.	G		R
Capital Cost|Electricity|Gas|w/o CCS	US$2010/kW	capital cost of a new gas power plant w/o CCS.	G		R
Capital Cost|Electricity|Geothermal	US$2010/kW	capital cost of a new geothermal power plant.	G	M	R
Capital Cost|Electricity|Hydro	US$2010/kW	capital cost of a new hydropower plant.		M	R
Capital Cost|Electricity|Nuclear	US$2010/kW	capital cost of a new nuclear power plants.	G	M	R
Capital Cost|Electricity|Solar|CSP	US$2010/kW	capital cost of a new concentrated solar power plant.	G		R
Capital Cost|Electricity|Solar|PV	US$2010/kW	capital cost of a new solar PV units.	G	M	R
Capital Cost|Electricity|Wind|Offshore	US$2010/kW	capital cost of a new offshore wind power plants.	G	M	R
Capital Cost|Electricity|Wind|Onshore	US$2010/kW	capital cost of a new onshore wind power plants.	G	M	R
Capital Cost|Gases|Biomass|w/o CCS	US$2010/kW	capital cost of a new biomass to gas plant w/o CCS.		M	R
Capital Cost|Gases|Coal|w/o CCS	US$2010/kW	capital cost of a new coal to gas plant w/o CCS.		M	R
Capital Cost|Hydrogen|Biomass|w/ CCS	US$2010/kW	capital cost of a new biomass to hydrogen plant with CCS.		M	R
Capital Cost|Hydrogen|Biomass|w/o CCS	US$2010/kW	capital cost of a new biomass to hydrogen plant w/o CCS.		M	R
Capital Cost|Hydrogen|Coal|w/ CCS	US$2010/kW	capital cost of a new coal to hydrogen plant with CCS.		M	R

Capital Cost|Hydrogen|Coal|w/o CCS	US$2010/kW	capital cost of a new coal to hydrogen plant w/o CCS.		M	R
Capital Cost|Hydrogen|Electricity	US$2010/kW	capital cost of a new hydrogen-by-electrolysis plant.		M	R
Capital Cost|Hydrogen|Gas|w/ CCS	US$2010/kW	capital cost of a new gas to hydrogen plant with CCS.		M	R
Capital Cost|Hydrogen|Gas|w/o CCS	US$2010/kW	capital cost of a new gas to hydrogen plant w/o CCS.		M	R
Capital Cost|Liquids|Biomass|w/ CCS	US$2010/kW	capital cost of a new biomass to liquids plant with CCS.		M	R
Capital Cost|Liquids|Biomass|w/o CCS	US$2010/kW	capital cost of a new biomass to liquids plant w/o CCS.		M	R
Capital Cost|Liquids|Coal|w/ CCS	US$2010/kW	capital cost of a new coal to liquids plant with CCS.		M	R
Capital Cost|Liquids|Coal|w/o CCS	US$2010/kW	capital cost of a new coal to liquids plant w/o CCS.		M	R
Capital Cost|Liquids|Gas|w/ CCS	US$2010/kW	capital cost of a new gas to liquids plant with CCS.		M	
Capital Cost|Liquids|Gas|w/o CCS	US$2010/kW	capital cost of a new gas to liquids plant w/o CCS.		M	
Capital Cost|Liquids|Oil	US$2010/kW	capital cost of a new oil refining plant.			R
Carbon Sequestration|CCS	Mt CO2/yr	total carbon dioxide emissions captured and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Biomass	Mt CO2/yr	total carbon dioxide emissions captured from bioenergy use and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Biomass|Energy|Demand|Industry	Mt CO2/yr	total carbon dioxide emissions captured from bioenergy use in industry (IPCC category 1A2) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Biomass|Energy|Supply	Mt CO2/yr	total carbon dioxide emissions captured from bioenergy use and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Biomass|Energy|Supply|Electricity	Mt CO2/yr	total carbon dioxide emissions captured from bioenergy use in electricity production (part of IPCC category 1A1a) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R

Carbon Sequestration|CCS|Biomass|Energy|Supply|Hydrogen	Mt CO2/yr	total carbon dioxide emissions captured from bioenergy use in hydrogen production (part of IPCC category 1A) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Biomass|Energy|Supply|Liquids	Mt CO2/yr	total carbon dioxide emissions captured from bioenergy use in liquid fuel production (part of IPCC category 1A) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Fossil	Mt CO2/yr	total carbon dioxide emissions captured from fossil fuel use and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Fossil|Energy|Demand|Industry	Mt CO2/yr	total carbon dioxide emissions captured from fossil fuel use in industry (IPCC category 1A2) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Fossil|Energy|Supply	Mt CO2/yr	total carbon dioxide emissions captured from fossil fuel use in energy supply (IPCC category 1A) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Fossil|Energy|Supply|Electricity	Mt CO2/yr	total carbon dioxide emissions captured from fossil fuel use in electricity production (part of IPCC category 1A1a) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Fossil|Energy|Supply|Hydrogen	Mt CO2/yr	total carbon dioxide emissions captured from fossil fuel use in hydrogen production (part of IPCC category 1A) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|CCS|Fossil|Energy|Supply|Liquids	Mt CO2/yr	total carbon dioxide emissions captured from fossil fuel use in liquid fuel production (part of IPCC category 1A) and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.		M	R
Carbon Sequestration|CCS|Industrial Processes	Mt CO2/yr	total carbon dioxide emissions captured from industrial processes (e.g., cement production, but not from fossil fuel burning) use and stored in geological deposits (e.g. in depleted oil and gas fields, unmined coal seams, saline aquifers) and the deep ocean, stored amounts should be reported as positive numbers.	G	M	R
Carbon Sequestration|Land Use	Mt CO2/yr	total carbon dioxide sequestered through land-based sinks (e.g., afforestation, soil carbon enhancement, biochar).		M	R
Carbon Sequestration|Land Use|Afforestation	Mt CO2/yr	total carbon dioxide sequestered through afforestation.		M	R

Consumption	billion US$2010/yr	total consumption of all goods, by all consumers in a region.		M	R
Emissions|BC	Mt BC/yr	total black carbon emissions.	G	M	R
Emissions|BC|AFOLU	Mt BC/yr	black carbon emissions from agriculture, forestry and other land use (IPCC category 3).	G	M	R
Emissions|BC|Energy	Mt BC/yr	black carbon emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|BC|Energy|Demand|Industry	Mt BC/yr	black carbon emissions from fuel combustion in industry (IPCC category 1A2).	G	M	R
Emissions|BC|Energy|Demand|Residential and Commercial	Mt BC/yr	black carbon emissions from fuel combustion in residential, commercial, institutional sectors and agriculture (IPCC category 1A4a, 1A4b).	G	M	R
Emissions|BC|Energy|Demand|Transportation	Mt BC/yr	black carbon emissions from fuel combustion in transportation sector (IPCC category 1A3), excluding pipeline emissions (IPCC category 1A3ei).	G	M	R
Emissions|BC|Energy|Supply	Mt BC/yr	black carbon emissions from fuel combustion and fugitive emissions from fuels: electricity and heat production and distribution (IPCC category 1A1a), other energy conversion (e.g. refineries, synfuel production, solid fuel processing, IPCC category 1Ab, 1Ac), incl. pipeline transportation (IPCC category 1A3ei), fugitive emissions from fuels (IPCC category 1B) and emissions from carbon dioxide transport and storage (IPCC category 1C).	G	M	R
Emissions|BC|Other	Mt BC/yr	black carbon emissions from other sources.			R
Emissions|BC|Waste	Mt BC/yr	black carbon emissions from waste (IPCC category 6).		M	R
Emissions|C2F6	kt C2F6/yr	total emissions of C2F6.	G		R
Emissions|C6F14	kt C6F14/yr	total perfluorohexane emissions (Mt C6F14/yr).			R
Emissions|CF4	kt CF4/yr	total emissions of CF4.	G	M	R
Emissions|CH4	Mt CH4/yr	total CH4 emissions.	G	M	R
Emissions|CH4|AFOLU	Mt CH4/yr	CH4 emissions from agriculture, forestry and other land use (IPCC category 3).	G	M	R
Emissions|CH4|Energy	Mt CH4/yr	CH4 emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|CH4|Energy|Demand|Industry	Mt CH4/yr	CH4 emissions from fuel combustion in industry (IPCC category 1A2).	G	M	
Emissions|CH4|Energy|Demand|Residential and Commercial	Mt CH4/yr	CH4 emissions from fuel combustion in residential, commercial, institutional sectors (IPCC category 1A4a, 1A4b).	G	M	
Emissions|CH4|Energy|Demand|Transportation	Mt CH4/yr	CH4 emissions from fuel combustion in transportation sector (IPCC category 1A3), excluding pipeline emissions (IPCC category 1A3ei).	G	M	

Emissions|CH4|Energy|Supply	Mt CH4/yr	CH_4 emissions from fuel combustion and fugitive emissions from fuels: electricity and heat production and distribution (IPCC category 1A1a), other energy conversion (e.g. refineries, synfuel production, solid fuel processing, IPCC category 1Ab, 1Ac), incl. pipeline transportation (IPCC category 1A3ei), fugitive emissions from fuels (IPCC category 1B) and emissions from carbon dioxide transport and storage (IPCC category 1C).	G	M	R
Emissions|CH4|Other	Mt CH4/yr	CH_4 emissions from other sources. For downscaled results, the "Other" sector has been recomputed accordingly to match the total emissions ("Emissions|CH4") which is usually larger than the sum of emissions from all the sub-sectors (Energy, AFOLU, Industrial Processes, Other). This value is strictly positive.	G		
Emissions|CH4|Waste	Mt CH4/yr	CH_4 emissions from waste (IPCC category 6).		M	R
Emissions|CO	Mt CO/yr	total CO emissions.	G	M	R
Emissions|CO2	Mt CO2/yr	total CO_2 emissions (not including CCS).	G	M	R
Emissions|CO2|AFOLU	Mt CO2/yr	CO_2 emissions from agriculture, forestry and other land use (IPCC category 3).	G	M	R
Emissions|CO2|Energy	Mt CO2/yr	CO_2 emissions from energy use on supply and demand side (IPCC category 1A, 1B).	G	M	R
Emissions|CO2|Energy and Industrial Processes	Mt CO2/yr	CO_2 emissions from energy use on supply and demand side (IPCC category 1A, 1B) and from industrial processes (IPCC categories 2A, B, C, E).	G	M	R
Emissions|CO2|Energy|Demand	Mt CO2/yr	CO_2 emissions from fuel combustion in industry (IPCC category 1A2), residential, commercial, institutional sectors and agriculture, forestry, fishing (AFOFI) (IPCC category 1A4a, 1A4b, 1A4c), and transportation sector (IPCC category 1A3), excluding pipeline emissions (IPCC category 1A3ei).	G	M	R
Emissions|CO2|Energy|Demand|AFOFI	Mt CO2/yr	CO_2 emissions from fuel combustion in agriculture, forestry, fishing (AFOFI) (IPCC category 1A4c).		M	
Emissions|CO2|Energy|Demand|Industry	Mt CO2/yr	CO_2 emissions from fuel combustion in industry (IPCC category 1A2).	G	M	R
Emissions|CO2|Energy|Demand|Industry|Cement	Mt CO2/yr	CO_2 emissions from fuel combustion in cement industry (IPCC category 1A2).	G	M	R
Emissions|CO2|Energy|Demand|Industry|Chemicals	Mt CO2/yr	CO_2 emissions from fuel combustion during chemicals production (IPCC category 1A2).	G	M	R
Emissions|CO2|Energy|Demand|Industry|Chemicals|Ammonia	Mt CO2/yr	CO_2 emissions from fuel combustion during the ammonia production (IPCC category 1A2).	G	M	
Emissions|CO2|Energy|Demand|Industry|Chemicals|High value chemicals	Mt CO2/yr	CO_2 emissions from fuel combustion during the high value chemicals production(IPCC category 1A2).		M	
Emissions|CO2|Energy|Demand|Industry|Non-ferrous metals	Mt CO2/yr	CO_2 emissions from fuel combustion in the non-ferrous metal sector including aluminum (IPCC category 1A2).	G	M	

Emissions|CO2|Energy|Demand|Industry|Other	Mt CO_2/yr	CO_2 emissions from fuel combustion in other industry sectors (IPCC category 1A2).	G		R
Emissions|CO2|Energy|Demand|Industry|Steel	Mt CO_2/yr	CO_2 emissions from fuel combustion in the steel industry sector (IPCC category 1A2).	G	M	R
Emissions|CO2|Energy|Demand|Residential and Commercial	Mt CO_2/yr	CO_2 emissions from fuel combustion in residential, commercial, institutional sectors (IPCC category 1A4a, 1A4b).	G	M	R
Emissions|CO2|Energy|Demand|Residential and Commercial|Commercial	Mt CO_2/yr	CO_2 emissions from fuel combustion in commercial and institutional sectors (IPCC category 1A4a).	G		
Emissions|CO2|Energy|Demand|Residential and Commercial|Residential	Mt CO_2/yr	CO_2 emissions from fuel combustion in residential (IPCC category 1A4b).	G		
Emissions|CO2|Energy|Demand|Transportation	Mt CO_2/yr	CO_2 emissions from fuel combustion in transportation sector (IPCC category 1A3), excluding pipeline emissions (IPCC category 1A3ei).	G	M	R
Emissions|CO2|Energy|Demand|Transportation|Aviation	Mt CO_2/yr	carbon dioxide emissions from transport by aviation mode.		M	
Emissions|CO2|Energy|Demand|Transportation|Aviation|Passenger	Mt CO_2/yr	CO_2 emissions from fuel combustion in the air passenger transportation sector (part of IPCC category 1A3).			R
Emissions|CO2|Energy|Demand|Transportation|Freight	Mt CO_2/yr	CO_2 emissions from fuel combustion in freight transportation sector (part of IPCC category 1A3), excluding pipeline emissions (IPCC category 1A3ei).	G		
Emissions|CO2|Energy|Demand|Transportation|Maritime|Freight	Mt CO_2/yr	CO_2 emissions from fuel combustion in the maritime freight transportation sector (part of IPCC category 1A3).			R
Emissions|CO2|Energy|Demand|Transportation|Passenger	Mt CO_2/yr	CO_2 emissions from fuel combustion in passenger transportation sector (part of IPCC category 1A3).	G		
Emissions|CO2|Energy|Demand|Transportation|Rail	Mt CO_2/yr	CO_2 emissions from fuel combustion in the rail transportation sector for both freight and passenger (part of IPCC category 1A3).			R
Emissions|CO2|Energy|Demand|Transportation|Rail|Freight	Mt CO_2/yr	CO_2 emissions from fuel combustion in the rail freight transportation sector(part of IPCC category 1A3).			R
Emissions|CO2|Energy|Demand|Transportation|Rail|Passenger	Mt CO_2/yr	CO_2 emissions from fuel combustion in the rail passenger transportation sector (part of IPCC category 1A3).			R
Emissions|CO2|Energy|Demand|Transportation|Road	Mt CO_2/yr	CO_2 emissions from fuel combustion in the road transportation sector for both freight and passenger (part of IPCC category 1A3).			R
Emissions|CO2|Energy|Demand|Transportation|Road|Freight	Mt CO_2/yr	CO_2 emissions from fuel combustion in the road freight transportation (part of IPCC category 1A3).			R
Emissions|CO2|Energy|Demand|Transportation|Road|Passenger	Mt CO_2/yr	CO_2 emissions from fuel combustion in the road passenger transportation sector (part of IPCC category 1A3).			R

Emissions|CO2|Energy|Demand|Transportation|Road|Passenger|Bus	Mt CO_2/yr	CO_2 emissions from fuel combustion for buses in the road passenger transportation sector (part of IPCC category 1A3).			R
Emissions|CO2|Energy|Demand|Transportation|Road|Passenger|LDV	Mt CO_2/yr	CO_2 emissions from fuel combustion for light duty vehicles in the road passenger transportation sector (part of IPCC category 1A3).			R
Emissions|CO2|Energy|Supply	Mt CO_2/yr	CO_2 emissions from fuel combustion and fugitive emissions from fuels: electricity and heat production and distribution (IPCC category 1A1a), other energy conversion (e.g. refineries, synfuel production, solid fuel processing, IPCC category 1Ab, 1Ac), incl. pipeline transportation (IPCC category 1A3ei), fugitive emissions from fuels (IPCC category 1B) and emissions from carbon dioxide transport and storage (IPCC category 1C).	G	M	R
Emissions|CO2|Energy|Supply|Electricity	Mt CO_2/yr	CO_2 emissions from electricity and CHP production and distribution (IPCC category 1A1ai and 1A1aii).	G	M	R
Emissions|CO2|Energy|Supply|Heat	Mt CO_2/yr	CO_2 emissions from heat production and distribution (IPCC category 1A1aiii).	G	M	R
Emissions|CO2|Energy|Supply|Gases	Mt CO_2/yr	CO_2 emissions from the production of gaseous fuels (natural gas, biogas, coal-gas).	G	M	R
Emissions|CO2|Energy|Supply|Liquids	Mt CO_2/yr	CO_2 emissions from fuel combustion and fugitive emissions from fuels: liquid fuel extraction and processing (e.g. oil production, refineries, synfuel production, IPCC category 1A1b, parts of 1A1cii, 1B2a).	G	M	R
Emissions|CO2|Energy|Supply|Other Sector	Mt CO_2/yr	CO_2 emissions from energy supply (other sector).			R
Emissions|CO2|Energy|Supply|Solids	Mt CO_2/yr	CO_2 emissions from the production of solid fuels (including coal and solid biomass).	G	M	R
Emissions|CO2|Industrial Processes	Mt CO_2/yr	CO_2 emissions from industrial processes (IPCC categories 2A, B, C, E).	G	M	R
Emissions|CO2|Industrial Processes|Cement	Mt CO_2/yr	CO_2 emissions from industrial processes (excl. fuel combustion IPCC 1A2) in the cement sector (IPCC categories 2A,B,C,E).		M	R
Emissions|CO2|Industrial Processes|Chemicals	Mt CO_2/yr	CO_2 emissions from industrial processes (excl. fuel combustion IPCC 1A2) in the chemicals sector (IPCC categories 2A,B,C,E).			R
Emissions|CO|AFOLU	Mt CO/yr	Land Use based carbon monoxide emissions.	G	M	R
Emissions|CO|Energy	Mt CO/yr	carbon monoxide emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|CO|Energy|Demand|Industry	Mt CO/yr	carbon monoxide emissions from Combustion in industry (IPCC 1A2) and industrial processes (IPCC 2C1-2C5).	G	M	R

Emissions|CO|Energy|Demand|Residential and Commercial	Mt CO/yr	carbon monoxide emissions from Combustion in Residential and Commercial/Institutional Sectors (IPCC 1A4A, 1A4B).	G	M	R
Emissions|CO|Energy|Demand|Transportation	Mt CO/yr	carbon monoxide emissions from Combustion in Transportation Sector (IPCC category 1A3).	G	M	R
Emissions|CO|Energy|Supply	Mt CO/yr	carbon monoxide emissions from Extraction and Distribution of Fossil Fuels (including fugitive emissions, IPCC category 1B); Electricity production and distribution, district heating and other energy conversion (e.g. refineries, synfuel production).	G	M	R
Emissions|F-Gases	Mt CO_2-equiv/yr	total F-gas emissions, including sulfur hexafluoride (SF6), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) (preferably use 100-year GWPs from AR4 for aggregation of different F-gases).	G	M	R
Emissions|HFC	kt HFC134a-equiv/yr	total emissions of hydrofluorocarbons (HFCs), provided as aggregate HFC134a-equivalents.	G	M	R
Emissions|HFC|HFC125	kt HFC125/yr	total emissions of HFC125.	G	M	R
Emissions|HFC|HFC134a	kt HFC134a/yr	total emissions of HFC134a.	G	M	R
Emissions|HFC|HFC143a	kt HFC143a/yr	total emissions of HFC143a.	G	M	R
Emissions|HFC|HFC227ea	kt HFC227ea/yr	total emissions of HFC227ea.	G	M	R
Emissions|HFC|HFC23	kt HFC23/yr	total emissions of HFC23.	G	M	R
Emissions|HFC|HFC245fa	kt HFC245fa/yr	total emissions of HFC245fa.	G	M	R
Emissions|HFC|HFC32	kt HFC32/yr	total emissions of HFC32.	G	M	R
Emissions|HFC|HFC43-10	kt HFC43-10/yr	total emissions of HFC343-10.		M	R
Emissions|Kyoto Gases	Mt CO_2-equiv/yr	total Kyoto GHG emissions, including CO_2, CH_4, N_2O and F-gases.	G	M	R
Emissions|Kyoto Gases|AFOLU	Mt CO_2-equiv/yr	total Kyoto GHG emissions in the AFOLU sector, including CO_2, CH_4, N_2O and F-gases.	G		R
Emissions|Kyoto Gases|Residential and Commercial	Mt CO_2-equiv/yr	total Kyoto GHG emissions from the residential and commercial sectors, including CO_2, CH_4, N_2O and F-gases.			R
Emissions|Kyoto Gases|Cement	Mt CO_2-equiv/yr	total Kyoto GHG emissions from cement production, including CO_2, CH_4, N_2O and F-gases.	G		
Emissions|Kyoto Gases|Chemicals	Mt CO_2-equiv/yr	total Kyoto GHG emissions from chemicals production, including CO_2, CH_4, N_2O and F-gases.	G		

Emissions|Kyoto Gases|Electricity	Mt CO_2-equiv/yr	total Kyoto GHG emissions from electricity production, including CO_2, CH_4, N_2O and F-gases.	G		
Emissions|Kyoto Gases|Industry	Mt CO_2-equiv/yr	total Kyoto GHG emissions from the industry sector, including CO_2, CH_4, N_2O and F-gases.	G		R
Emissions|Kyoto Gases|Other	Mt CO_2-equiv/yr	total Kyoto GHG emissions from other sectors, including CO_2, CH_4, N_2O and F-gases.	G		
Emissions|Kyoto Gases|Other Energy Supply	Mt CO_2-equiv/yr	total Kyoto GHG emissions from other energy supply, including CO_2, CH_4, N_2O and F-gases.	G		
Emissions|Kyoto Gases|Other Industry	Mt CO_2-equiv/yr	total Kyoto GHG emissions from other industry sectors, including CO_2, CH_4, N_2O and F-gases.	G		
Emissions|Kyoto Gases|Steel	Mt CO_2-equiv/yr	total Kyoto GHG emissions from the steel sector, including CO_2, CH_4, N_2O and F-gases.	G		
Emissions|Kyoto Gases|Supply	Mt CO_2-equiv/yr	total Kyoto GHG emissions from the energy supply sector, including CO_2, CH_4, N_2O and F-gases.	G		R
Emissions|Kyoto Gases|Transportation	Mt CO_2-equiv/yr	total Kyoto GHG emissions from the transportation sector, including CO_2, CH_4, N_2O and F-gases.	G		R
Emissions|N2O	kt N_2O/yr	total N_2O emissions.	G	M	R
Emissions|N2O|AFOLU	kt N_2O/yr	N_2O emissions from agriculture, forestry and other land use (IPCC category 3).	G	M	R
Emissions|N2O|Energy	kt N_2O/yr	N_2O emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|N2O|Industrial Processes	kt N_2O/yr	N_2O emissions from industrial processes.		M	R
Emissions|N2O|Other	kt N_2O/yr	N_2O emissions from other sources. For downscaled results, the "Other" sector has been recomputed accordingly to match the total emissions ("Emissions|N2O") which is usually larger than the sum of emissions from all the sub-sectors (Energy, AFOLU, Industrial Processes, Other). This value is strictly positive.	G		
Emissions|N2O|Waste	kt N_2O/yr	N_2O emissions from waste (IPCC category 6).		M	R
Emissions|NH3	Mt NH_3/yr	total ammonium (NH_3) emissions.	G	M	R
Emissions|NH3|AFOLU	Mt NH_3/yr	land use based Ammonia emissions.	G	M	R
Emissions|NH3|Energy	Mt NH_3/yr	Ammonia emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|NH3|Energy|Demand|Industry	Mt NH_3/yr	Ammonia emissions from Combustion in industry (IPCC 1A2) and industrial processes (IPCC 2C1-2C5).	G	M	R
Emissions|NH3|Energy|Demand|Residential and Commercial	Mt NH_3/yr	Ammonia emissions from Combustion in Residential and Commercial/Institutional Sectors (IPCC 1A4A, 1A4B).	G	M	R

Emissions|NH3|Energy|Demand|Transportation	Mt NH3/yr	Ammonia emissions from Combustion in Transportation Sector (IPCC category 1A3).	G	M	R
Emissions|NH3|Energy|Supply	Mt NH3/yr	Ammonia emissions from Extraction and Distribution of Fossil Fuels (including fugitive Emissions, IPCC category 1B); Electricity production and distribution, district heating and other energy conversion (e.g. refineries, synfuel production).	G	M	R
Emissions|NH3|Other	Mt NH3/yr	Ammonia emissions from other energy end-use sectors that do not fit to any other category.			R
Emissions|NH3|Waste	Mt NH3/yr	Ammonia emissions from waste.		M	R
Emissions|NOx	Mt NO2/yr	total NOx emissions.	G	M	R
Emissions|NOx|AFOLU	Mt NO2/yr	NOx emissions from agriculture, forestry and other land use (IPCC category 3).	G	M	R
Emissions|NOx|Energy	Mt NO2/yr	NOx emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|NOx|Energy|Demand|Industry	Mt NO2/yr	NOx emissions from fuel combustion in industry (IPCC category 1A2).	G	M	R
Emissions|NOx|Energy|Demand|Residential and Commercial	Mt NO2/yr	NOx emissions from fuel combustion in residential, commercial, institutional sectors (IPCC category 1A4a, 1A4b).	G	M	R
Emissions|NOx|Energy|Demand|Transportation	Mt NO2/yr	NOx emissions from fuel combustion in transportation sector (IPCC category 1A3), excluding pipeline emissions (IPCC category 1A3ei).	G	M	R
Emissions|NOx|Energy|Supply	Mt NO2/yr	NOx emissions from fuel combustion and fugitive emissions from fuels: electricity and heat production and distribution (IPCC category 1A1a), other energy conversion (e.g. refineries, synfuel production, solid fuel processing, IPCC category 1Ab, 1Ac), incl. pipeline transportation (IPCC category 1A3ei), fugitive emissions from fuels (IPCC category 1B) and emissions from carbon dioxide transport and storage (IPCC category 1C).	G	M	R
Emissions|NOx|Other	Mt NO2/yr	NOx emissions from other sources.			R
Emissions|NOx|Waste	Mt NO2/yr	NOx emissions from waste.		M	R
Emissions|OC	Mt OC/yr	total organic carbon emissions.	G	M	R
Emissions|OC|AFOLU	Mt OC/yr	organic carbon emissions from agriculture, forestry and other land use (IPCC category 3).	G	M	R
Emissions|OC|Energy	Mt OC/yr	organic carbon emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|OC|Energy|Demand|Industry	Mt OC/yr	organic carbon emissions from fuel combustion in industry (IPCC category 1A2).	G	M	R
Emissions|OC|Energy|Demand|Residential and Commercial	Mt OC/yr	organic carbon emissions from fuel combustion in residential, commercial, institutional sectors (IPCC category 1A4a, 1A4b).	G	M	R
Emissions|OC|Energy|Demand|Transportation	Mt OC/yr	organic carbon emissions from fuel combustion in transportation sector (IPCC category 1A3), excluding pipeline emissions (IPCC category 1A3ei).	G	M	R

Emissions|OC|Energy|Supply	Mt OC/yr	organic carbon emissions from fuel combustion and fugitive emissions from fuels: electricity and heat production and distribution (IPCC category 1A1a), other energy conversion (e.g. refineries, synfuel production, solid fuel prorganic carbonessing, IPCC category 1Ab, 1Ac), incl. pipeline transportation (IPCC category 1A3ei), fugitive emissions from fuels (IPCC category 1B) and emissions from carbon dioxide transport and storage (IPCC category 1C).	G	M	R
Emissions|OC|Other	Mt OC/yr	organic carbon emissions from other sources.			R
Emissions|OC|Waste	Mt OC/yr	organic carbon emissions from waste.		M	R
Emissions|PFC	kt CF4-equiv/yr	total emissions of perfluorocarbons (PFCs), provided as aggregate CF4-equivalents.	G		R
Emissions|SF6	kt SF6/yr	total emissions of sulfur hexafluoride (SF6).	G	M	R
Emissions|Sulfur	Mt SO2/yr	total sulfur (SO2) emissions.	G	M	R
Emissions|Sulfur|AFOLU	Mt SO2/yr	sulfur emissions from agriculture, forestry and other land use (IPCC category 3).	G	M	R
Emissions|Sulfur|Energy	Mt SO2/yr	sulfur emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|Sulfur|Energy|Demand|Industry	Mt SO2/yr	sulfur emissions from fuel combustion in industry (IPCC category 1A2).	G	M	R
Emissions|Sulfur|Energy|Demand|Residential and Commercial	Mt SO2/yr	sulfur emissions from fuel combustion in residential, commercial, institutional sectors (IPCC category 1A4a, 1A4b).	G	M	R
Emissions|Sulfur|Energy|Demand|Transportation	Mt SO2/yr	sulfur emissions from fuel combustion in transportation sector (IPCC category 1A3), excluding pipeline emissions (IPCC category 1A3ei).	G	M	R
Emissions|Sulfur|Energy|Supply	Mt SO2/yr	sulfur emissions from fuel combustion and fugitive emissions from fuels: electricity and heat production and distribution (IPCC category 1A1a), other energy conversion (e.g. refineries, synfuel production, solid fuel processing, IPCC category 1Ab, 1Ac), incl. pipeline transportation (IPCC category 1A3ei), fugitive emissions from fuels (IPCC category 1B) and emissions from carbon dioxide transport and storage (IPCC category 1C).	G	M	R
Emissions|Sulfur|Other	Mt SO2/yr	sulfur emissions from other sources.			R
Emissions|Sulfur|Waste	Mt SO2/yr	sulfur emissions from waste.		M	R
Emissions|VOC	Mt VOC/yr	total volatile organic compound (VOC) emissions.	G	M	R
Emissions|VOC|AFOLU	Mt VOC/yr	land use based volatile organic compounds Emissions.	G	M	R
Emissions|VOC|Energy	Mt VOC/yr	volatile organic compounds emissions from energy use on supply and demand side, including fugitive emissions from fuels (IPCC category 1A, 1B).	G	M	R
Emissions|VOC|Energy|Demand|Industry	Mt VOC/yr	volatile organic compounds Emissions from Combustion in industry (IPCC 1A2) and industrial processes (IPCC 2C1-2C5).	G	M	R

Emissions|VOC|Energy|Demand|Residential and Commercial	Mt VOC/yr	volatile organic compounds Emissions from Combustion in Residential and Commercial/Institutional Sectors (IPCC 1A4A, 1A4B).	G	M	R
Emissions|VOC|Energy|Demand|Transportation	Mt VOC/yr	volatile organic compounds Emissions from Combustion in Transportation Sector (IPCC category 1A3).	G	M	R
Emissions|VOC|Energy|Supply	Mt VOC/yr	volatile organic compounds Emissions from Extraction and Distribution of Fossil Fuels (including fugitive Emissions, IPCC category 1B); Electricity production and distribution, district heating and other energy conversion (e.g. refineries, synfuel production).	G	M	R
Emissions|VOC|Other	Mt VOC/yr	volatile organic compounds Emissions from other energy end-use sectors that do not fit to any other category.			R
Emissions|VOC|Waste	Mt VOC/yr	volatile organic compounds from waste.		M	R
Energy Service|Residential and Commercial|Floor Space	billion m2	energy service demand for total conditioned floor space in residential and commercial sector (bn m2).	G		R
Energy Service|Residential and Commercial|Residential|Floor Space	billion m2	energy service demand for total conditioned floor space in residential sector (bn m2).	G		
Energy Service|Transportation|Aviation	billion vkm/yr	annual demand for energy services related to air transportation (bn tkm/yr).	G		R
Energy Service|Transportation|Freight	billion tkm/yr	annual demand for energy services related to freight transportation (bn tkm/yr).	G		R
Energy Service|Transportation|Freight|International Shipping	billion tkm/yr	annual demand for energy services related to maritime freight transportation (bn tkm/yr).	G		R
Energy Service|Transportation|Freight|Navigation	billion tkm/yr	annual demand for energy services related to inland water freight transportation (bn tkm/yr).			R
Energy Service|Transportation|Freight|Railways	billion tkm/yr	annual demand for energy services related to rail freight transportation (bn tkm/yr).			R
Energy Service|Transportation|Freight|Road	billion tkm/yr	annual demand for energy services related to road freight transportation (bn tkm/yr).	G		R
Energy Service|Transportation|Navigation	billion vkm/yr	annual demand for energy services related to inland water transportation (bn tkm/yr).			R
Energy Service|Transportation|Passenger	billion pkm/yr	annual demand for energy services related to passenger transportation (bn pkm/yr).	G		R

Energy Service|Transportation|Passenger|Aviation	billion pkm/yr	annual demand for energy services related to air passenger transportation (bn tkm/yr).	G		R
Energy Service|Transportation|Passenger|Bicycling and Walking	billion pkm/yr	annual demand for energy services related to non-motorized transportation (bn tkm/yr).	G		R
Energy Service|Transportation|Passenger|Railways	billion pkm/yr	annual demand for energy services related to rail passenger transportation (bn tkm/yr).			R
Energy Service|Transportation|Passenger|Road	billion pkm/yr	annual demand for energy services related to road passenger transportation (bn tkm/yr).			R
Energy Service|Transportation|Passenger|Road|Bus	billion pkm/yr	annual demand for energy services related to bus passenger transportation (bn tkm/yr).			R
Energy Service|Transportation|Passenger|Road|LDV	billion pkm/yr	annual demand for energy services related to LDV transportation (bn tkm/yr).			R
Energy Service|Transportation|Rail	billion vkm/yr	annual demand for energy services related to rail transportation (bn tkm/yr).	G		R
Energy Service|Transportation|Road	billion vkm/yr	annual demand for energy services related to freight transportation (bn tkm/yr).	G		R
Fertilizer Use|Nitrogen	Tg N/yr	total nitrogen fertilizer use.		M	R
Fertilizer Use|Phosphorus	Tg P/yr	total phosphorus fertilizer use.		M	
Final Energy	EJ/yr	total final energy consumption by all end-use sectors and all fuels, excluding transmission/distribution losses.	G	M	R
Final Energy|Electricity	EJ/yr	final energy consumption of electricity (including on-site solar PV), excluding transmission/distribution losses.	G	M	R
Final Energy|Gases	EJ/yr	final energy consumption of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.	G	M	R
Final Energy|Geothermal	EJ/yr	final energy consumption of geothermal energy (e.g., from decentralized or small-scale geothermal heating systems) excluding geothermal heat pumps.		M	
Final Energy|Heat	EJ/yr	final energy consumption of heat (e.g., district heat, process heat, warm water), excluding transmission/distribution losses, excluding direct geothermal and solar heating.	G	M	R
Final Energy|Hydrogen	EJ/yr	final energy consumption of hydrogen, excluding transmission/distribution losses.	G	M	R

Final Energy|Industry	EJ/yr	final energy consumed by the industrial sector, including feedstocks, including agriculture and fishing.	G	M	R
Final Energy|Industry|Cement	EJ/yr	final energy consumption by the industrial cement sector, excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Cement|Electricity	EJ/yr	final energy consumption by the industrial cement sector of electricity, excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Cement|Gases	EJ/yr	final energy consumption by the industrial cement sector of gases, excluding transmission/distribution losses.		M	R
Final Energy|Industry|Cement|Heat	EJ/yr	final energy consumption by the industrial cement sector of heat, excluding transmission/distribution losses.		M	
Final Energy|Industry|Cement|Hydrogen	EJ/yr	final energy consumption by the industrial cement sector of hydrogen, excluding transmission/distribution losses.		M	R
Final Energy|Industry|Cement|Liquids	EJ/yr	final energy consumption by the industrial cement sector of liquids, excluding transmission/distribution losses.		M	R
Final Energy|Industry|Cement|Solids	EJ/yr	final energy consumption by the industrial cement sector of solids, excluding transmission/distribution losses.		M	R
Final Energy|Industry|Chemicals	EJ/yr	final energy consumption by the industrial chemicals sector, excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Chemicals|Ammonia	EJ/yr	final energy consumption by the industrial ammonia sector, excluding transmission/distribution losses.	G		
Final Energy|Industry|Chemicals|Ammonia|Gases	EJ/yr	final energy consumption by the industrial ammonia sector of gases, excluding transmission/distribution losses.	G		
Final Energy|Industry|Chemicals|Ammonia|Hydrogen	EJ/yr	final energy consumption by the industrial ammonia sector of hydrogen, excluding transmission/distribution losses.	G		
Final Energy|Industry|Chemicals|Ammonia|Liquids	EJ/yr	final energy consumption by the industrial ammonia sector of liquids, excluding transmission/distribution losses.	G		
Final Energy|Industry|Chemicals|Ammonia|Solids	EJ/yr	final energy consumption by the industrial ammonia sector of solids, excluding transmission/distribution losses.	G		

Final Energy|Industry|Chemicals|Ammonia|Solids|Fossil	EJ/yr	final energy consumption by the industrial ammonia sector of solids|fossil, excluding transmission/distribution losses.	G		
Final Energy|Industry|Chemicals|Electricity	EJ/yr	final energy consumption by the industrial chemicals sector of electricity, excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Chemicals|Gases	EJ/yr	final energy consumption by the industrial chemicals sector of gases, excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Chemicals|Heat	EJ/yr	final energy consumption by the industrial chemicals sector of heat, excluding transmission/distribution losses.	G	M	
Final Energy|Industry|Chemicals|High value chemicals	EJ/yr	final energy consumption by the high value chemicals sector, excluding transmission/distribution losses.		M	
Final Energy|Industry|Chemicals|High value chemicals|Electricity	EJ/yr	final energy consumption by the high value chemicals sector of electricity, excluding transmission/distribution losses.		M	
Final Energy|Industry|Chemicals|High value chemicals|Gases	EJ/yr	final energy consumption by the high value chemicals sector of gaseous fuels, excluding transmission/distribution losses.		M	
Final Energy|Industry|Chemicals|High value chemicals|Heat	EJ/yr	final energy consumption by the high value chemicals sector of heat, excluding transmission/distribution losses.		M	
Final Energy|Industry|Chemicals|High value chemicals|Hydrogen	EJ/yr	final energy consumption by the high value chemicals sector of hydrogen, excluding transmission/distribution losses.		M	
Final Energy|Industry|Chemicals|High value chemicals|Liquids	EJ/yr	final energy consumption by the high value chemicals sector of liquid fuels, excluding transmission/distribution losses.		M	
Final Energy|Industry|Chemicals|High value chemicals|Solids	EJ/yr	final energy consumption by the high value chemicals sector of solid fuels, excluding transmission/distribution losses.		M	
Final Energy|Industry|Chemicals|Hydrogen	EJ/yr	final energy consumption by the industrial chemicals sector of hydrogen, excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Chemicals|Liquids	EJ/yr	final energy consumption by the industrial chemicals sector of liquids, excluding transmission/distribution losses.	G	M	R

Final Energy|Industry|Chemicals|Solids	EJ/yr	final energy consumption by the industrial chemicals sector of solids,excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Chemicals|Solids|Bioenergy	EJ/yr	final energy consumption by the industrial chemicals sector of solids|bioenergy,excluding transmission/distribution losses.	G		
Final Energy|Industry|Chemicals|Solids|Fossil	EJ/yr	final energy consumption by the industrial chemicals sector of solids|fossil,excluding transmission/distribution losses.	G		
Final Energy|Industry|Electricity	EJ/yr	final energy consumption by the industrial sector of electricity (including on-site solar PV), excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Electricity|Share	%	final energy consumption by the industrial cement sector, excluding transmission/distribution losses (EJ/yr).			R
Final Energy|Industry|Gases	EJ/yr	final energy consumption by the industrial sector of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Gases|Bioenergy	EJ/yr	Final energy consumption by the industrial sector of bioenergy gases (biogas), excluding transmission/distribution losses.			R
Final Energy|Industry|Gases|Fossil	EJ/yr	Final energy consumption by the industrial sector of fossil-derived natural and synthetic gases (natural gas,coal gas), excluding transmission/distribution losses.			R
Final Energy|Industry|Gases|Hydrogen synfuel	EJ/yr	Final energy consumption by the industrial sector of hydrogen-derived syngases (e-fuels), excluding transmission/distribution losses.			R
Final Energy|Industry|Heat	EJ/yr	final energy consumption by the industrial sector of heat (e.g., district heat, process heat, solar heating and warm water), excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Hydrogen	EJ/yr	final energy consumption by the industrial sector of hydrogen.	G	M	R
Final Energy|Industry|Liquids	EJ/yr	final energy consumption by the industrial sector of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).	G	M	R
Final Energy|Industry|Liquids|Biomass	EJ/yr	final energy consumption by the industry sector of liquid biofuels, excluding transmission/distribution losses.		M	
Final Energy|Industry|Liquids|Coal	EJ/yr	final energy consumption by the industry sector of liquid produced from coal, excluding transmission/distribution losses.		M	
Final Energy|Industry|Liquids|Oil	EJ/yr	Final energy consumption by the industrial sector of traditional liquid petroleum oils (e.g. gasoline, diesel), excluding transmission/distribution losses.		M	
Final Energy|Industry|Non-ferrous metals	EJ/yr	final energy consumption by the industrial non-ferrous metals sector.	G	M	
Final Energy|Industry|Non-ferrous metals|Electricity	EJ/yr	final energy consumption by the industrial non-ferrous metals sector of electricity,excluding transmission/distribution losses.	G	M	

Final Energy|Industry|Non-ferrous metals|Gases	EJ/yr	final energy consumption by the industrial non-ferrous metals sector of gases,excluding transmission/distribution losses.	G	M	
Final Energy|Industry|Non-ferrous metals|Heat	EJ/yr	final energy consumption by the non-ferrous metal sector of heat, excluding transmission/distribution losses.		M	
Final Energy|Industry|Non-ferrous metals|Hydrogen	EJ/yr	final energy consumption by the non-ferrous metal sector of hydrogen, excluding transmission/distribution losses.		M	
Final Energy|Industry|Non-ferrous metals|Liquids	EJ/yr	final energy consumption by the industrial non-ferrous metals sector of liquids,excluding transmission/distribution losses.	G	M	
Final Energy|Industry|Non-ferrous metals|Solids	EJ/yr	final energy consumption by the industrial non-ferrous metals sector of solids,excluding transmission/distribution losses.	G	M	
Final Energy|Industry|Non-ferrous metals|Solids|Bioenergy	EJ/yr	final energy consumption by the industrial non-ferrous metals sector of solids|bioenergy,excluding transmission/distribution losses.	G		
Final Energy|Industry|Non-ferrous metals|Solids|Fossil	EJ/yr	final energy consumption by the industrial non-ferrous metals sector of solids|fossil,excluding transmission/distribution losses.	G		
Final Energy|Industry|Other	EJ/yr	final energy consumption by the industrial sector of other sources that do not fit to any other category.		M	
Final Energy|Industry|Other|Electricity	EJ/yr	final energy consumption by the industrial other sector of electricity, excluding transmission/distribution losses.			R
Final Energy|Industry|Other|Gases	EJ/yr	final energy consumption by the industrial other sector of gases, excluding transmission/distribution losses.			R
Final Energy|Industry|Other|Heat	EJ/yr	final energy consumption by the industrial other sector of heat, excluding transmission/distribution losses.			R
Final Energy|Industry|Other|Hydrogen	EJ/yr	final energy consumption by the industrial other sector of hydrogen, excluding transmission/distribution losses.			R
Final Energy|Industry|Other|Liquids	EJ/yr	final energy consumption by the industrial other sector of liquids, excluding transmission/distribution losses.			R
Final Energy|Industry|Other|Solids	EJ/yr	final energy consumption by the industrial other sector of solids, excluding transmission/distribution losses.			R
Final Energy|Industry|Solids	EJ/yr	final energy solid fuel consumption by the industrial sector (including coal and solid biomass).	G	M	R
Final Energy|Industry|Solids|Biomass	EJ/yr	final energy consumption by the industry sector of solid biomass.	G	M	R
Final Energy|Industry|Solids|Coal	EJ/yr	final energy consumption by the industry sector of coal.	G	M	R
Final Energy|Industry|Steel	EJ/yr	final energy consumption by the industrial steel sector.	G	M	R
Final Energy|Industry|Steel|Electricity	EJ/yr	final energy consumption by the industrial steel sector of electricity,excluding transmission/distribution losses.	G	M	R

Final Energy|Industry|Steel|Gases	EJ/yr	final energy consumption by the industrial steel sector of gases,excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Steel|Heat	EJ/yr	final energy consumption by the industrial steel sector of heat, excluding transmission/distribution losses.		M	
Final Energy|Industry|Steel|Hydrogen	EJ/yr	final energy consumption by the industrial steel sector of hydrogen,excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Steel|Liquids	EJ/yr	final energy consumption by the industrial steel sector of liquids,excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Steel|Solids	EJ/yr	final energy consumption by the industrial steel sector of solids,excluding transmission/distribution losses.	G	M	R
Final Energy|Industry|Steel|Solids|Bioenergy	EJ/yr	final energy consumption by the industrial steel sector of solids|bioenergy,excluding transmission/distribution losses.	G		
Final Energy|Industry|Steel|Solids|Fossil	EJ/yr	final energy consumption by the industrial steel sector of solids|fossil,excluding transmission/distribution losses.	G		
Final Energy|Liquids	EJ/yr	final energy consumption of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).	G	M	R
Final Energy|Non-Energy Use	EJ/yr	final energy consumption by the non-combustion processes.	G	M	
Final Energy|Non-Energy Use|Biomass	EJ/yr	final energy consumption of biomass by the non-combustion processes.	G	M	
Final Energy|Non-Energy Use|Coal	EJ/yr	final energy consumption of coal by the non-combustion processes.	G	M	
Final Energy|Non-Energy Use|Gas	EJ/yr	final energy consumption of gas by the non-combustion processes.	G	M	
Final Energy|Non-Energy Use|Oil	EJ/yr	final energy consumption of oil by the non-combustion processes.	G	M	
Final Energy|Other Sector	EJ/yr	total final energy consumption by other sectors.			R
Final Energy|Other Sector|Electricity	EJ/yr	final energy consumption by other sectors of electricity (including on-site solar PV), excluding transmission/distribution losses.			R
Final Energy|Other Sector|Gases	EJ/yr	final energy consumption by other sectors of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.			R
Final Energy|Other Sector|Heat	EJ/yr	final energy consumption by other sectors of heat (e.g.,district heat,process heat,solar heating and warm water), excluding transmission/distribution losses.			R
Final Energy|Other Sector|Hydrogen	EJ/yr	final energy consumption by other sectors of hydrogen.			R
Final Energy|Other Sector|Liquids	EJ/yr	final energy consumption by other sectors of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).			R

Final Energy|Residential and Commercial	EJ/yr	final energy consumed in the residential and commercial sector.	G	M	R
Final Energy|Residential and Commercial|Commercial|Cooling	EJ/yr	Final energy consumption by the commercial sector for cooling.	G		
Final Energy|Residential and Commercial|Commercial|Electricity	EJ/yr	final energy consumption by the commercial sector of electricity (including on-site solar PV), excluding transmission/distribution losses.	G		
Final Energy|Residential and Commercial|Commercial|Gases	EJ/yr	final energy consumption by the commercial sector of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.	G		
Final Energy|Residential and Commercial|Commercial|Heat	EJ/yr	final energy consumption by the commercial sector of heat (e.g., district heat, process heat, solar heating and warm water), excluding transmission/distribution losses.	G		
Final Energy|Residential and Commercial|Commercial|Heating|Space	EJ/yr	Final energy consumption by the commercial sector for heating space.	G		
Final Energy|Residential and Commercial|Commercial|Hydrogen	EJ/yr	final energy consumption by the commercial sector of hydrogen.	G		
Final Energy|Residential and Commercial|Commercial|Liquids	EJ/yr	final energy consumption by the commercial sector of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).	G		
Final Energy|Residential and Commercial|Commercial|Solids	EJ/yr	final energy solid fuel consumption by the commercial sector (including coal and solid biomass).	G		
Final Energy|Residential and Commercial|Commercial|Solids|Biomass	EJ/yr	final energy solid biomass consumption by the commercial sector.	G		
Final Energy|Residential and Commercial|Commercial|Solids|Coal	EJ/yr	final energy coal consumption by the commercial sector.	G		
Final Energy|Residential and Commercial|Cooling	EJ/yr	Final energy consumption by the residential and commercial sector for cooling.	G		
Final Energy|Residential and Commercial|Electricity	EJ/yr	final energy consumption by the residential and commercial sector of electricity (including on-site solar PV), excluding transmission/distribution losses.	G	M	R
Final Energy|Residential and Commercial|Gases	EJ/yr	final energy consumption by the residential and commercial sector of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.	G	M	R
Final Energy|Residential and Commercial|Gases|Biomass	EJ/yr	final energy consumption by the residential and commercial sector of biogas, excluding transmission/distribution losses.			R

Final Energy|Residential and Commercial|Gases|Natural Gas	EJ/yr	final energy consumption by the residential and commercial sector of natural gas, excluding transmission/distribution losses.			R
Final Energy|Residential and Commercial|Heat	EJ/yr	final energy consumption by the residential and commercial sector of heat (e.g., district heat, process heat, solar heating and warm water), excluding transmission/distribution losses.	G	M	R
Final Energy|Residential and Commercial|Heating	EJ/yr	final energy consumption by the residential and commercial sector for space heating, excluding transmission/distribution losses.			R
Final Energy|Residential and Commercial|Heating|Space	EJ/yr	Final energy consumption by the residential and commercial sector for heating|space.	G		
Final Energy|Residential and Commercial|Hydrogen	EJ/yr	final energy consumption by the residential and commercial sector of hydrogen.	G	M	R
Final Energy|Residential and Commercial|Liquids	EJ/yr	final energy consumption by the residential and commercial sector of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).	G	M	R
Final Energy|Residential and Commercial|Liquids|Biomass	EJ/yr	final energy consumption by the residential and commercial sector of biofuels.		M	R
Final Energy|Residential and Commercial|Liquids|Coal	EJ/yr	final energy consumption by the residential and commercial sector of coal-to-liquids.		M	
Final Energy|Residential and Commercial|Liquids|Oil	EJ/yr	final energy consumption by the residential and commercial sector of conventional and unconventional oil.		M	R
Final Energy|Residential and Commercial|Other	EJ/yr	final energy consumption by the residential and commercial sector of other sources that do not fit to any other category.		M	
Final Energy|Residential and Commercial|Residential|Cooling	EJ/yr	Final energy consumption by the residential sector for cooling.	G		
Final Energy|Residential and Commercial|Residential|Electricity	EJ/yr	final energy consumption by the residential sector of electricity (including on-site solar PV), excluding transmission/distribution losses.	G		
Final Energy|Residential and Commercial|Residential|Gases	EJ/yr	final energy consumption by the residential sector of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.	G		
Final Energy|Residential and Commercial|Residential|Heat	EJ/yr	final energy consumption by the residential sector of heat (e.g., district heat, process heat, solar heating and warm water), excluding transmission/distribution losses.	G		
Final Energy|Residential and Commercial|Residential|Heating|Space	EJ/yr	Final energy consumption by the residential sector for heating|space.	G		
Final Energy|Residential and Commercial|Residential|Hydrogen	EJ/yr	final energy consumption by the residential sector of hydrogen.	G		

Final Energy|Residential and Commercial|Residential|Liquids	EJ/yr	final energy consumption by the residential sector of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).	G		
Final Energy|Residential and Commercial|Solids	EJ/yr	final energy solid fuel consumption by the residential and commercial sector (including coal and solid biomass).	G	M	R
Final Energy|Residential and Commercial|Solids|Biomass	EJ/yr	final energy consumption by the residential and commercial sector of solid biomass (modern and traditional), excluding final energy consumption of bioliquids which are reported in the liquids category.	G	M	R
Final Energy|Residential and Commercial|Solids|Biomass|Traditional	EJ/yr	final energy consumed in the residential and commercial sector coming from biomass (traditional).	G	M	R
Final Energy|Residential and Commercial|Solids|Coal	EJ/yr	final energy coal consumption by the residential and commercial sector.	G	M	R
Final Energy|Solar	EJ/yr	final energy consumption of solar energy (e.g., from roof-top solar hot water collector systems).		M	
Final Energy|Solids	EJ/yr	final energy solid fuel consumption (including coal and solid biomass).	G	M	R
Final Energy|Solids|Biomass	EJ/yr	final energy consumption of solid biomass (modern and traditional), excluding final energy consumption of bioliquids which are reported in the liquids category.	G	M	R
Final Energy|Solids|Biomass|Traditional	EJ/yr	final energy consumption of traditional biomass.	G	M	R
Final Energy|Solids|Coal	EJ/yr	final energy coal consumption.	G	M	R
Final Energy|Transportation	EJ/yr	final energy consumed in the transportation sector, including bunker fuels, excluding pipelines.	G	M	R
Final Energy|Transportation|Aviation	EJ/yr	final energy consumption by the air transportation sector, excluding transmission/distribution losses.	G		
Final Energy|Transportation|Aviation|Passenger	EJ/yr	final energy consumption by the air passenger transportation sector, excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Electricity	EJ/yr	final energy consumption by the transportation sector of electricity (including on-site solar PV), excluding transmission/distribution losses.	G	M	R
Final Energy|Transportation|Freight	EJ/yr	final energy consumed for freight transportation.	G		R
Final Energy|Transportation|Freight|Electricity	EJ/yr	final energy consumption by the freight transportation sector of electricity (including on-site solar PV), excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Freight|Gases	EJ/yr	final energy consumption by the freight transportation sector of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.	G		R

Final Energy|Transportation|Freight|Hydrogen	EJ/yr	final energy consumption by the freight transportation sector of hydrogen, excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Freight|Liquids	EJ/yr	final energy consumption by the freight transportation sector of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).	G		R
Final Energy|Transportation|Freight|Other	EJ/yr	final energy consumption by the freight transportation sector of other sources that do not fit to any other category.	G		
Final Energy|Transportation|Gases	EJ/yr	final energy consumption by the transportation sector of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.	G	M	R
Final Energy|Transportation|Gases|Bioenergy	EJ/yr	final energy consumption by the freight transportation sector of biogas, excluding transmission/distribution losses.			R
Final Energy|Transportation|Gases|Fossil	EJ/yr	final energy consumption by the freight transportation sector of fossil gases, excluding transmission/distribution losses.			R
Final Energy|Transportation|Hydrogen	EJ/yr	final energy consumption by the transportation sector of hydrogen.	G	M	R
Final Energy|Transportation|Liquids	EJ/yr	final energy consumption by the transportation sector of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).	G	M	R
Final Energy|Transportation|Liquids|Bioenergy	EJ/yr	Final biofuels based (liquid or gas) energy consumed in the transport sector by passenger and freight vehicles.			R
Final Energy|Transportation|Liquids|Coal	EJ/yr	final energy consumption by the transportation sector of liquid synfuels from coal-to-liquids (CTL) technologies.		M	R
Final Energy|Transportation|Liquids|Natural Gas	EJ/yr	final energy consumption by the transportation sector of natural gas based liquids (gas-to-liquids).			R
Final Energy|Transportation|Liquids|Oil	EJ/yr	final energy consumption by the transportation sector of liquid oil products (from conventional and unconventional oil).		M	R
Final Energy|Transportation|Maritime	EJ/yr	final energy consumption by the maritime transportation sector, excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Maritime|Freight	EJ/yr	final energy consumption by the maritime freight transportation sector, excluding transmission/distribution losses.	G		R

Final Energy|Transportation|Other	EJ/yr	final energy consumption by the transportation sector of other fuels.	G	M	
Final Energy|Transportation|Passenger	EJ/yr	final energy consumed for passenger transportation.	G		R
Final Energy|Transportation|Passenger|Electricity	EJ/yr	final energy consumption by the passenger transportation sector of electricity (including on-site solar PV), excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Passenger|Gases	EJ/yr	final energy consumption by the passenger transportation sector of gases (natural gas, biogas, coal-gas), excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Passenger|Hydrogen	EJ/yr	final energy consumption by the passenger transportation sector of hydrogen.	G		R
Final Energy|Transportation|Passenger|Liquids	EJ/yr	final energy consumption by the passenger transportation sector of refined liquids (conventional and unconventional oil, biofuels, coal-to-liquids, gas-to-liquids).	G		R
Final Energy|Transportation|Rail	EJ/yr	final energy consumption by the rail transportation sector, excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Rail|Freight	EJ/yr	final energy consumption by the rail freight transportation sector, excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Rail|Passenger	EJ/yr	final energy consumption by the rail passenger transportation sector, excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Road|Freight	EJ/yr	Final energy consumed in the transport sector by road transport freight vehicles.	G		R
Final Energy|Transportation|Road|Freight|Electric	EJ/yr	Final energy consumed in the transport sector by road transport freight electric vehicles (e.g. PHEV, BEV).	G		R
Final Energy|Transportation|Road|Freight|FC	EJ/yr	final energy consumption by the road freight transportation sector of hydrogen from hybridized fuel cell freight trucks, excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Road|Freight|ICE	EJ/yr	final energy consumption by the road freight transportation sector through internal combustion engines, excluding transmission/distribution losses.	G		R

Final Energy|Transportation|Road|Passenger	EJ/yr	Final energy consumed in the transport sector by road transport passenger vehicles.	G		R
Final Energy|Transportation|Road|Passenger|2W&3W	EJ/yr	Final energy consumed in the transport sector by road passenger transport by 2W and 3W vehicles.	G		
Final Energy|Transportation|Road|Passenger|Bus	EJ/yr	final energy consumption by the bus road freight transportation sector, excluding transmission/distribution losses.	G		R
Final Energy|Transportation|Road|Passenger|LDV	EJ/yr	final energy consumed in the transport sector by road passenger transport (light-duty vehicles: passenger cars and light trucks/SUVs/vans).	G		R
Food Demand	kcal/cap/day	all food demand in calories (conversion factor: 1 kcal = 4,1868 kJ).		M	R
Food Demand|Crops	kcal/cap/day	crop related food demand in calories.		M	R
Food Demand|Livestock	kcal/cap/day	livestock related food demand in calories.		M	R
Forcing	W/m2	radiative forcing from all greenhouse gases and forcing agents, including contributions from albedo change, nitrate, and mineral dust.	G		R
Forcing|Kyoto Gases	W/m2	radiative forcing of the six Kyoto gases (CO_2, CH_4, N_2O, SF6, HFCs, PFCs).			R
Forestry Demand|Roundwood	million m3/yr	forestry demand level for all roundwood (consumption, not production).		M	
Forestry Demand|Roundwood|Industrial Roundwood	million m3/yr	forestry demand level for industrial roundwood (consumption, not production).		M	
Forestry Demand|Roundwood|Wood Fuel	million m3/yr	forestry demand level for fuel wood roundwood (consumption, not production).		M	
Forestry Production|Roundwood	million m3/yr	forestry production level for all roundwood (primary production, not consumption).		M	
Forestry Production|Roundwood|Industrial Roundwood	million m3/yr	forestry production level for industrial roundwood (primary production, not consumption).		M	
Forestry Production|Roundwood|Wood Fuel	million m3/yr	forestry production level for fuel wood roundwood (primary production, not consumption).		M	
GDP|MER	billion US$2010/yr	GDP at market exchange rate.	G	M	R
GDP|PPP	billion US$2010/yr	GDP at purchasing power parity.	G	M	R

Investment	billion US$2010/yr	total economy wide investments (macroecomic capital stock, energy system, RandD, ...).		M	R
Investment|Energy Supply	billion US$2010/yr	investments into the energy supply system.	G	M	R
Investment|Energy Supply|CO_2 Transport and Storage	billion US$2010/yr	investments in CO_2 transport and storage (note that investment in the capturing equipment should be included along with the power plant technology).	G	M	R
Investment|Energy Supply|Electricity	billion US$2010/yr	investments into electricity generation and supply (including electricity storage and transmission and distribution).	G	M	R
Investment|Energy Supply|Electricity|Biomass	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Biomass|w/ CCS	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Biomass|w/o CCS	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Coal	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Coal|w/ CCS	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Coal|w/o CCS	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Electricity Storage	billion US$2010/yr	investments in electricity storage technologies (e.g., batteries, compressed air storage reservoirs, etc.).		M	R
Investment|Energy Supply|Electricity|Fossil	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R

Investment|Energy Supply|Electricity|Gas	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Gas|w/ CCS	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Gas|w/o CCS	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Geothermal	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Hydro	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Non-Biomass Renewables	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Non-fossil	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R
Investment|Energy Supply|Electricity|Nuclear	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Oil	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Oil|w/ CCS	billion US$2010/yr	investments into the electricity supply system from oil equipped with CCS facilities.			R

Investment|Energy Supply|Electricity|Oil|w/o CCS	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Other	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R
Investment|Energy Supply|Electricity|Solar	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Electricity|Transmission and Distribution	billion US$2010/yr	investments in transmission and distribution of power generation.	G	M	R
Investment|Energy Supply|Electricity|Wind	billion US$2010/yr	investments in new power generation for the specified power plant category. If the model features several sub-categories, the total investments should be reported. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.	G	M	R
Investment|Energy Supply|Extraction|Coal	billion US$2010/yr	investments for extraction and conversion of coal. These should include mining, shipping and ports.	G	M	
Investment|Energy Supply|Extraction|Fossil	billion US$2010/yr	investments for all types of fossil extraction.	G	M	
Investment|Energy Supply|Extraction|Gas	billion US$2010/yr	investments for extraction and conversion of natural gas. These should include upstream, LNG chain and transmission and distribution.	G	M	
Investment|Energy Supply|Extraction|Oil	billion US$2010/yr	investments for extraction and conversion of oil. These should include upstream, transport and refining.	G	M	
Investment|Energy Supply|Extraction|Uranium	billion US$2010/yr	investments for extraction and conversion of uranium.		M	
Investment|Energy Supply|Heat	billion US$2010/yr	investments in heat generation facilities.		M	R
Investment|Energy Supply|Hydrogen	billion US$2010/yr	investments for the production of hydrogen.		M	R
Investment|Energy Supply|Hydrogen|Biomass	billion US$2010/yr	investments into the energy supply system of biomass-based hydrogen.			R
Investment|Energy Supply|Hydrogen|Electricity	billion US$2010/yr	investments into the energy supply system of electricity-based hydrogen.			R

Investment|Energy Supply|Hydrogen|Fossil	billion US$2010/yr	investments for the production of hydrogen from fossil fuels. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R
Investment|Energy Supply|Hydrogen|Other	billion US$2010/yr	investments for the production of hydrogen from biomass. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R
Investment|Energy Supply|Hydrogen|Renewable	billion US$2010/yr	investments for the production of hydrogen from renewable sources.		M	R
Investment|Energy Supply|Liquids	billion US$2010/yr	investments for the production of liquid fuels. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R
Investment|Energy Supply|Liquids|Biomass	billion US$2010/yr	investments for the production of biofuels. These should not include the costs of the feedstock. For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R
Investment|Energy Supply|Liquids|Coal and Gas	billion US$2010/yr	investments for the production of fossil-based synfuels (coal and gas). For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R
Investment|Energy Supply|Liquids|Oil	billion US$2010/yr	investments for the production of fossil fuels from oil refineries For plants equipped with CCS, the investment in the capturing equipment should be included but not the one on transport and storage.		M	R
Investment|Energy Supply|Other	billion US$2010/yr	investments into other uncategorized energy supply system.		M	R
Land Cover	million ha	total land cover.	G	M	R
Land Cover|Built-up Area	million ha	total built-up land associated with human settlement.	G		R
Land Cover|Cropland	million ha	total arable land, i.e. land in non-forest bioenergy crop, food, and feed/fodder crops, as well as other arable land (cultivated area).	G	M	R
Land Cover|Cropland|Cereals	million ha	land dedicated to cereal crops: wheat, rice and coarse grains (maize, corn, millet, sorghum, barley, oats, rye).		M	R
Land Cover|Cropland|Energy Crops	million ha	land dedicated to 2nd generation energy crops. (e.g., switchgrass, miscanthus, fast-growing wood species).	G	M	R
Land Cover|Cropland|Irrigated	million ha	irrigated arable land, i.e. land in non-forest bioenergy crop, food, and feed/fodder crops, as well as other arable land (cultivated area).		M	R
Land Cover|Forest	million ha	managed and unmanaged forest area.	G	M	R
Land Cover|Forest|Afforestation and Reforestation	million ha	area with afforestation and reforestation.		M	R
Land Cover|Forest|Managed	million ha	managed forests producing commercial wood supply for timber or energy (note: woody energy crops reported under "energy crops").	G	M	R

Land Cover|Forest|Natural Forest	million ha	undisturbed natural forests, modified natural forests and regrown secondary forests.	G	M	R
Land Cover|Forest|Secondary	million ha	regrown (unmanaged) secondary forests,e.g. from abandoned agricultural land.			R
Land Cover|Other Land	million ha	other land cover that does not fit into any other category (e.g., rock, ice, desert, water).	G	M	R
Land Cover|Pasture	million ha	pasture land. All categories of pasture land - not only high quality rangeland. Based on FAO definition of "permanent meadows and pastures".	G	M	R
Policy Cost|Additional Total Energy System Cost	billion US$2010/yr	additional energy system cost associated with the policy.			R
Policy Cost|Consumption Loss	billion US$2010/yr	consumption loss in a policy scenario compared to the corresponding baseline (losses should be reported as negative numbers).			R
Policy Cost|GDP Loss	billion US$2010/yr	GDP loss in a policy scenario compared to the corresponding baseline (losses should be reported as negative numbers).			R
Population	million	total population.	G	M	R
Population|Rural	million	total population living in rural areas.		M	
Population|Urban	million	total population living in urban areas.		M	
Price|Agriculture|Corn|Index	Index (2005 = 1)	price index of corn (Index (2005 = 1)).	G		R
Price|Agriculture|Non-Energy Crops and Livestock|Index	Index (2005 = 1)	weighted average price index of non-energy crops and livestock products (Index (2005 = 1)).		M	R
Price|Agriculture|Non-Energy Crops|Index	Index (2005 = 1)	weighted average price index of non-energy crops (Index (2005 = 1)).	G	M	R
Price|Agriculture|Soybean|Index	Index (2005 = 1)	price index of soybean (Index (2005 = 1)).	G		R
Price|Agriculture|Wheat|Index	Index (2005 = 1)	price index of wheat (Index (2005 = 1)).	G		R
Price|Carbon	US$2010/t CO_2	price of carbon (for regional aggregrates the weighted price of carbon by subregion should be used).	G	M	R
Price|Carbon|Demand|Industry	US$2010/t CO_2	price of carbon for the industry sector.	G		R
Price|Carbon|Demand|Residential and Commercial	US$2010/t CO_2	price of carbon for the residential and commerical sector.	G		R
Price|Carbon|Demand|Transportation	US$2010/t CO_2	price of carbon for the transportation sector.	G		R
Price|Carbon|Supply	US$2010/t CO_2	price of carbon for energy supply sectors (e.g. electricity).	G		R

Price|Final Energy|Industry|Electricity	US$2010/GJ	electricity price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.	G	R
Price|Final Energy|Industry|Gases	US$2010/GJ	gas price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.	G	R
Price|Final Energy|Industry|Gases|Bioenergy	US$2010/GJ	biogas price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.		R
Price|Final Energy|Industry|Gases|Fossil	US$2010/GJ	natural/coal gas price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.		R
Price|Final Energy|Industry|Hydrogen	US$2010/GJ	Hydrogen price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.		R
Price|Final Energy|Industry|Liquids	US$2010/GJ	Liquids price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.	G	R
Price|Final Energy|Industry|Liquids|Bioenergy	US$2010/GJ	liquid biofuel price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.		R
Price|Final Energy|Industry|Liquids|Fossil synfuel	US$2010/GJ	liquid fossil synfuel price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.		R
Price|Final Energy|Industry|Solids|Biomass	US$2010/GJ	solid biomass price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.		R
Price|Final Energy|Industry|Solids|Coal	US$2010/GJ	coal price at the final level in the Industry sector. Prices should include taxes and the effect of carbon prices.		R
Price|Final Energy|Residential and Commercial|Residential|Electricity	US$2010/GJ	electricity price at the final level in the residential sector. Prices should include the effect of carbon prices.		R
Price|Final Energy|Residential and Commercial|Residential|Electricity|Index	Index (2020 = 1)	electricity price at the final level in the residential sector. Prices should include the effect of carbon prices and are indexed on the year 2020.		R
Price|Final Energy|Residential and Commercial|Residential|Gases|Natural Gas	US$2010/GJ	natural gas price at the final level in the residential sector. Prices should include the effect of carbon prices.		R
Price|Final Energy|Residential and Commercial|Residential|Gases|Natural Gas|Index	Index (2020 = 1)	natural gas price at the final level in the residential sector. Prices should include the effect of carbon prices and are indexed on the year 2020.		R
Price|Final Energy|Residential and Commercial|Residential|Liquids|Biomass	US$2010/GJ	biofuel price at the final level in the residential sector. Prices should include the effect of carbon prices.		R

Price|Final Energy|Residential and Commercial|Residential|Liquids|Biomass|Index	Index (2020 = 1)	biofuel price at the final level in the residential sector. Prices should include the effect of carbon prices and are indexed on the year 2020.			R
Price|Final Energy|Residential and Commercial|Residential|Liquids|Oil	US$2010/GJ	light fuel oil price at the final level in the residential sector. Prices should include the effect of carbon prices.			R
Price|Final Energy|Residential and Commercial|Residential|Liquids|Oil|Index	Index (2020 = 1)	light fuel oil price at the final level in the residential sector. Prices should include the effect of carbon prices and are indexed on the year 2020.			R
Price|Final Energy|Residential and Commercial|Residential|Solids|Biomass	US$2010/GJ	biomass price at the final level in the residential sector. Prices should include the effect of carbon prices.			R
Price|Final Energy|Residential and Commercial|Residential|Solids|Biomass|Index	Index (2020 = 1)	biomass price at the final level in the residential sector. Prices should include the effect of carbon prices and are indexed on the year 2020.			R
Price|Final Energy|Residential and Commercial|Residential|Solids|Coal	US$2010/GJ	coal price at the final level in the residential sector. Prices should include the effect of carbon prices.			R
Price|Final Energy|Residential and Commercial|Residential|Solids|Coal|Index	Index (2020 = 1)	coal price at the final level in the residential sector. Prices should include the effect of carbon prices and are indexed on the year 2020.			R
Price|Final Energy|Transportation|Electricity	US$2010/GJ	electricity price at the final level in the transportation sector. Prices should include taxes and the effect of carbon prices.	G		R
Price|Final Energy|Transportation|Gases	US$2010/GJ	gas price at the final level in the transportation sector. Prices should include taxes and the effect of carbon prices.	G		R
Price|Final Energy|Transportation|Hydrogen	US$2010/GJ	Hydrogen price at the final level in the transportation sector. Prices should include taxes and the effect of carbon prices.			R
Price|Final Energy|Transportation|Liquids	US$2010/GJ	Liquids price at the final level in the transportation sector. Prices should include taxes and the effect of carbon prices.	G		R
Price|Final Energy|Transportation|Liquids|Fossil synfuel	US$2010/GJ	liquid fossil synfuel price at the final level in the transportation sector. Prices should include taxes and the effect of carbon prices.			R
Price|Primary Energy|Biomass	US$2010/GJ	biomass producer price.	G	M	R
Price|Primary Energy|Biomass|Index	Index (2020 = 1)	index of biomass producer price (Index (2020 = 1)).	G		R
Price|Primary Energy|Coal	US$2010/GJ	coal price at the primary level (i.e. the spot price at the global or regional market).	G	M	R

Price|Primary Energy|Coal|Index	Index (2020 = 1)	price index of coal at the primary level (Index (2020 = 1)) (i.e. the spot price at the global or regional market).	G		R
Price|Primary Energy|Gas	US$2010/GJ	natural gas price at the primary level (i.e. the spot price at the global or regional market).	G	M	R
Price|Primary Energy|Gas|Index	Index (2020 = 1)	price index of natural gas at the primary level (Index (2020 = 1)) (i.e. the spot price at the global or regional market).	G		R
Price|Primary Energy|Oil	US$2010/GJ	crude oil price at the primary level (i.e. the spot price at the global or regional market).	G	M	R
Price|Primary Energy|Oil|Index	Index (2020 = 1)	price index of crude oil at the primary level (Index (2020 = 1)) (i.e. the spot price at the global or regional market).	G		R
Price|Secondary Energy|Electricity	US$2010/GJ	electricity price at the secondary level, i.e. for large scale consumers (e.g. aluminum production). Prices should include the effect of carbon prices.	G	M	R
Price|Secondary Energy|Electricity|Index	Index (2020 = 1)	price index of electricity at the secondary level (Index (2020 = 1)), i.e. for large scale consumers (e.g. aluminum production). Prices should include the effect of carbon prices.	G		R
Price|Secondary Energy|Gases|Natural Gas	US$2010/GJ	natural gas price at the secondary level, i.e. for large scale consumers (e.g. gas power plant). Prices should include the effect of carbon prices.	G		R
Price|Secondary Energy|Gases|Natural Gas|Index	Index (2020 = 1)	price index of natural gas at the secondary level (Index (2020 = 1)), i.e. for large scale consumers (e.g. gas power plant).	G		R
Price|Secondary Energy|Hydrogen	US$2010/GJ	hydrogen price at the secondary level. Prices should include the effect of carbon prices.	G	M	R
Price|Secondary Energy|Hydrogen|Index	Index (2020 = 1)	hydrogen price at the secondary level (Index (2020 = 1)). Prices should include the effect of carbon prices.			R
Price|Secondary Energy|Liquids	US$2010/GJ	liquid fuel price at the secondary level, i.e. petrol, diesel, or weighted average.	G	M	R
Price|Secondary Energy|Liquids|Index	Index (2020 = 1)	price index of liquid fuel at the secondary level (Index (2020 = 1)), i.e. petrol, diesel, or weighted average.			R
Price|Secondary Energy|Liquids|Biomass	US$2010/GJ	biofuel price at the secondary level, i.e. for biofuel consumers.	G	M	R
Price|Secondary Energy|Liquids|Biomass|Index	Index (2020 = 1)	price index of biofuel at the secondary level (Index (2020 = 1)), i.e. for biofuel consumers.	G		R
Price|Secondary Energy|Liquids|Oil	US$2010/GJ	light fuel oil price at the secondary level, i.e. for large scale consumers (e.g. oil power plant). Prices should include the effect of carbon prices.	G	M	R
Price|Secondary Energy|Liquids|Oil|Index	Index (2020 = 1)	price index of light fuel oil at the secondary level (Index (2020 = 1)), i.e. for large scale consumers (e.g. oil power plant). Prices should include the effect of carbon prices.	G		R
Price|Secondary Energy|Solids|Coal	US$2010/GJ	coal price at the secondary level, i.e. for large scale consumers (e.g. coal power plant). Prices should include the effect of carbon prices.	G		R

Price|Secondary Energy|Solids|Coal|Index	Index (2020 = 1)	price index of coal at the secondary level (Index (2020 = 1)), i.e. for large scale consumers (e.g. coal power plant). Prices should include the effect of carbon prices.	G		R
Primary Energy	EJ/yr	total primary energy consumption (direct equivalent).	G	M	R
Primary Energy|Biomass	EJ/yr	primary energy consumption of purpose-grown bioenergy crops, crop and forestry residue bioenergy, municipal solid waste bioenergy, traditional biomass.	G	M	R
Primary Energy|Biomass|1st Generation	EJ/yr	biomass primary energy from 1st generation biofuel crops (e.g., sugar cane, rapeseed oil, maize, sugar beet).		M	R
Primary Energy|Biomass|Electricity	EJ/yr	primary energy input to electricity generation of purpose-grown bioenergy crops, crop and forestry residue bioenergy, municipal solid waste bioenergy, traditional biomass.		M	R
Primary Energy|Biomass|Electricity|w/ CCS	EJ/yr	purpose-grown bioenergy crops, crop and forestry residue bioenergy, municipal solid waste bioenergy, traditional biomass primary energy input to electricity generation used in combination with CCS.		M	R
Primary Energy|Biomass|Electricity|w/o CCS	EJ/yr	purpose-grown bioenergy crops, crop and forestry residue bioenergy, municipal solid waste bioenergy, traditional biomass primary energy input to electricity generation without CCS.		M	R
Primary Energy|Biomass|Energy Crops	EJ/yr	biomass primary energy from purpose-grown bioenergy crops.		M	R
Primary Energy|Biomass|Heat	EJ/yr	biomass primary energy input to heat generation.		M	R
Primary Energy|Biomass|Gases	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Biomass|Hydrogen	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Biomass|Liquids	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Biomass|Modern	EJ/yr	modern biomass primary energy consumption, including purpose-grown bioenergy crops, crop and forestry residue bioenergy and municipal solid waste bioenergy.	G	M	R
Primary Energy|Biomass|Residues	EJ/yr	biomass primary energy from residues.		M	R
Primary Energy|Biomass|Solids	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Biomass|Traditional	EJ/yr	traditional biomass primary energy consumption.	G	M	R
Primary Energy|Coal	EJ/yr	coal primary energy consumption.	G	M	R
Primary Energy|Coal|Electricity	EJ/yr	coal primary energy input to electricity generation.		M	R
Primary Energy|Coal|Electricity|w/ CCS	EJ/yr	coal primary energy input to electricity generation used in combination with CCS.		M	R

Primary Energy|Coal|Electricity|w/o CCS	EJ/yr	coal primary energy input to electricity generation without CCS.		M	R
Primary Energy|Coal|Gases	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Coal|Hydrogen	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Coal|Liquids	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Coal|Solids	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Coal|Heat	EJ/yr	coal primary energy input to heat generation.		M	R
Primary Energy|Coal|w/ CCS	EJ/yr	coal primary energy consumption used in combination with CCS.	G	M	R
Primary Energy|Coal|w/o CCS	EJ/yr	coal primary energy consumption without CCS.	G	M	R
Primary Energy|Fossil	EJ/yr	coal, gas, conventional and unconventional oil primary energy consumption.	G	M	R
Primary Energy|Fossil|w/ CCS	EJ/yr	coal, gas, conventional and unconventional oil primary energy consumption used in combination with CCS.	G	M	R
Primary Energy|Fossil|w/o CCS	EJ/yr	coal, gas, conventional and unconventional oil primary energy consumption without CCS.	G	M	R
Primary Energy|Gas	EJ/yr	gas primary energy consumption.	G	M	R
Primary Energy|Gas|Electricity	EJ/yr	gas primary energy input to electricity generation.		M	R
Primary Energy|Gas|Electricity|w/ CCS	EJ/yr	gas primary energy input to electricity generation used in combination with CCS.		M	R
Primary Energy|Gas|Electricity|w/o CCS	EJ/yr	gas primary energy input to electricity generation without CCS.		M	R
Primary Energy|Gas|Gases	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Gas|Heat	EJ/yr	gas primary energy input to heat generation.		M	R
Primary Energy|Gas|Hydrogen	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Gas|Liquids	EJ/yr	primary energy input to the fuel conversion sector.		M	R
Primary Energy|Gas|Solids	EJ/yr	primary energy input to the fuel conversion sector.		M	
Primary Energy|Gas|w/ CCS	EJ/yr	gas primary energy consumption used in combination with CCS.	G	M	R
Primary Energy|Gas|w/o CCS	EJ/yr	gas primary energy consumption without CCS.	G	M	R
Primary Energy|Geothermal	EJ/yr	total geothermal primary energy consumption.	G	M	R
Primary Energy|Hydro	EJ/yr	total hydro primary energy consumption.	G	M	R
Primary Energy|Non-Biomass Renewables	EJ/yr	non-biomass renewable primary energy consumption (direct equivalent, includes hydro electricity, wind electricity, geothermal electricity and heat, solar electricity and heat and hydrogen, ocean energy).	G	M	R

Primary Energy|Nuclear	EJ/yr	nuclear primary energy consumption (direct equivalent, includes electricity, heat and hydrogen production from nuclear energy).	G	M	R
Primary Energy|Ocean	EJ/yr	total ocean primary energy consumption.		M	
Primary Energy|Oil	EJ/yr	conventional and unconventional oil primary energy consumption.	G	M	R
Primary Energy|Oil|Electricity	EJ/yr	oil primary energy input to electricity generation.		M	
Primary Energy|Oil|Electricity|w/ CCS	EJ/yr	oil primary energy input to electricity generation used in combination with CCS.		M	
Primary Energy|Oil|Electricity|w/o CCS	EJ/yr	oil primary energy input to electricity generation without CCS.		M	
Primary Energy|Oil|w/ CCS	EJ/yr	conventional and unconventional oil primary energy consumption used in combination with CCS.	G		
Primary Energy|Oil|w/o CCS	EJ/yr	conventional and unconventional oil primary energy consumption without CCS.	G	M	R
Primary Energy|Other	EJ/yr	total other primary energy consumption.		M	
Primary Energy|Secondary Energy Trade	EJ/yr	trade in secondary energy carriers that cannot be unambiguously mapped to one of the existing primary energy categories (e.g. electricity, hydrogen, fossil synfuels, negative means net exports).		M	
Primary Energy|Solar	EJ/yr	total solar primary energy consumption.	G	M	R
Primary Energy|Wind	EJ/yr	total wind primary energy consumption.	G	M	R
Production|Cement	Mt/yr	production of cement (Mt/year).	G	M	R
Production|Chemicals	Mt/yr	production of chemicals (Mt/year).		M	
Production|Non-ferrous metals	Mt/yr	production of non-ferrous metals (e.g., aluminum) (Mt/year).	G	M	
Revenue|Government|Tax|Carbon	billion US$2010/yr	total carbon tax revenue.	G	M	R
Revenue|Government|Tax|Carbon|Demand|Residential and Commercial	billion US$2010/yr	carbon tax revenue from the residential and commercial sector.	G	M	R
Revenue|Government|Tax|Carbon|Demand|Industry	billion US$2010/yr	carbon tax revenue from the industry sector.	G	M	R
Revenue|Government|Tax|Carbon|Demand|Transportation	billion US$2010/yr	carbon tax revenue from the transportation sector.	G	M	R
Revenue|Government|Tax|Carbon|Supply	billion US$2010/yr	carbon tax revenue from the energy supply sector.	G	M	R
Secondary Energy	EJ/yr	the sum of all secondary energy carrier production, which includes double-counting (for example if electricity is used for hydrogen production or synfuels).	G		R
Secondary Energy|Electricity	EJ/yr	total net electricity production.	G	M	R

Secondary Energy|Electricity|Biomass	EJ/yr	net electricity production from municipal solid waste, purpose-grown biomass, crop residues, forest industry waste, biogas.	G	M	R
Secondary Energy|Electricity|Biomass|w/ CCS	EJ/yr	net electricity production from municipal solid waste, purpose-grown biomass, crop residues, forest industry waste with a CO_2 capture component.	G	M	R
Secondary Energy|Electricity|Biomass|w/o CCS	EJ/yr	net electricity production from municipal solid waste, purpose-grown biomass, crop residues, forest industry waste with freely vented CO_2 emissions.	G	M	R
Secondary Energy|Electricity|Coal	EJ/yr	net electricity production from coal.	G	M	R
Secondary Energy|Electricity|Coal|w/ CCS	EJ/yr	net electricity production from coal with a CO_2 capture component.	G	M	R
Secondary Energy|Electricity|Coal|w/o CCS	EJ/yr	net electricity production from coal with freely vented CO_2 emissions.	G	M	R
Secondary Energy|Electricity|Fossil	EJ/yr	net electricity production from fossil fuels.		M	
Secondary Energy|Electricity|Fossil|w/ CCS	EJ/yr	net electricity production from coal, gas, conventional and unconventional oil used in combination with CCS.		M	
Secondary Energy|Electricity|Fossil|w/o CCS	EJ/yr	net electricity production from coal, gas, conventional and unconventional oil without CCS.		M	
Secondary Energy|Electricity|Gas	EJ/yr	net electricity production from natural gas.	G	M	R
Secondary Energy|Electricity|Gas|w/ CCS	EJ/yr	net electricity production from natural gas with a CO_2 capture component.	G	M	R
Secondary Energy|Electricity|Gas|w/o CCS	EJ/yr	net electricity production from natural gas with freely vented CO_2 emissions.	G	M	R
Secondary Energy|Electricity|Geothermal	EJ/yr	net electricity production from all sources of geothermal energy (e.g., hydrothermal, enhanced geothermal systems).	G	M	R
Secondary Energy|Electricity|Hydro	EJ/yr	net hydroelectric production.	G	M	R
Secondary Energy|Electricity|Non-Biomass Renewables	EJ/yr	net electricity production from hydro, wind, solar, geothermal, ocean, and other renewable sources (excluding bioenergy). This is a summary category for all the non-biomass renewables.	G	M	R
Secondary Energy|Electricity|Nuclear	EJ/yr	net electricity production from nuclear energy.	G	M	R
Secondary Energy|Electricity|Oil	EJ/yr	net electricity production from refined liquid oil products.	G	M	R
Secondary Energy|Electricity|Oil|w/o CCS	EJ/yr	net electricity production from refined liquids with freely vented CO_2 emissions.	G	M	R

Secondary Energy|Electricity|Other	EJ/yr	net electricity production from other sources.		M	R
Secondary Energy|Electricity|Solar	EJ/yr	net electricity production from all sources of solar energy (e.g., PV and concentrating solar power).	G	M	R
Secondary Energy|Electricity|Solar|CSP	EJ/yr	net electricity production from concentrating solar power (CSP).	G	M	R
Secondary Energy|Electricity|Solar|PV	EJ/yr	net electricity production from solar photovoltaics (PV).	G	M	R
Secondary Energy|Electricity|Storage Losses	EJ/yr	total electric energy lost in electricity storage system.		M	
Secondary Energy|Electricity|Transmission Losses	EJ/yr	total electric energy lost in electricity transmission system.		M	
Secondary Energy|Electricity|Wind	EJ/yr	net electricity production from wind energy (on- and offshore).	G	M	R
Secondary Energy|Electricity|Wind|Offshore	EJ/yr	net electricity production from offshore wind energy.	G	M	R
Secondary Energy|Electricity|Wind|Onshore	EJ/yr	net electricity production from onshore wind energy.	G	M	R
Secondary Energy|Gases	EJ/yr	total production of gaseous fuels, including natural gas.	G	M	R
Secondary Energy|Gases|Biomass	EJ/yr	total production of biogas.	G	M	R
Secondary Energy|Gases|Coal	EJ/yr	total production of coal gas from coal gasification.	G	M	R
Secondary Energy|Gases|Natural Gas	EJ/yr	total production of natural gas.	G	M	R
Secondary Energy|Gases|Other	EJ/yr	total production of other gaseous fuels.		M	R
Secondary Energy|Heat	EJ/yr	total centralized heat generation.		M	R
Secondary Energy|Heat|Biomass	EJ/yr	total centralized heat generation from municipal solid waste, purpose-grown biomass, crop residues, forest industry waste, biogas.		M	R
Secondary Energy|Heat|Coal	EJ/yr	total centralized heat generation from coal.		M	R
Secondary Energy|Heat|Gas	EJ/yr	total centralized heat generation from natural gas.		M	R
Secondary Energy|Heat|Geothermal	EJ/yr	centralized heat generation from geothermal energy EXCLUDING geothermal heat pumps.		M	R
Secondary Energy|Heat|Oil	EJ/yr	total centralized heat generation from refined liquid oil products.		M	
Secondary Energy|Heat|Other	EJ/yr	total centralized heat generation from other sources.		M	
Secondary Energy|Hydrogen	EJ/yr	total hydrogen production.	G	M	R

Secondary Energy|Hydrogen|Biomass	EJ/yr	hydrogen production from biomass.	G	M	R
Secondary Energy|Hydrogen|Biomass|w/ CCS	EJ/yr	hydrogen production from biomass with a CO_2 capture component.	G	M	R
Secondary Energy|Hydrogen|Biomass|w/o CCS	EJ/yr	hydrogen production from biomass with freely vented CO_2 emissions.	G	M	R
Secondary Energy|Hydrogen|Coal	EJ/yr	hydrogen production from coal.		M	R
Secondary Energy|Hydrogen|Coal|w/ CCS	EJ/yr	hydrogen production from coal with a CO_2 capture component.		M	R
Secondary Energy|Hydrogen|Coal|w/o CCS	EJ/yr	hydrogen production from coal with freely vented CO_2 emissions.		M	R
Secondary Energy|Hydrogen|Electricity	EJ/yr	hydrogen production from electricity via electrolysis.	G	M	R
Secondary Energy|Hydrogen|Fossil	EJ/yr	hydrogen production from fossil fuels.	G	M	R
Secondary Energy|Hydrogen|Fossil|w/ CCS	EJ/yr	hydrogen production from fossil fuels with a CO_2 capture component.	G	M	R
Secondary Energy|Hydrogen|Fossil|w/o CCS	EJ/yr	hydrogen production from fossil fuels with freely vented CO_2 emissions.	G	M	R
Secondary Energy|Hydrogen|Gas	EJ/yr	hydrogen production from natural gas.	G	M	R
Secondary Energy|Hydrogen|Gas|w/ CCS	EJ/yr	hydrogen production from natural gas with a CO_2 capture component.	G	M	R
Secondary Energy|Hydrogen|Gas|w/o CCS	EJ/yr	hydrogen production from natural gas with freely vented CO_2 emissions.	G	M	R
Secondary Energy|Liquids	EJ/yr	total production of refined liquid fuels from all energy sources (incl. oil products, synthetic fossil fuels from gas and coal, biofuels).	G	M	R
Secondary Energy|Liquids|Biomass	EJ/yr	total liquid biofuels production.	G	M	R
Secondary Energy|Liquids|Biomass|w/ CCS	EJ/yr	total liquid biofuels production with CCS.	G	M	R
Secondary Energy|Liquids|Biomass|w/o CCS	EJ/yr	total liquid biofuels production without CCS.	G	M	R
Secondary Energy|Liquids|Coal	EJ/yr	total production of fossil liquid synfuels from coal-to-liquids (CTL) technologies.	G	M	R

Secondary Energy|Liquids|Coal|w/ CCS	EJ/yr	total production of fossil liquid synfuels from coal-to-liquids (CTL) technologies with CCS.		M	R
Secondary Energy|Liquids|Coal|w/o CCS	EJ/yr	total production of fossil liquid synfuels from coal-to-liquids (CTL) technologies without CCS.	G	M	R
Secondary Energy|Liquids|Fossil	EJ/yr	total production of fossil liquid synfuels.	G	M	R
Secondary Energy|Liquids|Fossil|w/ CCS	EJ/yr	total production of fossil liquid synfuels from facilities with CCS.		M	R
Secondary Energy|Liquids|Fossil|w/o CCS	EJ/yr	total production of fossil liquid synfuels from facilities without CCS.	G	M	R
Secondary Energy|Liquids|Gas	EJ/yr	total production of fossil liquid synfuels from gas-to-liquids (GTL) technologies.	G	M	R
Secondary Energy|Liquids|Gas|w/ CCS	EJ/yr	total production of fossil liquid synfuels from gas-to-liquids (GTL) technologies with CCS.		M	R
Secondary Energy|Liquids|Gas|w/o CCS	EJ/yr	total production of fossil liquid synfuels from gas-to-liquids (GTL) technologies without CCS.		M	R
Secondary Energy|Liquids|Oil	EJ/yr	total production of liquid fuels from petroleum, including both conventional and unconventional sources.	G	M	R
Secondary Energy|Solids	EJ/yr	total production of solid secondary energy carriers (e.g., briquettes, coke, wood chips, wood pellets).	G	M	R
Secondary Energy|Solids|Biomass	EJ/yr	total production of solid secondary biomass energy carriers (e.g., wood chips, wood pellets).	G	M	R
Secondary Energy|Solids|Coal	EJ/yr	total production of solid coal-based secondary energy carriers (e.g., briquettes, coke).	G	M	R
Trade|Primary Energy|Biomass|Volume	EJ/yr	net exports of solid, unprocessed biomass, at the global level these should add up to the trade losses only.		M	R
Trade|Primary Energy|Coal|Volume	EJ/yr	net exports of coal, at the global level these should add up to the trade losses only.	G	M	R
Trade|Primary Energy|Gas|Volume	EJ/yr	net exports of natural gas, at the global level these should add up to the trade losses only.	G	M	R
Trade|Primary Energy|Oil|Volume	EJ/yr	net exports of crude oil, at the global level these should add up to the trade losses only.	G	M	R
Transport|Stock|Road|Passenger|Bus	million vehicles	The stock of road transport passenger buses at the reported year.			R
Transport|Stock|Road|Passenger|LDV	million vehicles	The stock of road transport passenger LDVs at the reported year.			R
Water Consumption	km3/yr	total water consumption.		M	
Water Consumption|Irrigation	km3/yr	water consumption for irrigation.		M	
Water Withdrawal|Irrigation	km3/yr	water withdrawal for irrigation.		M	R

Yield|Cereal	t DM/ha/yr	total cereal yield in tonnes dry matter per hectare per year.	M	R
Yield|Oilcrops	t DM/ha/yr	total oil crop yield in tonnes dry matter per hectare per year.	M	R
Yield|Sugarcrops	t DM/ha/yr	total sugar crop yield in tonnes dry matter per hectare per year.	M	R

Downscaled IAM output

Table 26. Mapping from downscaled countries to IAM regions

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.3-4.8
ABW	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
AFG	South Asia	South Asia	Other Asia
AGO	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
AIA	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
ALA	Western Europe		EU 28
ALB	Eastern Europe	Europe_Non_EU	Non-EU28 Europe
AND	Western Europe	EU-15	Non-EU28 Europe
ANT	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
ARE	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
ARG	Latin America and the Caribbean	Argentina	Latin America and the Caribbean
ARM	Former Soviet Union	Central Asia	Countries from the Reforming Economies of the Former Soviet Union
ASM	Other Pacific Asia	Southeast Asia	Other Asia
ATA			Latin America and the Caribbean
ATF			Other Asia
ATG	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
AUS	Pacific OECD	Australia_NZ	Canada, NZ, Australia
AUT	Western Europe	EU-15	EU 28
AZE	Former Soviet Union	Central Asia	Countries from the Reforming Economies of the Former Soviet Union
BDI	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
BEL	Western Europe	EU-15	EU 28
BEN	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
BES			Latin America and the Caribbean
BFA	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
BGD	South Asia	South Asia	Other Asia
BGR	Eastern Europe	EU-12	EU 28
BHR	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
BHS	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
BIH	Eastern Europe	Europe_Non_EU	Non-EU28 Europe
BLM	Western Europe		Latin America and the Caribbean
BLR	Former Soviet Union	Europe_Eastern	Countries from the Reforming Economies of the Former Soviet Union
BLZ	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.3-4.8
BMU	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
BOL	Latin America and the Caribbean	South America_Southern	Latin America and the Caribbean
BRA	Latin America and the Caribbean	Brazil	Latin America and the Caribbean
BRB	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
BRN	Other Pacific Asia	Southeast Asia	Other Asia
BTN	South Asia	South Asia	Other Asia
BVT			Latin America and the Caribbean
BWA	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
CAF	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
CAN	North America	Canada	Canada, NZ, Australia
CCK	Other Pacific Asia	Southeast Asia	Other Asia
CHE	Western Europe	European Free Trade Association	Non-EU28 Europe
CHL	Latin America and the Caribbean	South America_Southern	Latin America and the Caribbean
CHN	China	China	China
CIV	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
CMR	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
COD	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
COG	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
COK	Other Pacific Asia	Southeast Asia	Other Asia
COL	Latin America and the Caribbean	Colombia	Latin America and the Caribbean
COM	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
CPV	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
CRI	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
CUB	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
CUW		Central America and Caribbean	Latin America and the Caribbean
CXR	Pacific OECD	Southeast Asia	Other Asia
CYM	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
CYP	Western Europe	EU-12	EU 28
CZE	Eastern Europe	EU-12	EU 28
DEU	Western Europe	EU-15	EU 28
DJI	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
DMA	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
DNK	Western Europe	EU-15	EU 28
DOM	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
DZA	Middle East and North Africa	Africa_Northern	Middle East, North Africa, Central Asia
ECU	Latin America and the Caribbean	South America_Southern	Latin America and the Caribbean
EGY	Middle East and North Africa	Africa_Northern	Middle East, North Africa, Central Asia
ERI	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
ESH	Sub-Saharan Africa	Africa_Northern	Middle East, North Africa, Central Asia
ESP	Western Europe	EU-15	EU 28

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.3-4.8
EST	Eastern Europe	EU-12	EU 28
ETH	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
FIN	Western Europe	EU-15	EU 28
FJI	Other Pacific Asia	Southeast Asia	Other Asia
FLK	Latin America and the Caribbean	EU-15	Latin America and the Caribbean
FRA	Western Europe	EU-15	EU 28
FRO	Western Europe	EU-15	EU 28
FSM	Other Pacific Asia	Southeast Asia	Other Asia
GAB	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
GBR	Western Europe	EU-15	EU 28
GEO	Former Soviet Union	Central Asia	Countries from the Reforming Economies of the Former Soviet Union
GGY	Western Europe		EU 28
GHA	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
GIB	Western Europe	EU-15	EU 28
GIN	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
GLP	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
GMB	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
GNB	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
GNQ	Sub Saharan Africa	Africa_Western	Sub-Saharan Africa
GRC	Western Europe	EU-15	EU 28
GRD	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
GRL	Western Europe	EU-15	Non-EU28 Europe
GTM	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
GUF	Latin America and the Caribbean	South America_Northern	Latin America and the Caribbean
GUM	North America	Southeast Asia	Other Asia
GUY	Latin America and the Caribbean	South America_Northern	Latin America and the Caribbean
HKG	China	China	China
HMD	Pacific OECD		Canada, NZ, Australia
HND	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
HRV	Eastern Europe	Europe_Non_EU	EU 28
HTI	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
HUN	Eastern Europe	EU-12	EU 28
IDN	Other Pacific Asia	Indonesia	Other Asia
IMN	Western Europe	EU-15	EU 28
IND	South Asia	India	India
IOT	Western Europe		Other Asia
IRL	Western Europe	EU-15	EU 28
IRN	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
IRQ	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
ISL	Western Europe	European Free Trade Association	Non-EU28 Europe

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.3-4.8
ISR	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
ITA	Western Europe	EU-15	EU 28
JAM	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
JEY	Western Europe		EU 28
JOR	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
JPN	Pacific OECD	Japan	Japan
KAZ	Former Soviet Union	Central Asia	Countries from the Reforming Economies of the Former Soviet Union
KEN	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
KGZ	Former Soviet Union	Central Asia	Countries from the Reforming Economies of the Former Soviet Union
KHM	Rest Centrally Planned Asia	Southeast Asia	Other Asia
KIR	Other Pacific Asia	Southeast Asia	Other Asia
KNA	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
KOR	Other Pacific Asia	South Korea	Other Asia
KWT	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
LAO	Rest Centrally Planned Asia	Southeast Asia	Other Asia
LBN	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
LBR	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
LBY	Middle East and North Africa	Africa_Northern	Middle East, North Africa, Central Asia
LCA	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
LIE	Western Europe	European Free Trade Association	Non-EU28 Europe
LKA	South Asia	South Asia	Other Asia
LSO	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
LTU	Eastern Europe	EU-12	EU 28
LUX	Western Europe	EU-15	EU 28
LVA	Eastern Europe	EU-12	EU 28
MAC	Rest Centrally Planned Asia	China	China
MAF	Western Europe		Latin America and the Caribbean
MAR	Middle East and North Africa	Africa_Northern	Middle East, North Africa, Central Asia
MCO	Western Europe	EU-15	Non-EU28 Europe
MDA	Former Soviet Union	Europe_Eastern	Countries from the Reforming Economies of the Former Soviet Union
MDG	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
MDV	South Asia	South Asia	Other Asia
MEX	Latin America and the Caribbean	Mexico	Latin America and the Caribbean
MHL	Other Pacific Asia	Southeast Asia	Other Asia
MKD	Eastern Europe	Europe_Non_EU	Non-EU28 Europe

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.3-4.8
MLI	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
MLT	Western Europe	EU-12	EU 28
MMR	Other Pacific Asia	Southeast Asia	Other Asia
MNE	Eastern Europe	Europe_Non_EU	Non-EU28 Europe
MNG	Rest Centrally Planned Asia	Central Asia	Other Asia
MNP	Other Pacific Asia	Southeast Asia	Other Asia
MOZ	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
MRT	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
MSR	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
MTQ	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
MUS	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
MWI	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
MYS	Other Pacific Asia	Southeast Asia	Other Asia
MYT	Western Europe	Southeast Asia	Sub-Saharan Africa
NAM	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
NCL	Other Pacific Asia	Southeast Asia	Other Asia
NER	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
NFK	Western Europe	Southeast Asia	Other Asia
NGA	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
NIC	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
NIU	Other Pacific Asia	Southeast Asia	Other Asia
NLD	Western Europe	EU-15	EU 28
NOR	Western Europe	European Free Trade Association	Non-EU28 Europe
NPL	South Asia	South Asia	Other Asia
NRU	Other Pacific Asia	Southeast Asia	Other Asia
NZL	Pacific OECD	Australia_NZ	Canada, NZ, Australia
OMN	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
PAK	South Asia	Pakistan	Other Asia
PAN	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
PCN	Western Europe	Southeast Asia	Other Asia
PER	Latin America and the Caribbean	South America_Southern	Latin America and the Caribbean
PHL	Other Pacific Asia	Southeast Asia	Other Asia
PLW	Other Pacific Asia	Southeast Asia	Other Asia
PNG	Other Pacific Asia	Southeast Asia	Other Asia
POL	Eastern Europe	EU-12	EU 28
PRI	North America	USA	Latin America and the Caribbean
PRK	Rest Centrally Planned Asia	Southeast Asia	Other Asia
PRT	Western Europe	EU-15	EU 28
PRY	Latin America and the Caribbean	South America_Southern	Latin America and the Caribbean
PSE	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
PYF	Other Pacific Asia	Southeast Asia	Other Asia

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.3-4.8
QAT	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
REU	Western Europe	Africa_Eastern	Sub-Saharan Africa
ROU	Eastern Europe	EU-12	EU 28
RUS	Former Soviet Union	Russia	Countries from the Reforming Economies of the Former Soviet Union
RWA	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
SAU	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
SDN	Middle East and North Africa	Africa_Eastern	Middle East, North Africa, Central Asia
SEN	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
SGP	Other Pacific Asia	Southeast Asia	Other Asia
SGS	Western Europe		Latin America and the Caribbean
SHN	Western Europe	EU-15	Sub-Saharan Africa
SJM	Western Europe	European Free Trade Association	Non-EU28 Europe
SLB	Other Pacific Asia	Southeast Asia	Other Asia
SLE	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
SLV	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
SMR	Western Europe	EU-15	Non-EU28 Europe
SOM	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
SPM	Western Europe	EU-15	Canada, NZ, Australia
SRB	Eastern Europe	Europe_Non_EU	Non-EU28 Europe
SSD	Middle East and North Africa	Africa_Eastern	Sub-Saharan Africa
STP	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
SUR	Latin America and the Caribbean	South America_Northern	Latin America and the Caribbean
SVK	Eastern Europe	EU-12	EU 28
SVN	Eastern Europe	EU-12	EU 28
SWE	Western Europe	EU-15	EU 28
SWZ	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
SXM		Central America and Caribbean	Latin America and the Caribbean
SYC	Sub-Saharan Africa	Southeast Asia	Sub-Saharan Africa
SYR	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
TCA	Latin America and the Caribbean	EU-15	Latin America and the Caribbean
TCD	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
TGO	Sub-Saharan Africa	Africa_Western	Sub-Saharan Africa
THA	Other Pacific Asia	Southeast Asia	Other Asia
TJK	Former Soviet Union	Central Asia	Countries from the Reforming Economies of the Former Soviet Union
TKL	Pacific OECD	Southeast Asia	Other Asia
TKM	Former Soviet Union	Central Asia	Countries from the Reforming Economies of the Former Soviet Union

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.3-4.8
TLS	Other Pacific Asia	Southeast Asia	Other Asia
TON	Other Pacific Asia	Southeast Asia	Other Asia
TTO	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
TUN	Middle East and North Africa	Africa_Northern	Middle East, North Africa, Central Asia
TUR	Western Europe	Europe_Non_EU	Non-EU28 Europe
TUV	Other Pacific Asia	Southeast Asia	Other Asia
TWN	Other Pacific Asia	Taiwan	China
TZA	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
UGA	Sub-Saharan Africa	Africa_Eastern	Sub-Saharan Africa
UKR	Former Soviet Union	Europe_Eastern	Countries from the Reforming Economies of the Former Soviet Union
UMI	North America		Other Asia
URY	Latin America and the Caribbean	South America_Southern	Latin America and the Caribbean
USA	North America	USA	United States of America
UZB	Former Soviet Union	Central Asia	Countries from the Reforming Economies of the Former Soviet Union
VAT	Western Europe	EU-15	Non-EU28 Europe
VCT	Latin America and the Caribbean	Central America and Caribbean	Latin America and the Caribbean
VEN	Latin America and the Caribbean	South America_Northern	Latin America and the Caribbean
VGB	Western Europe	EU-15	Latin America and the Caribbean
VIR	North America	USA	Latin America and the Caribbean
VNM	Rest Centrally Planned Asia	Southeast Asia	Other Asia
VUT	Other Pacific Asia	Southeast Asia	Other Asia
WLF	Western Europe	EU-15	Other Asia
WSM	Other Pacific Asia	Southeast Asia	Other Asia
YEM	Middle East and North Africa	Middle East	Middle East, North Africa, Central Asia
ZAF	Sub-Saharan Africa	South Africa	Sub-Saharan Africa
ZMB	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
ZWE	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa

Table 38. NGFS Phase IV Scenario Explorer downscaling output

Sector	Subsector	Variable	IAM[119]		
Carbon Sequestration	CCS	Biomass	G	M	R
Carbon Sequestration	CCS	Fossil	G	M	R
Emissions	CO_2	Energy	G	M	R
Final Energy		Final Energy	G	M	R
Final Energy		Electricity	G	M	R
Final Energy		Gases	G	M	R
Final Energy		Heat	G	M	R
Final Energy		Hydrogen	G	M	R
Final Energy		Liquids	G	M	R
Final Energy		Solids	G	M	R
Final Energy	Industry	Electricity	G	M	R
Final Energy	Industry	Gases	G	M	R
Final Energy	Industry	Heat	G	M	R
Final Energy	Industry	Hydrogen	G	M	R
Final Energy	Industry	Liquids	G	M	R
Final Energy	Industry	Solids	G	M	R
Final Energy	Residential and Commercial	Electricity	G	M	R
Final Energy	Residential and Commercial	Gases	G	M	R
Final Energy	Residential and Commercial	Heat	G	M	R
Final Energy	Residential and Commercial	Liquids	G	M	R
Final Energy	Residential and Commercial	Solids	G	M	R
Final Energy	Transportation	Electricity	G	M	R
Final Energy	Transportation	Gases	G	M	R
Final Energy	Transportation	Hydrogen	G	M	R
Final Energy	Transportation	Liquids	G	M	R
Primary Energy		Biomass	G	M	R
Primary Energy		Coal	G	M	R
Primary Energy	Coal	w/ CCS	G	M	R
Primary Energy	Coal	w/o CCS	G	M	R
Primary Energy		Fossil	G	M	R
Primary Energy	Fossil	w/ CCS	G	M	R
Primary Energy	Fossil	w/o CCS	G	M	R
Primary Energy		Gas	G	M	R
Primary Energy	Gas	w/ CCS	G	M	R
Primary Energy	Gas	w/o CCS	G	M	R

[119] G = GCAM, M = MESSAGE-GLOBIOM, R = REMIND-MAgPIE

Sector	Subsector	Variable	IAM119		
Primary Energy		Geothermal	G		R
Primary Energy		Hydro	G		R
Primary Energy		Nuclear	G	M	R
Primary Energy		Oil	G	M	R
Primary Energy	Oil	w/ CCS	G		
Primary Energy	Oil	w/o CCS	G	M	R
Primary Energy		Solar	G		R
Primary Energy		Wind	G		R
Secondary Energy	Electricity	Biomass	G	M	R
Secondary Energy	Electricity	Coal	G	M	R
Secondary Energy	Electricity	Gas	G	M	R
Secondary Energy	Electricity	Geothermal	G	M	R
Secondary Energy	Electricity	Hydro	G	M	R
Secondary Energy	Electricity	Nuclear	G	M	R
Secondary Energy	Electricity	Oil	G	M	R
Secondary Energy	Electricity	Solar	G	M	R
Secondary Energy	Electricity	Wind	G	M	R
Secondary Energy	Gases	Biomass	G	M	R
Secondary Energy	Gases	Coal	G	M	R
Secondary Energy	Gases	Natural Gas	G	M	R
Secondary Energy	Liquids	Biomass	G	M	R
Secondary Energy	Liquids	Coal	G	M	R
Secondary Energy	Liquids	Oil	G	M	R
Secondary Energy	Solids	Biomass	G	M	R
Secondary Energy	Solids	Coal	G	M	R

NiGEM outputs variables

Table 27. List of NiGEM variables available in the NGFS Scenarios

Variable	Unit	Real	IAM transition input (exogenous)	Notes
Carbon pricing	\$ per Tn CO_2		Yes	Converted from IAM data into current prices. Use depreciated in NiGEM since Phase III. Impact replaced by use of carbon revenue
Central bank Intervention rate (policy interest rate)	%			
Coal price	US\$ per barrel (equiv)			Country price: World coal price + 0.652*carbon price
Consumption (private)	Domestic currency	Yes		
Domestic demand	Domestic currency	Yes		
Effective exchange rate (trade weighted sum of nominal FX)	Index			
Energy consumption (total)	MnToe			
Equity prices (composite index for that economy)	Index			
Exchange rate (nominal)	domestic currency per US\$			
Exports (goods and services)	Domestic currency	Yes		
Gas price	US\$ per barrel (equiv)			Country price: World gas price + 0.316*carbon price
Gov. consumption	Domestic currency	Yes		
Gross domestic income	Domestic currency	Yes		
Gross Domestic Product (GDP)	Domestic currency	Yes		
Gross operating surplus	Domestic currency			
House prices (residential)	Index			
IMF region GDP	Bn US\$(PPP)	Yes		
IMF region inflation rate	%			
Imports (goods and services)	Domestic currency	Yes		
Inflation rate (based on consumer expenditure deflator)	%			

Investment (gov.)	Domestic currency	Yes		
Investment (private sector)	Domestic currency	Yes		
Long term interest rate (10 year bond)	%			10 year forward convolution of nominal short rates (bank intervention rate)
Long term real interest rate (10 year bond)	%			10 year forward convolution of short rates
Oil price	US$ per barrel			Country price: World oil price + 0.432*carbon price
Productivity (output per hour worked)	Domestic currency	Yes		
Quarterly consumption of coal	MnToe		Yes	Converted from ExoJooules to MnTnoe
Quarterly consumption of gas	MnToe		Yes	Converted from ExoJooules to MnTnoe
Quarterly consumption of non-carbon	MnToe		Yes	Converted from ExoJooules to MnTnoe
Quarterly consumption of oil	MnToe		Yes	Converted from ExoJooules to MnTnoe
Real personal disposable income	Domestic currency			
Revenue from carbon price or BCA tax	Domestic currency		Yes	Converted from IAM data into domestic currency and current prices
Trend output for capacity utilisation	Domestic currency	Yes		
Unemployment rate	%			
Volume energy use as a share of GDP	Bn US$(PPP)	Yes		

Acronyms and meanings

Table 28. Acronyms and meanings

Acronym	Term
AFOLU	Agriculture, forestry and other land use
AgLU	Agriculture and land use
BC	Black carbon
C_2F_6	Hexafluoroethane
CCS	Carbon capture and storage
CF_4	Tetrafluoromethane
CH_4	Methane
CMIP5	Coupled Model Intercomparison Project – phase 5
CO	Carbon monoxide
CO_2	Carbon dioxide
EJ	Exajoule
Gg	Gigagram
GHG	Greenhouse gases
GJ	Gigajoule
GLU	GLOBE Land Unit
HFC	Hydrofluorocarbon
HFC23	Fluorophore
HFC32	Difluoromethane
HFC43-10mee	1,1,1,2,3,4,4,5,5,5-Decafluoropentane
HFC125	Pentafluoroethane
HFC134a	1,1,1,2-Tetrafluoroethane
HFC143a	1,1,1-Trifluoroethane
HFC152a	1,1-Difluoroethane
HFC227ea	1,1,1,2,3,3,3-Heptafluoropropane
HFC236fa	1,1,1,3,3,3-Hexafluoropropane
HFC245fa	1,1,1,3,3-Pentafluorpropan
HFC365mfc	1,1,1,3,3-Pentafluorobutane
IPCC	Intergovernmental Panel on Climate Change
Kyoto gases	Basket of CO_2, CH_4, N_2O, HFC, PFC, SF_6

Acronym	Term
MAC	Marginal abatement cost
MCal	Million calories
MER	Market exchange rate
MtC	Million tonnes carbon
N_2O	Nitrous oxide
NH_3	Ammonia
NO_x	Nitrogen oxides
PFC	Perfluorocarbon
PPP	Purchasing power parity
Tg	Teragram
VOC	Volatile organic compounds
BECCS	Bioenergy with Carbone capture storage
CCS	Carbone capture storage
CES	Constant Elasticity of Substitution
DACCS	Direct air capture with Carbone capture storage
ETS	Emissions trading system
EW	Enhanced weathering of rocks
HDV	Heavy-duty vehicles
ETS	Emissions trading system
EW	Enhanced weathering of rocks
HDV	Heavy-duty vehicles
LDV	Light-duty vehicles
VRE	Variable renewable energy
RCP	Representative Concentration Pathways
SSP	Socioeconomic Development Pathways
TC	technological change

Complementary information on IAM inputs

Table 29. GCAM external inputs used for demand of energy

Name	Description	Type
Historical demand for energy	Demand for energy in the historical period; used for initialisation/calibration of GCAM	External data
Historical demand for floorspace	Demand for floorspace in the historical period; used for initialisation/calibration of GCAM	External data

Name	Description	Type
Price elasticity of demand	Elasticity determining how demand responds to changes in price	Assumption
Value of time in transit multiplier	Factor multiplied by the wage rate to determine the value of time in transit, used in the transportation module	Assumption
Cost	Cost of production	Assumption
Default input-output coefficients	Default amount of input required per unit of output produced; can be overwritten by region-specific information derived from historical data	Assumption
Default efficiencies	Default amount of output produced per unit of input; can be overwritten by region-specific information derived from historical data	Assumption
CO_2 capture rates	Fraction of CO_2 captured in CCS technologies	Assumption
Retirement rules	For vintaged technologies, GCAM requires the user to specify the lifetime, and the parameters required for phased and profit-based shutdown	Assumption
Logit exponents	GCAM requires the user to specify the logit exponents that determine the substitutability between technologies	Assumption
Share weight interpolation rules	These rules dictate how share weights (GCAM's calibration parameter) are specified in future years	Assumption
Fuel preference elasticity	Elasticity dictating how share weights change with GDP per capita	Assumption
Residential floorspace parameters	Estimated parameters for residential floorspace demand	Analysis/assumption
Satiation levels	Assumed satiation values for commercial floorspace and building energy services	Assumption
Income elasticity of demand	Elasticity determining how demand responds to changes in per capita output for industry and cement	Assumption
Energy intensities	Energy intensity for energy-for-water processes (desalination, abstraction, treatment, distribution, wastewater treatment)	External data
Desalinated water production	Water produced through desalination, used to estimate energy-for-water	External data
Shares of wastewater treated	Shares of wastewater treated, used to estimate energy-for-water	External data
Non-renewable groundwater supply curves – electricity inputs	Electricity inputs to groundwater production	External data
Historical non-CO_2 emissions	Historical emissions of non-CO_2	External data

Table 30. GCAM external inputs used for demand of water

Name	Description	Type
Agriculture water coefficients	Water coefficients for agricultural commodities, including blue (irrigation) and green (rain) water, includes data for a single year circa 2000	External data set
Industrial manufacturing water coefficients	Water coefficients for industrial manufacturing for 1995	External data set
Livestock water coefficients	Water coefficients for drinking and the servicing of livestock commodities, includes data for the period 1996-2005	Mekonnen, M.M. and A.Y. Hoekstra (2010). Volume 2: Appendices
Electricity cooling system shares	Historical shares of cooling system types associated with power plants aggregated to GCAM3 regions	UCS and Schakel Inventories
Electricity water coefficients	Water withdrawal and consumption coefficients for power plants and cooling system types	External data set
Primary energy water coefficients	Water coefficients for the consumption of water during the process of mining primary energy fuel sources	Maheu, A. (2009)
Municipal water withdrawals	Water withdrawal values for municipalities include data, as reported, from 1987 to 2017	FAO Aquastat
Municipal water use efficiency	Water efficiency values for municipalities	Shiklomanov, I.A. (2000)
Municipal water cost	Price per unit of water delivered to municipalities	International Benchmarking Network for Water and Sanitation Utilities (IBNET)

Table 31. GCAM external inputs used for demand of food, feed, and forestry

Name	Description	Type
Historical demand for crops	Demand for agricultural commodities in the historical period; used for initialization/calibration of GCAM	External data
Historical demand for livestock	Demand for livestock commodities in the historical period; used for initialisation/calibration of GCAM	External data
Historical demand for forest	Demand for forest products in the historical period; used for initialisation/calibration of GCAM	External data
Income and price elasticity	Income and price elasticity of demand (for non-food, non-feed demand)	Assumption
Food demand parameters	Set of 11 parameters required for the food demand model	External data
Logit exponents	Share parameters dictating substitution between different commodities	Assumption

Table 32. GCAM external inputs used for economics

Name	Description	Type
Population	Population by country and year, used for 1700-1900	External data set
Population	Population by country and year, used for 1950-2015	External data set
Population	Population by country and year, used for 2015-2100	External data set
GDP	Historical GDP used for most countries for GDP prior to 2015	External data set
GDP	Historical GDP used for remaining countries for GDP prior to 2015	External data set
GDP growth rate	Near-term growth rate of GDP (2015-2024)	External data set
GDP	GDP by country and year, used for 2025-2100	External data set

Table 33. GCAM external inputs used by the land model

Name	Description	Type
Historical land use and land cover	Land area by region, land type and year. Land cover data is provided beginning in 1700 in order to spin-up the carbon cycle within GCAM. Crop-specific harvested area is used to downscale FAO data to a subnational level; however, this data is only available for a single year. Similarly, the division between irrigated and rainfed land is only available for a single year only.	External data set
Historical harvested area	Harvested land area by country, crop, and year	External data set
Historical cropland cover	Arable land, temporary crops, and temporary fallow land area by country and year	External data set
Terrestrial carbon information	Inputs include potential vegetation and soil carbon density (i.e., carbon density if the land grew to equilibrium), and mature age for vegetation carbon. Note that vegetation carbon contents for crops are calculated from crop yields. All other carbon parameters are external inputs.	External data set

Name	Description	Type
Soil time scale	Inputs include the number of years for soil carbon changes to occur. Note that this is not the time to equilibrium, which is much longer.	Assumption
Value of unmanaged land	GCAM requires profit rates for all land types in the historical period for calibration. Managed land profit is calculated in the supply model. For unmanaged land, however, the value is input into the model.	External data set
Share parameters	GCAM requires the user to specify the logit exponents that determine the substitutability between different leaves and nodes in the land model. These parameters were chosen to produce land supply elasticities comparable to those found in the literature, although it should be noted that there is not a transformation between logit exponents and supply elasticities for all land types.	Assumption
Parameters to introduce a new land type	For land types that do not exist in the historical period, GCAM requires parameters to introduce these land types in the future. Specifically, GCAM needs to know how that land type will compete with other land types in its nest *if* it were to have equal profit.	Assumption

Table 34. GCAM external inputs used for supply of energy

Name	Description	Type
Historical supply of energy	Supply of energy in the historical period; used for initialization/calibration of GCAM	External data
CO_2 capture rates	Fraction of CO_2 captured in CCS technologies	Assumption
Retirement rules	For vintaged technologies, GCAM requires the user to specify the lifetime, and the parameters required for phased and profit-based shutdown	Assumption
Logit exponents	GCAM requires the user to specify the logit exponents that determine the substitutability between technologies	Assumption
Share weight interpolation rules	These rules dictate how share weights (GCAM's calibration parameter) are specified in future years	Assumption

Name	Description	Type
Cost of conversion technologies	Cost of production for conversion technologies	External data
Capital cost	Overnight capital cost of electricity generation technologies	External data
Fixed O&M costs	Fixed operating and maintenance (O&M) costs for electricity generation technologies	External data
Variable O&M costs	Variable operating and maintenance (O&M) costs for electricity generation technologies	External data
Capacity factor	Ratio of generation to capacity for electricity generation technologies	Assumption
Fixed charge rate	Factor used to levelise capital cost	Assumption
Default efficiencies	Default amount of output produced per unit of input; can be overwritten by region-specific information derived from historical data	Assumption
Default input-output coefficients	Default amount of input required per unit of output produced; can be overwritten by region-specific information derived from historical data	Assumption
Resource supply curves	Mapping between cost and resource extraction. Resource extraction is cumulative for depletable resources and annual for renewable resources	External data
Historical non-CO_2 emissions	Historical emissions of non-CO_2	External data
CO_2 emissions coefficients	Default carbon content of fuels	External data
Historical CO_2 emissions	Historical emissions of CO_2	External data

Table 35. GCAM external inputs used for supply of water

Name	Description	Type
Surface water supply curves (cost and availability)	Xanthos derived total maximum runoff values, combined with accessible water calculation to determine water available at very low price and the level of accessible water for cost-curve inflection	Exogenous Data
Groundwater supply curves (cost and availability)	Amount of groundwater available in each basin at increasingly high graded levels	Turner *et al.* (2019)
Desalination cost	Cost of desalinated water within a basin which is available at high cost and available once the price of water within a basin surpasses a certain threshold	Exogenous Data

Table 36. GCAM external inputs used for supply of food, feed, and forestry

Name	Description	Type
Historical country-level production of crops	Production of agricultural commodities by country in the historical period; used for initialisation/calibration of GCAM	External data
Historical country-level harvested area for crops	Harvested area for agricultural commodities by country in the historical period; used for initialisation/calibration of GCAM	External data
Historical sub-national production of crops	Production of agricultural commodities by water basin in a single year; used for initialisation/calibration of GCAM	External data
Historical sub-national harvested area of crops	Harvested area of agricultural commodities by water basin in a single year; used for initialisation/calibration of GCAM	External data
Historical production of livestock	Production of livestock commodities in the historical period; used for initialisation/calibration of GCAM	External data
Livestock feed coefficients	Livestock feed input, animal output, and meat output by systems	External data
Historical cost of production	Historical cost of crop production in the USA	External data

Name	Description	Type
Historical prices	Historical prices of agriculture and livestock commodities; used for initialisation/calibration of GCAM	External data
Agriculture productivity growth	Projected yields through 2050 for agricultural commodities	External data
Logit exponents	Share parameters dictating substitution between different feed options for livestock	Assumption
Historical non-CO_2 emissions	Historical emissions of non-CO_2	External data

Table 37. Regional net-zero targets implemented in the 3 IAMs.

Country	Net-zero year	GCAM	MESSAGE-GLOBIOM	REMIND-MAgPIE
Argentina	2050	CO2	GHG	GHG (as LAM)
Australia	2050	GHG (as AUS_NZ)	GHG	GHG (as CAZ)
Brazil	2050	CO2†	GHG	GHG (as LAM)
Canada	2050	GHG	GHG	GHG (as CAZ)
China	2060	GHG	GHG	GHG
Colombia	2050	CO2	CO2‡	GHG (as LAM)
EU+UK	2050	GHG (for total EU12 and EU15)	GHG	GHG
India	2070	CO2†	GHG	CO2
Indonesia	2060	CO2†	GHG	
Japan	2050	GHG	GHG	GHG
New Zealand	2050	GHG (as AUS_NZ)	GHG	GHG (as CAZ)
Russia	2060	GHG†	GHG	GHG (as REF)
South Africa	2050	CO2	GHG	
South Korea	2050	GHG	CO2‡	
USA	2050	GHG	GHG	GHG

† In GCAM, these country targets are implemented as one rest of world (ROW) constraint, and results show that all net-zero targets are met (or very close to be met in the case of India).

‡ MESSAGE-GLOBIOM applies the net-zero GHG constraint for all countries/regions in its model implementation. Thus, for those countries with CO2-only targets, we assume an approximation of a 10-year lag for changing CO2 targets with GHG targets. E.g., for Colombia, the model sets GHG net-zero target by 2060 (instead of CO2 net-zero by 2050).

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