NGFS Climate Scenarios Technical Documentation

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Contents

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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 2023), the NGFS consists of 127 central banks and supervisors (and 20 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 Bloomberg Philanthropies and ClimateWorks Foundation.

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

Introduction

This document provides technical information on the NGFS 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 eight modules. **Module 1** provides a high-level overview of the NGFS scenarios, their rationale, and their broader context, and presents the fourth vintage of NGFS scenarios, including main characteristics and improvements. 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.

2 The previous version of the Technical Documentation for NGFS Phase III scenarios, published in September 2022, 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:

- Taking 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.

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

- Representing 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 two more followed in fall 2021 and 2022. This documentation has been published together with the fourth 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 IV, 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,

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

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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, 15, issue, number 1.

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

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].

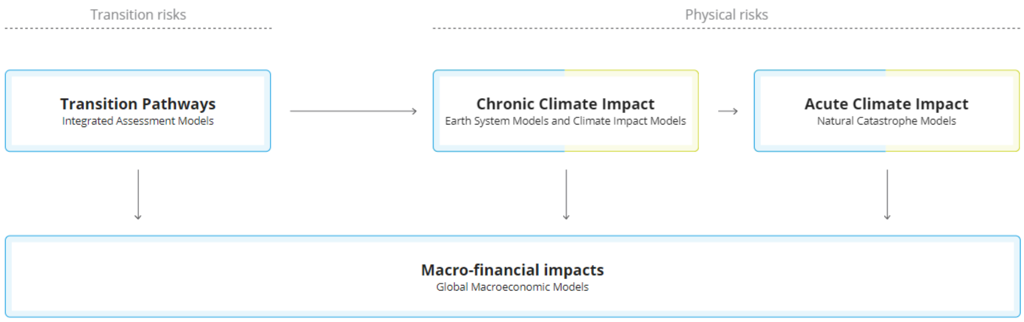

Figure 1. NGFS suite-of-models approach

- **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:

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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.

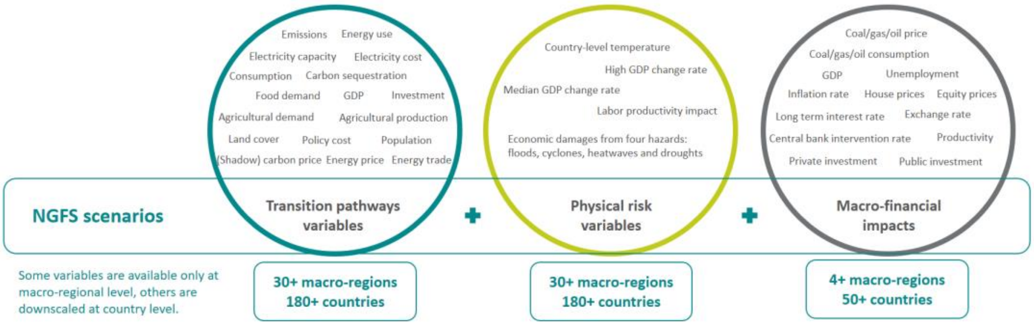

Figure 2. Overview of the range of data provided by NGFS scenarios.
Note: this visual does not contain the full list of variables and is for illustrative purposes only. The names of the variables do not necessarily correspond to the ones used in the databases. The number of countries/regions available 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[10] focus on transition risk only and IPCC focus on the possible evolution of greenhouse gas emissions[11]. The NGFS Scenarios also include more macroeconomic details.

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[10] Based on the Global Energy and Climate Model
[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 house 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 fourth vintage, the NGFS scenarios have been enriched and updated, including both narrative-related and technical improvements, as well as increased usability.**
    - The NGFS scenarios narratives have been updated and expanded to reflect the most recent developments, including geopolitical (e.g. the Russian invasion of Ukraine) and technological ones (e.g. the availability of CDR), as well as delays in policy implementation.
    - The technical refinement of the modelling framework has improved the design of the NGFS scenarios, especially in the area of physical risk.
    - Improvements in the usability of the accompanying materials have increased the transparency of the NGFS scenarios and their underlying models. The documentation has been adapted to different user needs, making it more accessible to both expert and non-expert users, based on user feedback collected.

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.

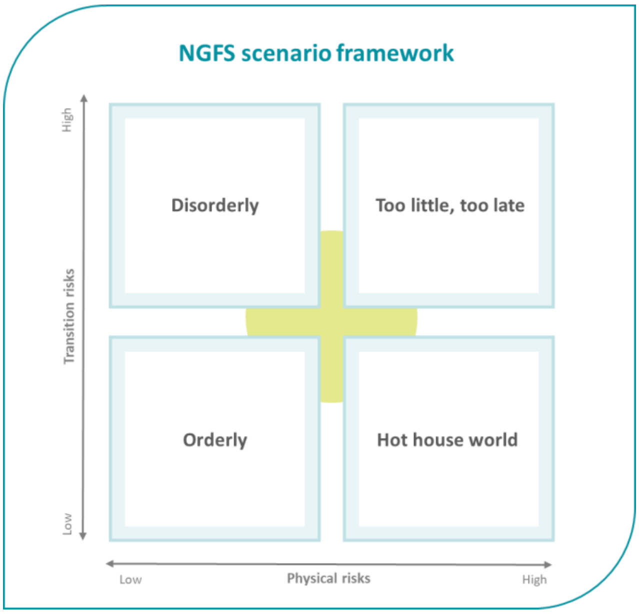


Figure 3. Overview of the NGFS scenario framework

- **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** scenarios assume that a late and uncoordinated transition fails to limit physical risks.

2.1 Description of narratives

In this fourth 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** 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. Given the policy delays, this orderly scenario shows that achieving these targets will require even greater ambition in future compared with the previously published 'orderly transition' scenarios. - **Net Zero 2050** limits global warming to 1.5°C through stringent climate policies and innovation, reaching global net zero CO2 emissions around 2050. Some jurisdictions such as the US, EU, UK, Canada, Australia, and Japan reach net zero for all GHGs. - **Below 2°C** Below 2°C gradually increases the stringency of climate policies, giving a 67% chance of limiting global warming to below 2°C. Additionally, countries with net zero targets reach them partially (80% of the target).
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).

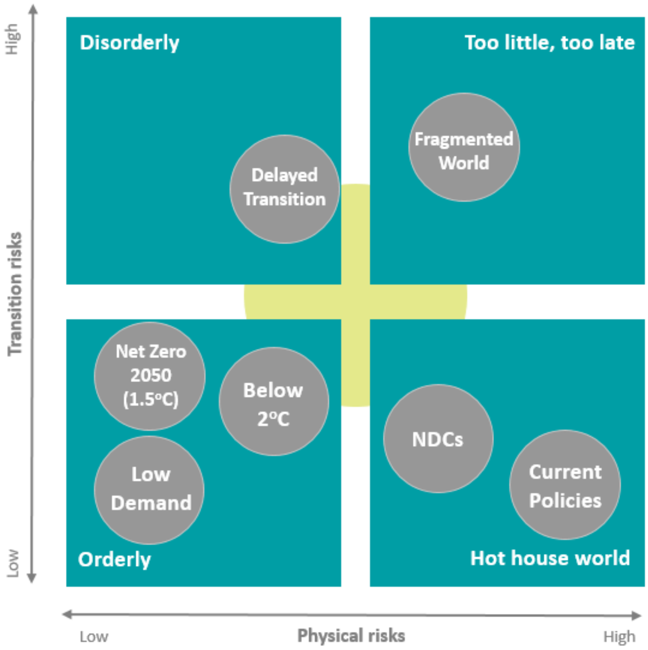


Figure 4. The NGFS scenario framework in Phase IV

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 our 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 February 2023 reach net zero at their target year or earlier. • 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 2023 reach net zero at their target year or earlier. • 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 2023[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 – model average	Policy reaction	Technology change	Carbon dioxide removal -	Regional policy variation +
Orderly	Low Demand **(NEW)**	1.4°C (1.6°C)	Immediate and smooth	Fast change	Medium use	Medium Variation
	Net Zero 2050	1.4°C (1.6°C)	Immediate and smooth	Fast change	Medium-high use	Medium Variation
	Below 2°C	1.7°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)	2.4°C (2.4°C)	NDCs	Slow change	Low-medium use	Medium variation
	Current Policies	2.9°C (2.9°C)	None - current policies	Slow change	Low use	Low variation
Too-little-too-late	Fragmented World **(NEW)**	2.3°C (2.3°C)	Delayed and Fragmented	Slow/ Fragmented change	Low-medium use	High variation

2.2 What is new in the NGFS scenario framework?

In this fourth vintage, all NGFS scenarios have been substantially enriched in their key features to better reflect a more pronounced disorderly future considering recent developments. Delayed implementation of climate policies, persistently high emissions, and the consequences of the war in Ukraine on energy system trajectories are contributing to an overall increase in disorderliness of the NGFS scenarios. Figure 5 displays the movements in scenario mapping in the NGFS scenario framework. The main changes are described as follows:

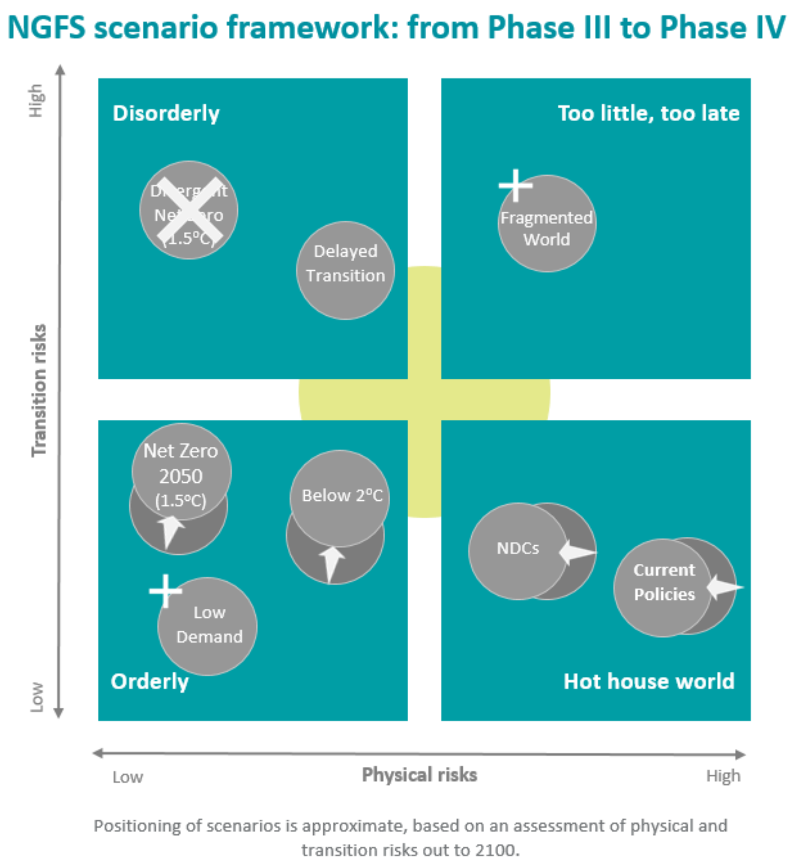


Figure 5. NGFS scenario framework: from Phase III to Phase IV. Movements in the scenario mapping are represented by arrows, new scenarios introduced in Phase IV are indicated with a plus (+) symbol, and the phased out scenario is marked with a cross (x).

- **Net Zero 2050** (1.5°C) has shifted upwards and right in the framework given the higher baseline emissions (2021-2025), leading to increased disorderliness with higher physical and transition risks. This scenario assumes higher peak warming temperatures, and steeper increases in carbon tax programmes to reach global net zero CO_2 around 2050. CDR availability is kept "medium" as in Phase III, but with lower Bioenergy with Carbon Capture and Storage (BECCS) use.

- **Below 2°C** has shifted upwards in the framework, showing an increased transition risk and slightly lower physical risk. It assumes that countries limit global warming to +2°C in 2100 (with 67% probability). Compared to Phase III, country net zero targets have been added, assuming an emissions reduction of at least 80% compared to 2020 would be reached by countries with such targets. This inclusion slightly lowers peak warming and increases disorderliness, resulting in less physical risk but more transition risk.

- **Delayed transition** has been updated without a change in its narrative. It assumes annual emissions do not decrease until 2030. Strong policies are needed to limit warming to below 2°C. Negative emissions are limited.

- **Divergent Net Zero** (1.5C) scenario, previously included in Phase III, has been phased out in this new fourth vintage given the reduced likelihood of a successful uncoordinated transition. This streamlining decision also contributes to the ongoing efforts to improve the usability of NGFS scenarios for its broad user community, striking the right balance between usability and complexity of its framework.

- **Nationally Determined Contributions (NDCs)** foresees that currently pledged conditional NDCs are implemented fully, and respective targets on energy and emissions in 2025 and 2030 are reached in all countries, even if not yet backed up by implemented effective policies. The cut-off date for targets being considered here is until end of March 2023, as published by the UNFCCC. This results in a slight decrease in long-term physical risk compared to Phase III due to newly announced commitments. Nevertheless, physical risk remains high.

- **Current Policies** existing climate policies remain in place, but there is no strengthening of the ambition level of these policies. The scenario has been updated to take new policies into account (EU Fit-for-55, US IRA, etc.). This results in a slight decrease in long-term physical risk compared to Phase III due to newly implemented policies. Nevertheless, physical risk remains very high.

Second, the NGFS scenarios framework has been further expanded in the set of scenarios to capture more and less adverse disruptions. To account for "too-little-too-late" climate policies, as well as the possibility of still meeting the Paris Agreement, two new scenarios have been designed and introduced.

- First, there is a risk of further delays and fragmentation in the international climate policy landscape, made more severe by the energy crisis following the war in Ukraine. A new too-little-too-late scenario **Fragmented World** has been added to explore such adverse developments. It entails delayed policy action until 2030 and divergence in policy ambition thereafter, with countries having net zero targets supposedly following these, and countries without net zero targets supposedly following the current policies.

  Given its design features, the FW scenario can be particularly useful for regulators, as well as central banks and supervisors. It emphasizes the critical role played by international policy coordination (or the lack thereof), and it explores more adverse impacts if we fail to implement climate mitigation policies in a timely and globally coordinated manner. Therefore, it can be used as a baseline for climate stress tests.

- Second, the +1.5°C end-of-century warming limit, which the world has committed to in the Paris agreement, becomes ever more challenging to achieve due to persistently high and rising global emissions. This is reflected in the increasing disorderliness of the Net Zero 2050 scenario. Therefore, a new Paris-aligned orderly transition scenario **Low Demand** has been added.

  This scenario includes lower energy demand and stronger behavioural changes, mapping out the challenging path to still reach the Paris goals in an orderly way.

  Low Demand shows that greater energy sobriety, deep electrification, and improved energy efficiency will be needed to reach the 1.5°C target – all of which will, however, be less costly than inaction or disorderly transition in the long term. This scenario can be particularly informative to policymakers and regulators, as it illustrates the challenges as well as the feasibility and benefits of carrying on with the net zero transition.

Third, 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 the war in Ukraine, delays in government climate action and lock-in of fossil fuel technologies in many jurisdictions. Updates have also been made to the use of Carbon Dioxide Removal (CDR) technologies, which has been limited compared to the Phase

III scenarios. These updates have been applied consistently across scenarios and models to improve comparability of results. Table 3 summarises the main changes in Phase IV.

Table 3. Overview of main changes in Phase IV compared to Phase III

Quadrant	NGFS scenario	Main changes in Phase IV (compared to Phase III)
All NGFS scenarios		**All scenarios are more disorderly in Phase IV reflecting delays in policy action and the current geopolitical situation/energy crisis** • **Updates reflecting energy market disruption due to the Russian war in Ukraine.** All scenarios and their underlying models have been updated, e.g., including recent policy actions, and including energy sector ramifications of the Russian war in Ukraine. • **Limits to the use of carbon dioxide removal (CDR) technologies.** All scenarios assume limited availability of BECCS and dropping the availability of direct air carbon capture and storage (DACCS). This makes scenarios more adverse in the sense that reductions of fossil fuel use need to be more severe. The carbon tax implementing these demand reductions would be higher.
Orderly	Low Demand (1.5°C)	**NEW** scenario
	Net Zero 2050 (1.5°C)	**New net zero targets considered, less CDR** Update of net zero targets (see table 38)
	Below 2°C (2°C)	**Countries with net zero targets follow through on 80% of pledged reductions, less CDR** NDCs partial achievement: net zero targets are assumed to be 80% fulfilled, to better reflect the actual policy ambition globally
Disorderly	Delayed Transition (2°C)	**Net zero targets updated** • Update of net zero targets (see table 38)
Hot house world	Nationally Determined Contributions (NDCs)	**New NDCs considered** • Updated NDCs, including IRA and Fit for 55.
	Current Policies	**Inclusion of additional policies (IRA, Fit for 55), updated assumptions regarding technical change and GDP.**

Too little, too late	**Fragmented World**	**NEW** scenario

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). 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.

To account for the COVID-19 pandemic and its impact on economic systems including the near-term recovery until 2025, the GDP and final energy demand trajectories have been adjusted based on projections from the IMF (IMF 2021, Koch & Leimbach 2023).

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 6.

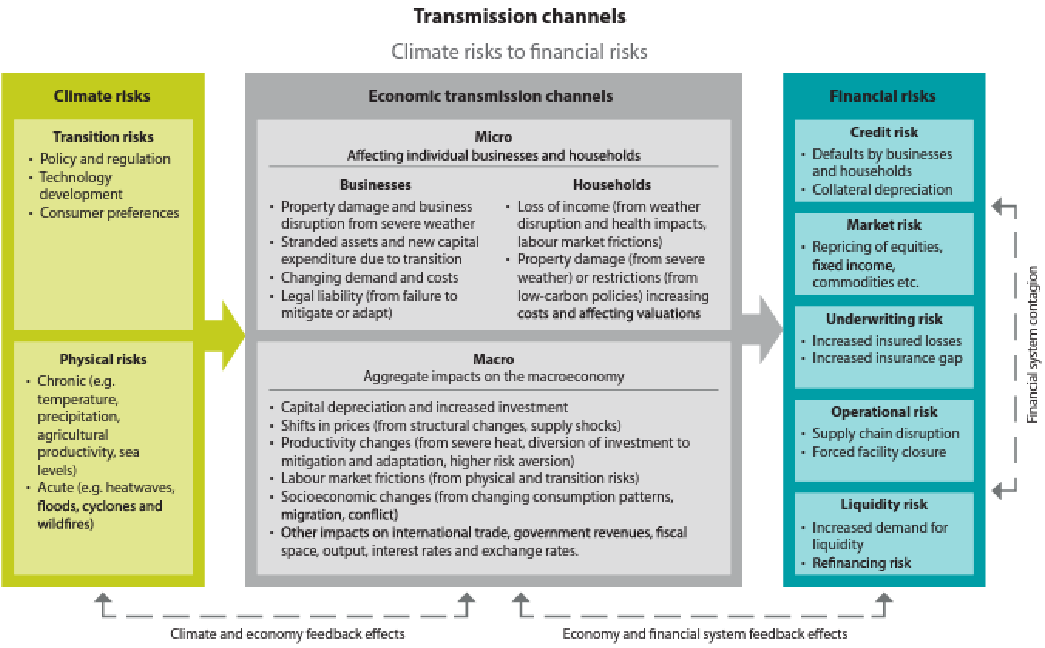


Figure 6. Transmission channels: climate risks to financial risks. Source: NGFS (2022)

- **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. The NGFS suite of models is aligned in a coherent way to produce results that are internally consistent.

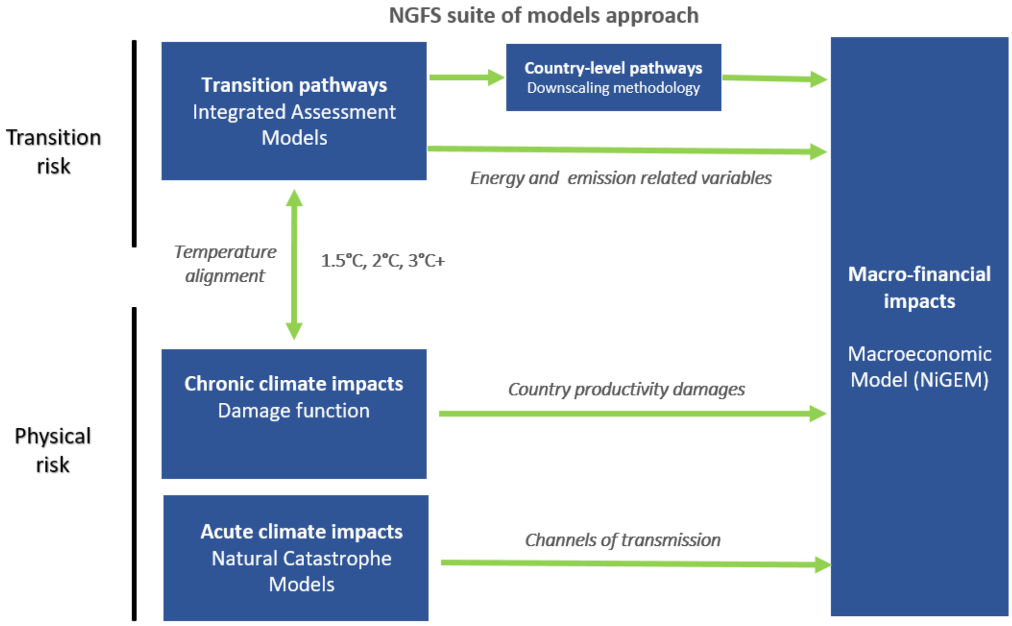


Figure 7. Interactions between the three model categories in the NGFS framework

Figure 7 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**.

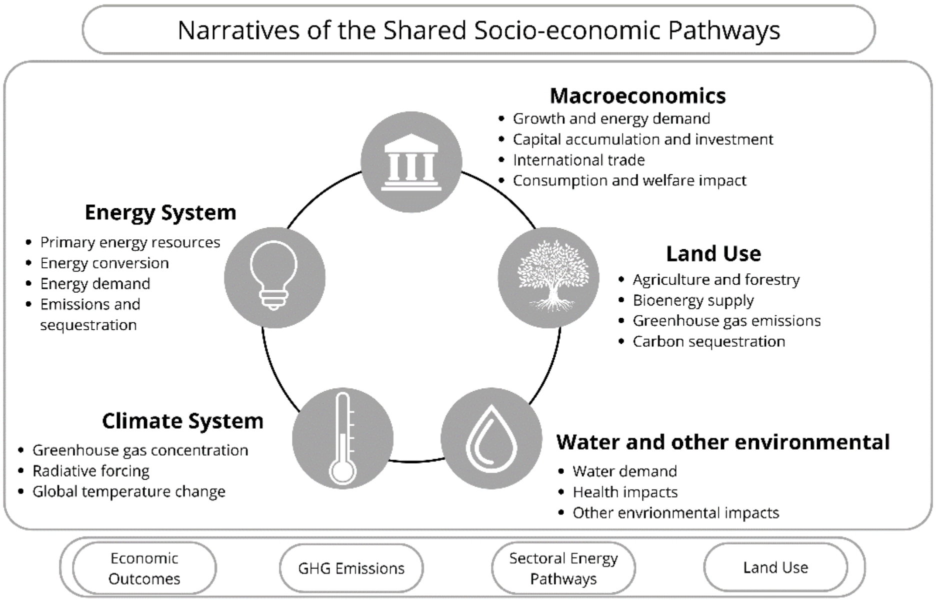


Figure 8. Simplified diagram of the elements that integrate the IAM models

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 andMESSAGE 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 3 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.

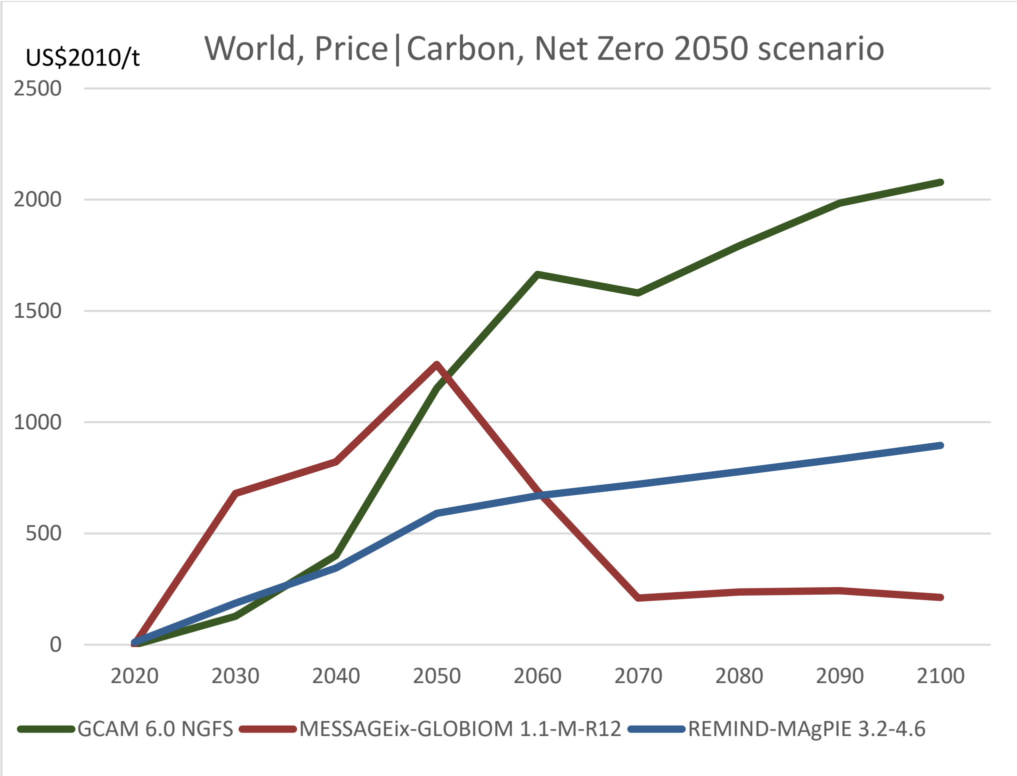


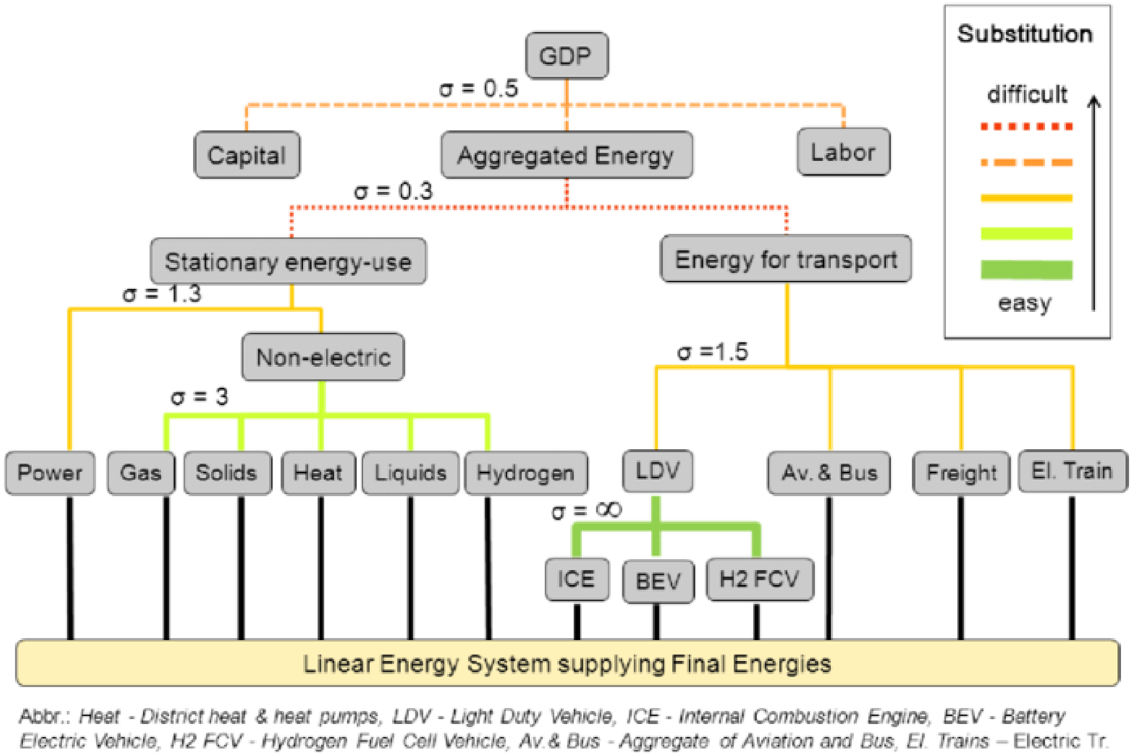
Figure 9. Carbon price IAM comparison in Net Zero Scenario.

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.

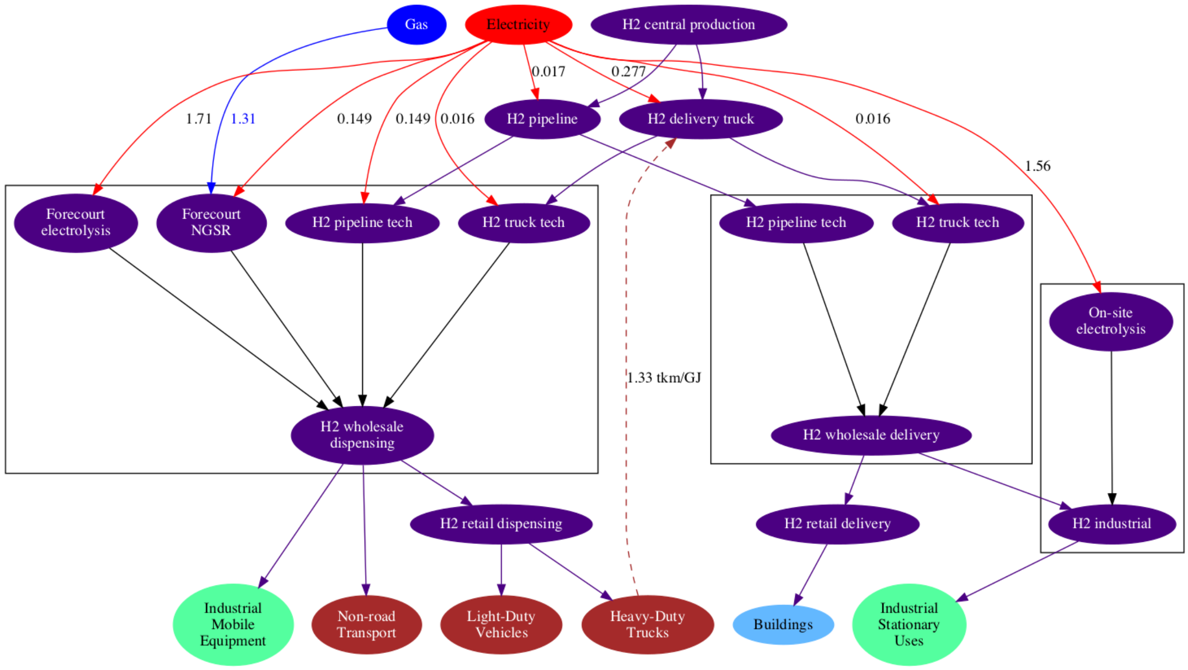


Figure 11: GCAM hydrogen technology nesting structure, including approximate energy requirements at each stage.

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**.

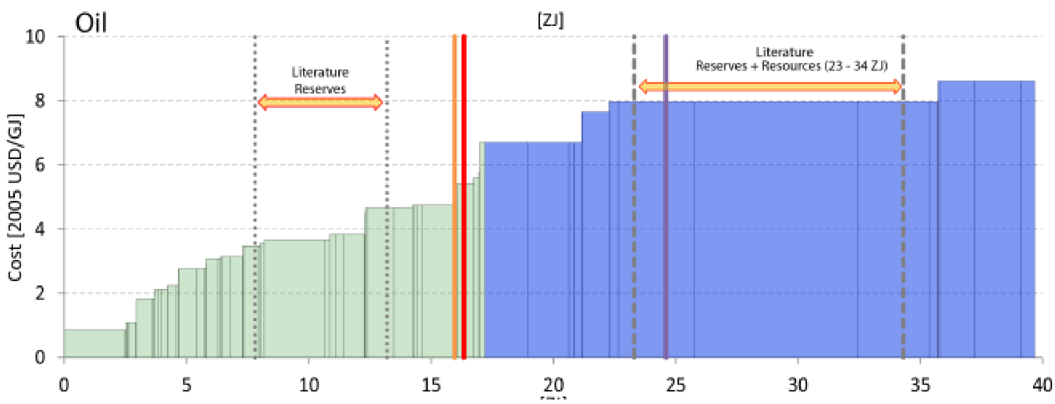


Figure 12: Oil resource endowment curve, MESSAGE.

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.

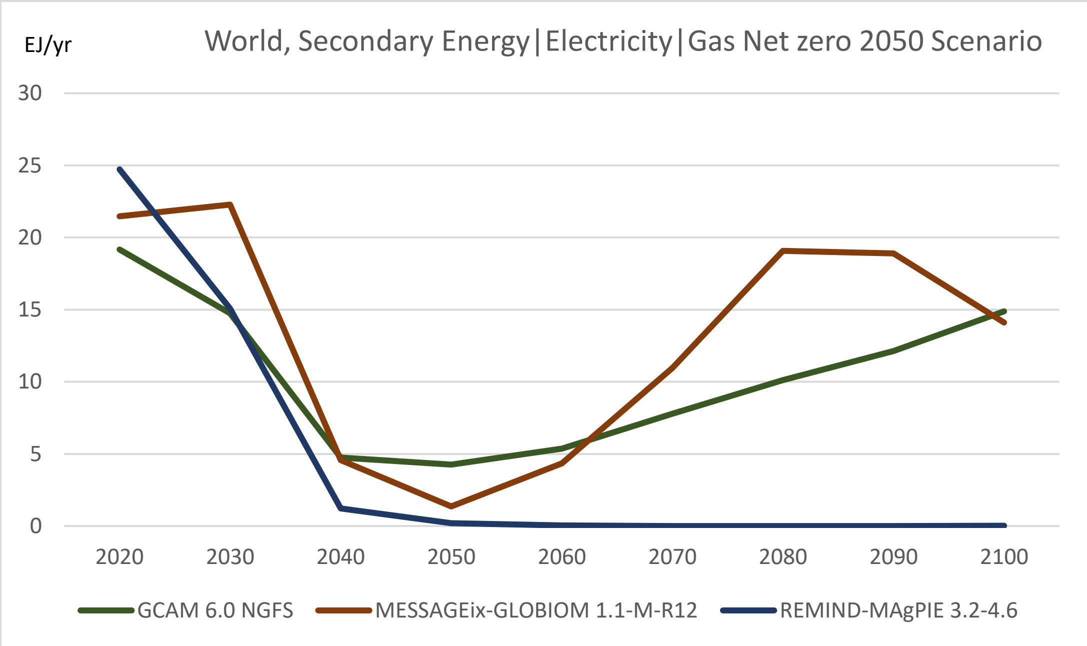


Figure 13: Gas-powered electricity production, net zero scenario.

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 depending on 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 3.2-4.6	**MESSAGEix-GLOBIOM 1.1-M-R12**	**GCAM 6.0**
Hosting Institution	PIK	IIASA	PNNL
Economic Equilibrium	General equilibrium (GE)	GE	Partial equilibrium (PE)
Agriculture Sector Modelling	PE with recursive dynamic	GE 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	Only in Low Demand	Yes	No

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.

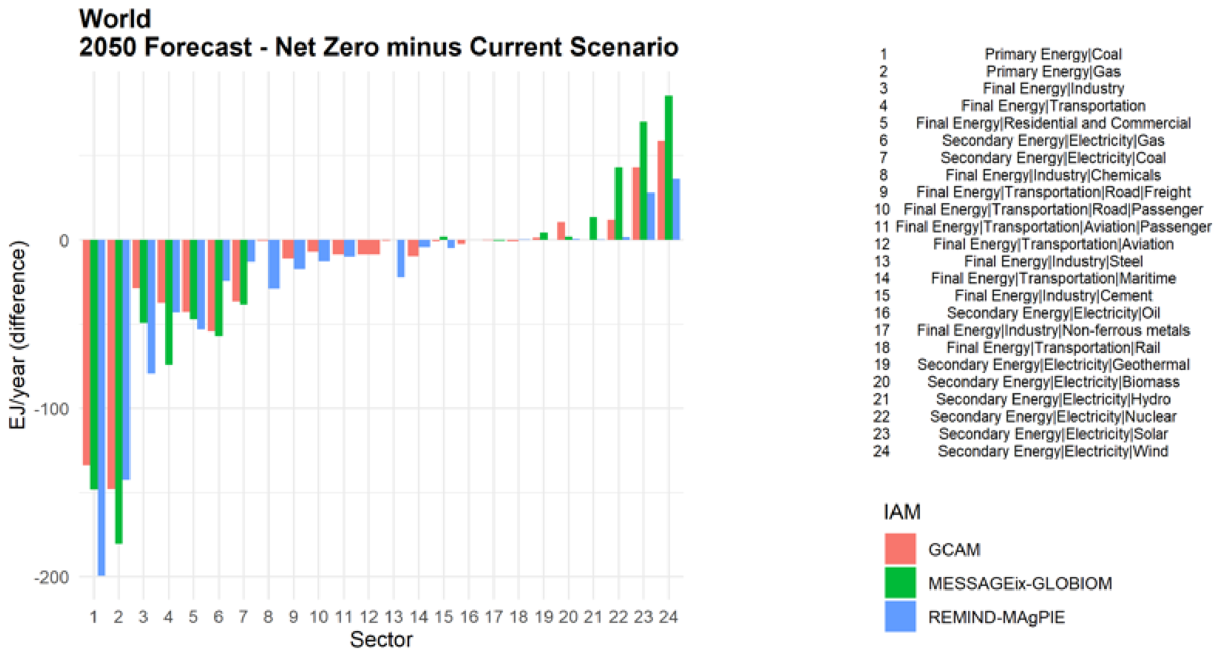


Figure 14 Energy series dynamics comparison between the IAMs. Metric shown is the absolute difference between the net zero and current scenario for the year 2050.

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[25], 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.

[25] The "Temperature|Global Mean" variable that existed in Phase 3 data for REMIND and GCAM and was not harmonized across models was superseded by "AR6 climate diagnostics|Surface Temperature (GSAT)|MAGICCv7.5.3|50.0th Percentile".

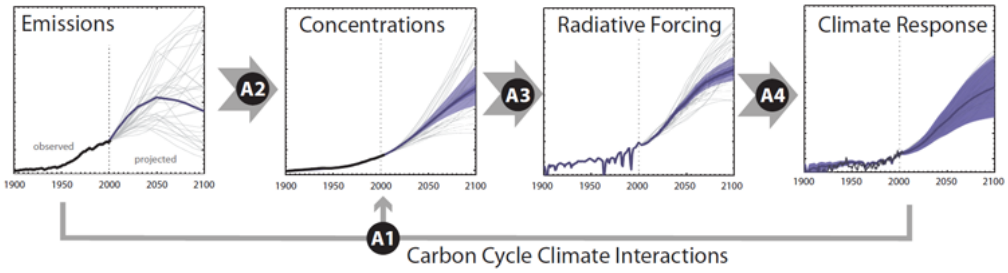


Figure 15. Schematic overview of MAGICC calculations showing the key steps from emissions to global and hemispheric climate responses.

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).

3.4 Physical risk modelling approach

Physical risk modelling is split between chronic and acute risk. Chronic risk macro-economic impacts are calculated with the damage function developed by Kalkuhl and Wenz (2020), 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 modelling approach has not changed compared to the previous phase; hence additional impacts derive from updated temperature paths.

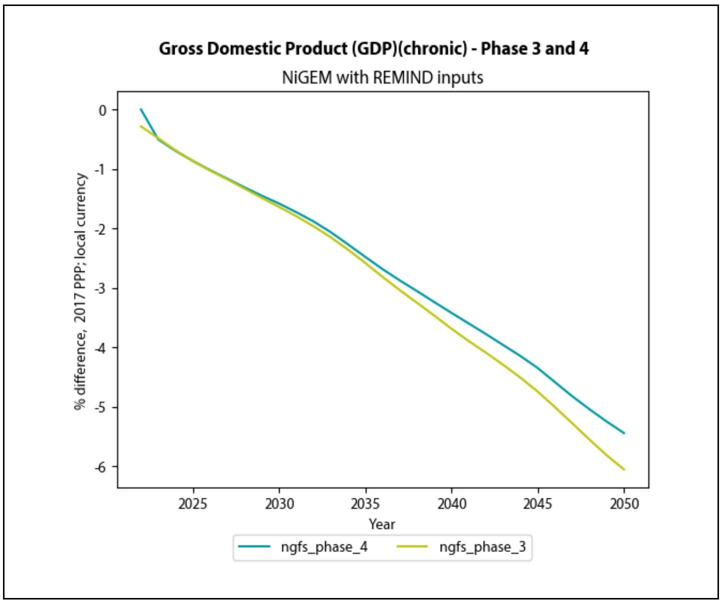


Figure 16. Gross Domestic Product deviation due to chronic physical risk between Phase 3 and 4. Nigem with REMIND inputs

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.

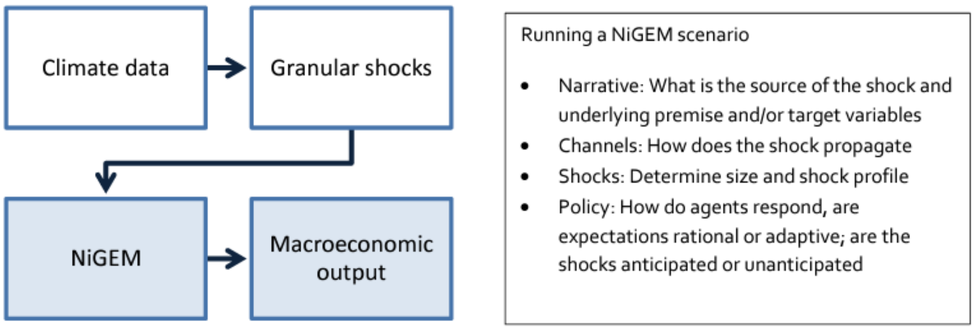


Figure 17. implementation of climate shock in the NiGEM macreconomic model

4. Main results of the NGFS scenarios[26]

Key messages

- Reaching global net zero CO2 emissions by 2050 will require ambitious transition efforts across all sectors of the economy. The NGFS scenarios, however, show that immediate coordinated transition will be less costly than inaction or disorderly transition in the long run.
- More precisely, physical risks in hot house world scenarios (Current Policies or Nationally Determined Contributions scenarios) will lead to the strongest negative impacts on GDP with economic cost diverging significantly after 2040.
- Reducing greenhouse gas emissions continues to affect all sectors of the economy and gives rise to transition risks for the economy and financial system
- Policy intensity increases as timelines for net zero 2050 scenarios shorten. Precisely, the shadow emissions prices continue to rise drastically in respective scenarios.
- Energy is a key sector. Extensive energy investments pathways continue to rise. Until 2030 all scenarios predict a rapid scale-up of spending on overall energy supply.
- Global mean temperatures strongly depend on the policy assumptions of the respective scenarios. In general, the modelled pathways reach from 1.5 to above 3 degrees.

This section presents key results from the seven NGFS scenarios described above and corresponding to the four quadrants of the NGFS scenarios framework as follows:

- **Orderly** scenarios: **Low Demand, Below 2°C** and **Net Zero 2050**
- **Disorderly** scenario: **Delayed Transition**
- **Hot house world** scenarios: **Current policies** and **NDCs**
- **Too-little-too-late** scenario: **Fragmented World**

The results can differ based on the model and the type of climate risk considered (transition and/or physical risk). The macro-financial impacts of transition and physical risks are expressed as deviations from a baseline scenario, where there is no climate-related risk. The NiGEM model is able to determine the contribution of each type of risk (transition or physical) in deviation from this hypothetical scenario.

The time horizon covers a period from 2020 until 2050 or 2100, depending on the variable. The geographic sample includes more than 180 countries and more than 30 regions. The following sub-sections describe the key output variables available in the NGFS scenarios distinguishing between three categories: macro-financial impacts, transition risk and physical risk.

[26] The plots of this section have been generated with this EnTry script.

4.1 Key macro-financial impacts

Gross domestic product

NGFS scenarios differ markedly in their economic impact, with some difference across models and significant variation across regions. Impacts on GDP are specified relative to a forecast representing prior trends but also incorporating most recent impacts (e.g., the consequences of the Russian war in Ukraine). **Transition risks** have a moderately negative impact on world GDP in Net Zero 2050 as negative impacts on demand from higher carbon prices and energy costs are partially offset by the recycling of carbon revenues into government investment and lower employment taxes. GDP impacts from transition risks are more markedly negative in the Disorderly scenarios as the speed of the transition combined with investment uncertainty affects consumption and investment. GDP losses from **physical risks** vary in line with different temperatures projected for each scenario. Chronic physical risk becomes gradually more important over time – both in absolute and relative terms – but acute physical risk remains the main source of risk until 2050. In all scenarios, the impact of physical risk rapidly outweighs the impact of transition efforts. Indeed, the GDP deviation from baseline due to the combined impact of transition, chronic and acute risks ranges from 5 to 7 pp over the next 30 years in the Net Zero 2050 scenario, while it reaches almost 10 pp in 2040 and 14 pp in 2050 in the Current Policies scenario. Stringent mitigation initiatives that are in line with the Net Zero 2050 scenario will already be beneficial by 2040 and strongly reduce risks towards the end of the century. This also underlines the need to add investments on **adaptation**. Finally, impacts diverge even more thereafter. By 2100 impacts are highest in the Current Policies scenario (up to 20 % of GDP relative to prior trend) as temperature targets and the corresponding decarbonization efforts are missed.

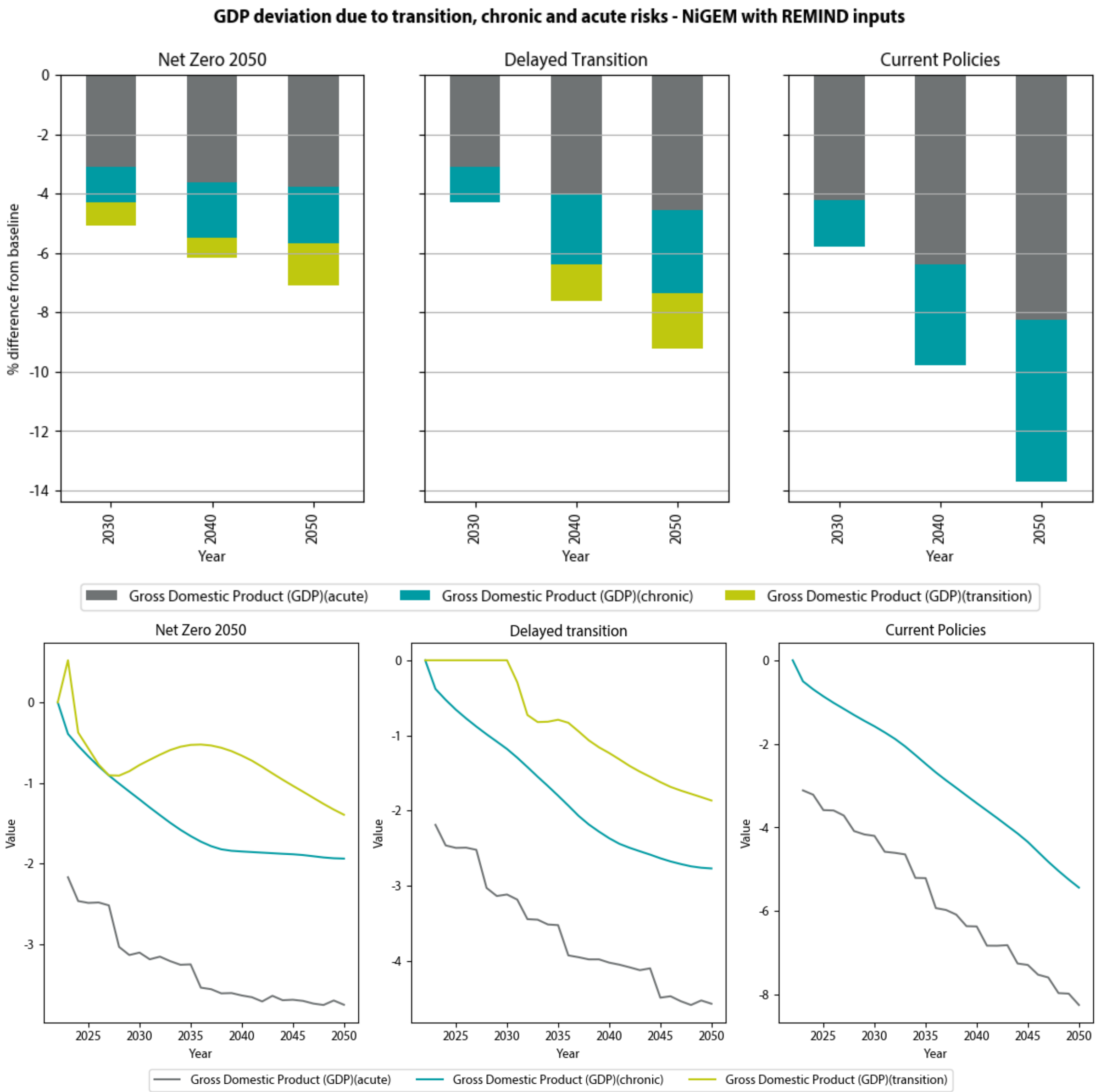


Figure 18. GDP deviation due to transition, chronic and acute risks - REMIND model

The NiGEM model provides economic impacts per country and region, giving estimates of country's exposure to transition and physical risks. In the NGFS scenarios, both transition and physical risk impacts vary across countries based on several factors. Transition risk depends, among others, on the structure of the economy, the reliance on fossil fuels and the trade composition. Physical risk depends on the exposure and vulnerability to temperature increase and extreme weather events, with tropical and subtropical regions facing larger risk increases. NiGEM provides country and regional pathways for GDP. Impacts are higher for countries and regions that face higher emissions reduction, higher carbon prices, lower fossil fuel exports or higher physical risk damages. Impacts also vary across models, depending on model structure and assumptions. To estimate GDP impacts, the NiGEM model is calibrated based on inputs from the three IAMs (REMIND, MESSAGE, GCAM). Results from MESSAGE are more adverse because of lower CDR use, more ambitious temperature outcomes and stronger decarbonization strategies needed due to structurally higher energy demand in MESSAGE, therefore inducing higher carbon prices.

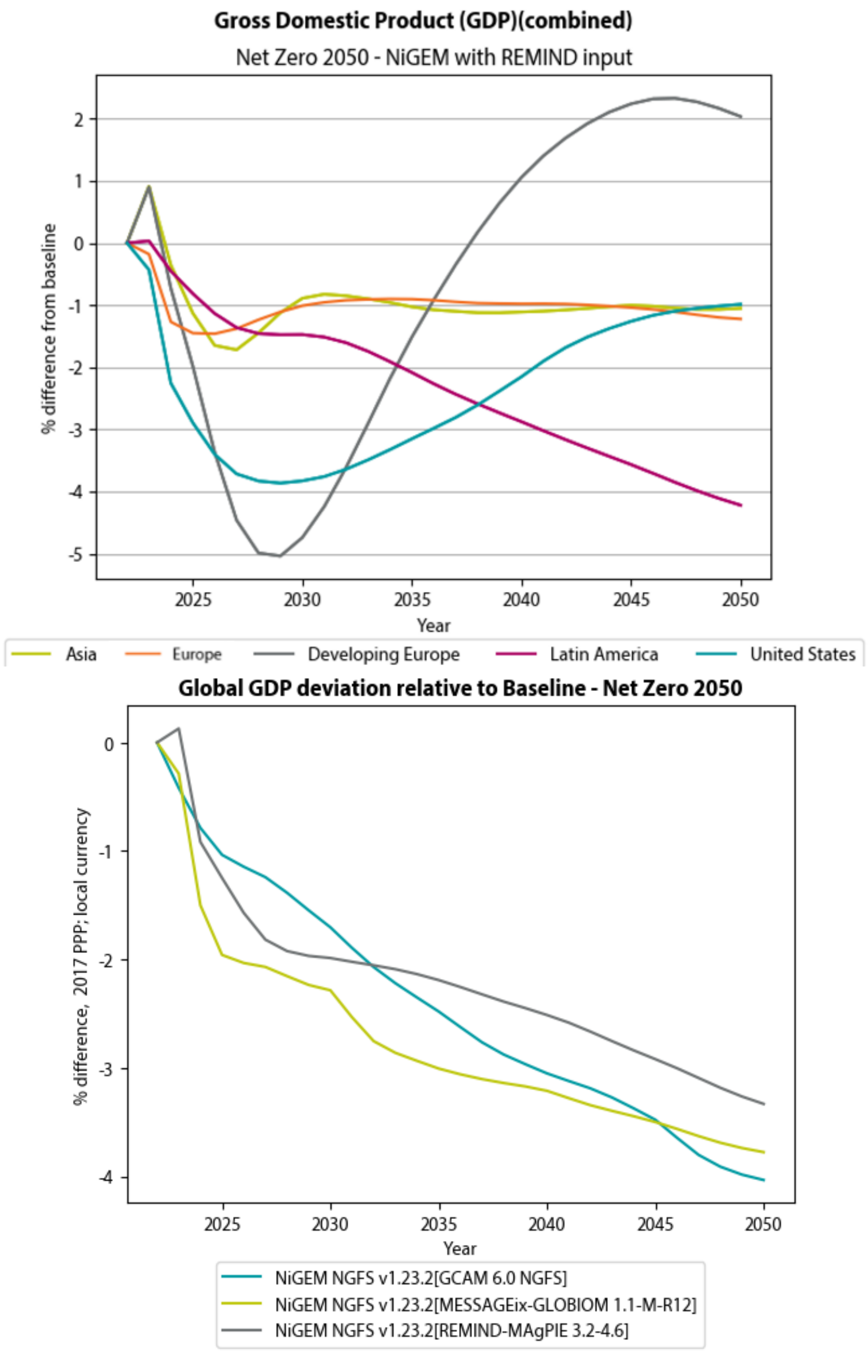


Figure 19. GDP deviation relative to Baseline across countries and models in the Net Zero 2050 scenario.

Inflation and unemployment

The scenarios include a wide range of macroeconomic variables, capturing structural relationships between key aggregates such as unemployment and inflation. In many countries, the implementation of carbon prices in the transition scenarios tends to raise energy costs in the short-term, initially weighing down on prices (as lower demand and financial market losses hit outputs). Rising carbon prices subsequently induce modest increases in **inflation** and **unemployment** before returning to prior trends. In some countries and periods, the offsetting growth effects stemming from carbon revenue recycling leads to a reduction in unemployment. In some scenarios this leads to a potential **monetary policy trade-off**. The NGFS modelling framework assumes a 'two-pillar' strategy, targeting a combination of inflation and nominal GDP as a default. This can be adjusted in the NiGEM model alongside fiscal policy assumptions. The negligible impacts in the Current Policies scenario reflect not only limited transition risk, but also the fact that only one potential chronic physical risk transmission channel (productivity) has been modelled. More research is needed on the potential for climate impacts to raise inflation (e.g., through supply-side shortages) and/or unemployment (e.g., due to displacement). The impact is much more sizable in the Too-little-to-late scenario, given the higher transition risk.

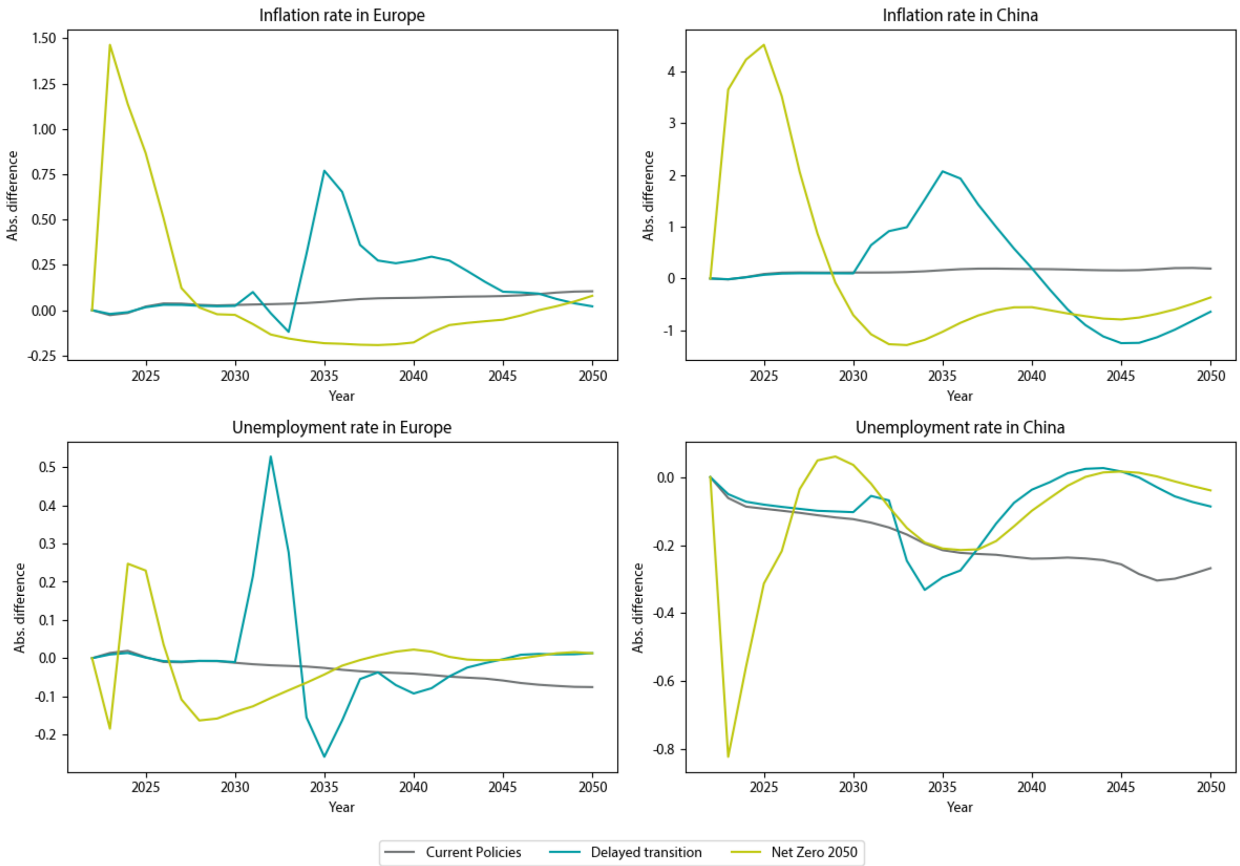


Figure 20. Inflation rate and unemployment rate: Europe vs. China

Financial Markets

Climate change and transition policies create significant financial fluctuations. The macro-financial results reflect both risks and opportunities. **Long-term interest rates** tend to increase in the transition scenarios, reflecting the inflationary pressure created by carbon prices, as well as the increased investment demand that the transition spurs. A disorderly transition can affect **real financial asset valuations** significantly, with considerable differences across regions. Although the NiGEM model's results cannot be disaggregated into individual sectors, it is likely that sectors that can decarbonize to a lesser extent will be affected more than other sectors. The NGFS is working to further develop sectoral impacts. In the disorderly transition scenarios, it is assumed that policy uncertainty leads to a higher investment premium for two years, with the premium gradually returning to the baseline thereafter. This occurs in a period ranging between 2030 and 2031 in both the Delayed Transition and the Fragmented World scenarios.

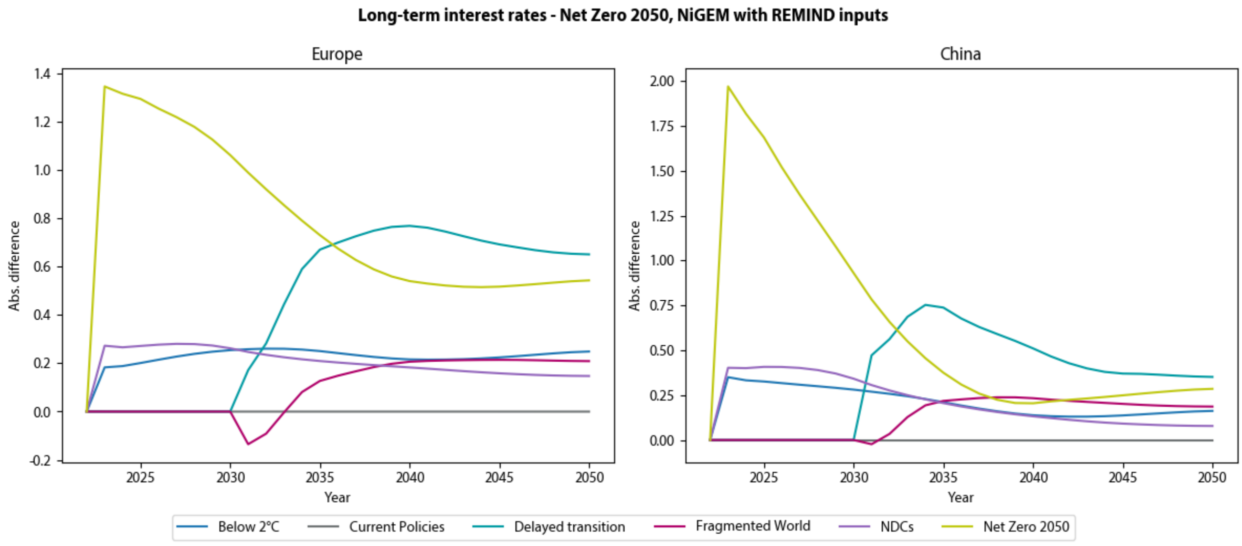


Figure 21. Long-term interest rate in Europe vs. Long-Term interest rate in ChinaTransition risk

Understanding transition risk

Cutting greenhouse gas emissions affects all sectors of the economy and gives rise to transition risks for the economy and financial system. Transitioning away from fossil fuels and carbon intensive production and consumption requires a significant shift towards emission-neutral alternatives in all sectors. Policy makers can induce this transition by increasing the implicit cost of emissions. As it takes time to develop and deploy alternative technologies, climate policies may lead to higher costs in the interim. The transition pathways have been modelled using three detailed Integrated Assessment Models (IAMs)[27]. They can be used to assess the changes in energy, land-use and policy needed to meet a particular temperature outcome or carbon budget. The shadow carbon price underpinning those changes has been derived for each model. This price is distinct of, and may differ from, the social cost of carbon, which depends on an assessment of avoided damages and valuing impacts on present versus future generations. The increased cost of emissions, combined with a consistent (re-)allocation of investments and the employment of Carbon Dioxide Removal technologies, results in a reduction in GHG emission in all sectors under the Net Zero scenario. The energy supply sector is projected to experience the largest drop in those emissions, followed by industry.

27 These models have been used extensively to inform policy and decision makers and feature in several climate assessment reports, c.f. IPCC, 2018, IPCC, 2022, UNEP, 2018.

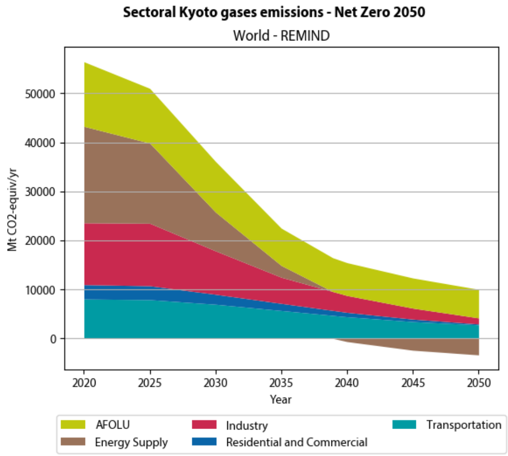


Figure 22. Sectoral GHG (Kyoto Gases) emissions – Net Zero 2050 scenario, REMIND

Emissions prices

A key indicator of the level of transition risk is the shadow emissions price, a proxy for government policy intensity and changes in technology and consumer preferences. In the IAMs used to produce the NGFS scenarios, a higher emissions price[28] implies more stringent policy. Models suggest that a carbon price of around $_{(2010)}200/ton would be needed and assumed to be applied by all the countries in the next decade to encourage a transition towards net zero by 2050. The largest increase in carbon price is projected under the Net Zero 2050 scenario, reaching over 600$_{(2010)}/ton in 2050. The different IAMs' 2050 projections of the carbon prices under the Net Zero scenario vary within a 1.5°C range of temperature and $_{(2010)} 1150 /ton range of carbon price.

This shadow price is a measure of overall policy intensity. Governments are pursuing a range of fiscal and regulatory policies, which have varying costs and benefits. Shadow emission prices are sensitive to:

- The **level of ambition** to mitigate climate change. Higher ambition translates into higher emissions prices.
- The **timing of policy implementation**. Higher emissions prices are needed in the medium to long-term if action is delayed.
- The **distribution of policy measures** across sectors and regions, which are assumed to be differentiated in the Fragmented World scenario.
- **Technology assumptions** such as the availability and viability of carbon dioxide removal

[28] Emissions prices are defined as the marginal abatement cost of an incremental tonne of greenhouse gas emissions. Prices are influenced by the stringency of policy as well as how technology costs will evolve. Prices tend to be lower in emerging economies as there tends to be a greater number of low-cost abatement options still available.

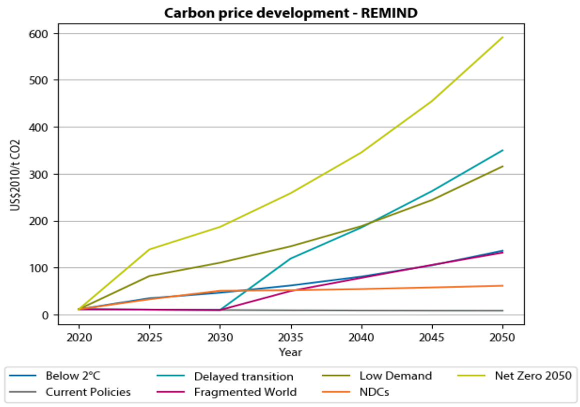


Figure 23. Carbon price development

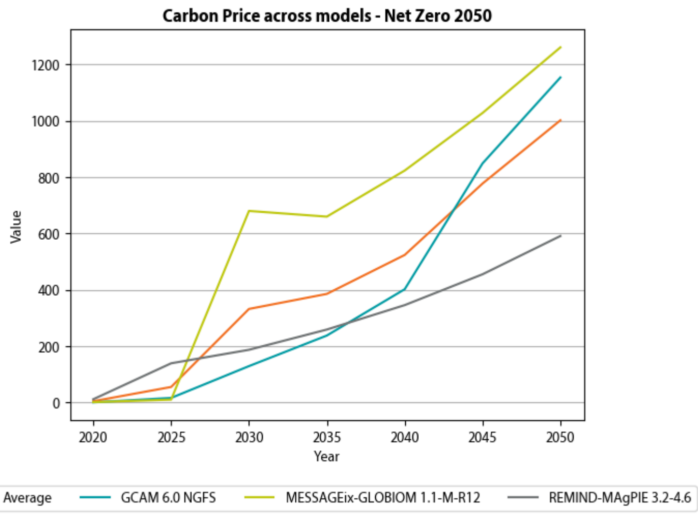


Figure 24. Carbon price across models – Net Zero 2050 scenario

Carbon dioxide removal

Large-scale Carbon dioxide removal (CDR), also known as negative emissions, or carbon drawdown, aims at addressing the primary human source of climate change by removing carbon dioxide (CO2) permanently from the atmosphere. CDR encompasses a w.ide array of approaches, including removing carbon from the atmosphere through increasing forest cover and soil sequestration (land use) or growing crops for bioenergy (BioEnergy with Carbon Capture and Storage, BECCS).

CDR assumptions play an important role in IAMs. If deployed effectively, lower warming outcomes could be achieved, or targets could be reached sooner given the practical difficulty of eliminating all (gross) emissions in the near term. For example, under the Net Zero 2050 scenario, approximately 5 GtCO2 per year should have been removed via CDR by 2050. However, these strategies currently take place on a limited scale only and face several challenges.

The NGFS scenarios assume limited availability of these technologies. The patterns vary strongly across models depending on cost assumptions. They also vary substantially across countries depending on the costs and availability of CDR options. [...]

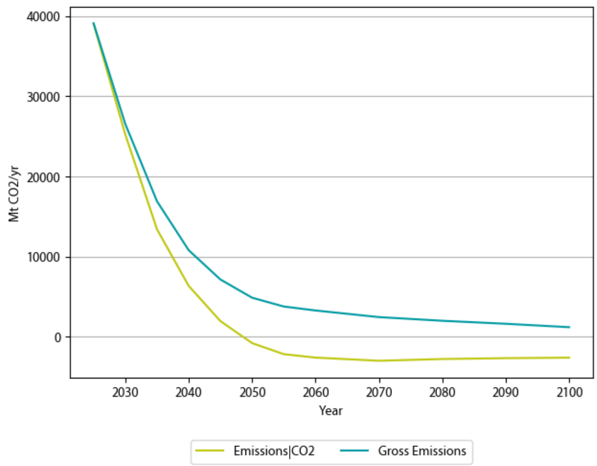


Figure 25. CO2 emissions in Net Zero 2050

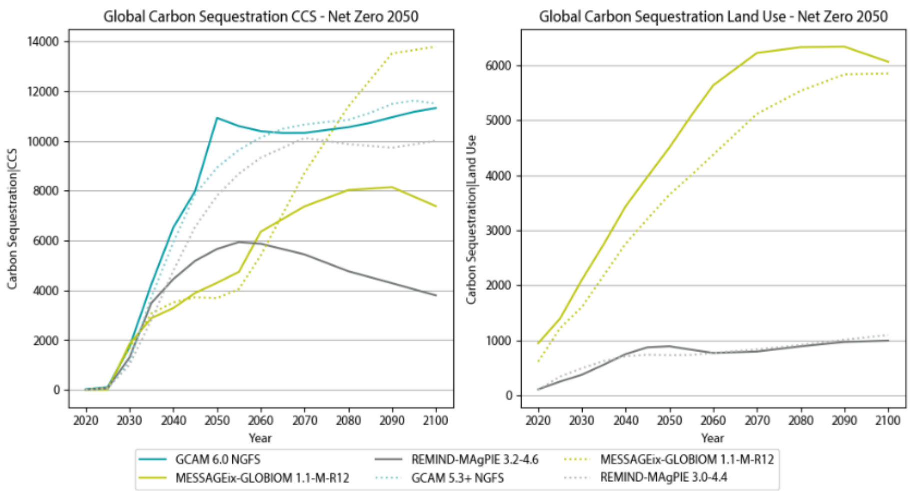


Figure 26. CO2 removals across models

Energy Investment

Significant investment flows would need to be directed towards green energy in the coming decades to achieve net zero. Transitioning to a net zero economy would require investment flows to be allocated towards mass deployment of green electricity and electricity storage. There is some legacy capital investment in fossil fuel extraction, which is a measure of all investments in mining, shipping and ports for fossil fuels, transmission, and distribution for gas as well as the transport and refining of oil to maintain the infrastructure while decreasing the overall capacity. Average annual investment by 2050 in renewable electricity and storage amounts to about 1.8 trillion US$ under the Net Zero scenario, about 0.5 trillion more than under the current policies. Given its high CO2 emissions relative to other fossil fuel alternatives, the share of coal is rapidly dwindling in the energy mix from 28% in 2020 to 7% in 2030 and close to 0% in 2050 in the Net Zero 2050 scenario. By 2050, renewables and biomass will deliver roughly 75% of global primary energy needs in the same scenario. This is in marked contrast to the Current Policies scenario where fossil fuels continue to be the dominant source of primary energy, even after accounting for current technology trends.

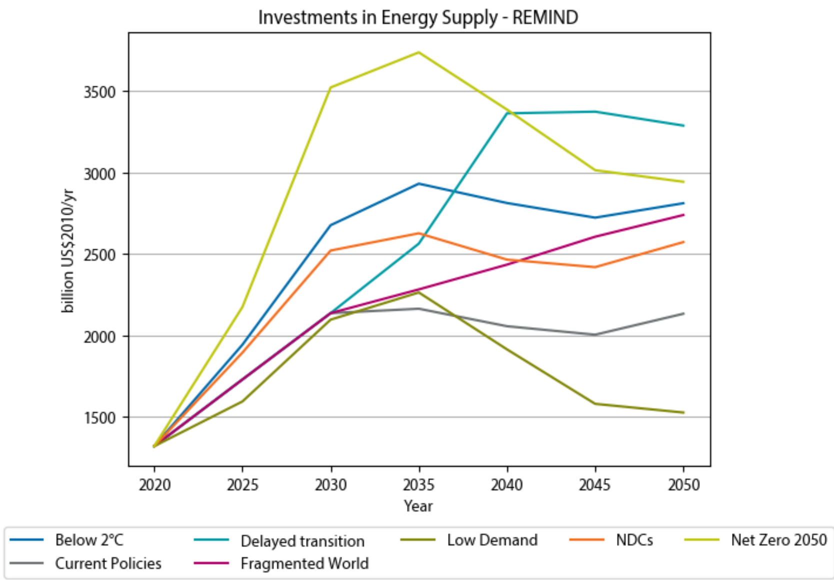


Figure 27. Current and expected annual energy investments until 2050

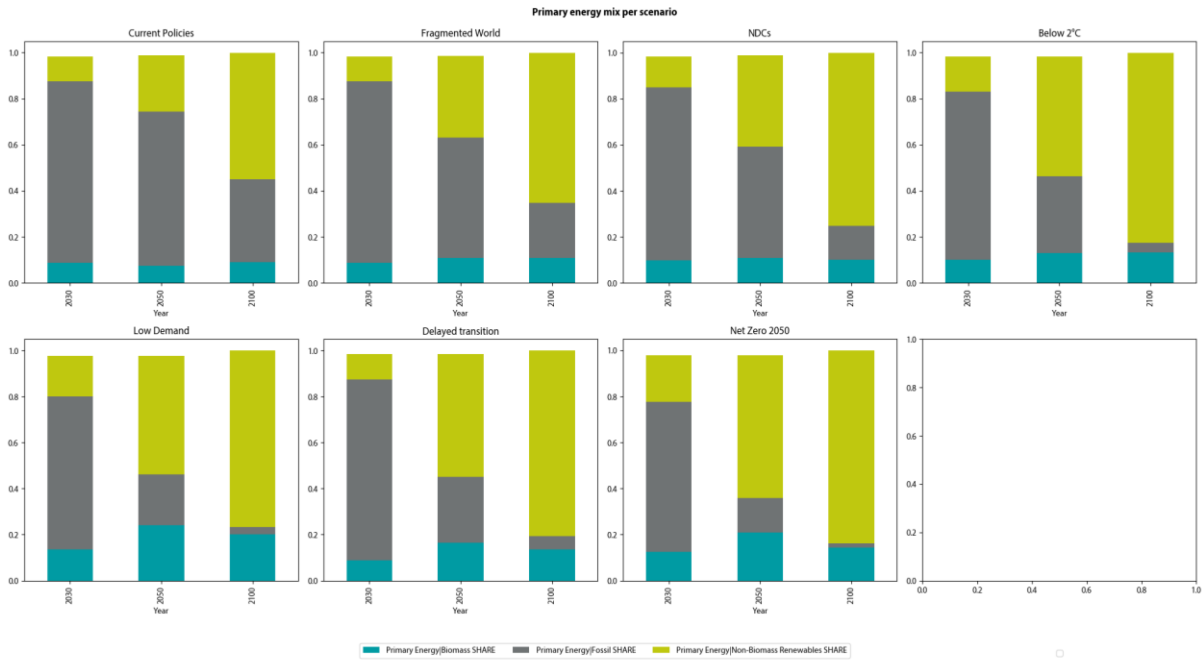


Figure 28. Energy mix per scenario

4.2 Physical risk

Temperature increases

Mean temperatures rise in all scenarios, exceeding 3°C in Current Policies. Changing climate conditions affect physical labour productivity and lead to severe impacts. Projected annual average temperatures are estimated to increase across scenarios, however with different magnitudes, exceeding 3°C in later decades of the 21st century in the current policies scenario. At present, global mean temperatures have increased by around 1.1°C from pre-industrial levels and have accelerated since 1975 at a rate of approximately 0.15 to 0.20 °C per decade (according to NASA's Goddard Institute for Space Studies (GISS)).

Deep reductions in emissions are needed to limit the rise in global mean temperatures to below 1.5°C or 2°C by the end of the century. This does not occur in the Current Policies scenario, leading to a temperature rise exceeding 3°C with severe impacts. Temperatures are increasing unevenly across the world with dry land warming faster than oceans and regions located at high latitudes experiencing greater warming. Temperature changes lead to chronic changes in living conditions affecting health, labour productivity, agriculture, ecosystems, and sea-level rise. It is also changing the frequency and severity of acute weather events such as heatwaves, droughts, wildfires, hurricanes, tropical cyclones, and flooding. Figure 29 shows estimated global temperature dynamics across various scenarios.

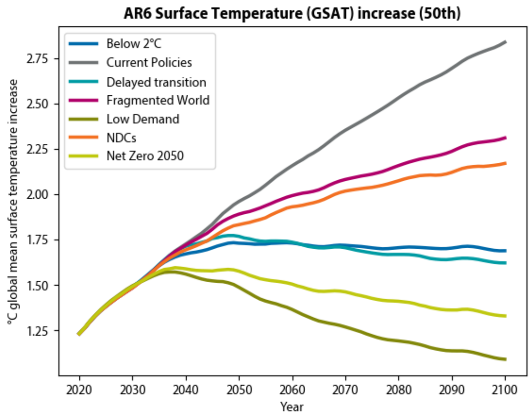


Figure 29. Global temperature dynamics

GDP loss estimates stemming from acute physical risks

Observed temperature increase of 1.1°C has already more than doubled both the global land area and the global population annually exposed to riverine flooding, crop failures, hurricanes, tropical cyclones, wildfire, droughts, and heatwaves (Lange et al., 2020). Global temperature increases of 2°C relative to preindustrial conditions are projected to lead to a fivefold increase in exposure to all types of natural hazards worldwide. The most pronounced increases are expected to stem from droughts and heatwaves. Changes in exposure are unevenly distributed across the globe, with tropical and subtropical regions facing larger increases than regions situated at higher latitudes. The NGFS scenarios now include estimates of global GDP impacts emanating from acute physical risks[29] for three NGFS scenarios. Information from the international disaster database Emergency Events Database (EM-DAT) is used to approximate historic damages from weather-related extreme events to derive stochastic shocks as inputs to the NiGEM model. Projections for selected Climate Impact Explorer (CIE) indicators[30] are used to derive changes to projected damages for the three NGFS scenarios in the CIE. GDP is projected to fall compared to the baseline scenario more rapidly under Current Policies. While the drop in GDP is projected also under the Net Zero and Delayed Transition scenarios, it is overall milder. Figure 30 shows GDP loss estimates across scenarios:

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[29] The impact of acute physical risk on macro-financial variables other than GDP is not available in this iteration of the NGFS Scenarios

[30] Acute risks for these projected damages include cyclones and riverine flooding based on the CLIMADA model. See https://climate-impact-explorer.climateanalytics.org/methodology/

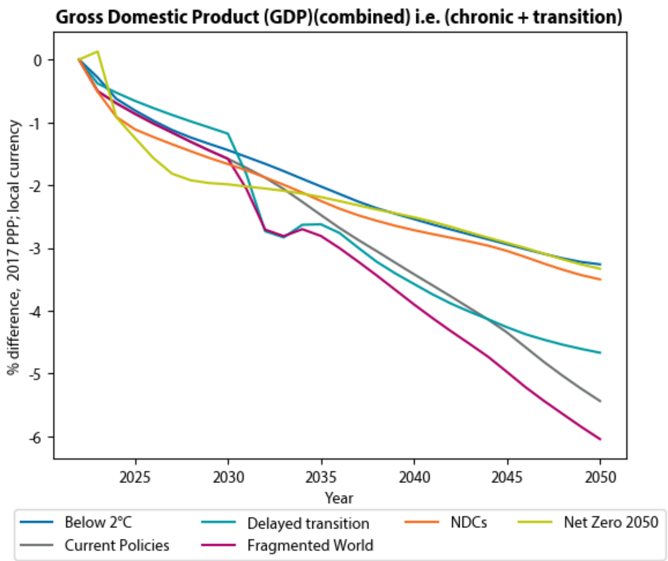

Figure 30 . GDP loss estimates from acute risk across scenarios (NiGEM model with REMIND input).

GDP loss estimates stemming from chronic physical risks

Estimates of GDP losses from chronic risks vary considerably depending on assumptions about climate sensitivity and the method used to estimate the damages. Estimates suggest a global GDP impact of up to 18% relative to a prior trends baseline in the current policies scenario; GDP decrease would be more contained, but still sizeable, in the Net Zero scenario. Losses are much higher in tropical regions under any scenario. The NGFS estimates have been updated to account for model uncertainty and now include higher damages. GDP losses were calculated based on the methodology set out in Kalkuhl and Wenz (2020) at the country level for the change in average temperature in each scenario compared to the previous year. The methodology does not include impacts related to extreme weather, sea-level rise or wider societal impacts from migration or conflict. For given countries these would likely strongly increase the physical risk. These estimates also do not fully capture adaptation, which would reduce impacts but require significant investment.

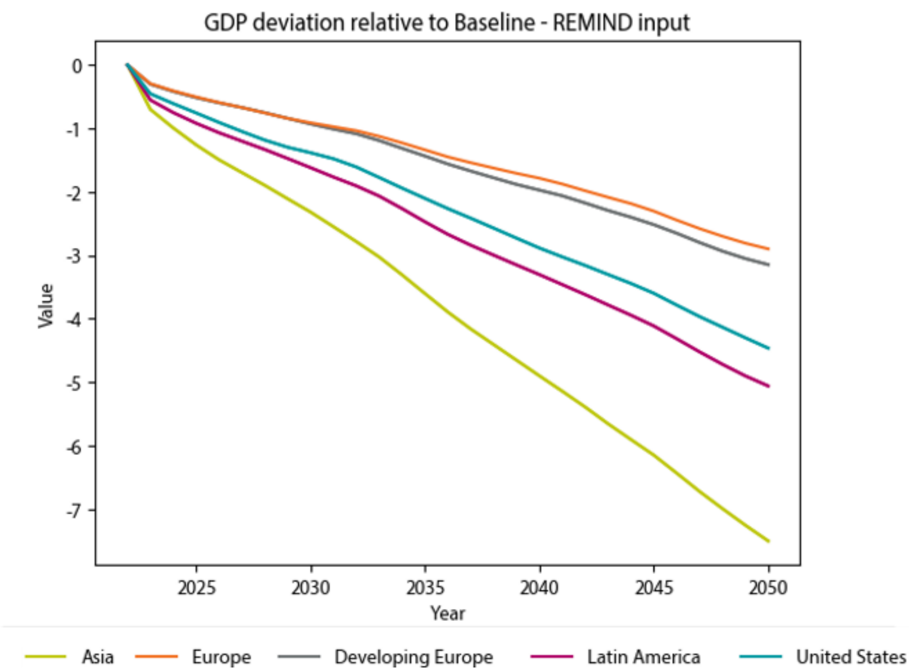

Figure 31. GDP loss estimates by country – Current Policies scenario

5. Phase III vs. Phase IV: what is new in the main results of NGFS scenarios?

Key messages

- The NGFS scenarios have been brought up to date with new economic and climate data, policy commitments and model versions, as usual. Phase IV accounts for the post-covid recovery and the Russian war in Ukraine.
- The possibility of using Carbon Dioxide Removal (CDR) technologies has been limited in this vintage by switching off Direct Air Carbon Capture and Storage (DACCS) technologies and limiting Bioenergy Carbon Capture and Storage (BECCS) capacities.
- The NGFS scenarios have been upgraded with improved and more granular estimates of the macroeconomic impact of acute physical risks, based on new models and now accounting for four hazards, therefore expanding the set of risk drivers considered.
- These changes, combined with the shortening of the time available to reach the temperature targets, result in more disorderly scenarios and more adverse GDP impacts.

The NGFS scenarios have been brought up to date with new economic and climate data, policy commitments and model versions. The NGFS Phase IV scenarios reflect the most recent **economic events** that have occurred after the implementation of Phase III and the end of 2022, notably the resumption of global economic growth after the Covid-19 crisis and Russia's war on Ukraine. The scenarios also include data to reflect the latest trends in **renewable energy technologies** (e.g., solar and wind), and key mitigation technologies. As in previous phases, data for **short-term GDP** and **final energy demand** trajectories have been updated using the latest snapshot from the IMF World Economic Outlook 2023. These trajectories are used as exogenous variables in the IAMs. Similarly, Phase IV reflects the new **country-level commitments** made until March 2023. It also considers new **climate policy announcements**, for example as part of European Union's Fit for 55 package or the Inflation Reduction Act in the USA.

The mapping of the NGFS scenarios has been updated accordingly within the NGFS scenario framework. As described in **NGFS scenario** narratives, the new scenario positioning reflects an increased overall disorderliness to account for the latest macroeconomic and geopolitical developments, as well as the shortening of the time available to reach the temperature targets that are characterising and driving these scenarios.

5.1 Accounting for the post-covid recovery and the Russian war in Ukraine

Since the implementation of Phase III, new shocks have modified the short-term macroeconomic outlook, notably the post-covid economic recovery and the Russian war in Ukraine. As a result, the calibration of the models has been modified for Phase IV to consider these shocks and their consequences on inflation and energy markets.

The main consequence of the post-covid economic recovery is a rebound in Fossil Fuel and Industrial (FFI) emissions. Indeed, FFI CO_2 emissions in 2022 returned to 2019 levels of ~37 Gt CO_2 after the Covid shock with its largest dip in 2020 (to ~35 Gt CO_2) (GCP, 2022). As a result, this rebound generated higher FFI emissions than expected by Phase III, and thus weakened the likelihood of achieving the Phase III emissions reductions at equal cost. More concretely, this translates into higher shadow carbon price through 2025, relative to Phase III.[31]

Emissions

In the Net Zero 2050 scenario, Phase IV assumes higher emissions in the short/medium term compared to Phase III, in line with the latest trends, and slightly lower emissions in the long term for all IAMs. The latter are necessary to achieve the (unchanged) temperature targets despite differences in the short-term development and the shortening of the time available. In the Current Policies scenario, emissions in the second half of the century significantly lower in REMIND and MESSAGE models, reflecting the implementation of new policies and the translation of previous commitments into action (**Figure 32**).

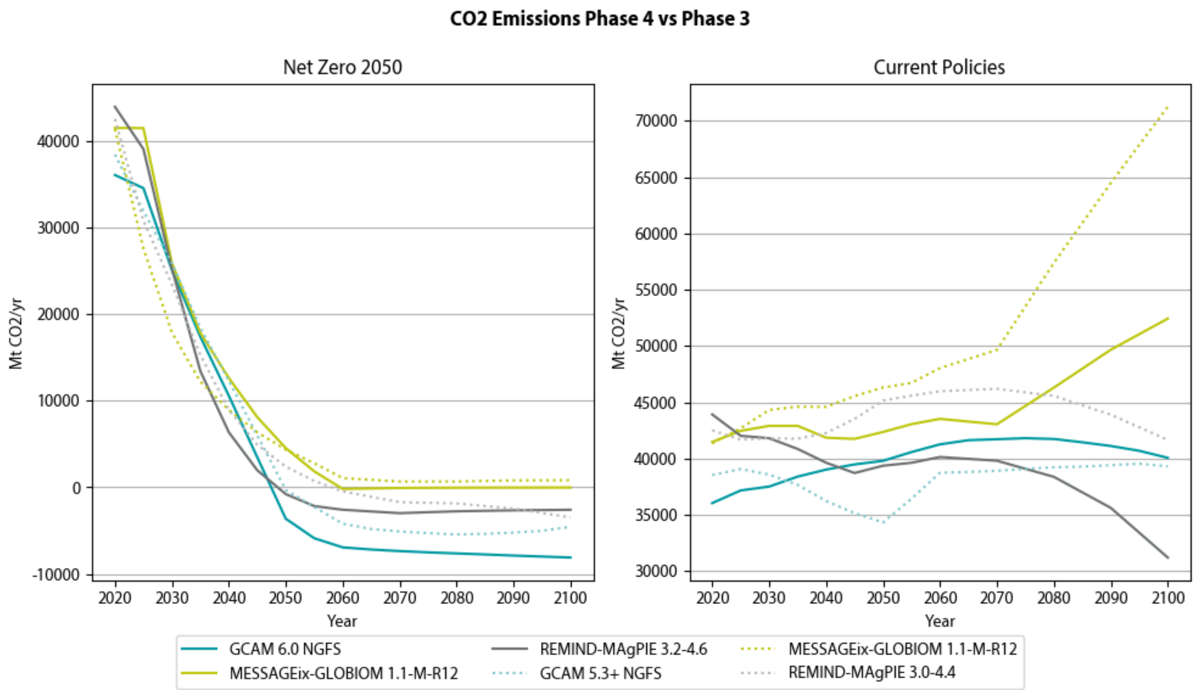

Figure 32. Phase III vs. Phase IV: Global CO2 emissions in Net Zero 2050 and Current Policies scenarios

Carbon prices

As described in the previous sections, NGFS (shadow) carbon prices are strongly linked to the emission pathways. In the Net Zero 2050 scenario, carbon prices have much steeper trends compared to Phase III, mainly due to adverse changes in the starting points coupled with the need to still reach global net zero CO2 around 2050. As for Current Policies scenarios, the new GCAM 6.0 model version uses shadow carbon constraints to match the current policy trajectory with estimates from Climate Action Tracker, but does not account for these in the carbon prices, as the majority of existing policies globally are not using carbon pricing. (**Figure 33**).

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[31] The use of the updated GCAM 6.0 version resulted in slightly different model near-term dynamics, which had a bigger impact than the updated historic record and near-term expectations.

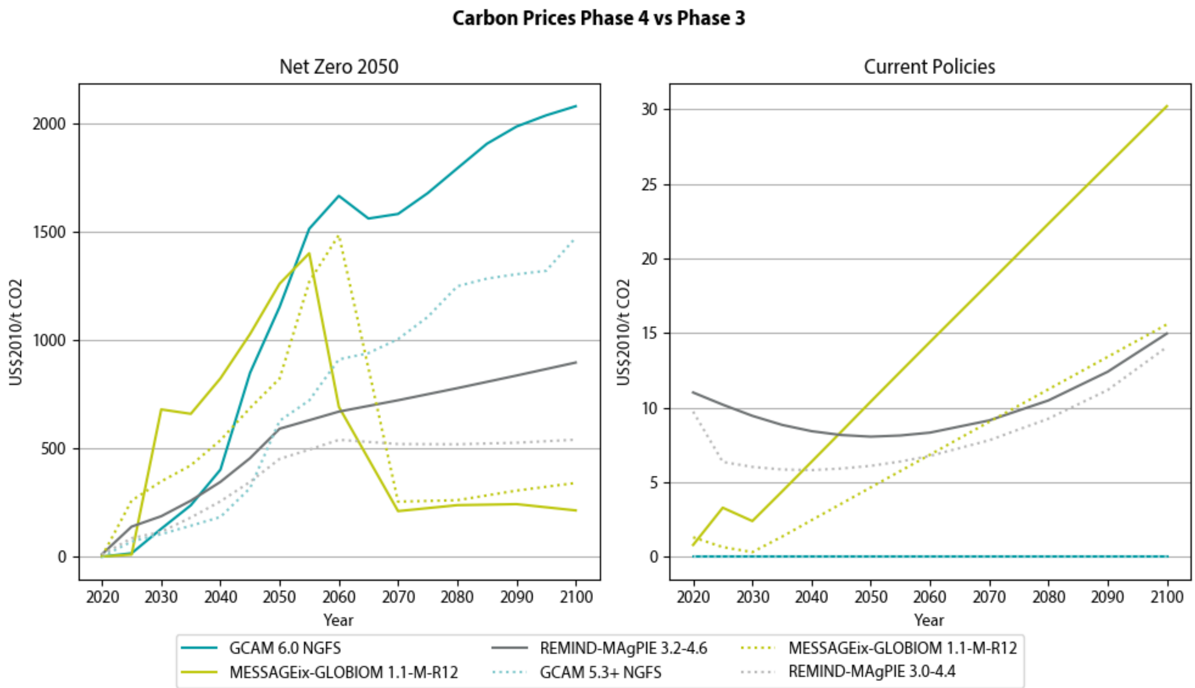

Figure 33. Phase III vs. Phase IV: Carbon Price in Net Zero 2050 and Current Policies scenarios

Energy-related variables

The Russian war in Ukraine has strongly disrupted the energy markets by rationing the supply of Russian gas to Europe. The modelling of Phase IV has therefore reinforced the constraints on European gas supply in the long term, assuming limits to European gas and fossil consumption to capture the energy-market disruptions. Overall, global fossil energy consumption in Phase IV is lower in all models and scenarios, exception made for MESSAGE in Net Zero (due to limitations in emission reduction in the year 2025) 2050 and GCAM in Current Policies, where the impact is more than offset by changes in the modelling assumptions and dynamics. (**Figure 34**).

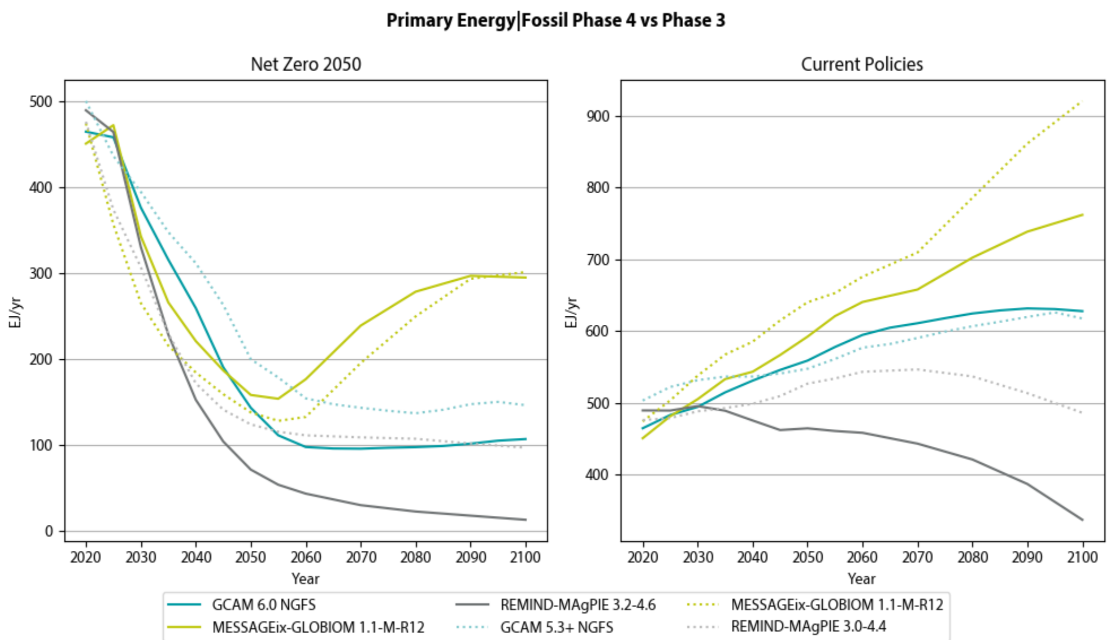

Figure 34. Phase III vs Phase IV: Fossil fuels consumption in Net Zero 2050 and Current Policies scenarios

At the same time, the consumption of renewables under both Net Zero 2050 and Current Policies scenarios is higher in Phase IV (**Figure 35**).

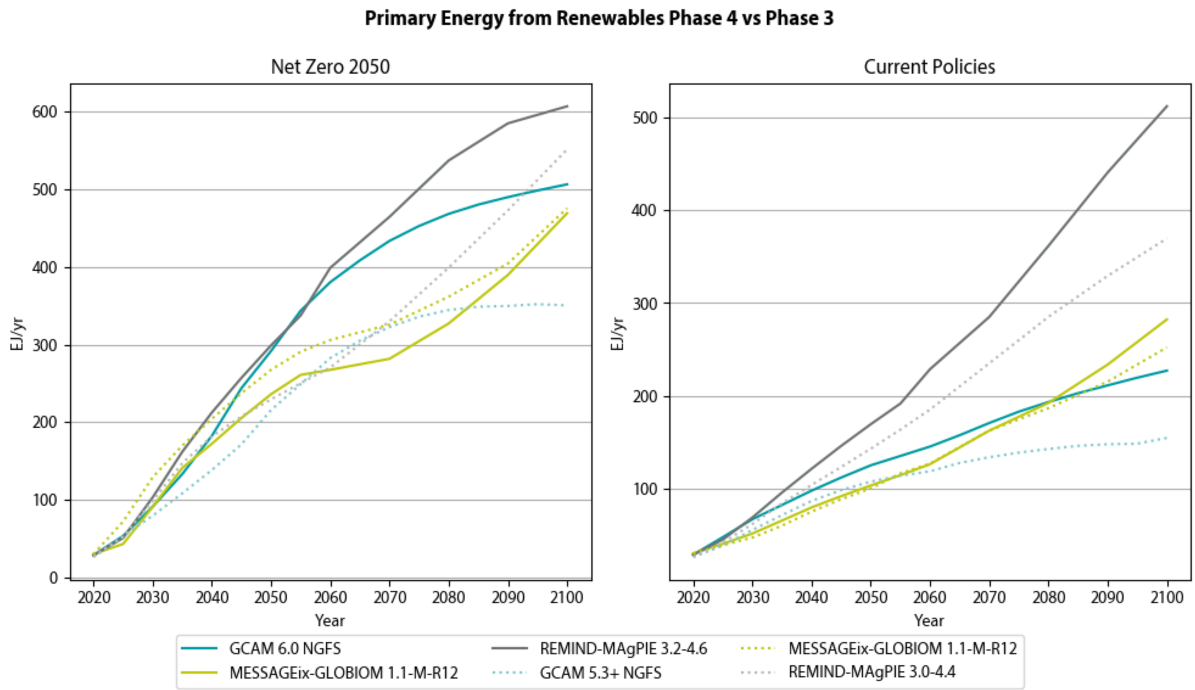

Figure 35. Phase III vs Phase IV: Consumption of renewables in Net Zero 2050 and Current Policies scenarios.

When it comes to secondary energy, the major update is related to the electricity consumption. While showing some heterogeneity in the Net Zero 2050 scenario, the models agree on a stronger electrification by the end of the century with respect to Phase III in the Current Policies scenario (**Figure 36**).

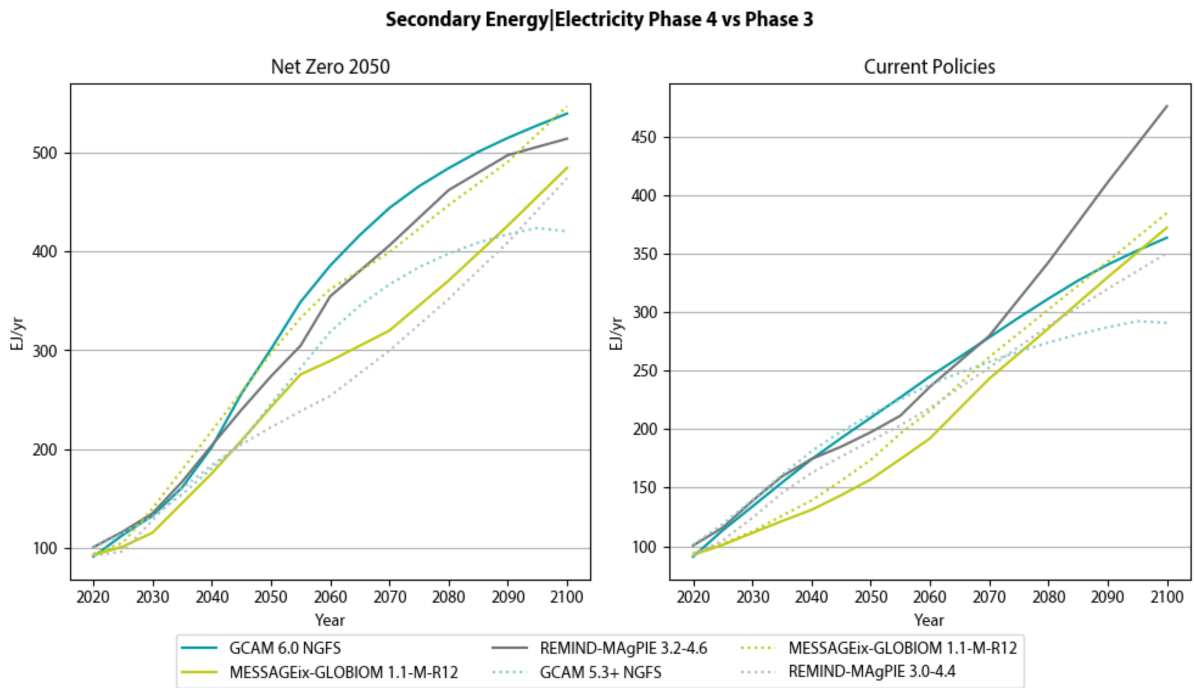

Figure 36. Phase III vs Phase IV: Electricity consumption in Net Zero 2050 and Current Policies scenarios

Phase IV features updated final energy prices. While the average electricity price for the industry sector differs in GCAM and REMIND, the models agree on its increase with respect to Phase III. This applies almost to the entire horizon, with differences in the shortterm being more marked, especially in the Current Policies scenarios (**Figure 37**).

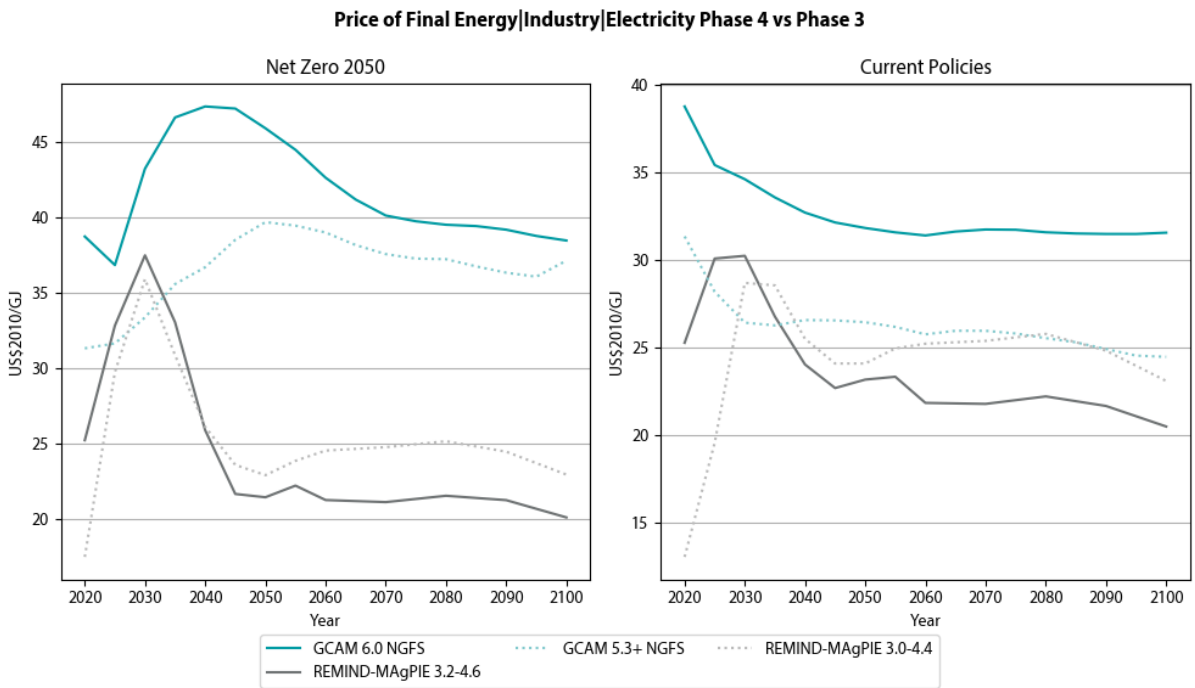

Figure 37. Phase III vs Phase IV: Industry-related energy prices

5.2 Updates on Carbon Dioxide Removal availability

Phase IV also includes limits to the availability of Carbon Direct Removal Technologies based on new projections, resulting in a lower overall availability of these technologies compared to Phase III. This is modelled via explicit constraints on the process level (time-dependent maximum area available for afforestation, maximum yearly injection rate for geological sequestration, maximum yearly bioenergy potentials). More concretely, Direct Air Carbon Capture and Storage (DACCS) technologies were switched off in all scenarios and Bioenergy Carbon Capture and Storage (BECCS) capacities have been limited. **Figure** 38 shows the reduced BECCS capacity for REMIND and MESSAGE. The same changes in GCAM are offset by the need to compensate for higher fossil fuel emissions compared to the other models.

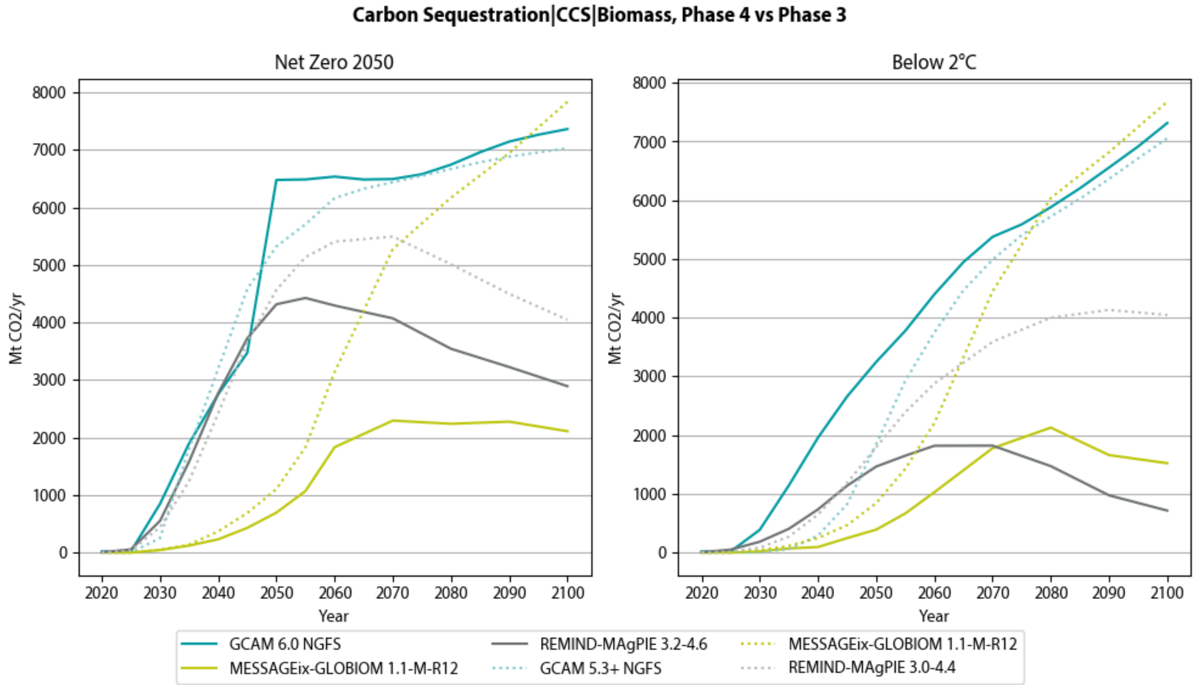

Figure 38. BECCS availability in Orderly scenarios

5.3 Updates in the data model

An effort has been made to keep the NGFS Phase 4 data model as much in line with Phase 3 as possible. Nonetheless, there are a few changes:

- The MESSAGE model (IAM and Downscaling) does not report GDP for the Low demand scenario as they are consistent with the 1.5c scenario.
- The Divergent net Zero scenario has been terminated while a new one, Fragmented World has been created.
- From the MAGICC climate model, we now report more percentiles ranging from 5th to 95th of previously only the 50th percentile.
- In addition we also report atmospheric concentrations from MAGICC for CO2, CH4, and N2O.
- The damages post processing was moved under the downscaling model as it reports country level data. Previously it was filed under the native IAM models.
- Due to limitation in Excel data size the Downscaling data have now been split into three files, one for each IAM.

Box: Towards a more disorderly climate transition

Since their inception, every update of the NGFS scenarios has shown more adverse macro-economic impacts. There are two main reasons for this.

- The NGFS has been modelling more and more climate impact channels in the NGFS Scenarios, leading to increasing estimates of physical risk impacts.
- The delay in political action makes it more and more difficult to reach climate targets in an orderly way, leading to higher transition risks in each iteration.

More climate impact channels

Over time, the NGFS scenarios are becoming more and more detailed, but also increasingly adverse, with the inclusion of additional transmission channels.

- In 2021, the NGFS scenarios included for the first time an assessment of chronic physical risks.
- In 2022, the modelling of chronic physical risks was improved to account for model uncertainty, leading to higher estimates in the Hot-house world scenarios. For the first time, they additionally included a basic assessment of acute physical risks, adding some adversity to all scenarios.
- In this 2023 edition, the modelling of acute physical risks was improved to include more hazards and provide a country-level breakdown The inclusion of new hazards directly translates into an increased adversity of the NGFS scenarios, while the country-level breakdown shows that the results are very heterogeneous, with tropical countries being most exposed to both chronic and acute physical risks.

However, it is certain that the NGFS scenarios still underestimate the impact of physical risks on the macro-economy, as many hazards and transmission channels are not modelled yet, and our understanding of the links between climate change and the economy is still partial. The NGFS scenarios will continue to evolve as common knowledge is being built in the academic and central banking communities.

Trend toward more adversity in a context of inaction

The increasing adversity of the orderly transition scenarios stems from persistently elevated levels of global emissions against the backdrop of a limited carbon budget associated with reaching any particular climate goal (e.g. net zero by 2050). In other words, as ambitious transition efforts at the global level are delayed and levels of emissions remain elevated, carbon budget runs out, and more rapid and stringent action is needed to achieve the same emission reductions over a shorter period. In addition, the IAMs calculate cost-efficient future pathways, which usually represent smooth adjustments. Thus, not only are current emissions higher than what would have been projected as an optimal pathway for reaching net zero by 2050 in Phase III, but also near-future emissions will be higher until 2035, likely driven by the high costs that would be necessary for stronger changes in the energy sector at an even shorter time scale.

Figure *39* shows the net zero emission pathways in the three most recent NGFS scenario vintages. The pathways of this fourth iteration assume higher emissions in the mid-term future, and intensified emission reduction in the long term compared to previous phases. The changes are quantitatively significant: the remaining 'carbon budget' for the period 2025-2050 in the Net Zero 2050 scenario decreased from 275 Gt Co2 in Phase III to 231 Gt Co2 in Phase IV, corresponding to a 16% drop. In line with these changes to the emissions pathways, the global carbon price in the NGFS Net Zero by 2050 scenario is higher at each point in time in the future in Phase IV as compared to Phase III, indicating more pressure on high-emitting firms to mitigate their emissions (

Figure 40).

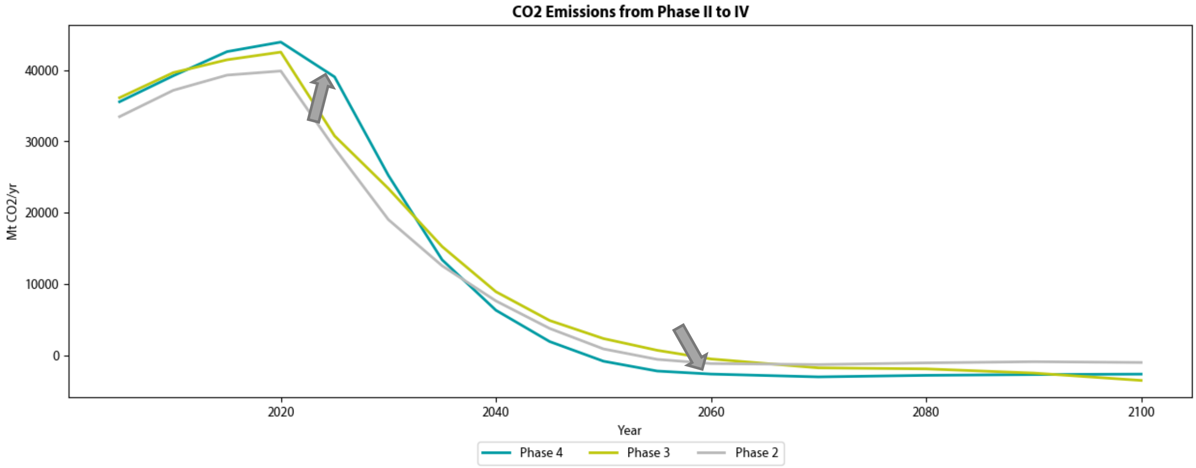

Figure 39. Current emissions vs Phase I or II emission pathways in the Net Zero 2050 scenario.

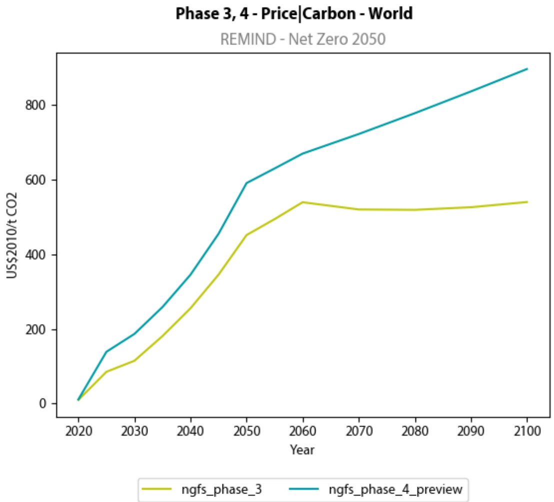

Figure 40. Shadow carbon price, Phase III vs Phase IV, Net Zero 2050 scenario.

The energy sector is central for the low-carbon transition and likely to shoulder the strongest adjustments and associated costs by a less orderly transition in Phase IV as compared to Phase III. Specifically, while overall energy demand is projected to be higher in Phase IV as compared to Phase III, reflecting smooth trajectories starting at higher base levels in 2025 as mentioned above, the aggregate development masks strong changes in the energy mix over time. Specifically, fossil fuel demand reductions are much more intense in Phase IV as compared to Phase III starting in 2040. The increase in energy demand is thus mostly driven by an increase in primary energy based on Biomass or Non-Biomass Renewables. The fossil fuel demand reductions would be felt most directly by companies in sectors highly reliant on fossil fuels, such as mining, manufacturing, and utilities, who now have less time in switching their business processes to renewables-based activities.

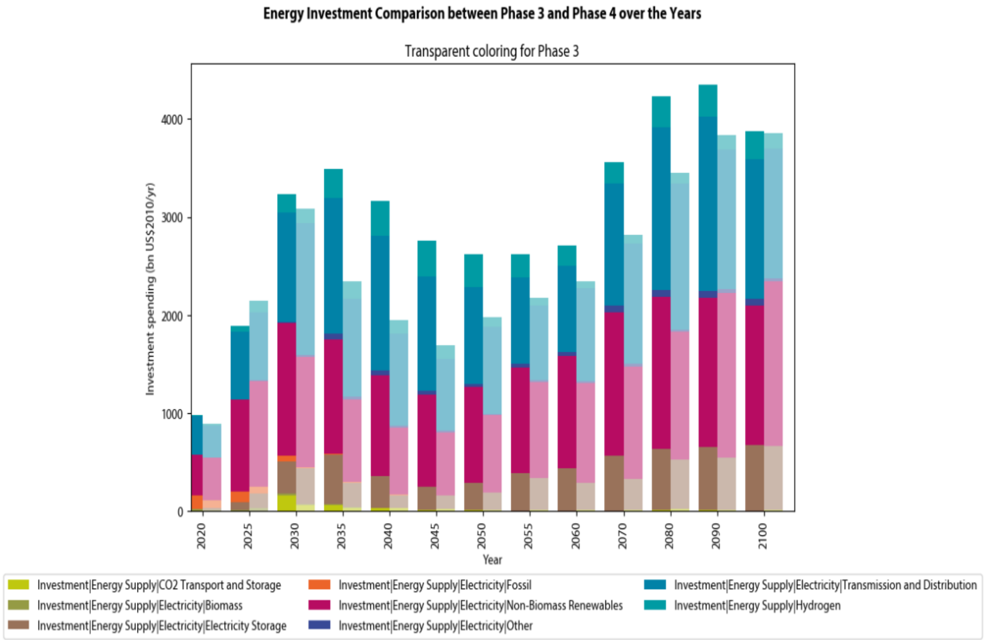

Figure 41. Energy investments by source, Phase III vs Phase IV, Net Zero 2050 scenario.

Facilitating the previously described changes in energy demand will require a faster and much more extensive investment push in the energy sector in Phase IV as compared to Phase III (**Figure 41**). While overall energy investments in Phase IV are projected to lag what was projected as needed in 2025 under Phase III, they are much higher starting in 2030, reflecting the need for a strong investment push. The strongest increase in investments across phases occurs between 2035 and 2055 and is focused on renewables-based electricity generation, electricity storage, electricity transmission and distribution and hydrogen. The overall cumulative increase in investments is quantitatively significant, in that, it requires an additional 20.2tn USD (578bn USD/year) by 2050 and 34.4tn USD (530bn USD/year) by 2100 compared to phase III.

As a result, scenarios that were previously labelled as orderly shift towards the disorderly category. Net Zero 2050, which is the most ambitious scenario in terms of temperature target (<1.5°C), can hardly be called an orderly scenario anymore, leaving room for a new Low Demand orderly scenario. This scenario uses new hypotheses (some aligned with SSP1) and describes a world with rapid and important changes in consumer behaviours (e.g., reduced plane transportation, meat consumption, etc.), leading to a reduced demand in energy and CO_2 emissions. The decrease in energy demand is achieved via improvement in energy efficiency and a redirection of consumption towards less carbon-intensive goods and services. This consumer-led decrease in energy demand (as opposed to a carbon price-led decrease) makes the transition to the 1.5°C target more orderly.

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).

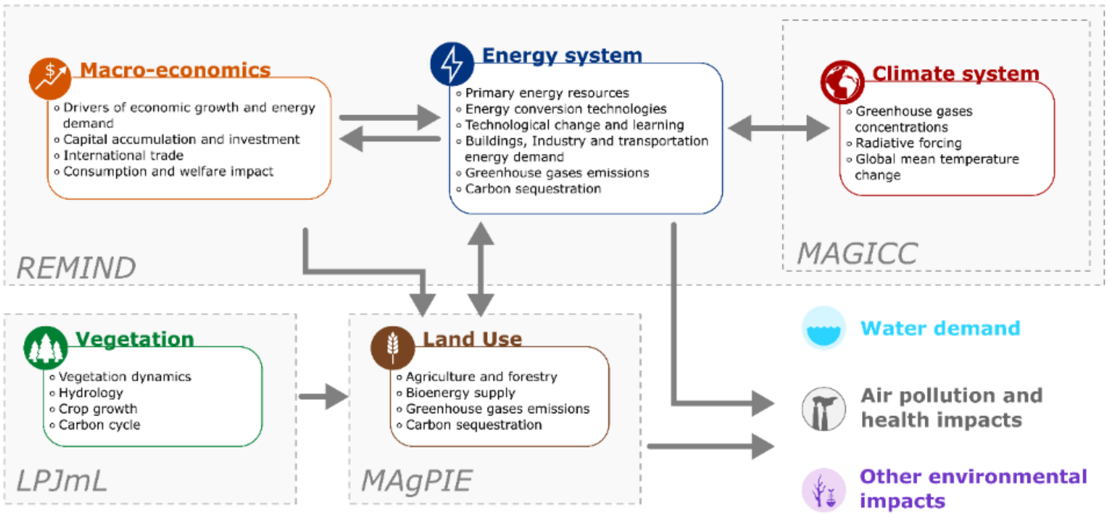

Figure 42. Overview of REMIND-MAgPIE framework

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. Thus, REMIND and MAgPIE can be run 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.

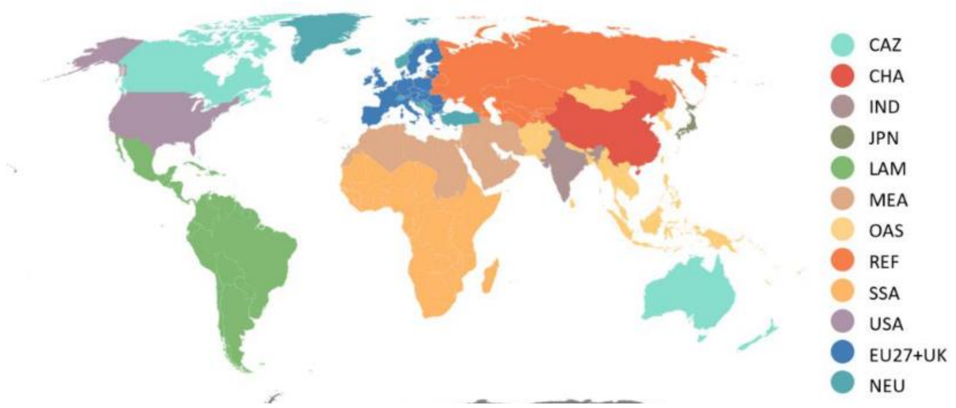

Figure 43. Regions in REMIND

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 2023 edition?

The REMIND-MAgPIE version 3.2-4.6 contains new datasets from UNFCCC, IEA WEO, UBA, IRENA, EDGAR7 and EEA to improve the quality of the calibration. The policy database for NDC and net Zero targets was updated. Compared to Phase 3, the flexibility of the model to adapt its 2025 value was reduced. To reflect the energy crisis, import restrictions on fossil gas in Europe were implemented.

2. Overview of model scope and methods

REMIND[32] 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.

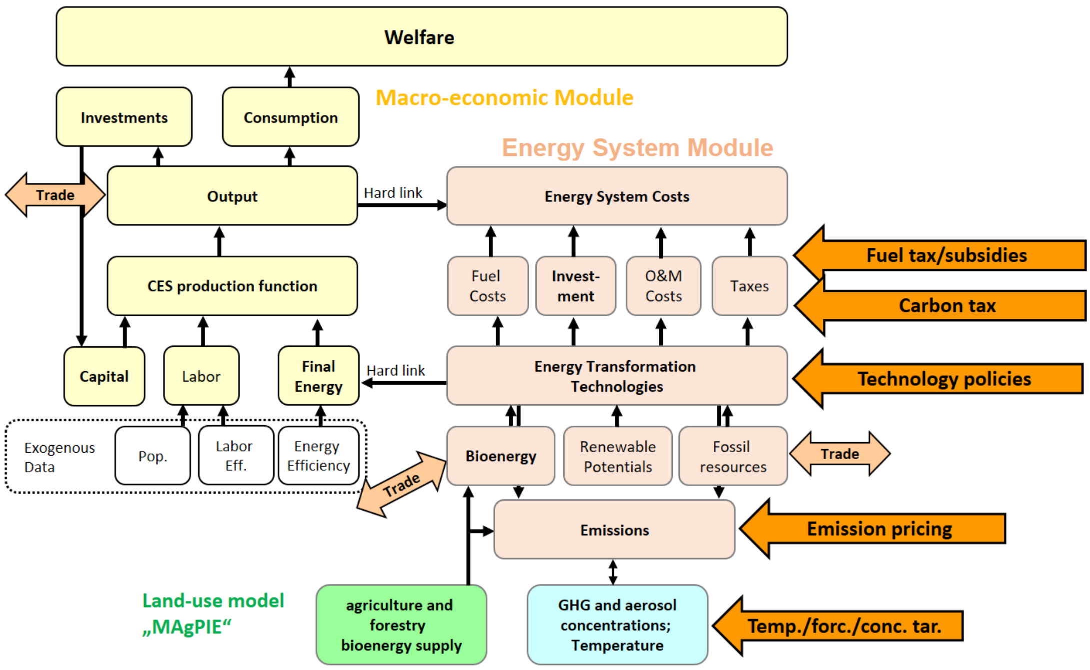

Figure 44: Structure of REMIND model

A Ramsey-type[33] 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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[32] Phase IV NGFS scenarios have used version 3.2 of REMIND. The last release of the model is available at https://github.com/remindmodel/remind and https://doi.org/10.5281/zenodo.7852740. The REMIND Documentation is available at: https://rse.pik-potsdam.de/doc/remind/3.2.0/.

[33] 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.

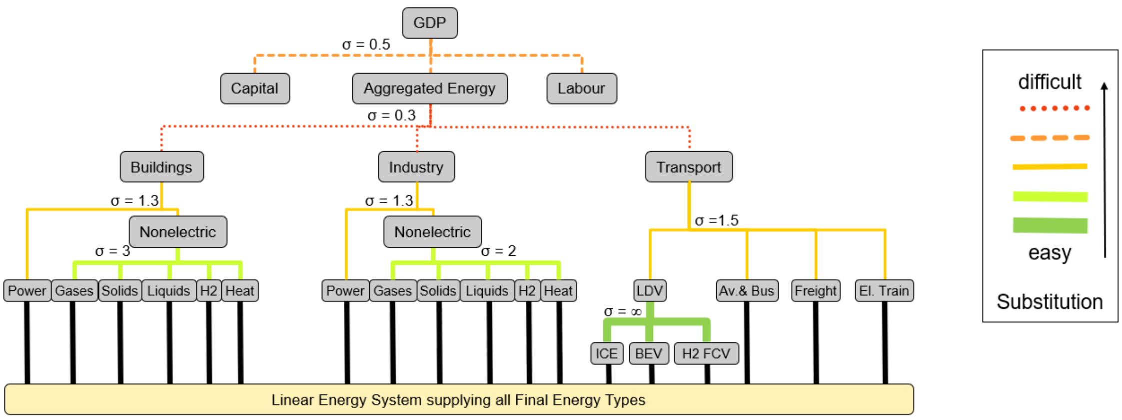
Physical capital is a major driver of economic growth, and related investments are endogenous in such models. In each period, the representative agent, endowed with perfect foresight, has to make the choice of using output for consumption or for investment, which can be used to produce consumption goods 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.

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[34]; 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.

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[34] 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.

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 CO2 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
Resource extraction subsidies	Status quo of extraction subsidies	Calculated as the subsidy rate times fuel extraction
Primary to secondary energy technology	Non-explicitly represented externalities of different technologies (water use, emissions	Calculated as the effective tax rate (tax minus subsidy)

taxes, specified by technology	of substances beyond SO_2 and CO_2)	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 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).

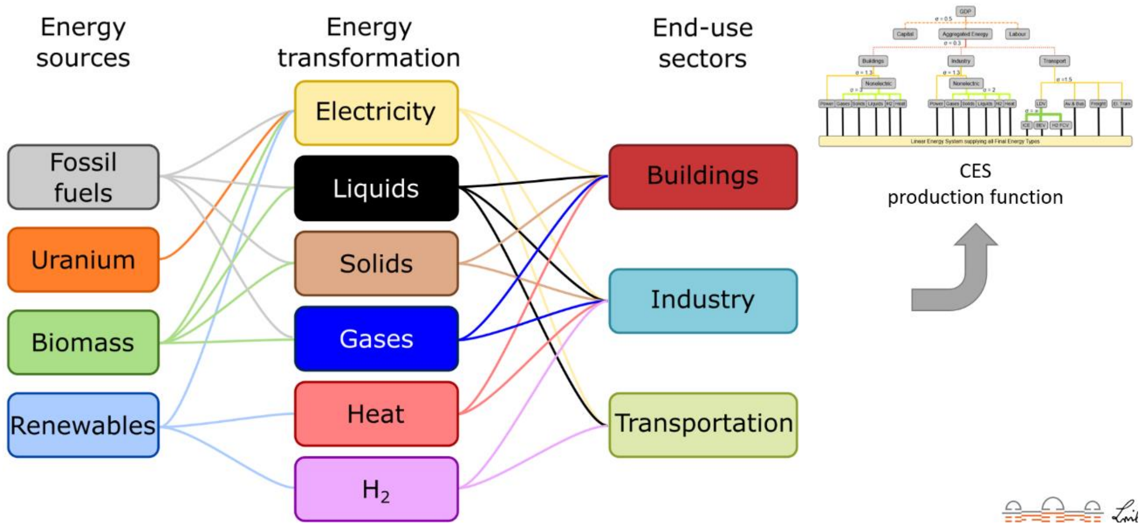

Figure 46: Energy module structure for REMIND

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 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.

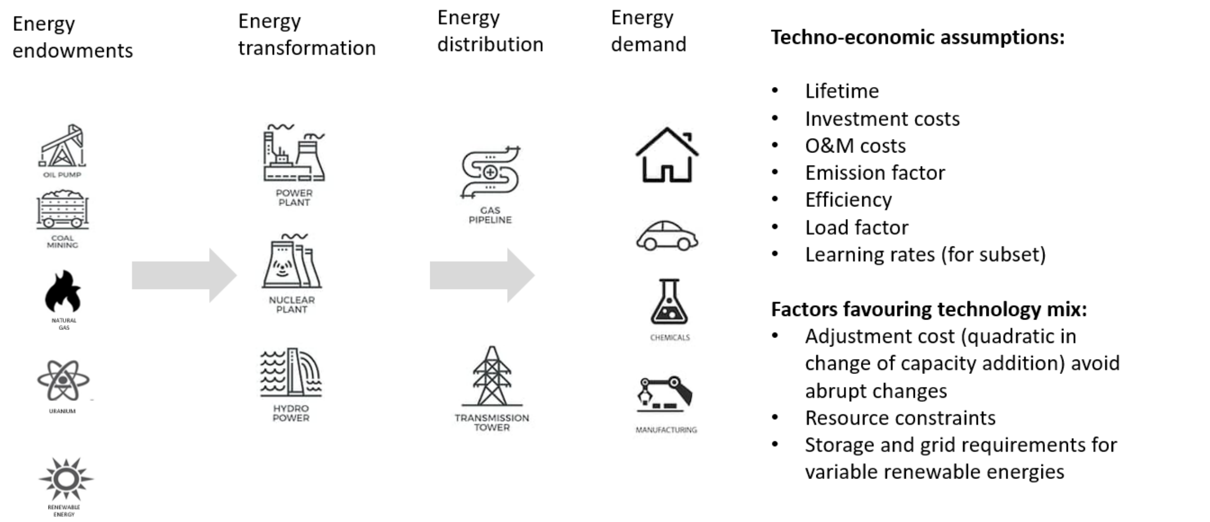

Figure 47: Energy module technologies of REMIND

The renewable energy potentials of REMIND[35] 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.

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

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

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 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.

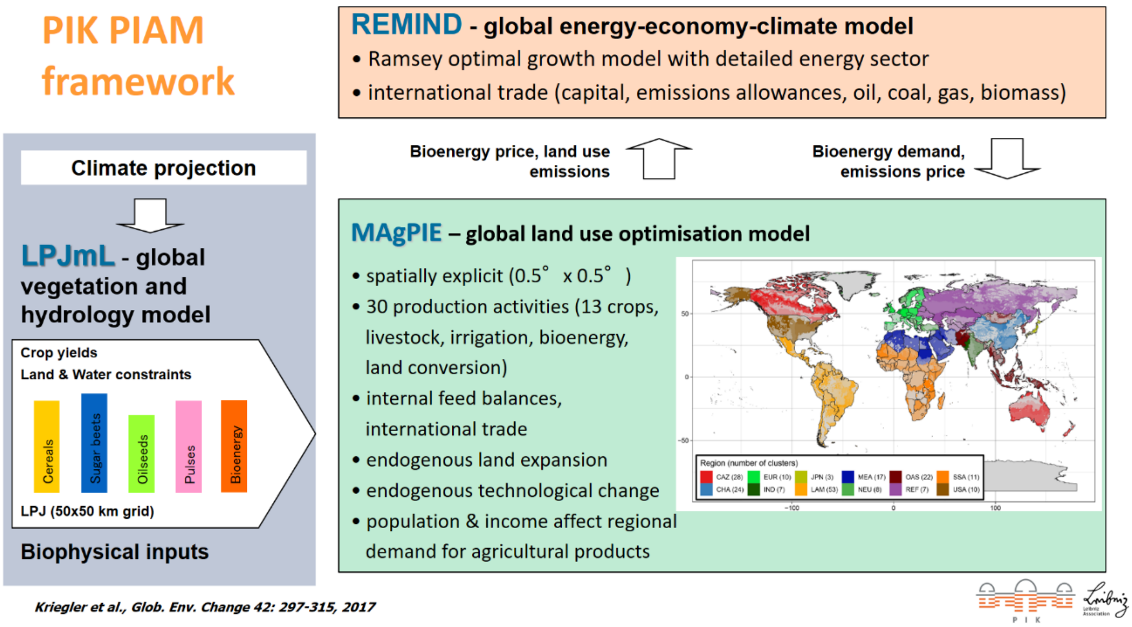

Figure 48. Integration of REMIND with MAgPIE

MAgPIE[36] 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.

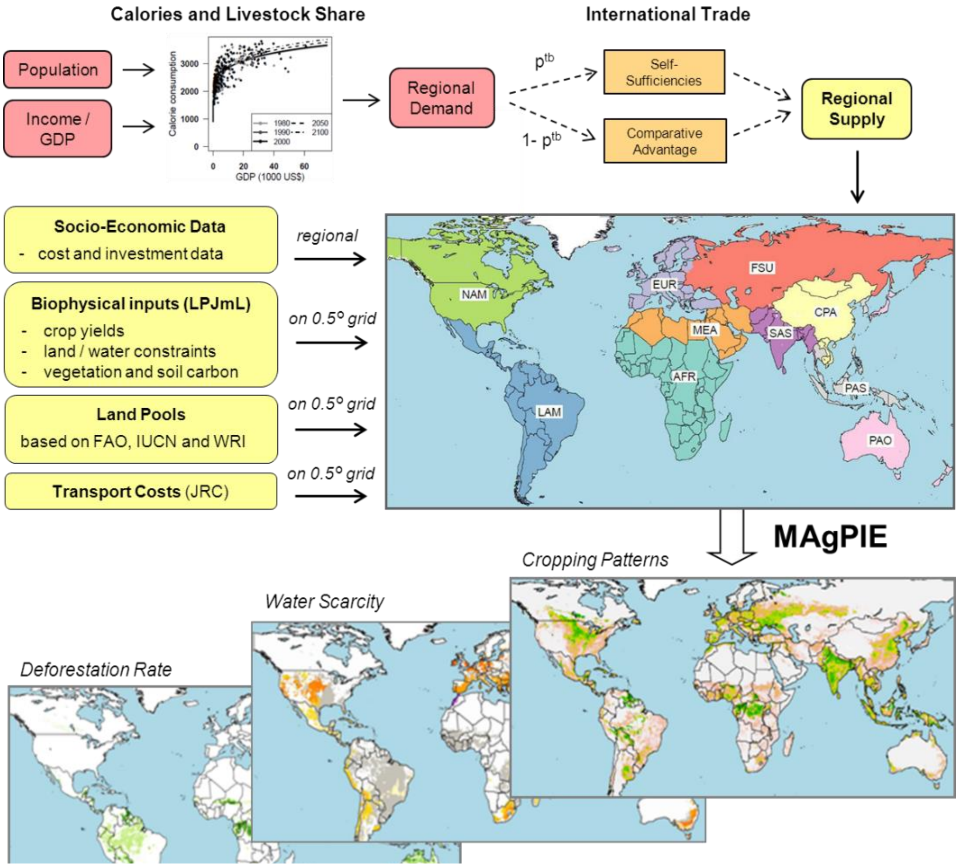

Figure 49. Simplified MAgPIE flowchart of key processes (demand and trade implementation, data inputs from LPJmL and spatially explicit water shadow prices).

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 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

[36] Phase IV NGFS scenarios use version 4.6 of MAgPIE. See https://github.com/magpiemodel/magpie for the last version and documentation of the model.

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**[37] 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).

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). CO2 emissions from afforestation and reforestation are derived from the land-use optimization model MAgPIE. 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

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

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 6 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 **dedicated 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 through 2019 ensure that the 2020 point of departure in current policy cases is proximal to actual developments. The ability to also run the simulation without these constraints enables important comparisons of model dynamics from 2005 to 2020 with real world 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).

Gross Domestic Product[38] 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 the sum of the derivatives times the quantity of inputs. Combining both constraints means that the output is

[38] This series is provided in the NGFS database with the name GDP|PPP|counterfactual without damage.

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

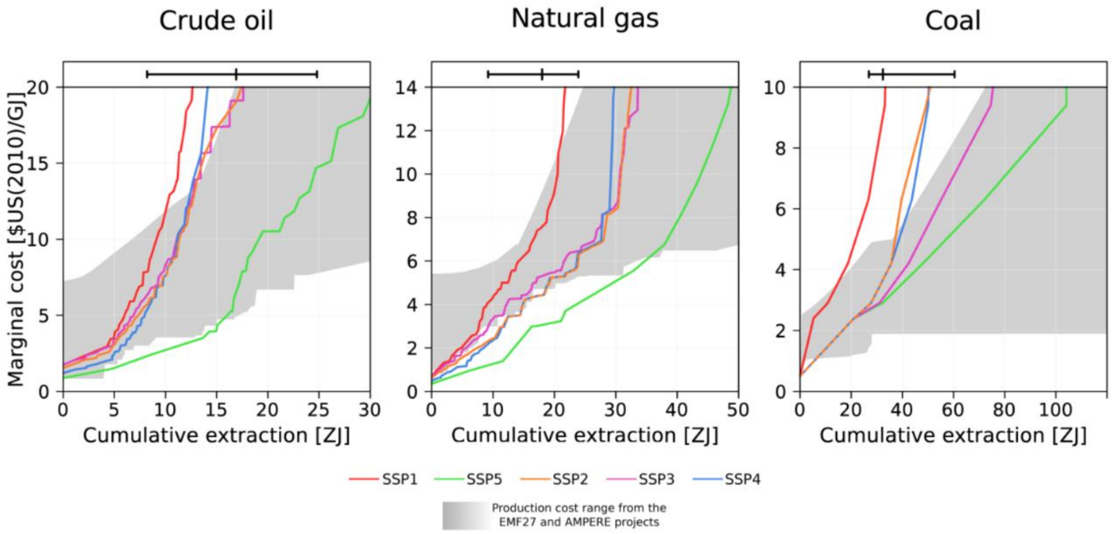

Figure 50. Extraction marginal costs by fossil resource. Bauer et al. (Energy, 2016)

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−1 (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−1. 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).

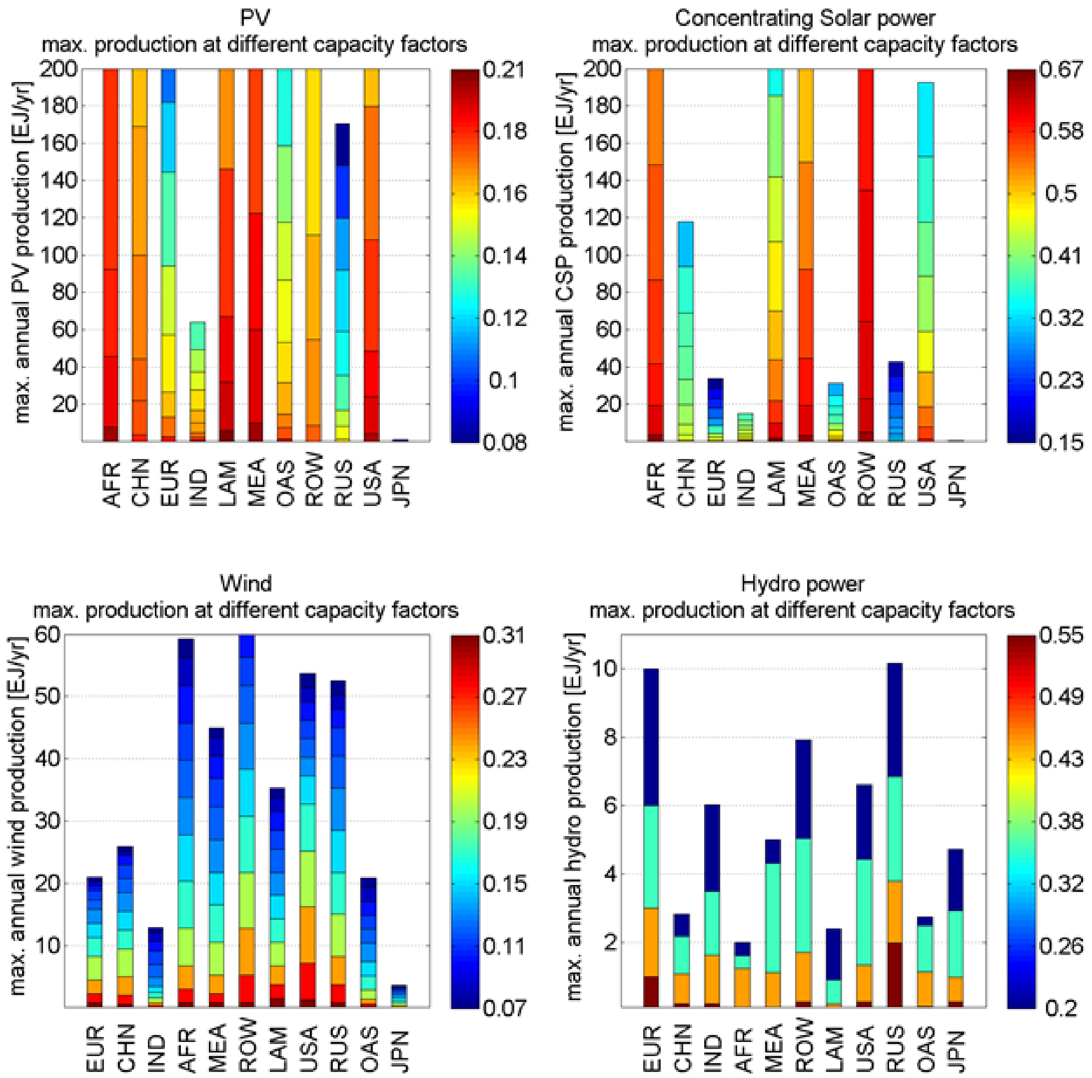

Figure 51. Renewables maximum production by regions. Pietzcker et al. (Applied Energy, 2014)

3.4 Emissions

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***[39] (**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.

[39] 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 2023 edition?

The 2023 edition for Phase IV does not have many changes compared to the 2022 edition used for Phase III. However, some of the notable differences are:

1. Chemical industry sectors expanded to include ammonia and methanol production processes.
2. A new interpolation scheme for aggregating country-level net-zero trajectories.
3. Updated policy details for the Current Policies and NDC scenarios.
4. Improved method for regionally different carbon price reporting.

2. Overview of model scope and methods

The MESSAGE-GLOBIOM model[40] was originally developed to represent global and regional energy systems[41] 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.

[40] 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

[41] 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*

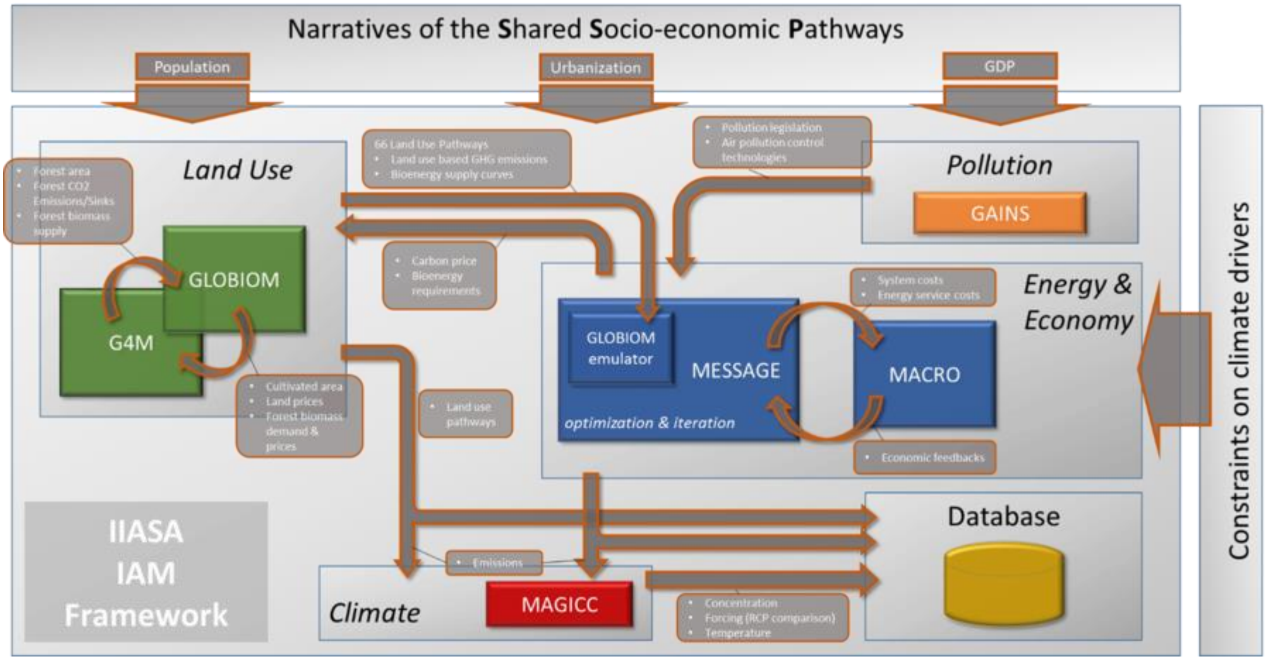

Figure 52. Overview of the IIASA IAM Framework. Coloured boxes represent respective specialized disciplinary models which are integrated for generating internally consistent scenarios. Figure from Riahi et al. (2016).

MESSAGE*ix*[42] represents the core of the IIASA IAM framework. Its main task 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 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.

[42] 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.

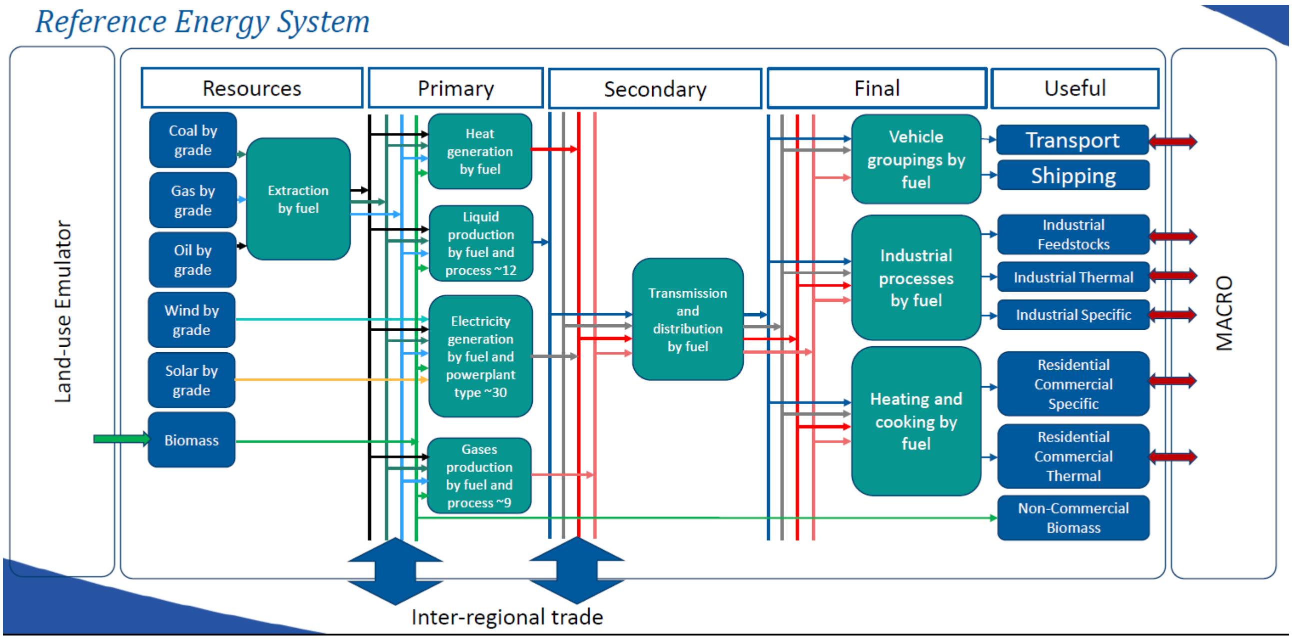

Figure 53. Reference Energy System in MESSAGEix

GLOBIOM is a partial-equilibrium model representing the mainland-use sectors, which include agriculture and forestry. The supply side of the model is built-up from the bottom (spatially explicit land cover, land use, management systems and economic cost information) to the top (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.

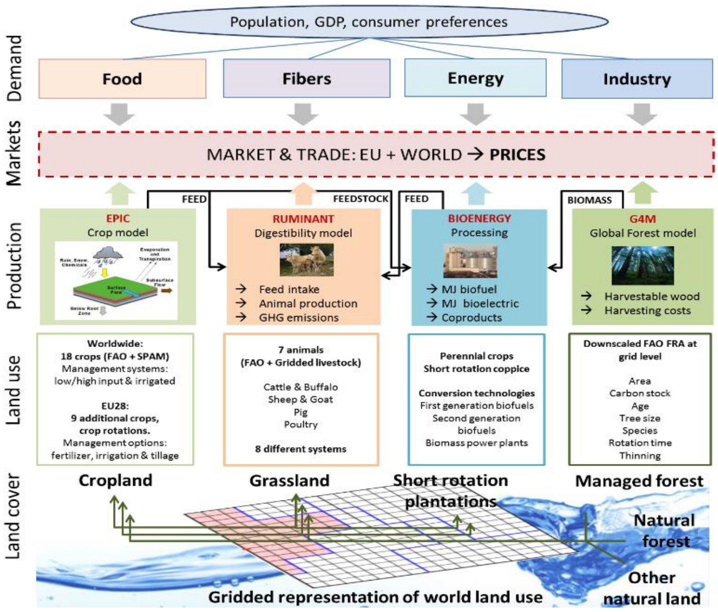

Figure 54. Overview of the GLOBIOM model

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.

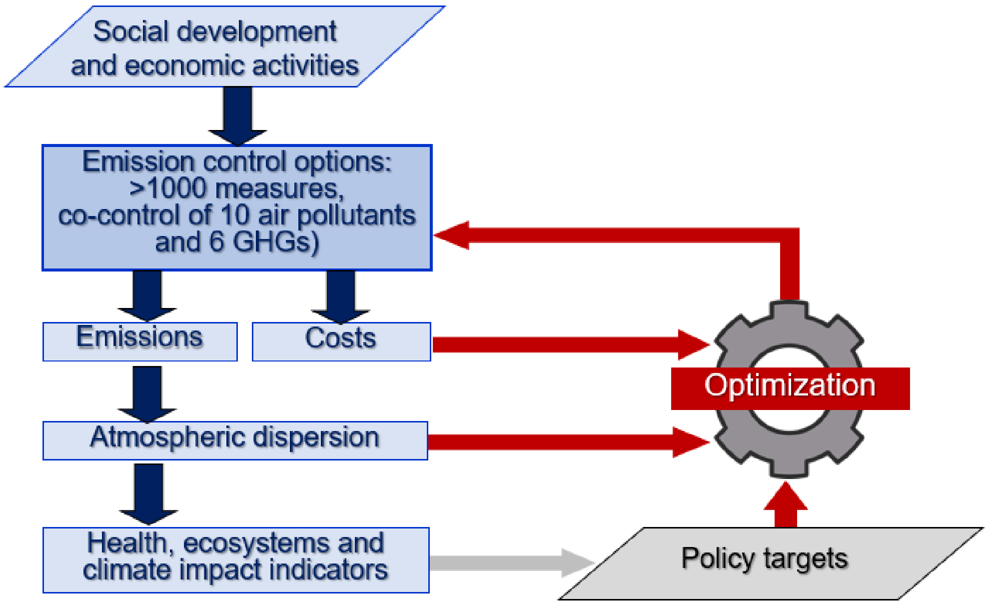

Figure 55. Overview of the GAINS model

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).[43] 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.

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[44] is then aligned with the particular storyline of the chosen SSP, i.e.,

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[43] 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.

[44] 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.[45]

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 builtupon earlier work developed in the Global Energy Assessment (see Riahi et al., 2012). In the SSP2 narrative, which underlies NGFS scenarios, the cumulative uranium extracted is assumed at 30 Mt (metric tonnes) with an approximate price range of 120-230 USD/kg depending on different models of uranium distribution in the crust and its extraction costs.[46]

Non-Biomass Renewable Resources: The resources considered are hydro, wind (on-/offshore), solar PV, concentrating solar power (CSP)[47] 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).[48] 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).

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

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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.

[45] 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

[46] For more details: https://docs.messageix.org/projects/global/en/latest/energy/resource/nuclear.html

[47] 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.

[48] 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.

across SSPs as a result of different levels of competition over land for food and fibre, but ultimately only vary 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).

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.[49] 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"[50] and "Grid, Infrastructure and System Reliability"[51,52]. 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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[49] 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).

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

[51] 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.

[52] 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.[53]
- 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[54] –to account for a key option to reduce emissions; switching depends on fuel-specific relative

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[53] 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.

[54] 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

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.[55] The following Figure 56 displays a schematic diagram of the stylized transport sector representation in MESSAGEix.

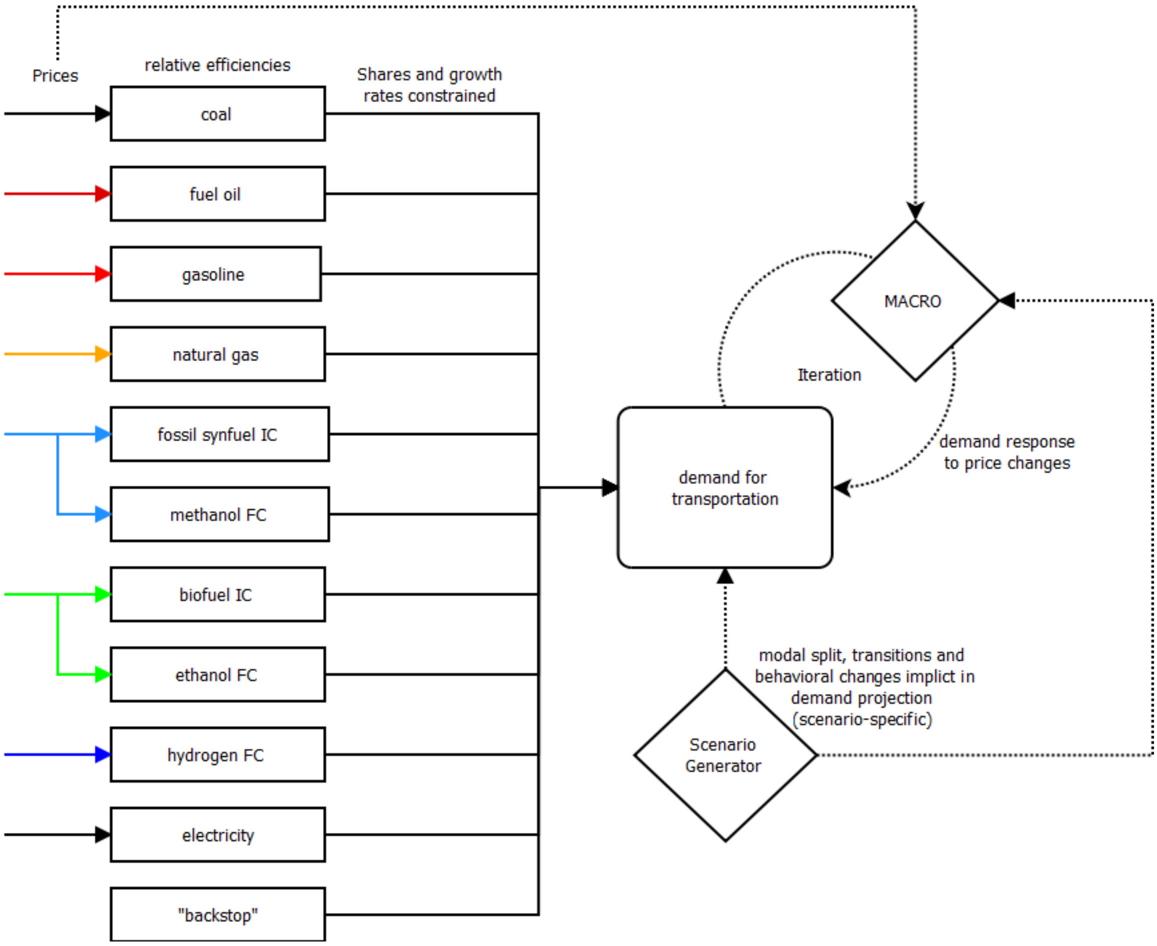

Figure 56 . Stylized transport sector representation in MESSAGEix

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).

supply chains, not explicitly represented in MESSAGEix (e.g., non-energy related infrastructure). Both the share as well as the diffusion constraints are usually parametrized based on transport sector studies that analyse such developments and their feasibility in much greater detail.

[55] 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,[56] 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).[57].

[56] 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).

[57] 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).

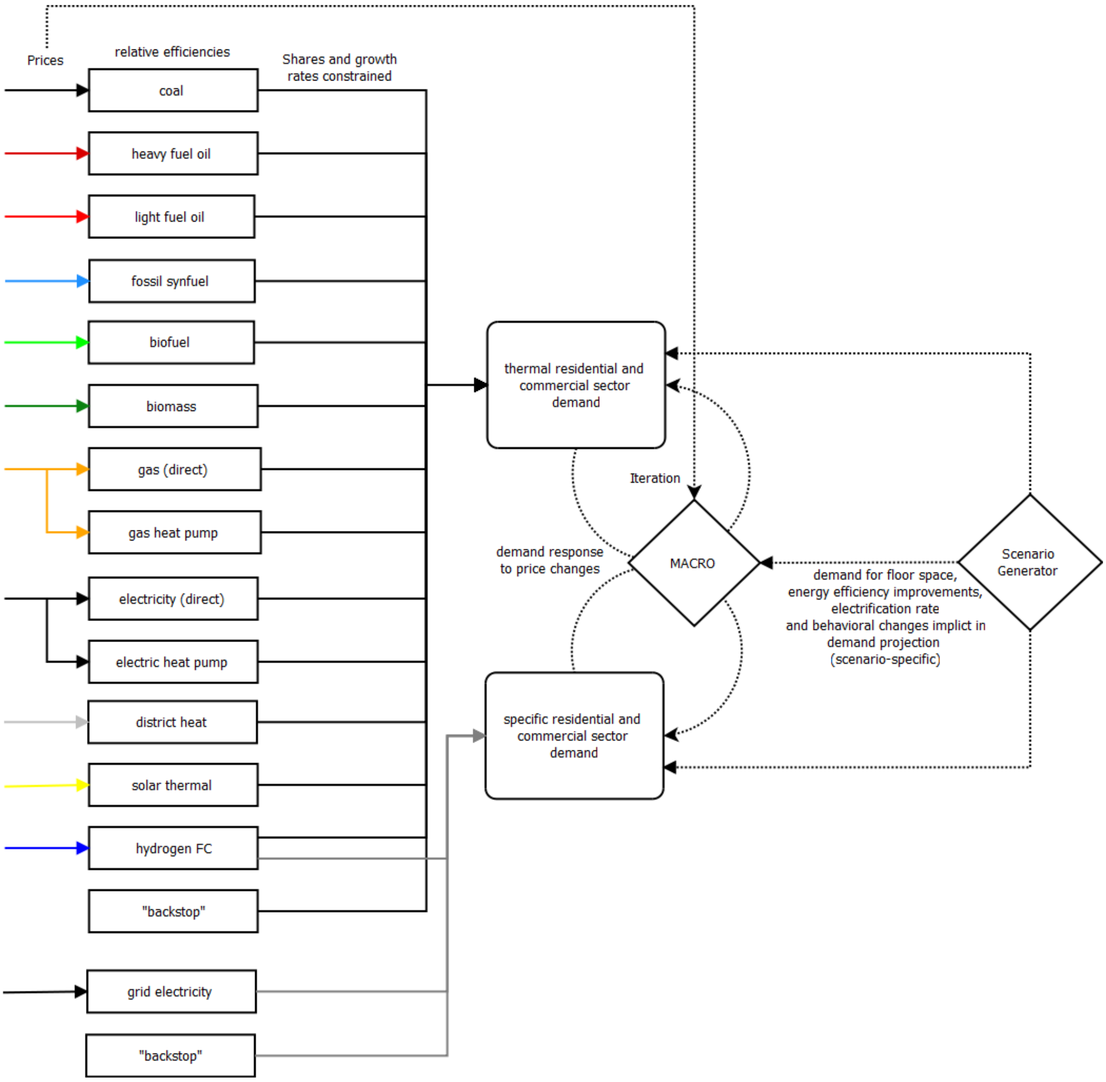

Figure 57 . Schematic diagram of the residential and commercial sector representation in MESSAGEix

Industrial sector. 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.

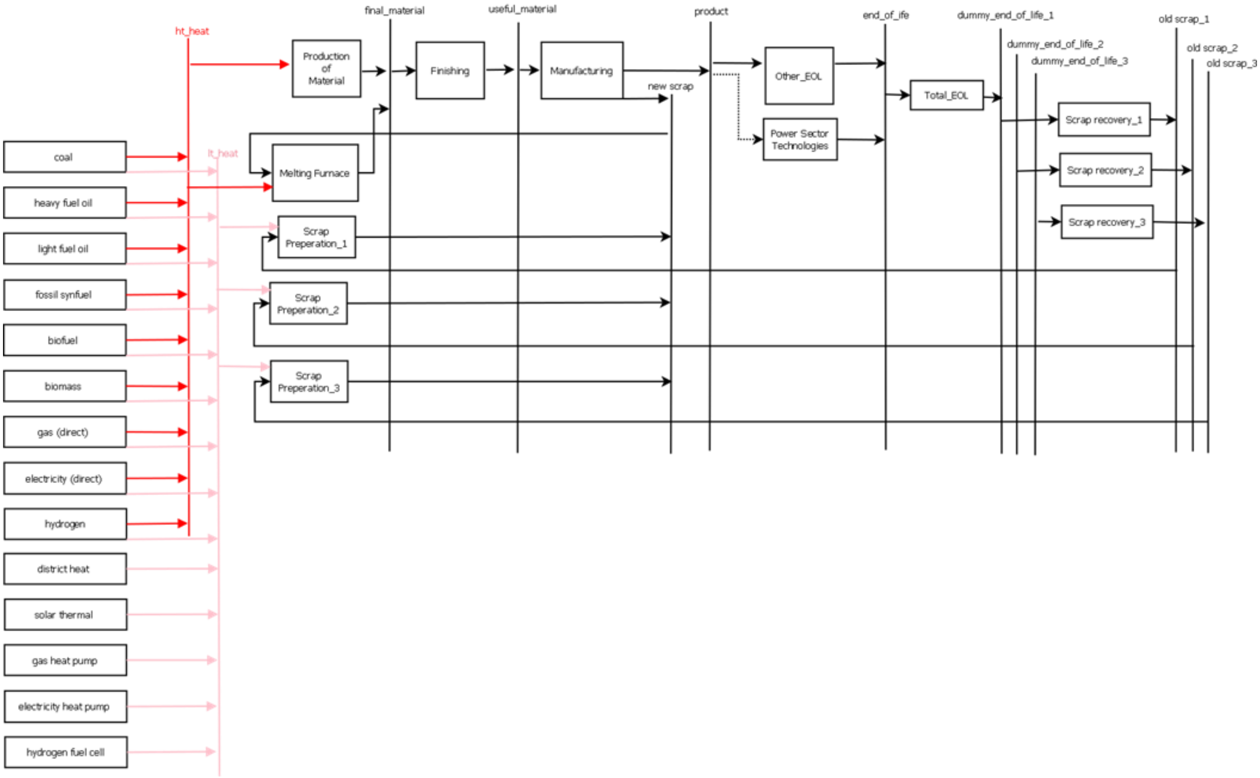

Figure 58 . Generic representation of an industry sector modelled in MESSAGEix

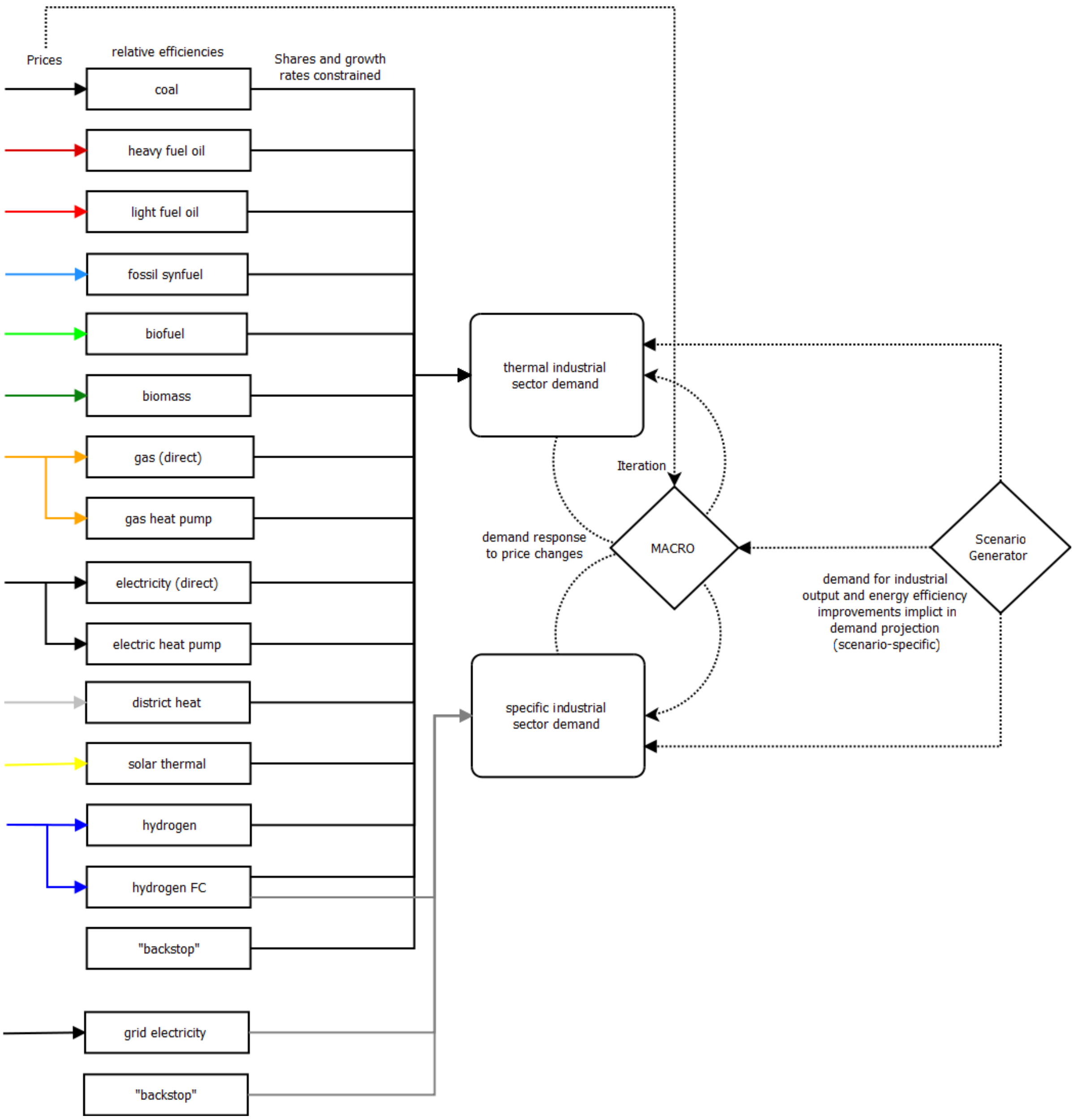

Figure 59 . Schematic diagram of the residual industrial sector representation in MESSAGEix

Technological change (MESSAGEix)

Technological change in MESSAGEix is generally treated exogenously.[58] The current cost and performance parameters, including conversion efficiencies and emission coefficients, are generally derived from the relevant engineering literature.

[58] 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 data (IEA, 2014) with convergence of costs assumed over time driven by economic development (GDP per capita).[59] Estimates for present-day and fully learned-out technology costs are from the Global Energy Assessment (Riahi et al., 2012) and World Energy Outlook (IEA, 2014).

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.[60] 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.[61]

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:[62] the blending of natural gas with other synthetic gases and. the blending of light oil with coal derived synthetic liquids.[63]

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[59] 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.

[60] 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).

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

[62] 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.

[63] 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.[64] 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;[65] b) depicting emission mitigation options.[66] 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 SSP2 with a COVID update based on Kikstra et al., 2021. 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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[64] For more details please refer to https://docs.messageix.org/projects/global/en/latest/energy/fuel_blending.html

[65] 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.

[66] 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.

These demands are generated by relating historical country-level GDP per capita to final energy. and using projections of GDP and population to extrapolate the seven-energy service demands into the future.[67], [68]

Modelling policies (MESSAGEix):

MESSAGEix distinguishes between twelve global regions.[69] 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[70], to be able to adequately account for future changes in the scenario development processes.[71] 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.[72] 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.

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

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[67] 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).

[68] 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

[69] 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.

[70] 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.

[71] 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.

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

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). [73]

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.[74]

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.[75]

Livestock: GLOBIOM distinguishes between (i) livestock population, (ii) livestock products, (iii) livestock feed, (iv) grazing forage availability and (vi) livestock dynamics.[76]

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 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.[77]

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.[78]

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

74 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

75 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

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

77 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

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

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.[79]

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.[80] 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.

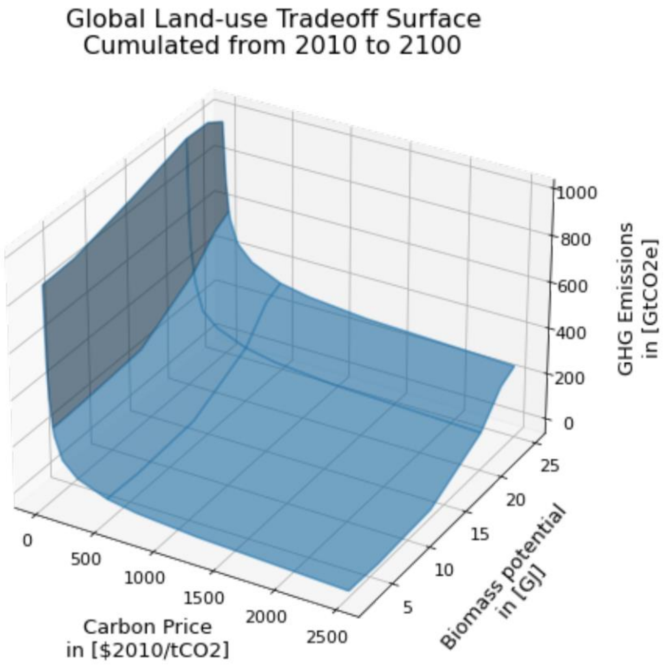

Figure 60. Land-Use Pathway Trade-Off Surface for SSP2

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[79] 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

[80] 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.

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 NGFS Phase IV scenarios?

What is new in the 2023 edition?

In the internal representation of the model, the chemical industry sectors are expanded to include ammonia and methanol production processes. These variables are currently not specifically reported in the NGFS scenarios.

A new interpolation scheme for aggregating country-level net-zero trajectories has been used. We now use a linear reduction of emissions over time rather than an endogenous model-determined timing based on a cumulative budget in each region.

Policy details and assumptions for the Current Policies and NDC scenarios are updated to include relevant information up to the cut-off date of Fall 2022.

We apply an improved method for regionally different carbon price reporting based on regionally defined emission trajectories. Before, the price derived from the global targets was dominant on the regional level, but now MESSAGEix produces regional prices consistent with mitigation at the regional level.

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.

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).

GDP (MER)

- Apply own MER-PPP conversions to the base GDP (PPP) and apply the cumulative growth rates to our base year GDP

Baseline demand

- Multiply the derived GDP trajectory to the end-use energy intensities extracted from an own COVID-adjusted scenario (Kikstra et al., 2021)

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 IV 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 IV 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 2023 edition of GCAM (version 6.0) used for the NGFS phase IV scenarios, includes 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.

2. 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.

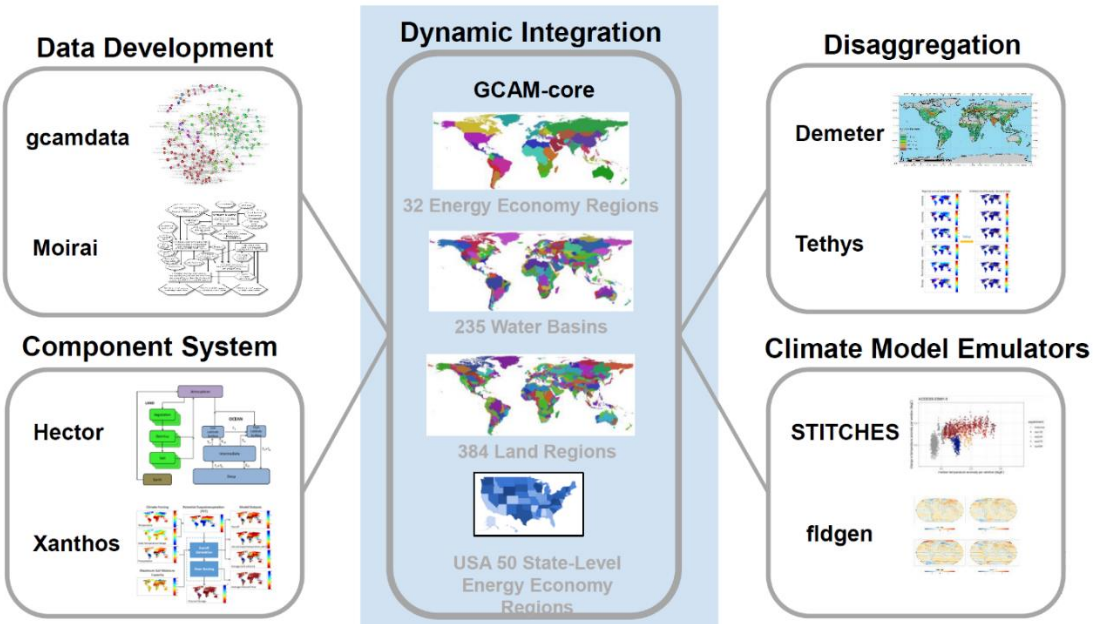

Figure 61. GCAM Model Integration

GCAM allows users[81] 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,

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

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).

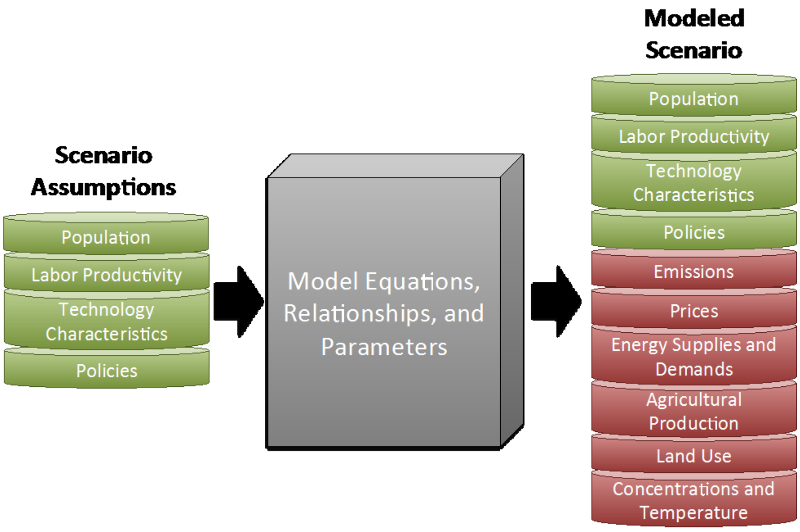

Figure 62. Use of scenario assumptions to produce fuller, modelled scenarios

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 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.

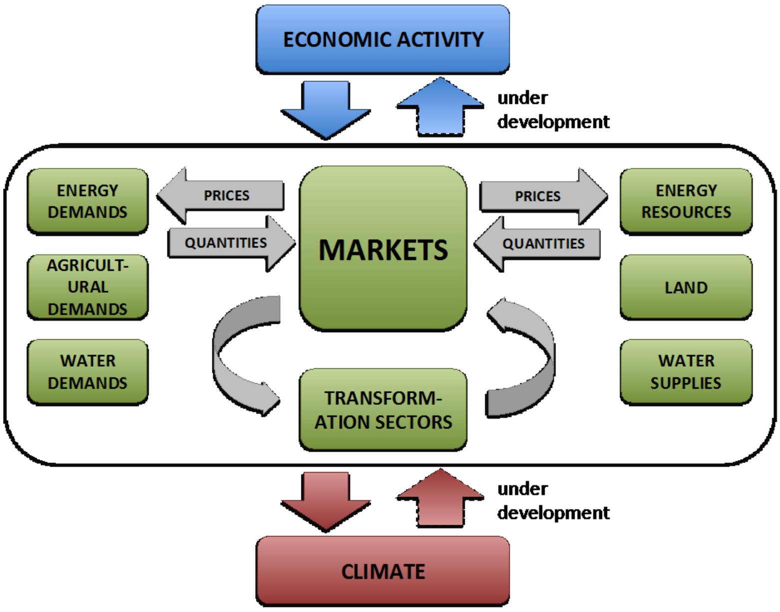

Figure 63. Conceptional schematic of GCAM core operation

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.

3. 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

Name	Resolution
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.[82] 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 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[83] 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.

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

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

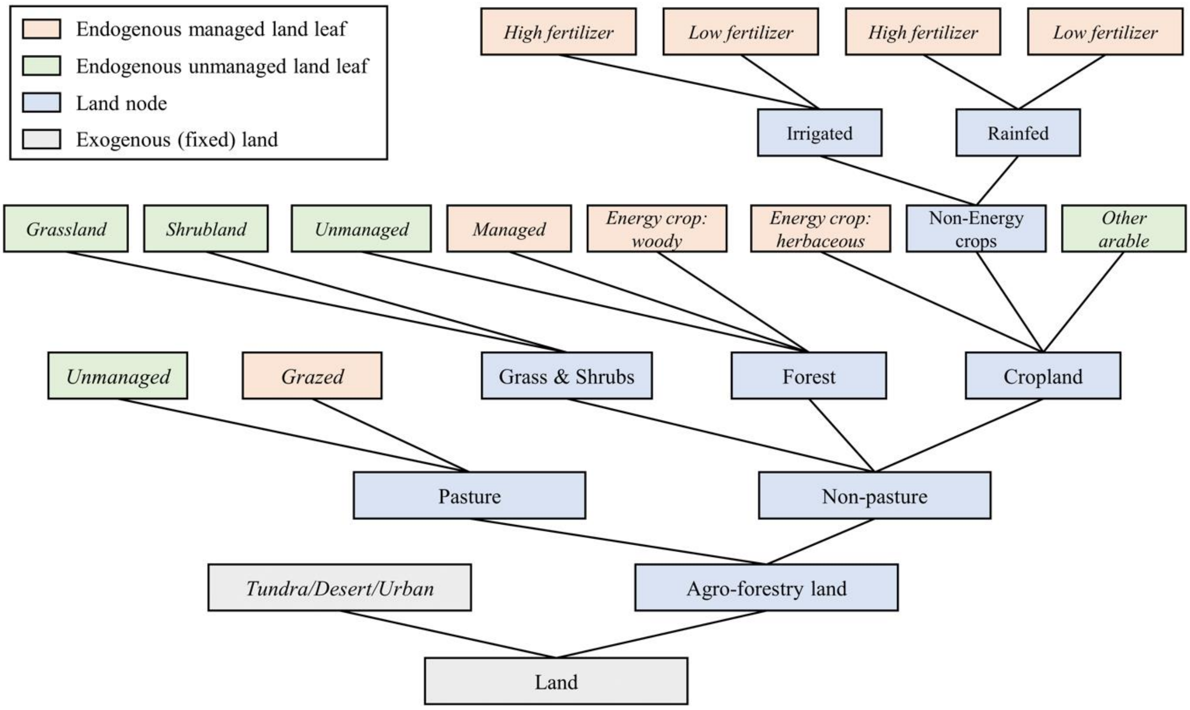

Figure 64. Agriculture and land use (AgLU) land nesting structure

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

Table 7. Inputs required by the land allocation module[84]

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
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

[84] Note that this table differs from *Table 29* in that it 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.

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
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[85], 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[86]. 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.

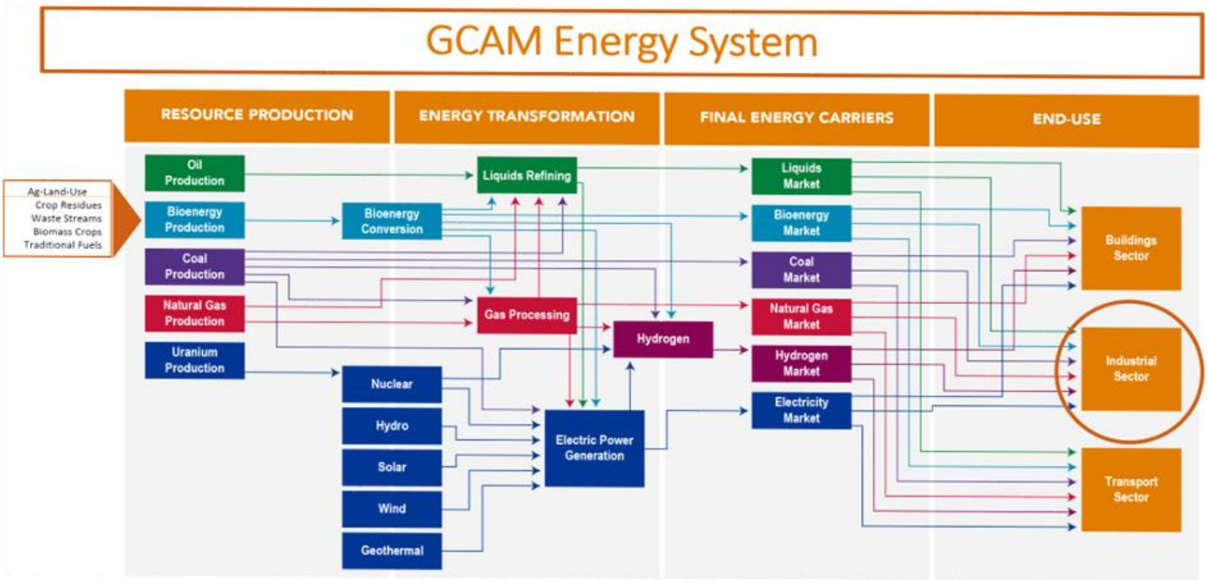

Figure 65. GCAM energy system

85 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.

86 See the **Key model inputs**for explanations.

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.[87] In all cases, GCAM implements the policy approach by placing a price on

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

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 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.[88] 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.[89] 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.

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[88] 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.

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

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.

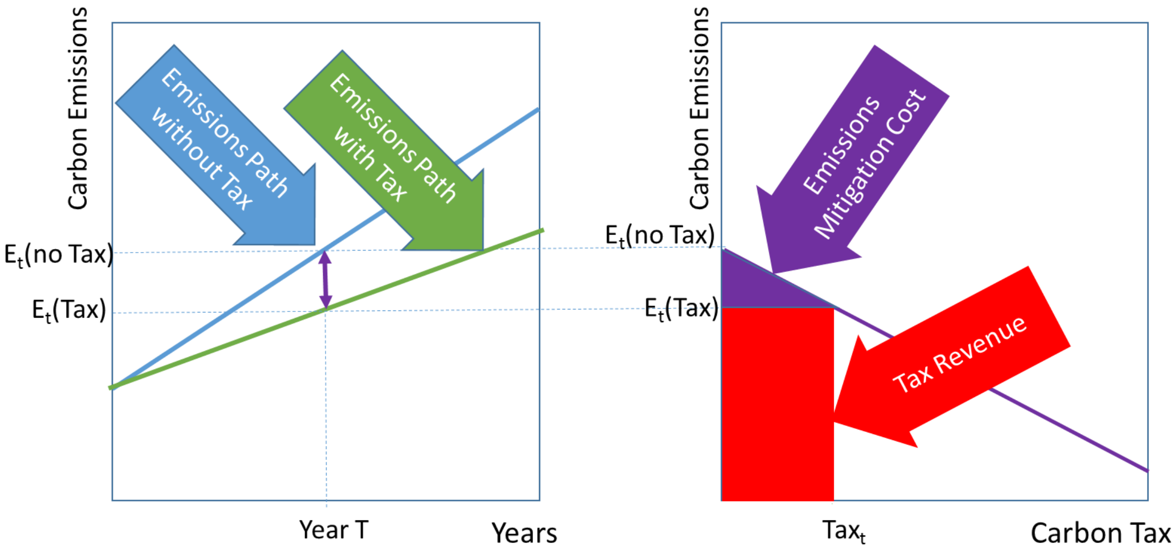

Figure 66. Carbon emissions paths, costs, and tax revenues

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).

4. 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 km²
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 km²

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 m³/yr., and water outputs are in km³/yr.

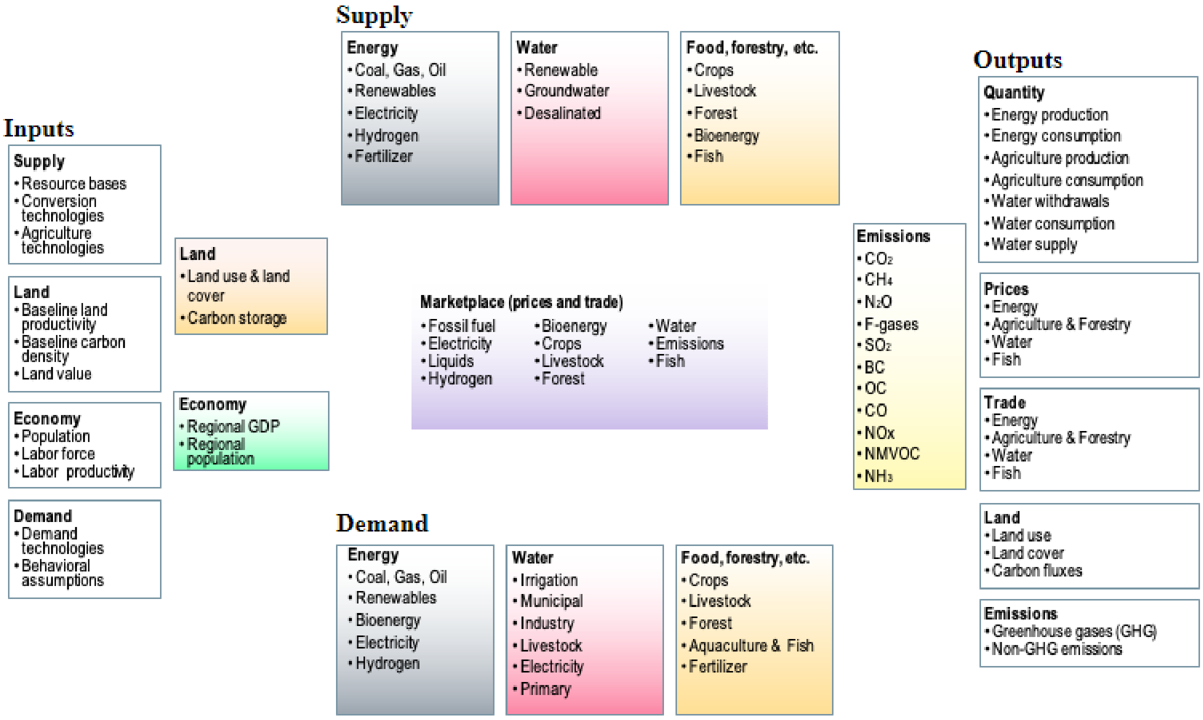

Figure 67. Overview of GCAM inputs and outputs

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 IV Scenario Explorer (indicated as "G" in the IAM column). There, the main variables (variable groups) are also explained briefly.

GCAM 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:

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

Where, the reference scenario, ref, is the Current Policies scenario. GDP is measured in a common currency using purchasing power parity, PPP. The regional marginal cost of emissions mitigation is measured as the price of CO2 or P_{CO_2}, $\frac{\%\Delta GDP_{ref}^{REMIND}(t)}{P_{CO2}^{REMIND}(t)}$. 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 to 10% for losses, and to 1% for gains.

5. What is new in GCAM modeling for NGFS Phase IV scenarios?

1. A new residential floorspace expansion model
2. Bio-energy updates: additional limits to "unsustainable" deployment
3. Default hotelling rate for climate stabilization scenarios is now 3%
4. Split out six detailed industrial sectors from the aggregate industry sector[90]
5. Updated hydrogen production, distribution, and end-use technologies
6. A new protected lands definition
7. Expanded crop commodities
8. Use spatially explicit soil and vegetation carbon data from Moirai[91]
9. HFC MAC curve fixes
10. New pollutant emissions controls
11. Solution improvements, particularly related to water markets
12. Change the XML parser library to RapidXML
13. Add the ability to exit the model early due to solution failure
14. Reduce memory usage (offsets additional memory from expanded crop commodities)
15. GCAM-data: Renv and user modification chunks

[90] GCAM 5.3+ from NGFS phase 3 included a preliminary version of the industry split-up. The differences in these industry module versions and the other differences in this list explain the scenario-independent result changes from phase 3 to phase 4 for GCAM.

[91] The Moirai Land Data System (Moirai LDS) is designed to produce recent historical land data inputs for the AgLU module of the GCAM data system.

Module 5: Chronic physical risks

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.[92]

The IAM models described in previous sections are capable of calculating policy costs associated with the goals of different scenarios. However, these models 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.

The approach used for the economic impact estimates from chronic physical risks in this year's edition of the NGFS scenarios is the same as the approach used in the 2022 edition. However, the temperature paths for which the results have been produced have been updated.

The methodology used for the NGFS estimation of chronic physical risk calculates macro-economic impacts based on damage functions. 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). The NGFS methodology uses a damage function based on mean temperature developed by Kalkuhl and Wenz (2020). While there are several advantages of this approach (including its global coverage), it is important to recognize that this is an active research area with large uncertainties.

Explainer box 5

What is new in the 2023 edition of the NGFS Scenarios ?

- The approach used for the economic impact estimates from chronic physical risks in this year's edition of the NGFS scenarios is the same as the approach used in the 2022 edition. **However, the temperature paths for which the results have been produced have been updated.**

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

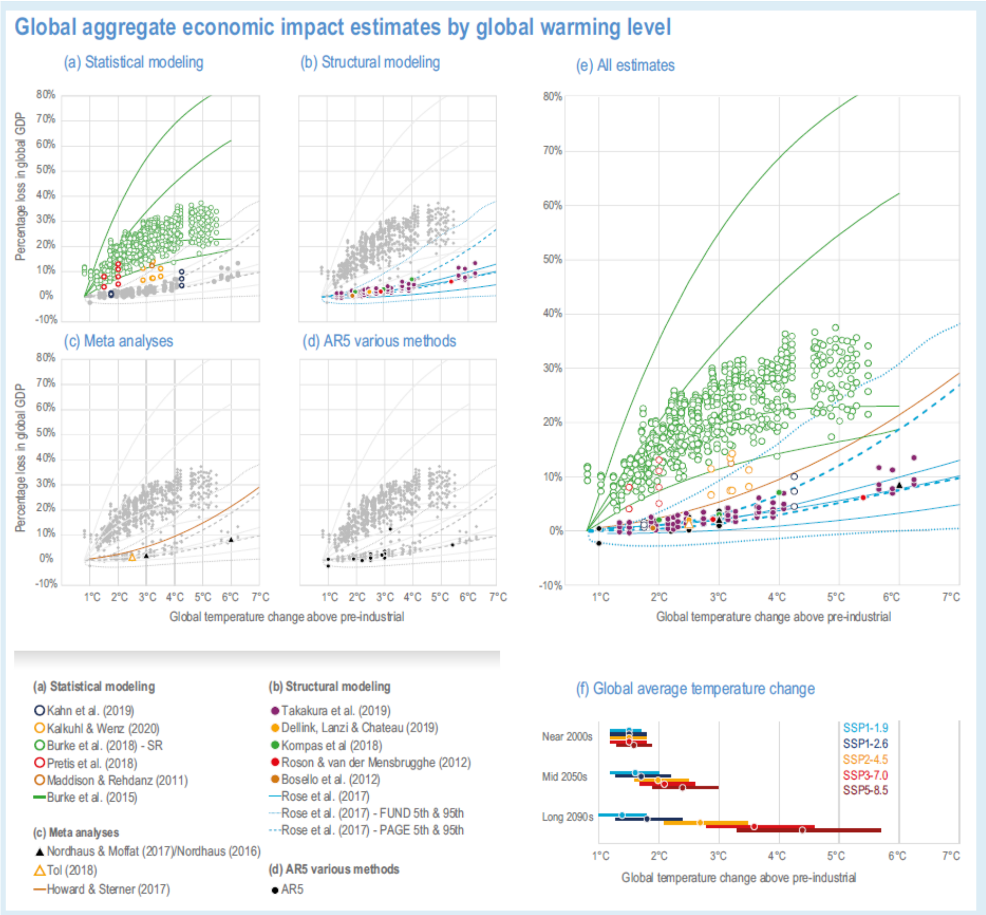

Figure 68. Global aggregate economic impact estimates by global warming level (annual % global GDP loss relative to GDP without additional climate change). Source: IPCC AR6 WGII Chapter 16, 2022.

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 estimates of the damage function used. However, the scope of uncertainties on chronic damages is much wider. Regarding the damage functions, for example, it remains an open question if the damages affect the level or the growth rate of economic output (i.e., persistence effects). 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 temperature and GDP; (ii) damages from sea level rise, ocean acidification, and other chronic impacts beyond temperature; and (iii) effects beyond impacts on labor and land productivity and capital depreciation, including conflict, violence and migration, and biodiversity and ecosystem impacts.

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

For the NGFS scenarios, we use the results of a recent, state-of-the art econometric estimate by Kalkuhl & Wenz (2020) to calculate country-level macroeconomic losses. The conceptual model is a stylised Ramsey-type growth model focusing on aggregate productivity effects $\Theta(T)$ and labour productivity growth $g_A(T)$ on GDP growth (g_y), where T is the global mean temperature change and $g_A := \frac{d \ln A}{dt}$. The equation below shows the different drivers of growth, with s = savings rate, δ = capital depreciation rate, L = quantity of labour (equal to population), g_L = growth rate of labor, K is capital, Y is GDP. The first term represents the immediate (short-run) climate effect on the level of productivity, via $\Theta(T)$ which captures immediate productivity damages produced by T diverging from pre-industrial levels. The middle term lists elements related to capital accumulation and population growth and can be interpreted as transitory effect on the growth rate converging to zero; the third represents permanent productivity changes driven by T and hence can be interpreted as the the long-term balanced growth path effect.

$$g_y = \frac{\Theta'(T)}{\Theta(T)}\dot{T} + \Phi\left(s\frac{Y}{K} - \delta - g_L\right) + (1-\Phi)\big(g_A(T)\big) =$$

$$\underbrace{\frac{\Theta'(T)}{\Theta(T)}\dot{T}}_{Immediate\ climate\ effect} \quad \underbrace{+\,\Phi\left(s\frac{Y}{K} - \delta - g_L - g_A(T)\right)}_{\Psi(\mathrm{T})\ ;\ \mathrm{(ii)\ transitory\ effect}} \underbrace{+g_A(T)}_{\mathrm{BGP\ effect}} =$$

where $\Phi = \frac{\partial F}{\partial K}\frac{K}{F}$.

Based on this framework, Kalkuhl & Wenz use an annual panel approach and specify a regression model linking temperature change and per capita output growth rate as

$$g_{i,t} = \alpha\big(T_{i,t} - T_{i,t-1}\big) + \beta T_{i,t}\big(T_{i,t} - T_{i,t-1}\big) + \gamma_1 T_{i,t} + \gamma_2 T_{i,t}^2 + p_i(t) + \delta_i + \mu_t + \varepsilon_{i,t}$$

with $p_i(t)$ controls for slow-moving regional changes affecting growth (like technological or institutional change), δ_i and μ_t are country- and year-fixed effects. The regression is done on subnational level (administrative regions), using data from 1900-2014. It should be noted that only α, β and δ capture the impact on growth related to temperature changes. The coefficients α and β capture immediate effects of weather shocks on country level (where T_i is based on temperature downscaling as discussed in the next section), while γ_1 and γ_2 capture transitory and long-run growth effects, in line with the different terms in the conceptual model. Note that the approach used in the study by Burke et al. (2015) only captures the latter part, i.e., transitory and long-term effects. The empirical analysis finds strong evidence for immediate productivity effects (α and β), but not significant evidence for permanent long-run growth reductions ($\gamma's$). The preferred model based on various experiments with lag structures, which we use for the calculation of future changes in the per capita growth rate based on alternative temperature paths, is the one focused on immediate effects:

$$\hat{g}_{i,t} = \alpha_1 \Delta T_{i,t} + \alpha_2 \Delta T_{i,t-1} + \beta_1 T_{i,t-1}\Delta T_{i,t} + \beta_2 T_{i,t-1}\Delta T_{i,t-1}$$

To reflect the uncertainty in these estimates, we also perform calculations at the 95th confidence interval of the estimates (reflected in Figure 1 of Kalkuhl & Wenz 2020). We calculate the standard error for $g_{i,t}$, based on variance and co-variance parameters of the coefficients obtained from the authors, and provide as "high damage" estimates based on $\hat{g}_{i,t}^{high} = \hat{g}_{i,t} - 1.96SE_{i,t}$ [93]

Parameters are listed in

Table 15 below.

Table 15. Parameter values for damage function from Kalkuhl & Wenz (2020). Values correspond to their specification 5 (Table 4 in the paper, column 5), which reports the results for all parameters under various specifications. The coefficients for delta T and lag delta T not interacted with T were kept because removing them would risk a biased estimation. Running a regression on an interaction term between dT and T, the control for T and dT should be kept to avoid an omitted variable bias and to correctly calculate marginal effects.

	α_1	α_2	β_1	β_2
Value	0.006410	0.00345	−0.00109	−0.000718
Variance (Var)	$38.11 \cdot 10^{-6}$	$26.16 \cdot 10^{-6}$	$0.288 \cdot 10^{-6}$	$0.1797 \cdot 10^{-6}$

Note that these effects capture productivity impacts (e.g., labour and land productivity, capital depreciation) related to changes in annual temperature. Therefore, non-market effects as well as effects from extreme events, sea-level rise or indirectly related societal dynamics like migration or conflicts are not included in those estimates.

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[94] and the damage function by Kalkuhl & Wenz (2020) to provide estimates of chronic damages. 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 (or regional after downscaling, see below) 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 related with the methodology, two estimates are presented: one with the median estimates of the damage function parameters and another with the 95th percentile. The latter can serve as a way of gauging the damages that are not captured in the methodology used, such as sea-level rise and climate-change induced conflicts.

93 With $SE_{i,t}^2 = Var(\delta_{i,t}) = \Delta T_{i,t}^2 Var(\alpha_1) + \Delta T_{i,t-1}^2 Var(\alpha_2) + \Delta T_{i,t}^2 T_{i,t-1}^2 Var(\beta_1) + \Delta T_{i,t-1}^2 T_{i,t-1}^2 Var(\beta_2) + 2\{\Delta T_{i,t}\Delta T_{i,t-1}Cov(\alpha_1\alpha_2) + \Delta T_{i,t}^2 T_{i,t-1}Cov(\alpha_1\beta_1) + \Delta T_{i,t}\Delta T_{i,t-1}T_{i,t-1}Cov(\alpha_1\beta_2) + \Delta T_{i,t}\Delta T_{i,t-1}T_{i,t-1}Cov(\alpha_2\beta_1) + \Delta T_{i,t-1}^2 T_{i,t-1}Cov(\alpha_2\beta_2) + \Delta T_{i,t}\Delta T_{i,t-1}T_{i,t-1}^2 Cov(\beta_1\beta_2)\}$

94 MAGICC climate module is described in Box: MAGICC: A reduced complexity Earth system model

The change in per capita growth rate given by the previous equation is taken into account calculating a projection of country-level per capita output under climate change following

$$y_{c,t}^{clim} = y_{c,t-1}^{clim}(1 + g_{c,t} + \hat{g}_{c,t})$$

Where $g_{c,t}$ is the unperturbed growth rate in a given country obtained from the downscaled IAM GDP projections and $\delta_{c,t}$ is the perturbation calculated with the previous equation, depending on country-level temperature changes. Note that this approach calculates damages compared to present-day conditions, i.e., it starts with present day GDP (2020), assuming that this already incorporates the effects of past temperature increases. As the damages are cumulative, this underestimates the overall losses. Furthermore, losses are underestimated due to the lack of dynamic effects that GDP changes would have, for instance, through the savings rate or capital accumulation. Results are provided as annual, country-level output change in %, with losses reported as negative values (e.g. Diagnostics|**high/median** GDP change|KW panel population-weighted|GMT AR6 climate diagnostics|Surface Temperature (GSAT)|MAGICCv7.5.3**|*.*th Percentile**), as well as net GDP values (e.g. net net GDP|PPP|**median/high** damage|KW panel population-weighted|GMT AR6 climate diagnostics|Surface Temperature (GSAT)|MAGICCv7.5.3**|*.*th Percentile**), where **median/high** indicates whether the median or the 95th percentile of the damage function estimates are used and **|*.*th Percentile** refers to the percentile of the temperature pathway used as input.

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

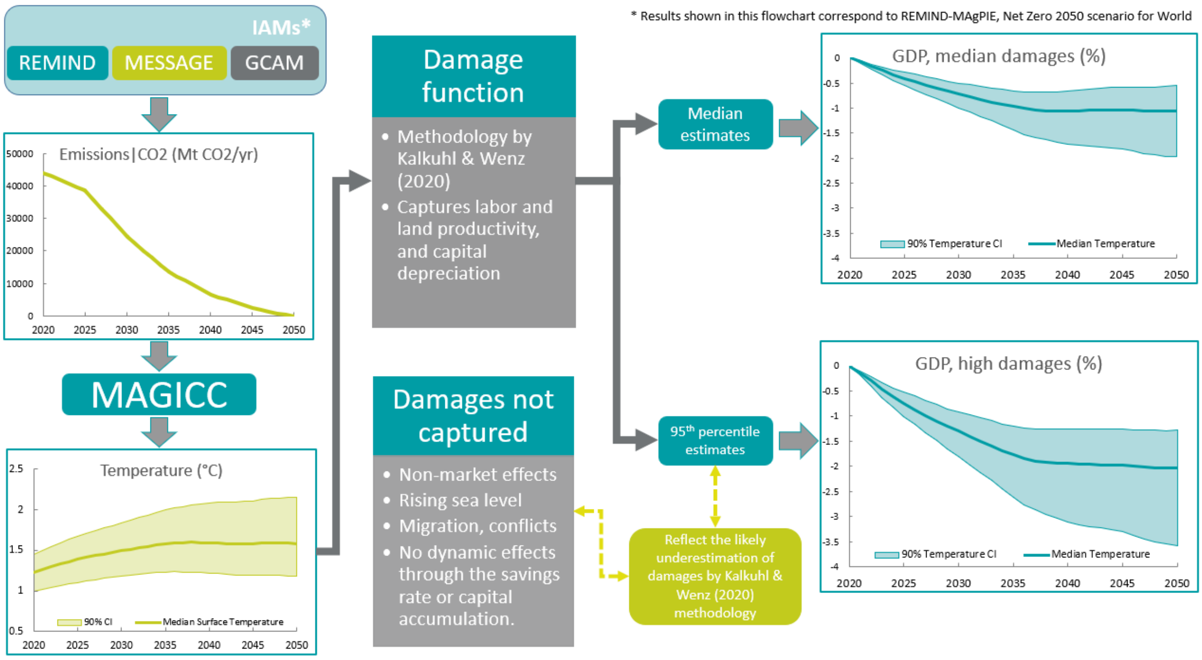

Figure 69. How post-processing chronic damages are calculated and sources of uncertainty.

4. Temperature downscaling

The global mean temperature pathways provided by the MAGICC postprocessing have to be downscaled to country-level for the calculation of country-level macroeconomic damages as described in the previous section. For this we use a statistical downscaling approach based on the multi-model climate data set from Phase 5 of the Coupled Model Intercomparison Project of global climate models (CMIP5, https://esgf-node.llnl.gov/search/cmip5/). This is aligned with the physical risk data from ISIMIP2b, which are also based on CMIP5 climate projections.

The country-level mean temperature (in absolute terms) is calculated as

$$T_{c,t} = \tilde{T}_{c,2005} + \kappa_{c,t}\,(T_t - T_{2005})$$

with the scaling factor $\kappa_{c,t} = \frac{\bar{T}_{c,t} - \bar{T}_{c,2005}}{\bar{T}_t - \bar{T}_{2005}}$.

Here, T_t is the global mean temperature change from the transition scenario as calculated with MAGICC, $\tilde{T}_{c,2005}$ is the observed 2005 mean temperature of a country calculated from the University of Delaware Air Temperature and Precipitation v4.01 data set [95]The scaling factor $\kappa_{c,t}$ is calculated based on gridded mean temperature anomaly data from CMIP5 (where $\bar{T}_{c,t}$ is for a given region and $\bar{T}_t$ is the global value). Gridded data are aggregated to the country level using population weights based on SSP2 population data.

5. 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 Kalkuhl & Wenz (2020) into the REMIND-MAgPIE model.

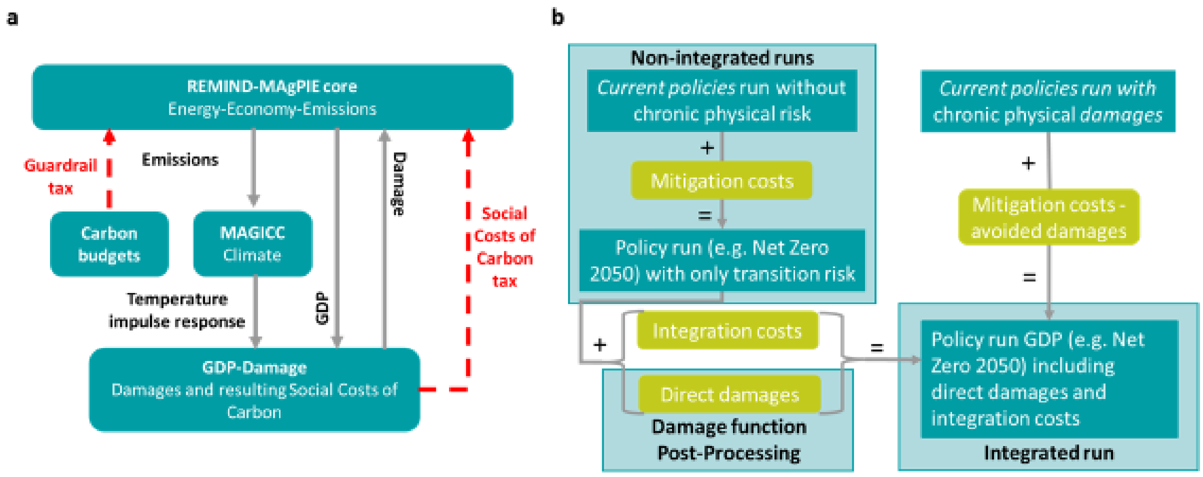

Figure 70. Conceptual framework of scenarios with integrated damages, and (b) comparison of GDP output (dark green) for non-integrated and integrated runs of REMIND

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[95] Data can be found here.

Overview of the integration

The approach is shown schematically in **Figure 70** (left panel). A module that calculates chronic damages based on Kalkuhl & Wenz (2020) 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*[96] 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, which is then downscaled to regional temperature.

Using the temperature pathways, the damage module calculates regional damages based on the approach by Kalkuhl & Wenz (2020) and computes the associated SCC tax, by solving a global planner problem with Negishi weights[97] 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.

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. [98]

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

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96 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.

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

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

response to the damages. Right panel in **Figure 70** provides a guide[99] 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[100].

To capture the effect of climate uncertainty in the damage estimate, we select MAGICC6[101] configurations at the median and 95th percentile of the temperature distribution in 2100 from a probabilistic run with 500 outcomes for an RCP2.6 emissions scenario. This climate uncertainty is combined with the damage function estimates uncertainty to produce two set of output series. "REMIND-MAgPIE 3.2-4.6IntegratedPhysicalDamages (median)" uses the median estimates of the damage function and the median of temperature distribution. "REMIND-MAgPIE 3.2-4.6 IntegratedPhysicalDamages (95th-high)" uses the 95th percentile of both the damage function and the temperature distribution. **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)
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)

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

100 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.

101 Note that the MAGICC6 version used in the REMIND-MAgPIE framework is different from the version 7.5.3 used to post-process IAM results, however this just affects the internal damage calculation.

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.

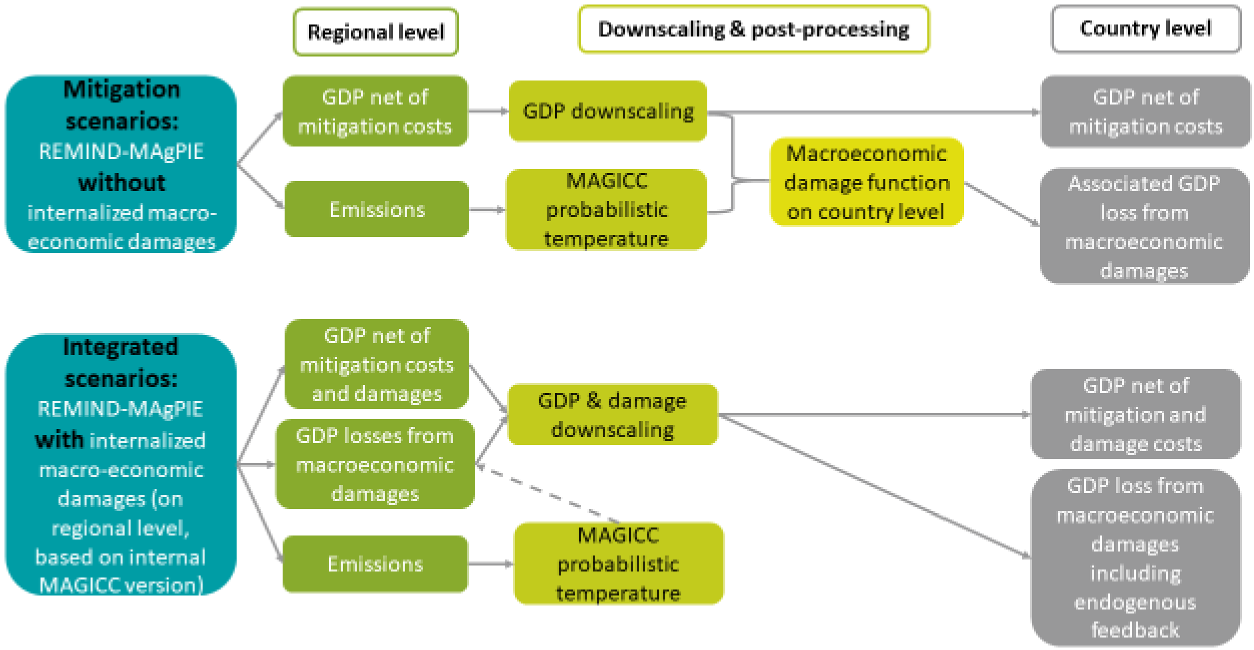


Figure 71. Non-Integrated REMIND runs vs Integrated REMIND runs

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 IV, acute physical risk modelling substantially advanced. Firstly, it covers four perils: heatwaves, tropical cyclones, floods, and droughts. Additionally, estimates are provided at country level, while for each peril the most relevant transmission channel is used.

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. Differences relative to Phase III

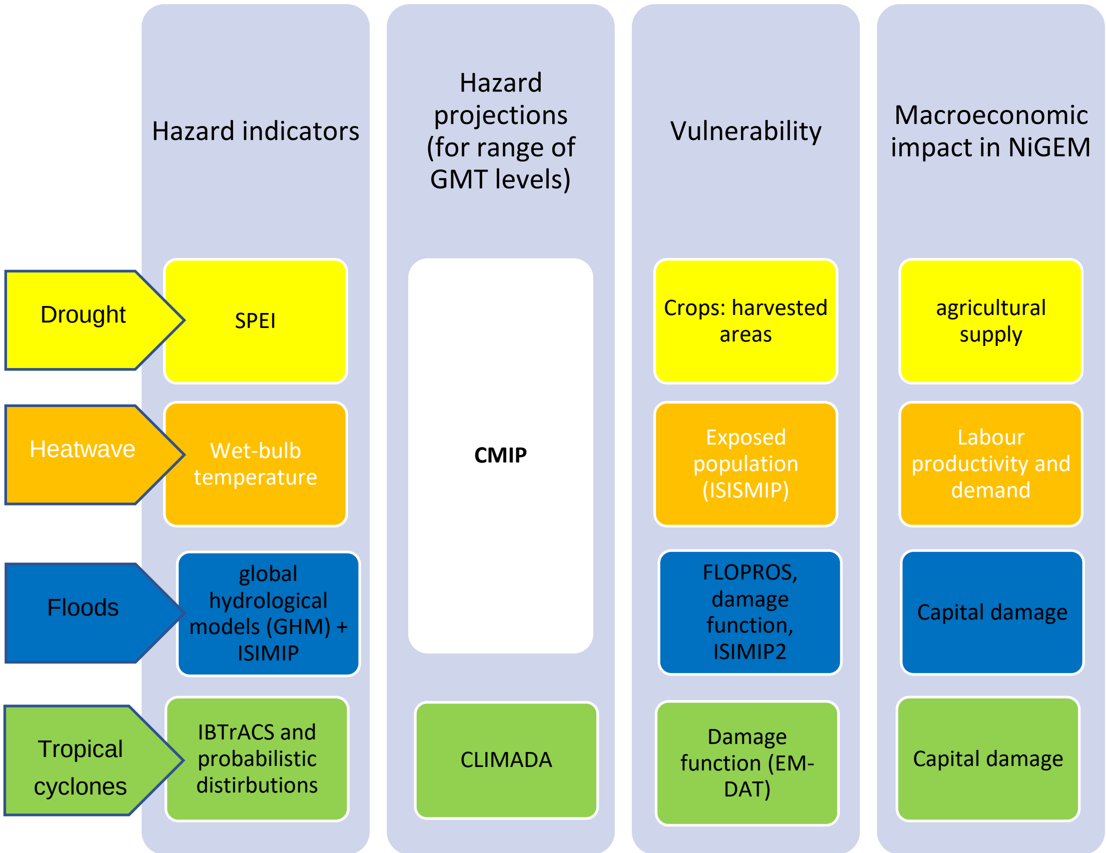
The approach used for acute physical risk characterization in NGFS Phase IV differs from that used for NGFS Phase III:

Perils covered: The Phase III estimation methodology focuses primarily on floods and tropical cyclones, whereas the range of perils modelled in Phase IV has been expanded to include droughts and heatwaves.

Method for estimating acute shocks: In Phase III, the representation of acute physical risks was mostly based on historical shocks (based on EM-DAT) with future multipliers based on productions from the Climate Impact Explorer. In Phase IV the range of indicators used was extended to cover additional perils and countries to use an approach based on catastrophe modelling principles.

Macroeconomic modelling: The method for modelling of these shocks in NiGEM has also been updated to reflect the lack of direct estimates between country GDPs or assets and events like droughts or heatwaves. To this end, additional channels of transmissions have been used, like yields loss for droughts and labour productivity for heatwaves. The results using these additional channels also show how much of the physical risk impacts, which go along various and sometimes very indirect transmission channels (one example is supply chain disruption, very difficult to model and yet affected by physical risk), is still to be uncovered.

Granularity: Whereas world aggregate impacts were reported in Phase III, in Phase IV country-level results are also provided. The country level results are a great advancement and a significant step toward making these models available for exercises like stress tests or climate risk analyses, especially if further enriched with further breakdown like the sectoral one. However, the approach is novel and had to overcome significant data and model gaps and will benefit from extensive data validation and improvements based on the use.



The structure of this chapter

The rest of the chapter is structured as follows: the first part covers hazard-modelling, with one section per hazard. These sections focus on explaining how acute risks can be measured, the exposures and vulnerabilities quantified, and predictions made on the basis of Global Mean Temperature paths. The last section explains the implementation in NiGEM, which is also split per hazard.

3. Modelling of acute physical risk hazards

3.1 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[102]). 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 Standardized Precipitation Index (SPI) (Touma et al. 2015). For a detailed description on how the SPEI is determined we refer to NCAR Climate guide [103]. 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[104]). 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[105]. 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.

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[102] https://www.ncei.noaa.gov/access/monitoring/dyk/drought-definition

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

[104] 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.

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

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 1/12th.

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:

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

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

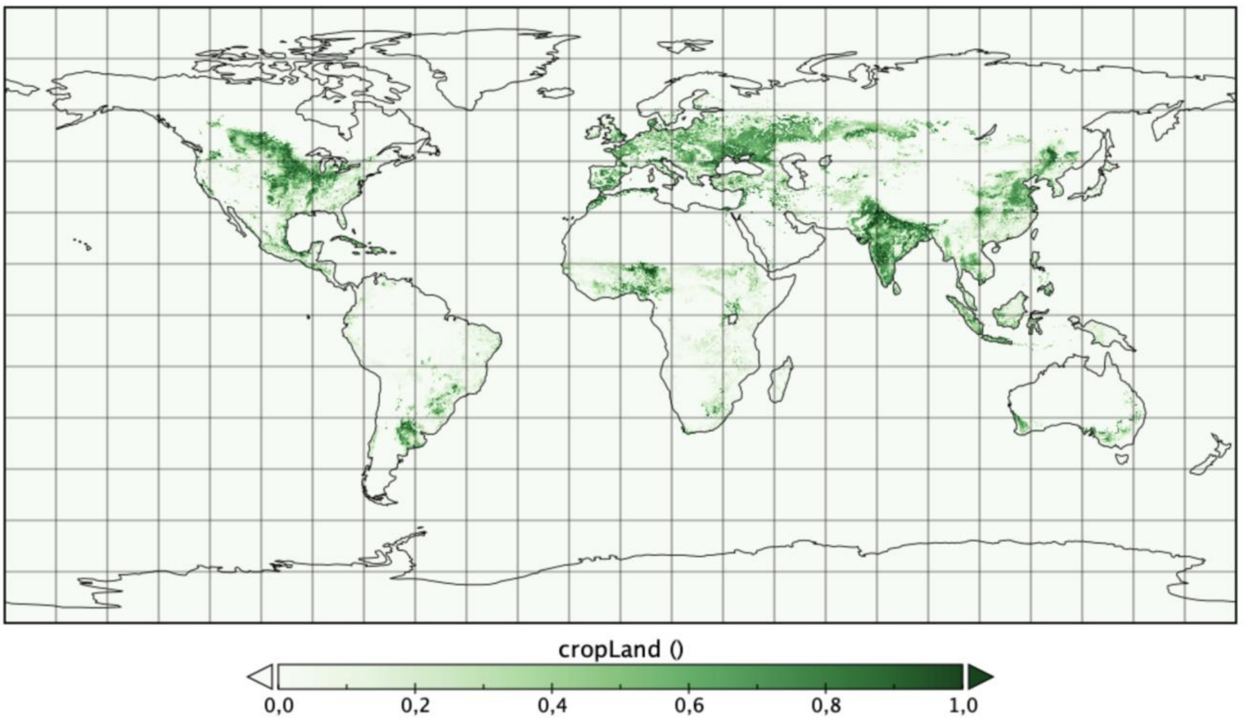


Figure 72. Intensity of agricultural activity as indicated by harvested area based on data provided by Ray et al 2015. Data is based on 2005 estimates.

Determining future drought conditions and projecting at different levels warming levels

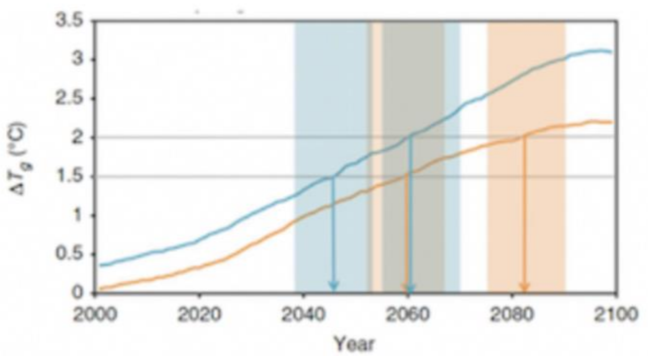
We use the bias-adjusted and down-scaled output from four climate models of the fifth phase of the Coupled Model Intercomparison Project (CMIP5[106]): IPSL-CM5A-LR, GFDL-ESM2M, MIROC5, HadGEM2-ES. Following the approach used in other climate impact studies, four different models are employed to improve the sample size and provide a better range of possible climate futures.

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.

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).



[106] https://wcrp-cmip.org/cmip-phase-5-cmip5/

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.

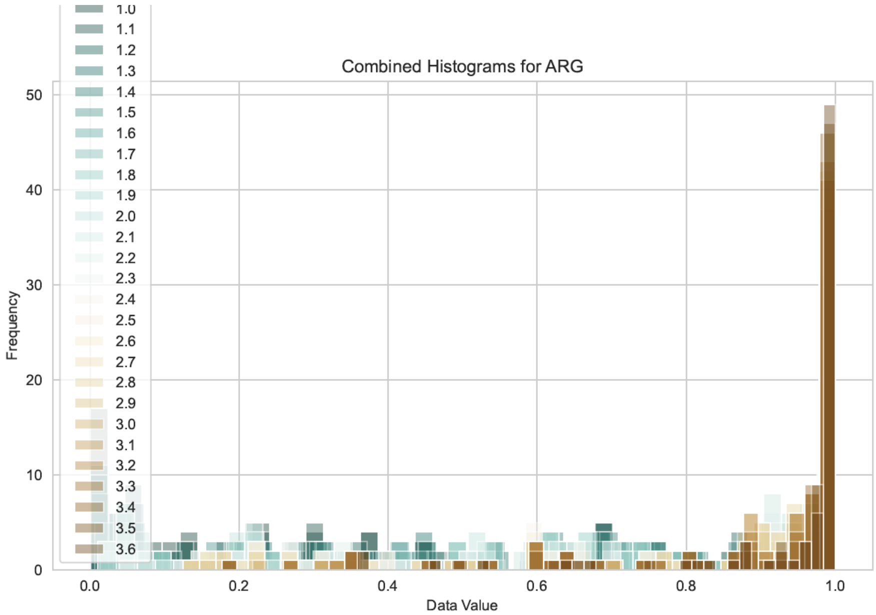


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Figure 74. Increased risk of yield losses from enhanced exposure to drought conditions under future warming levels.

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.

3.2 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[107] 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

[107] 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)

consider 29.1 degrees[108] 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.

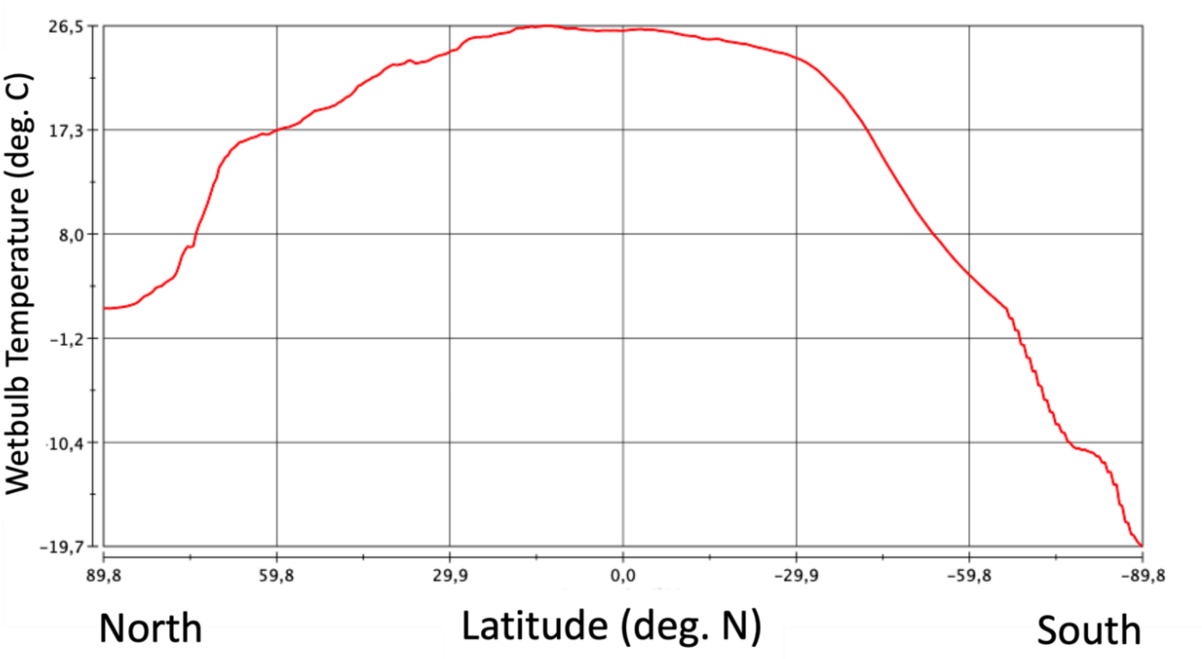

Figure 75. Latitudinal dependence of wet-bulb temperatures ranging from North pole (left) to South pole (right) determined by averaging the 84th percentile values over longitudes and years 1981 – 2019 including ocean and land areas. Highest wet bulb temperatures are occurring in the tropics around the 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[109] 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.

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

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

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).

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).

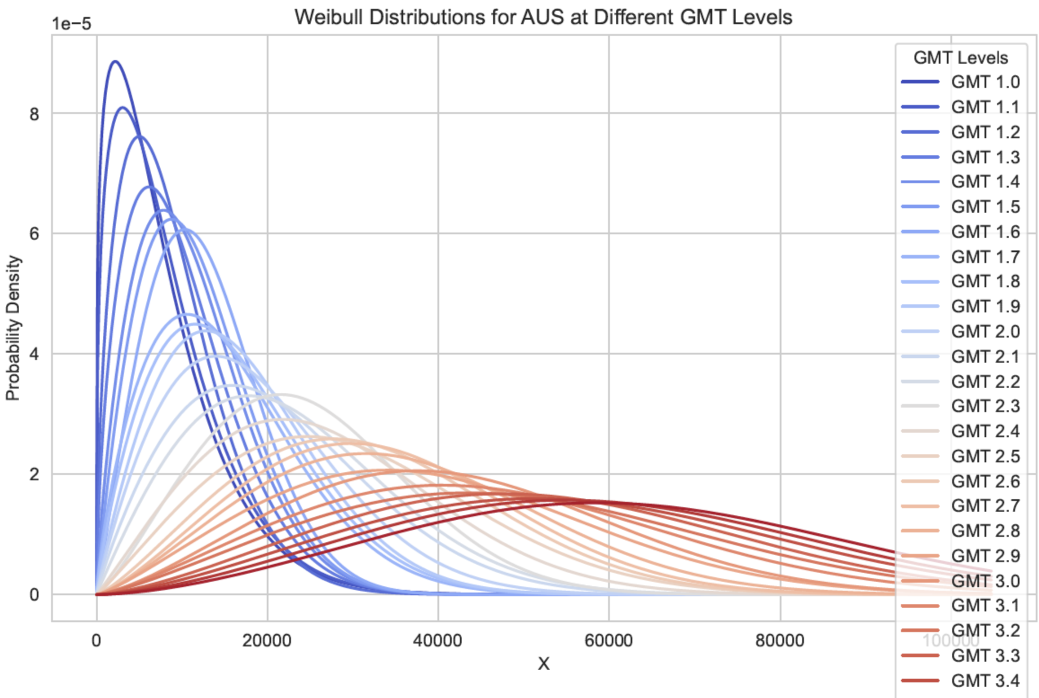

Figure 76. Increased Risk of heat stress exposure under higher global mean temperature levels.

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.

3.3 Floods damage modelling

Data for flood detection and protections

Different modelling groups from around the world derived harmonized data on flood depth and flood fraction at grid point level (150arcsec)[110] by running global hydrological models (GHM) and submitted this data to the ISIMIP project. These GHM's were driven by four General Circulation Models (GCM) resulting in a number of GHM/ GCM combination datasets[111], that participated in the ISIMIP2 project for the scenarios RCP 2.5, RCP 6.0 and RCP 8.5. This data was used as the basis to calculate average annual economic losses from riverine flood under different scenarios.

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110 ISIMIP, Inter-Sectoral Impact Model Intercomparison Project; www.isimip.org; Database accessible under https://files.isimip.org/cama-flood

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

A correction for flood protection is taken into account (FLOPROS database, Scussolini et. al, 2016[112]) representing the maximum return period (interpretable also as intensity of event) of flood that each country/ region can prevent. The global FLOPROS database consists of several layers: The consolidated or overall layer is called "Merged layer" which is a combination of three other layers: the "Design layer" combines empirical data about existing protection infrastructure; the "Policy layer" consists of data on protection standards and requirements set by policy measures; the "Model layer" is a model output from an observed relationship between gross domestic product per capita and flood protection. The design layer is considered the most reliable as it reports information on actual protection standards, while the other two layers are proxies of actual protection. This threshold procedure[113] implies that when the protection level (intended as the maximum return period) is exceeded, the flood occurs as if there was no initial protection, while below the threshold, no flooding takes place. For the final assessment, the high-resolution flood depth data from 0.3′ to a 2.5′ resolution (~5 km × 5 km) is re-aggregate 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 greater than zero.

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

[112] While the FLOPROS protection layer data has global coverage, it has limitations relative to quality of coverage (in particular EMDEs) and spatial resolution.

[113] Flopros 2015, Scussolini, P., Aerts, J. C. J. H., Jongman, B., Bouwer, L. M., Winsemius, H. C., de Moel, H., and Ward, P. J.: FLOPROS: an evolving global database of flood protection standards, Nat. Hazards Earth Syst. Sci., 16, 1049–1061, https://doi.org/10.5194/nhess-16-1049-2016, 2016. Tresholds (return frequencies) are displayed in figure 3 of the publication available under https://nhess.copernicus.org/articles/16/1049/2016/nhess-16-1049-2016.pdf

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[114] 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.

[114] Global Climate Models

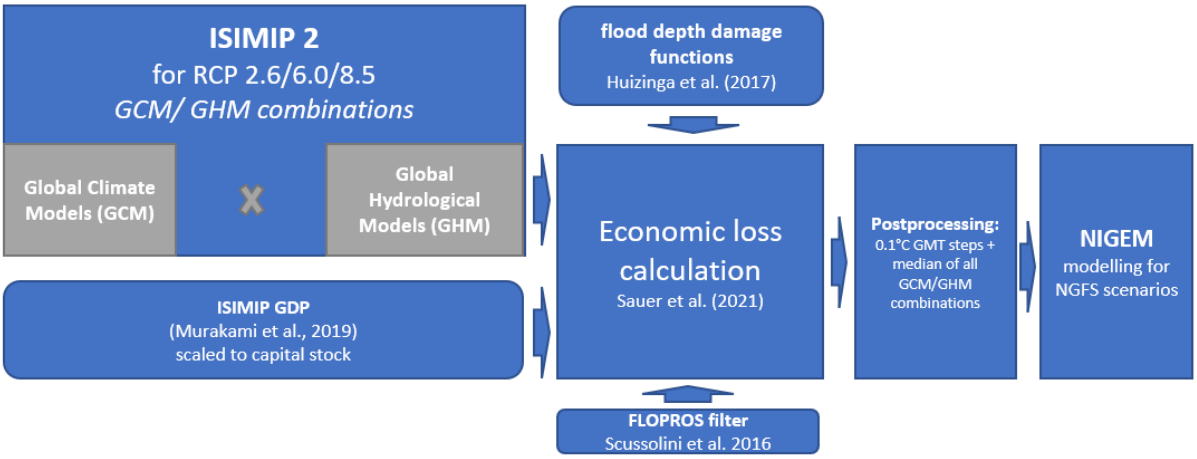
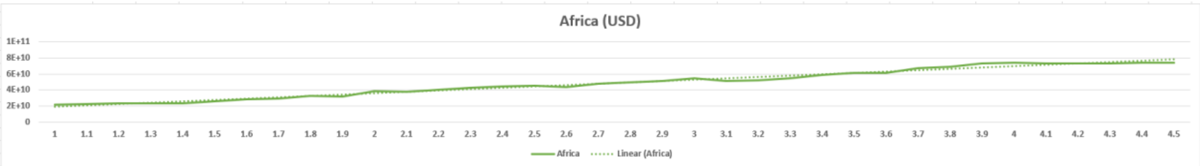
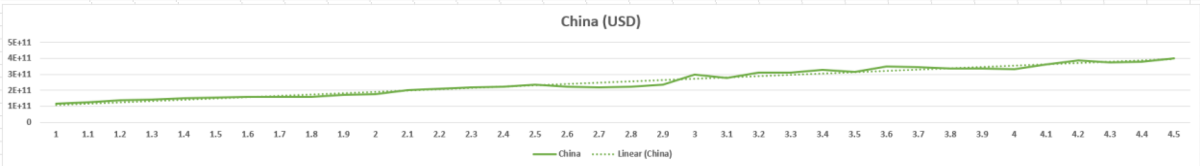
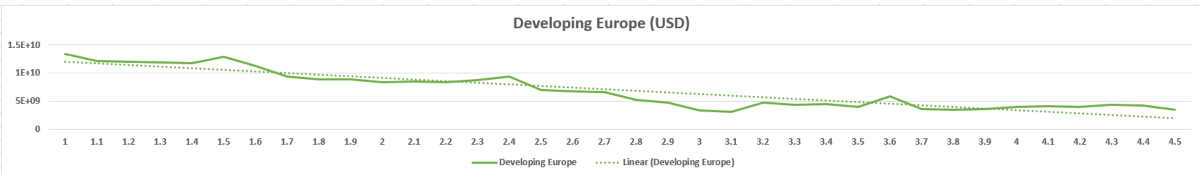


Figure 77. Modelling chain for flood per country/region losses based on ISIMIP2 data.

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 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.







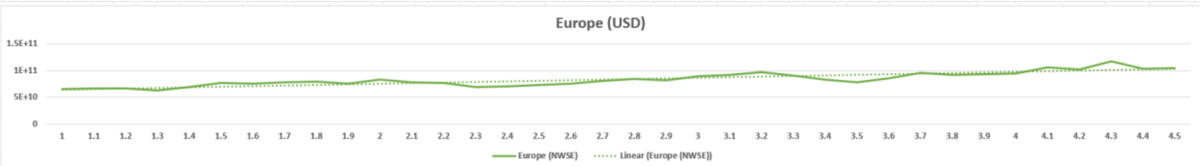


Figure 78. Flood loss (USD) for different warming levels for selected regions.

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).

3.4 Tropical cyclones damage modelling[115]

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*.

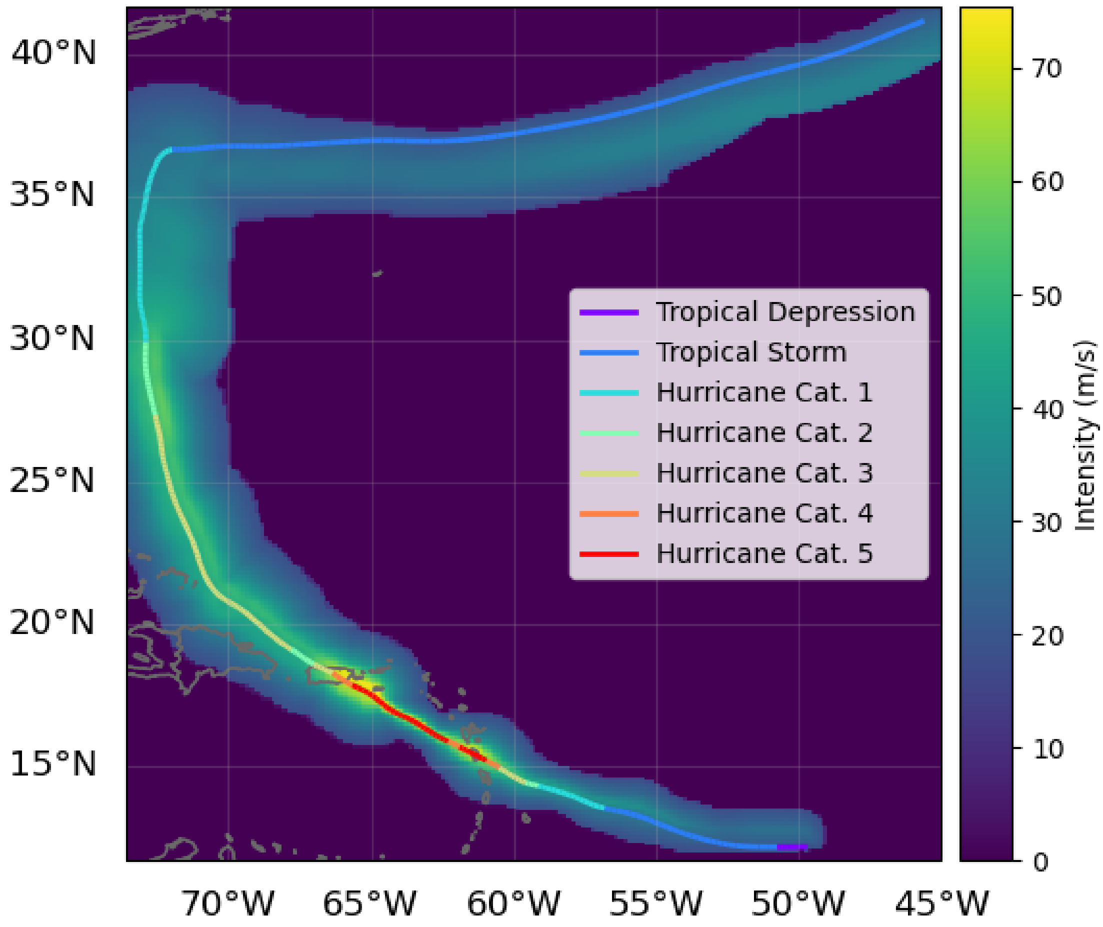


Figure 79 Track and wind field of tropical cyclone Maria (2017)

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[116].

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).

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

These functions were calibrated using EM-DAT loss data[117]. They are defined globally and are divided into 9 distinct regions*. Figure 80* shows the functions and regions.

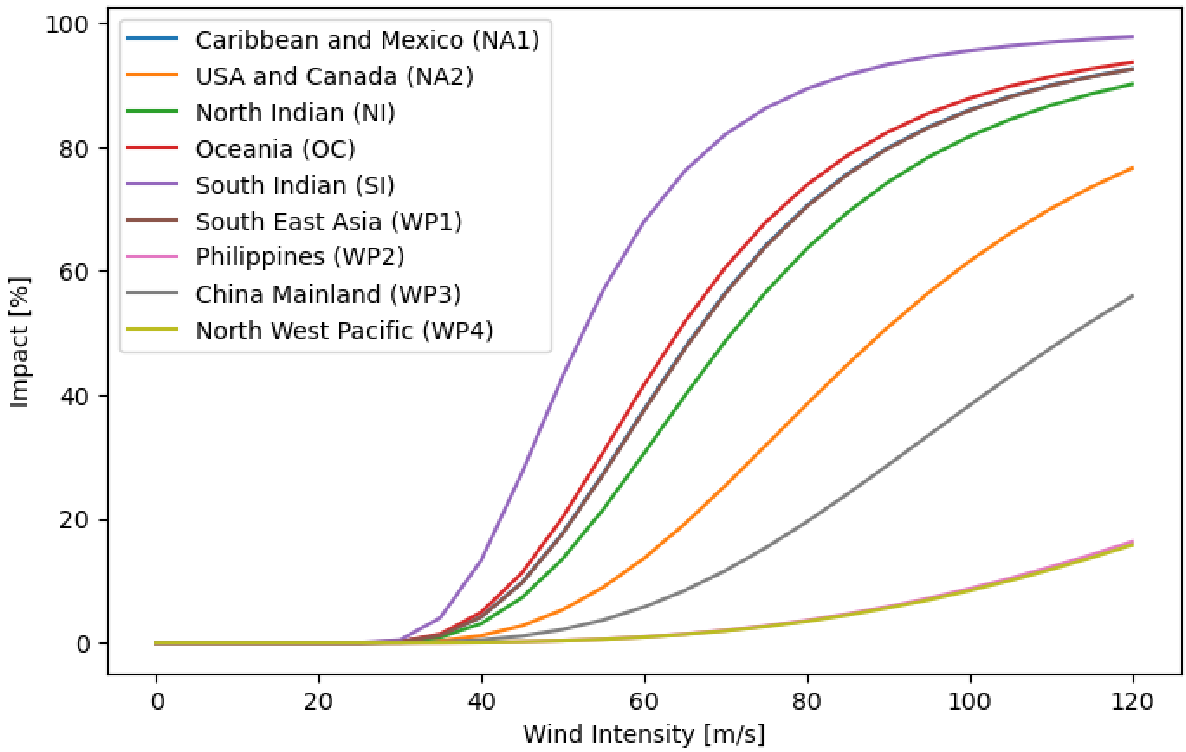


Figure 80. The calibrated impact functions as defined by Eberenz et al. (2021)

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.

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

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

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.

4. 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[118] 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.

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.

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[118] 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.

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[119] 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.

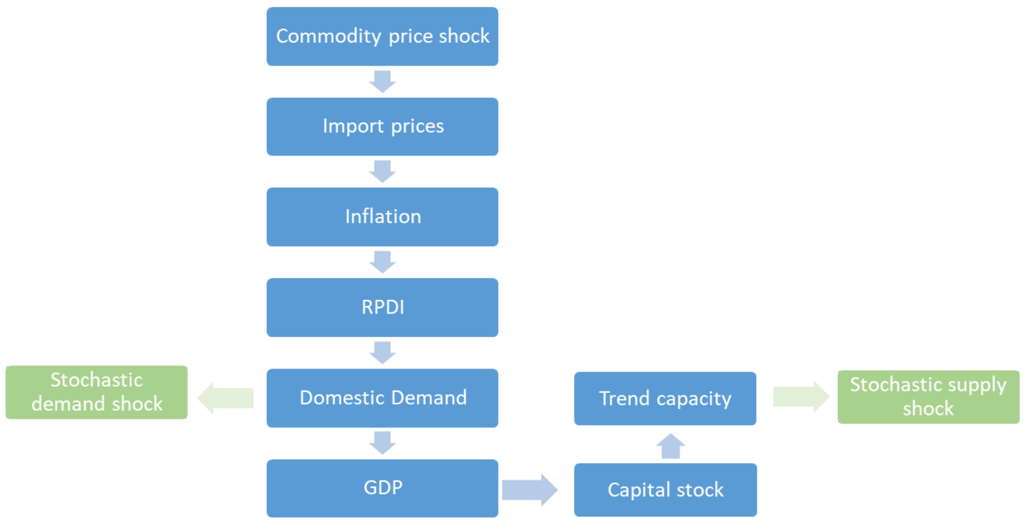


Figure 81.Example calibration shock process

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.

[119] 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.

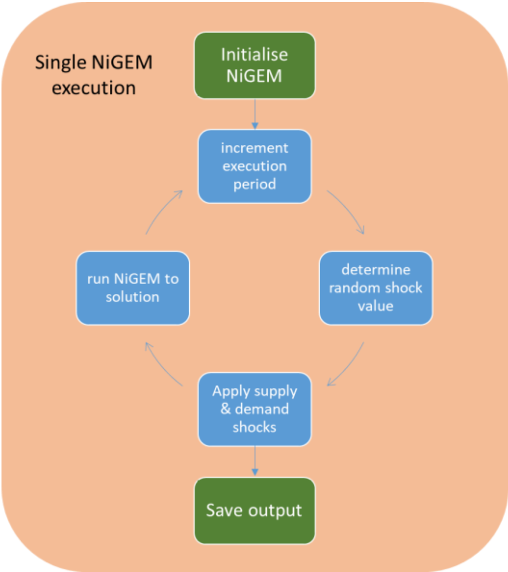


Figure 82. NiGEM stochastic execution

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.

5. Stochastic Implementation

5.1 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.

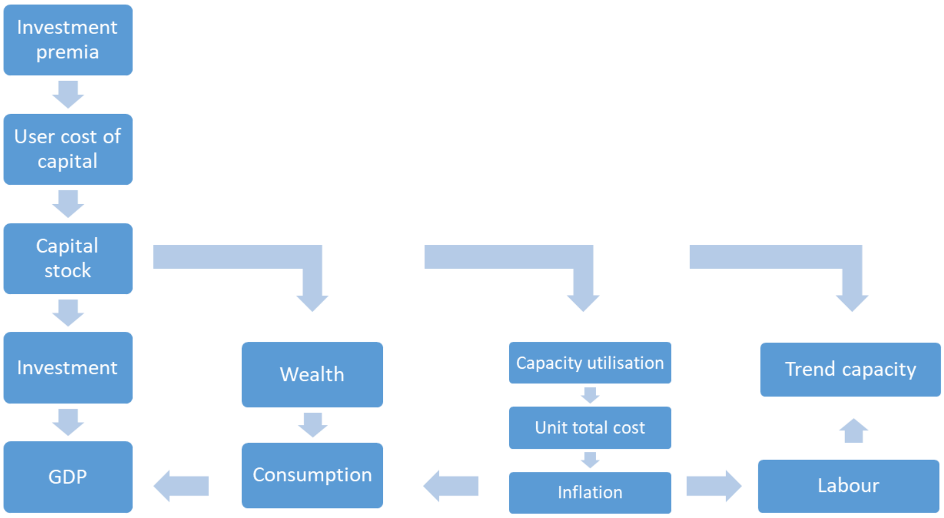


Figure 83. IPREM shock channels

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.

5.2 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.

5.3 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.

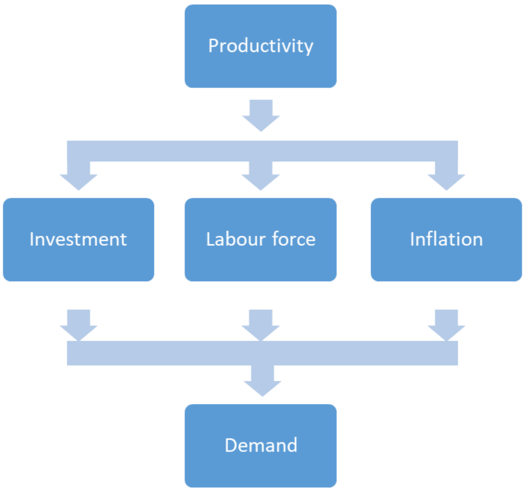


Figure 84. Productivity -- demand channels

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.

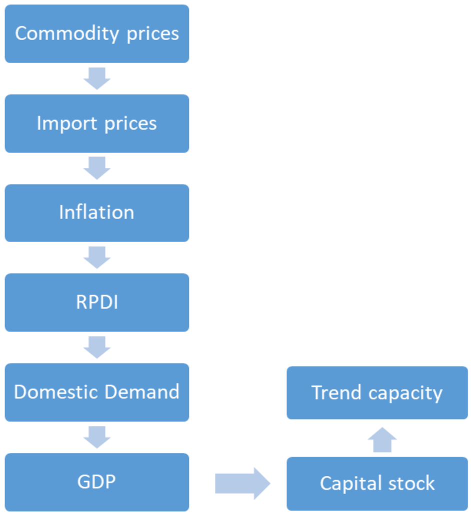


Figure 86. Prices transmission channel

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.

5.4 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[120].
    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

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

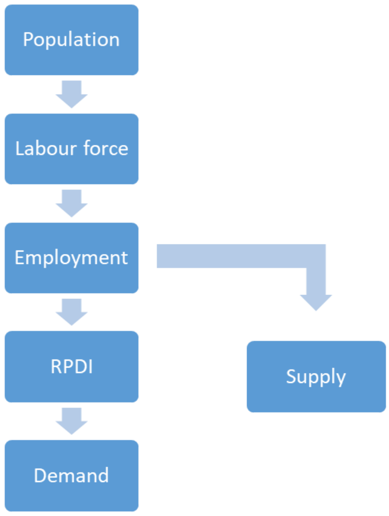


Figure 87. Population shock channels

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.

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 ***Figure*** *88*, the downscaling tool generates two pathways to provide results that are both consistent with historical data and IAMs results:[121]

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

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

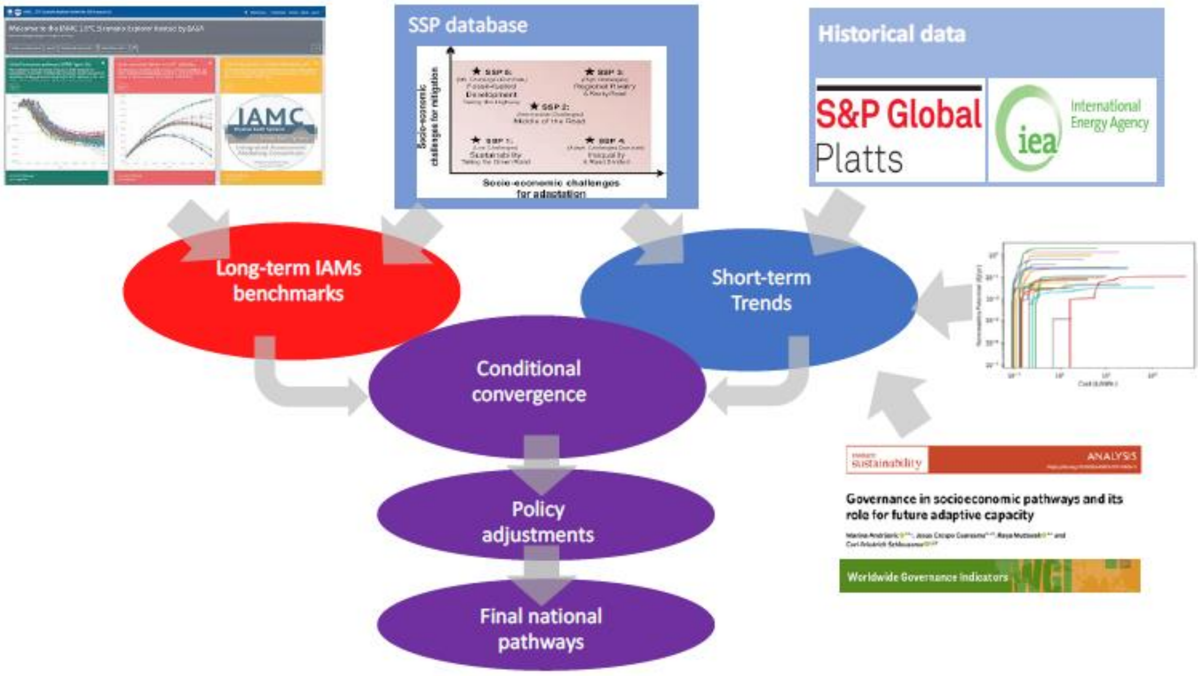


Figure 88. Conceptual framework for downscaling variables to the country level

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[122]
Delayed transition	Slow	SSP2
Fragmented World	Slow	SSP2
Low Energy Demand	Fast	SSP2
Net Zero 2050	Fast	SSP2
Current policies	Medium	SSP2

[122] Shared socioeconomic pathway.

NGFS Scenario	Convergence	SSP[122]
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

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.[123] 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

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

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 36**.

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

$$FEN_{c,t} = \frac{FEN_{c,t}}{GDP_{c,t}} \times \frac{GDP_{c,t}}{POP_{c,t}} \times POP_{c,t} \tag{3}$$

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***).

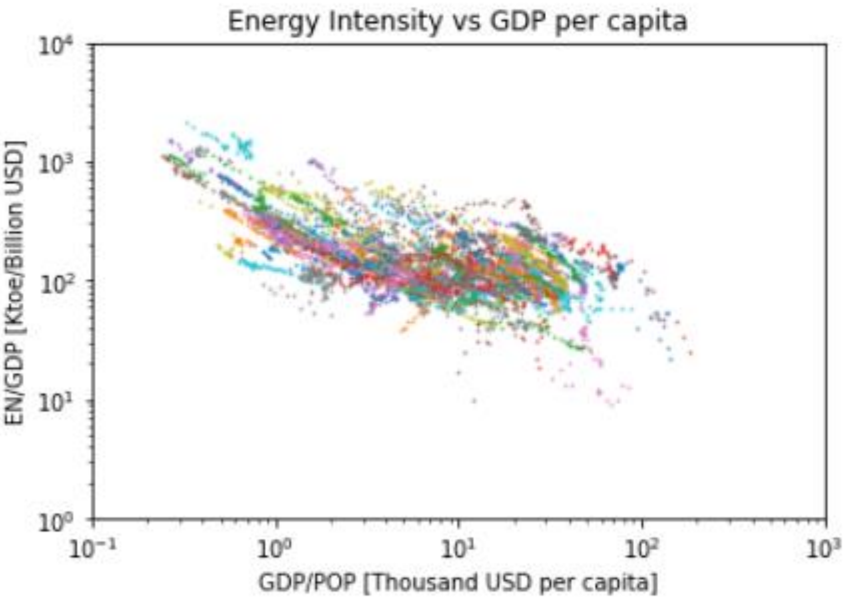


Figure 89. Historical energy intensities over GDP per capita across countries, from 1972 to 2017

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):

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

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).[124]
- 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

[124] 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.

intensities at the country level. Short-term projections are finally also harmonized 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 harmonized 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.

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:

- Harmonizing 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.[125]

To allocate **direct land use** emissions from IAMs at the country level, a two-step process is employed. For land use emissions, historical data are available until 2020. As a result, land use emissions are projected starting from 2020 *(t=0)* onwards. Firstly, the land use emissions in 2020 are initialized by using the average 2010-2020 data. Secondly, the change in land use emissions over time is distributed from regional IAM results to the country level using the following formulas: $share_c = \frac{abs(hist\_average\_direct\_LU_c)}{abs(\sum_c hist\_average\_direct\_LU_c)}$ (14)

$$delta\_direct\_LU_{r,t} = IAM\_direct\_LU_{r,t+1} - IAM\_direct\_LU_{r,t} \quad (15)$$

$$downscaled\_LU_{c,t} = hist\_average\_direct\_LU_{c,t0} + delta\_Direct\_LU_{r,t} * share_c \quad (16)$$

As land use (*LU*) emissions can exhibit positive or negative values, the absolute value of historical emissions shares is employed for allocating regional (*r*) data to the country level (*c*), for each time period (*t*).

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 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
SSP2 RCP 2.6	Delayed transition, Below 2°C
SSP2 RCP 3.4	Fragmented World, NDCs
SSP2 RCP 4.5	Current policies

[125] 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.

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.

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.

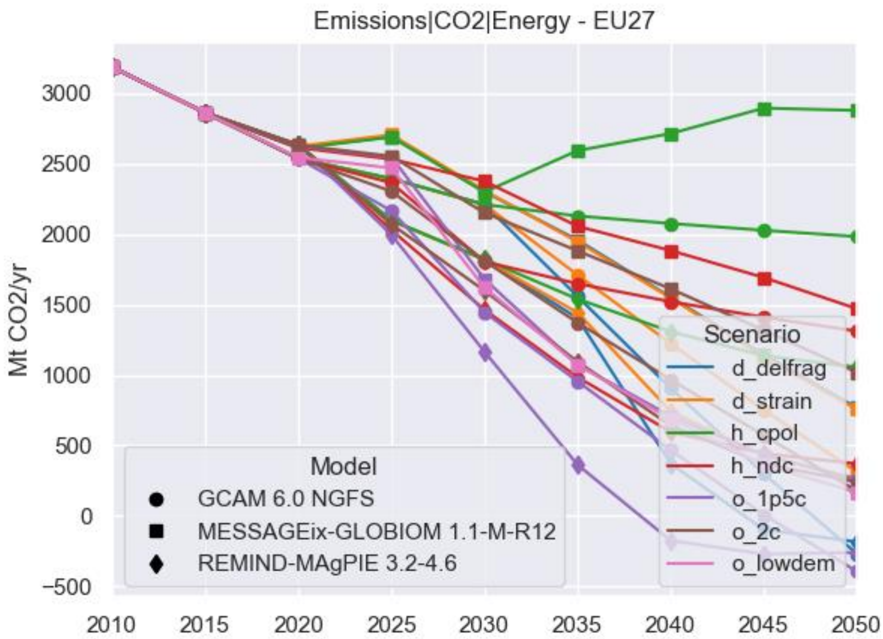


Figure 90. Energy related CO2 emissions in the EU27 region across models and scenarios

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 different assumptions regarding final energy demand, as shown in the graph in ***Figure 91*** below.

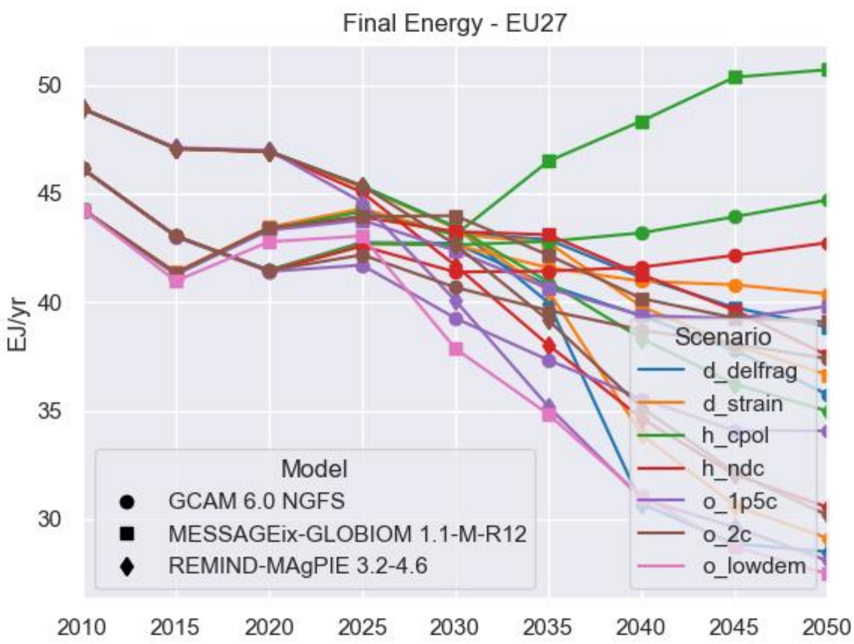
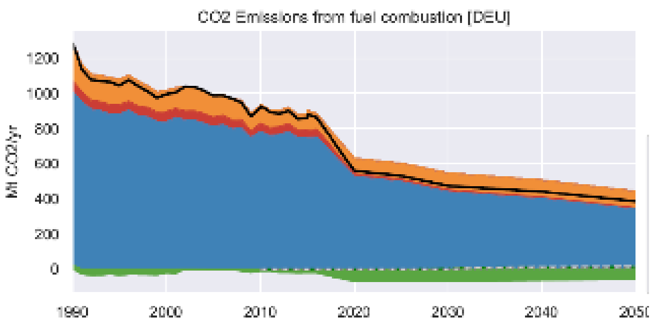


Figure 91. Final energy in the EU27 region across models and scenarios

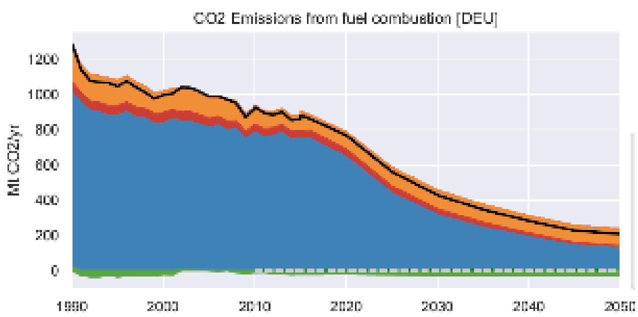
In **Table 36**, the list of output variables that are made available by the downscaling algorithm in the NGFS Phase IV Scenario Explorer for all individual countries[126] is provided. For convenience, subsectors are named up to a specific level. For the full trees of IAM- and input-dependent disposable 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



MESSAGE

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

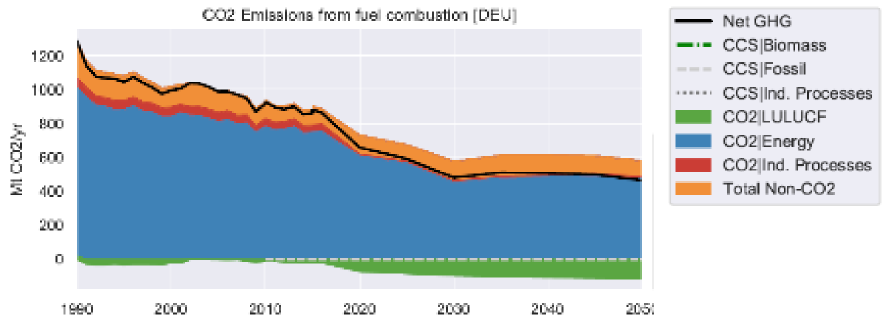


Figure 92. Germany's downscaled GHG emissions in the Current policies scenario across the three IAMs

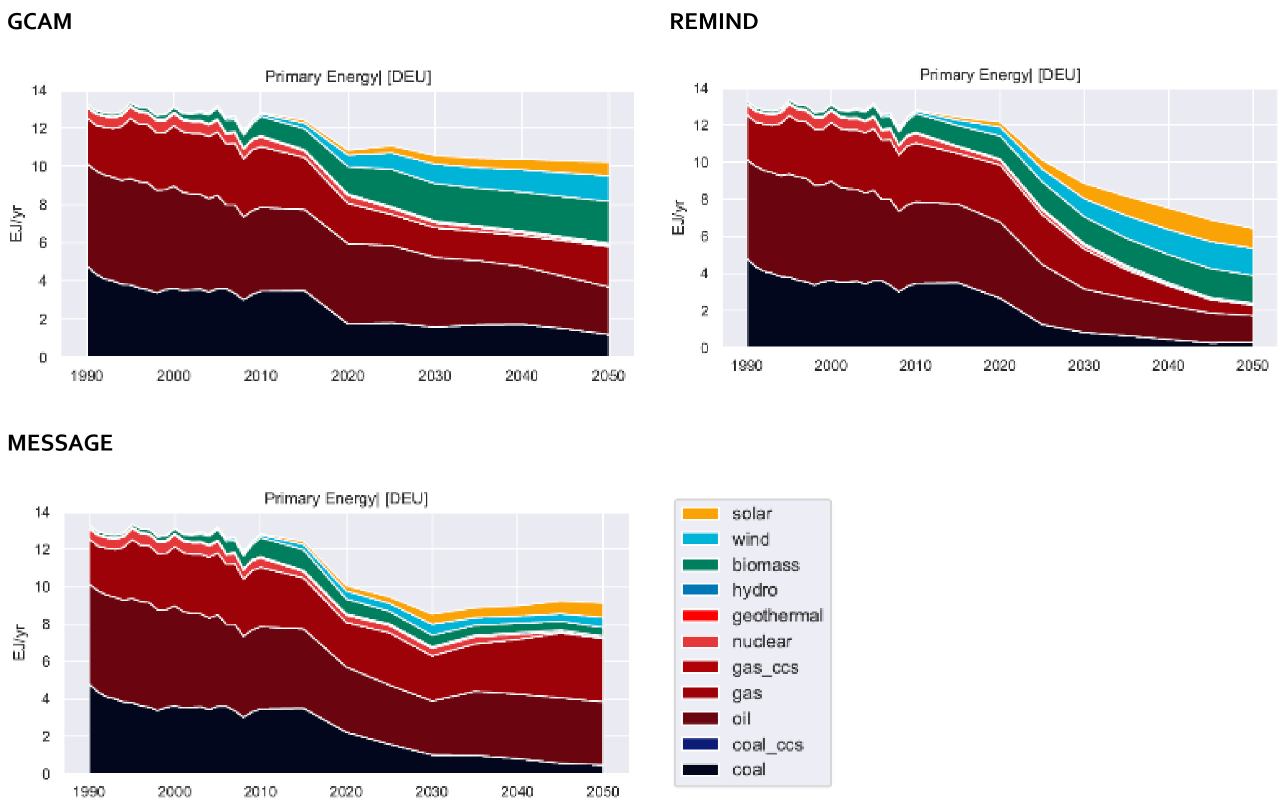


Figure 93. Germany's downscaled primary energy mix in the Current policies scenario across the three IAMs

5. What is new in the 2023 edition?

- **Non-CO2 GHG** emissions are linked with the GAINS (Greenhouse Gas – Air Pollution Interactions and Synergies) country-level results (Höglund-Isaksson *et al.*, 2020, Winiwarter *et al.*, 2018). 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. The country-level results from GAINS are interpolated and harmonized to be consistent with the regional IAMs pathways.

- **Accounting for the Grassi issue**: IAMs results do not consider indirect emissions from the land use sector. This leads to a mismatch of around 5.5 GtCO2e when comparing global IAMs results with aggregated national inventories (Grassi *et al*., 2021). To solve this issue, indirect emissions are added from land use to total GHG emissions, by applying regional growth rates – estimated by the IMAGE/LPJmL model – to the country level data. As these growth rates are influenced by global mean temperature, a scenario mapping is utilised that aligns the NGFS scenarios with the RCP emissions trajectory reported by Grassi *et al*., 2021 (see **Table 20**).

- **Benchmarking of variables to historic data rather than to IAM base year quantities.** Downscaled 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). Regarding the historical data sources, the IEA energy statistics (2022) are used for primary and secondary energy variables, and PRIMAP (Gütschow *et al*., 2021) for emissions.

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.

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 2023 edition?

Several country model were added (Malaysia, Croatia), or expanded from a reduced country model to a full country model (Romania, South Africa). Trade matrices and commodity equations updated to 2019 trade figures (from 2017). The modelling of acute physical risks was expanded (see also Module 6).

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 30 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)[127]. 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)[128].

NiGEM v1.23.2 currently forms part of the NGFS Phase IV 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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[127] 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

[128] 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).

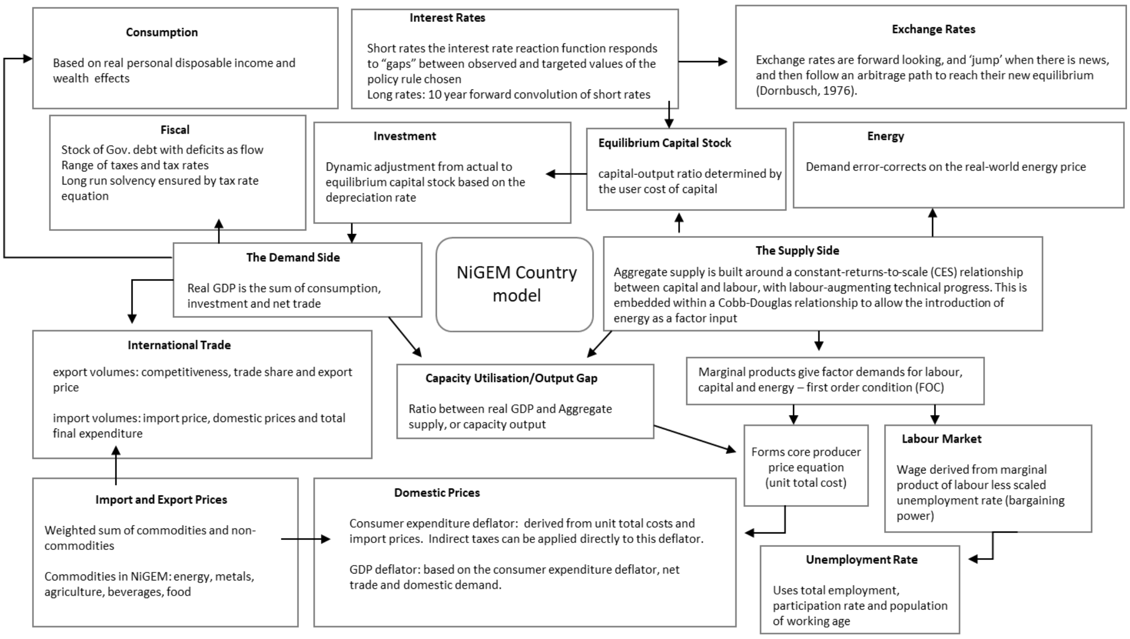

Figure 94. NiGEM country model structure

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.

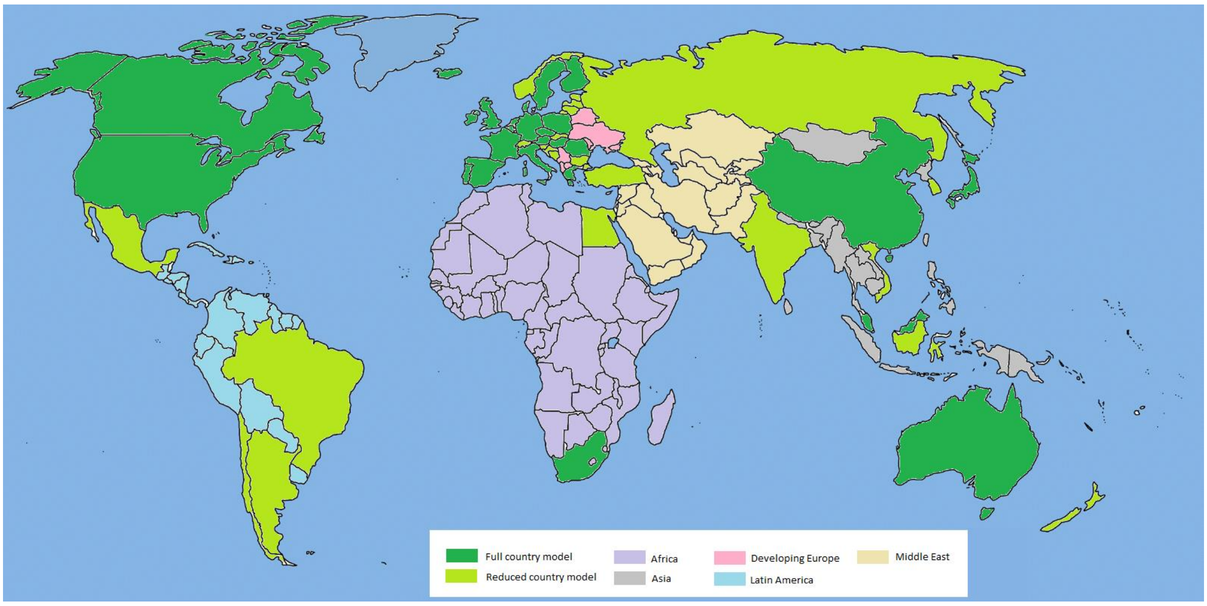

Figure 95. NiGEM coverage

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.

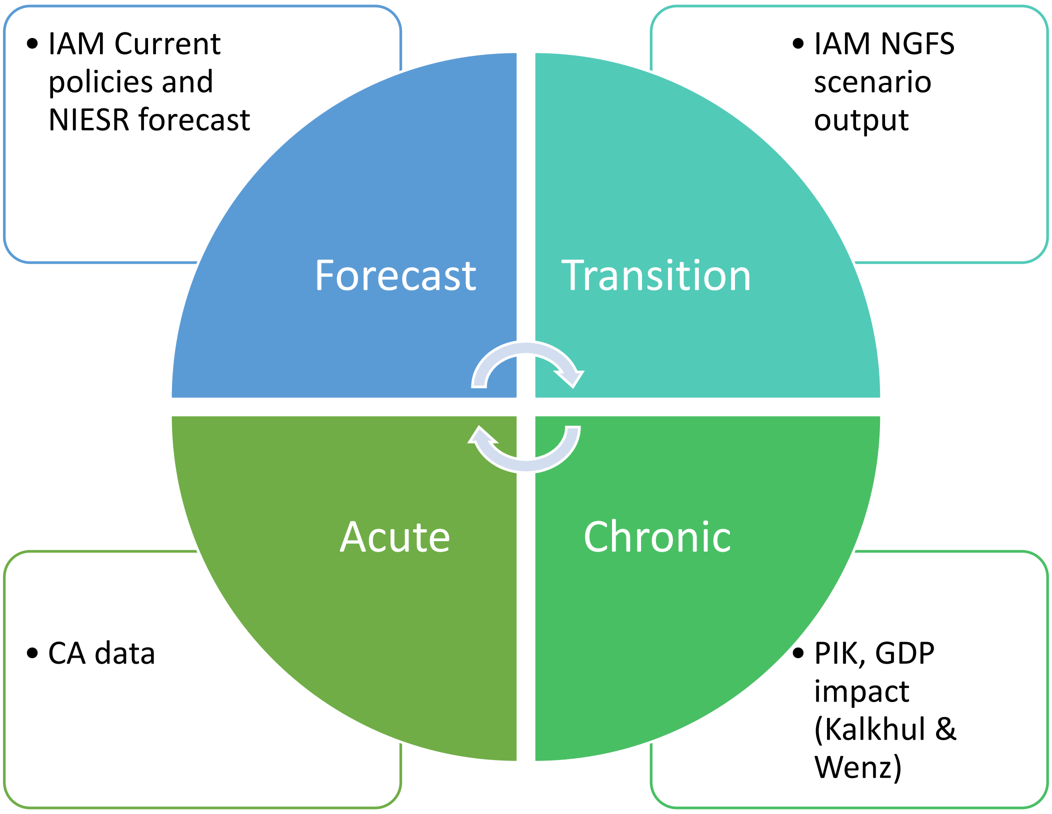

Figure 96. External data links with NiGEM

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 v1.23 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.

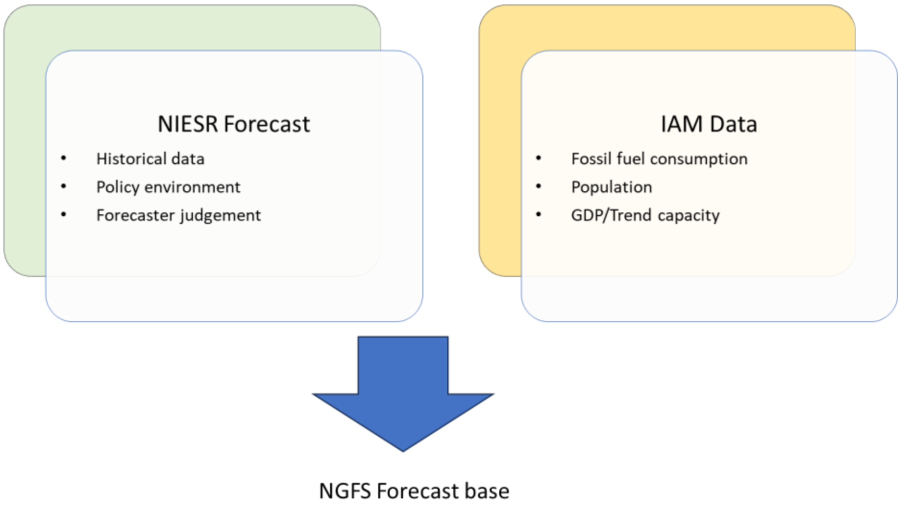

Figure 97. Creating the climate neutral forecast.

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.

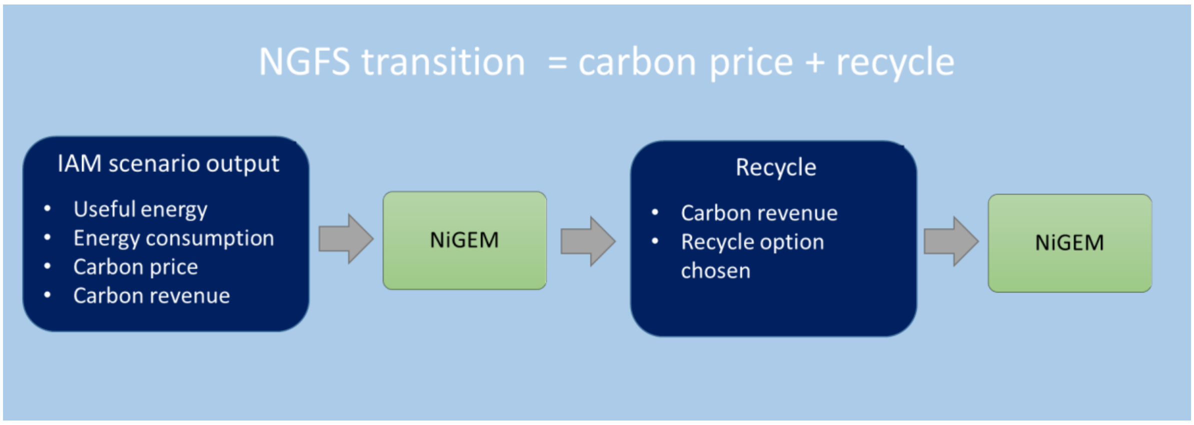

Figure 98. NiGEM transition risk scenario

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

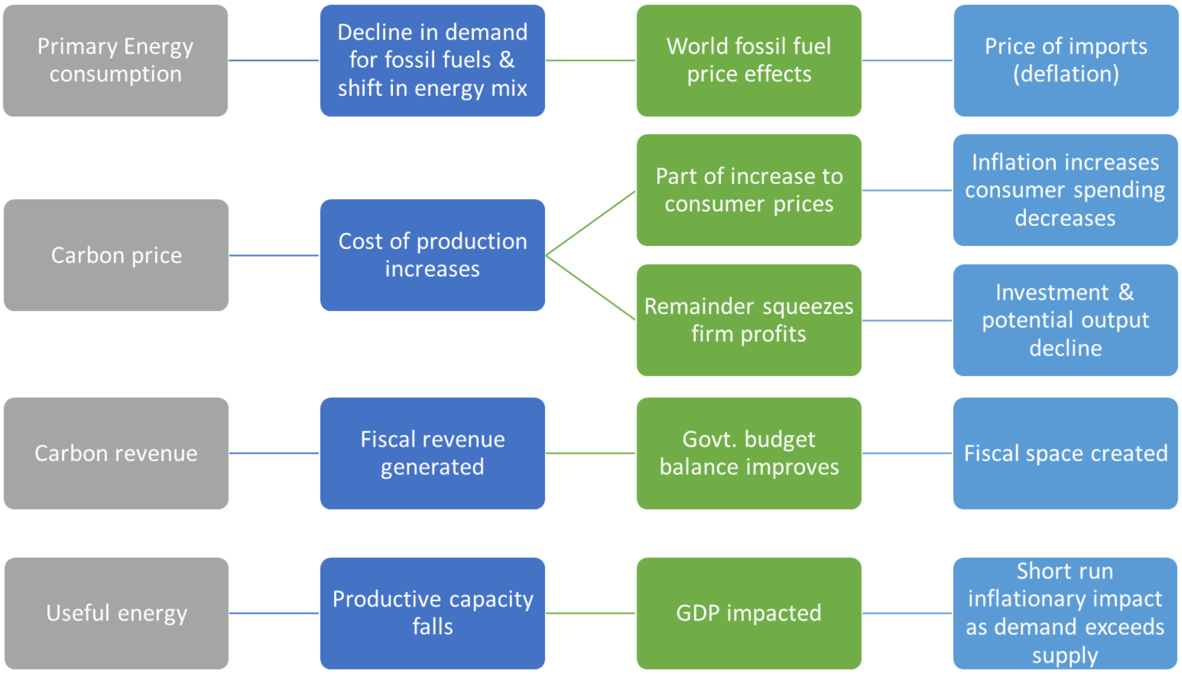

Figure 99. Transition risk channels from IAM inputs

The carbon price shock uses a combination of energy consumption, carbon tax revenue and useful energy[129] from the IAM scenario output to create the transition risk simulation connected to the application of a carbon

[129] 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

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 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.

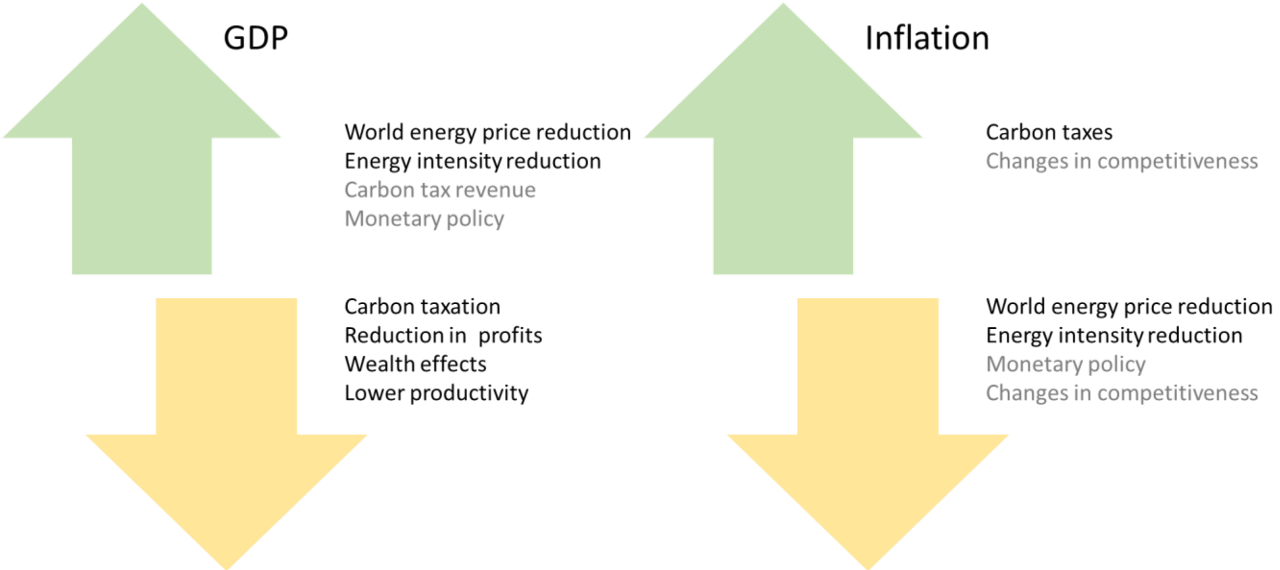

Figure 100.Factors affecting GDP and inflation.

3.3 Chronic physical impacts

The GDP percentage country damages for each scenario are provided directly by the Kalkuhl and Wenz damage function, as described in **section 5.2**.Those shocks are implemented in NiGEM to obtain the associated macrovariables paths..

3.4 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 [130].

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

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
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

130 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|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
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.

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 input variables

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

Table 25. 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
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

Name	Description	Type
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 26. 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)

Name	Description	Type
Municipal water cost	Price per unit of water delivered to municipalities	International Benchmarking Network for Water and Sanitation Utilities (IBNET)

Table 27. 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 28. 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

Name	Description	Type
GDP	GDP by country and year, used for 2025-2100	External data set

Table 29. 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
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

Name	Description	Type
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 30. 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
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

Name	Description	Type
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 31. 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)

Name	Description	Type
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 32. 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
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 33. Mapping from GCAM region to country

GCAM Region	Countries
Africa_Eastern	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda
Africa_Northern	Algeria, Egypt, Western Sahara, Libya, Morocco, Tunisia
Africa_Southern	Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe
Africa_Western	Benin, Burkina Faso, Central African Republic, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Cape Verde, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sao Tome and Principe, Chad, Togo
Argentina	Argentina
Australia_NZ	Australia, New Zealand
Brazil	Brazil
Canada	Canada
Central America and the Caribbean	Aruba, Anguilla, Netherlands Antilles, Antigua & Barbuda, Bahamas, Belize, Bermuda, Barbados, Costa Rica, Cuba, Cayman Islands, Dominica, Dominican Republic, Guadeloupe, Grenada, Guatemala, Honduras, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Montserrat, Martinique, Nicaragua, Panama, El Salvador, Trinidad and Tobago, Saint Vincent and the Grenadines
Central Asia	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Mongolia, Tajikistan, Turkmenistan, Uzbekistan
China	China
Colombia	Colombia
EU-12	Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovakia, Slovenia
EU-15	Andorra, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Monaco, Netherlands, Portugal, Sweden, Spain, United Kingdom
Europe_Eastern	Belarus, Moldova, Ukraine
European Free Trade Association	Iceland, Norway, Switzerland
Europe_Non_EU	Albania, Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, Turkey
India	India
Indonesia	Indonesia
Japan	Japan

GCAM Region	Countries
Mexico	Mexico
Middle East	United Arab Emirates, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Yemen
Pakistan	Pakistan
Russia	Russia
South Africa	South Africa
South America_Northern	French Guiana, Guyana, Suriname, Venezuela
South America_Southern	Bolivia, Chile, Ecuador, Peru, Paraguay, Uruguay
South Asia	Afghanistan, Bangladesh, Bhutan, Sri Lanka, Maldives, Nepal
Southeast Asia	American Samoa, Brunei Darussalam, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Federated States of Micronesia, Guam, Cambodia, Kiribati, Lao Peoples Democratic Republic, Marshall Islands, Myanmar, Northern Mariana Islands, Malaysia, Mayotte, New Caledonia, Norfolk Island, Niue, Nauru, Pacific Islands Trust Territory, Pitcairn Islands, Philippines, Palau, Papua New Guinea, Democratic People's Republic of Korea, French Polynesia, Singapore, Solomon Islands, Seychelles, Thailand, Tokelau, Timor Leste, Tonga, Tuvalu, Viet Nam, Vanuatu, Samoa
South Korea	South Korea
Taiwan	Taiwan
USA	United States

Table 34. NGFS Phase IV Scenario Explorer IAM sector output

Sector	Subsector	Variable	IAM[131]		
Agricultural Demand		Agricultural Demand (TOTAL)	G	M	R
Agricultural Demand	Crops	Crops (TOTAL)	G	M	R
Agricultural Demand	Crops	Energy (TOTAL)	G	M	
Agricultural Demand	Crops	Feed	G	M	
Agricultural Demand	Crops	Food		M	R
Agricultural Demand	Crops	Other	G	M	R
Agricultural Demand	Livestock	Livestock (TOTAL)	G	M	R
Agricultural Demand	Livestock	Food		M	R
Agricultural Demand	Livestock	Other	G	M	R
Agricultural Production		Agricultural Production (TOTAL)		M	R
Agricultural Production	Energy	Energy (TOTAL)		M	R
Agricultural Production	Energy	Crops (TOTAL)		M	R
Agricultural Production	Energy	Residues			R
Agricultural Production	Non-Energy	Non-Energy (TOTAL)		M	R
Agricultural Production	Non-Energy	Crops (TOTAL)		M	R
Agricultural Production	Non-Energy	Livestock (TOTAL)		M	R
Capacity Additions	Electricity	Biomass (TOTAL)	G	M	R
Capacity Additions	Electricity	Biomass w/ CCS	G	M	R
Capacity Additions	Electricity	Biomass w/o CCS	G	M	R
Capacity Additions	Electricity	Coal (TOTAL)	G	M	R
Capacity Additions	Electricity	Coal w/ CCS	G	M	R
Capacity Additions	Electricity	Coal w/o CCS	G	M	R
Capacity Additions	Electricity	Gas (TOTAL)	G	M	R
Capacity Additions	Electricity	Gas w/ CCS	G	M	R
Capacity Additions	Electricity	Gas w/o CCS	G	M	R
Capacity Additions	Electricity	Geothermal	G	M	R
Capacity Additions	Electricity	Hydro			R
Capacity Additions	Electricity	Nuclear	G	M	R
Capacity Additions	Electricity	Oil (TOTAL)	G	M	R
Capacity Additions	Electricity	Oil w/o CCS	G	M	

[131] G = GCAM, M = MESSAGE-GLOBIOM, R = REMIND-MAgPIE

Sector	Subsector	Variable	IAM131		
Capacity Additions	Electricity	Solar (TOTAL)	G	M	R
Capacity Additions	Electricity	Solar CSP	G	M	R
Capacity Additions	Electricity	Solar PV	G	M	R
Capacity Additions	Electricity	Wind (TOTAL)	G	M	R
Capacity Additions	Electricity	Wind Offshore	G	M	R
Capacity Additions	Electricity	Wind Onshore	G	M	R
Capacity	Electricity	Electricity (TOTAL)	G	M	R
Capacity	Electricity	Biomass (TOTAL)	G	M	R
Capacity	Electricity	Biomass w/ CCS	G	M	R
Capacity	Electricity	Biomass w/o CCS	G	M	R
Capacity	Electricity	Coal (TOTAL)	G	M	R
Capacity	Electricity	Coal w/ CCS	G	M	R
Capacity	Electricity	Coal w/o CCS	G	M	R
Capacity	Electricity	Gas (TOTAL)	G	M	R
Capacity	Electricity	Gas w/ CCS	G	M	R
Capacity	Electricity	Gas w/o CCS	G	M	R
Capacity	Electricity	Geothermal	G	M	R
Capacity	Electricity	Hydro	G	M	R
Capacity	Electricity	Nuclear	G	M	R
Capacity	Electricity	Oil (TOTAL)	G	M	R
Capacity	Electricity	Oil w/o CCS	G	M	R
Capacity	Electricity	Other			R
Capacity	Electricity	Solar (TOTAL)	G	M	R
Capacity	Electricity	Solar CSP	G	M	R
Capacity	Electricity	Solar PV	G	M	R
Capacity	Electricity	Storage			R
Capacity	Electricity	Wind (TOTAL)	G	M	R
Capacity	Electricity	Wind Offshore	G	M	R
Capacity	Electricity	Wind Onshore	G	M	R
Capacity	Gases	Gases (TOTAL)		M	R
Capacity	Gases	Biomass (TOTAL)		M	R
Capacity	Gases	Biomass w/o CCS		M	
Capacity	Gases	Coal(TOTAL)		M	R
Capacity	Gases	Coal w/o CCS		M	
Capacity	Hydrogen	Hydrogen (TOTAL)		M	R
Capacity	Hydrogen	Biomass (TOTAL)		M	R
Capacity	Hydrogen	Biomass w/ CCS		M	R
Capacity	Hydrogen	Biomass w/o CCS		M	R
Capacity	Hydrogen	Coal (TOTAL)		M	R

Sector	Subsector	Variable	IAM131		
Capacity	Hydrogen	Coal w/ CCS		M	R
Capacity	Hydrogen	Coal w/o CCS		M	R
Capacity	Hydrogen	Electricity (TOTAL)		M	R
Capacity	Hydrogen	Gas (TOTAL)		M	R
Capacity	Hydrogen	Gas w/ CCS		M	R
Capacity	Hydrogen	Gas w/o CCS		M	R
Capacity	Liquids	Liquids (TOTAL)		M	R
Capacity	Liquids	Biomass (TOTAL)		M	R
Capacity	Liquids	Biomass w/ CCS		M	
Capacity	Liquids	Biomass w/o CCS		M	
Capacity	Liquids	Coal (TOTAL)		M	R
Capacity	Liquids	Coal w/ CCS		M	
Capacity	Liquids	Coal w/o CCS		M	
Capacity	Liquids	Gas (TOTAL)		M	
Capacity	Liquids	Gas w/ CCS		M	
Capacity	Liquids	Gas w/o CCS		M	
Capacity	Liquids	Oil (TOTAL)		M	R
Capital Cost	Electricity	Biomass w/ CCS	G		R
Capital Cost	Electricity	Biomass w/o CCS	G		R
Capital Cost	Electricity	Coal w/ CCS	G		R
Capital Cost	Electricity	Coal w/o CCS	G		R
Capital Cost	Electricity	Gas w/ CCS	G		R
Capital Cost	Electricity	Gas w/o CCS	G		R
Capital Cost	Electricity	Geothermal	G	M	R
Capital Cost	Electricity	Nuclear	G	M	R
Capital Cost	Electricity	Solar CSP	G		R
Capital Cost	Electricity	Solar PV	G	M	R
Capital Cost	Electricity	Wind Offshore	G	M	R
Capital Cost	Electricity	Wind Onshore	G	M	R
Carbon Sequestration	CCS	CCS (TOTAL)	G	M	R
Carbon Sequestration	CCS	Biomass (TOTAL)	G	M	R
Carbon Sequestration	CCS	Biomass Energy Demand Industry	G		R
Carbon Sequestration	CCS	Biomass Energy Supply (TOTAL)	G	M	R
Carbon Sequestration	CCS	Biomass Energy Supply Electricity	G	M	R
Carbon Sequestration	CCS	Biomass Energy Supply Hydrogen	G	M	R
Carbon Sequestration	CCS	Biomass Energy Supply Liquids	G	M	R
Carbon Sequestration	CCS	Fossil (TOTAL)	G	M	R
Carbon Sequestration	CCS	Fossil Energy Demand Industry	G		
Carbon Sequestration	CCS	Fossil Energy Supply (TOTAL)	G	M	R

Sector	Subsector	Variable	IAM131		
Carbon Sequestration	CCS	Fossil Energy Supply Electricity	G	M	R
Carbon Sequestration	CCS	Fossil Energy Supply Hydrogen	G	M	R
Carbon Sequestration	CCS	Fossil Energy Supply Liquids		M	R
Carbon Sequestration	CCS	Industrial Processes	G	M	R
Carbon Sequestration	Land Use	Land Use (TOTAL)		M	R
Carbon Sequestration	Land Use	Afforestation		M	R
Emissions	BC	BC (TOTAL)	G	M	R
Emissions	BC	AFOLU	G	M	R
Emissions	BC	Energy (TOTAL)	G	M	R
Emissions	BC	Energy Demand Industry	G	M	R
Emissions	BC	Energy Demand Residential and Commercial	G	M	R
Emissions	BC	Energy Demand Transportation	G	M	R
Emissions	BC	Energy Supply	G	M	R
Emissions		C_2F_6	G		R
Emissions		CF_4	G	M	R
Emissions	CH_4	CH_4 (TOTAL)	G	M	R
Emissions	CH_4	AFOLU	G	M	R
Emissions	CH_4	Energy (TOTAL)	G	M	
Emissions	CH_4	Energy Demand Industry	G	M	
Emissions	CH_4	Energy Demand Residential and Commercial	G	M	
Emissions	CH_4	Energy Demand Transportation	G	M	
Emissions	CH_4	Energy Supply	G	M	R
Emissions	CH_4	Other	G		
Emissions	CO	CO (TOTAL)	G	M	R
Emissions	CO	AFOLU	G	M	R
Emissions	CO	Energy (TOTAL)	G	M	R
Emissions	CO	Energy Demand Industry	G	M	R
Emissions	CO	Energy Demand Residential and Commercial	G	M	R
Emissions	CO	Energy Demand Transportation	G	M	R
Emissions	CO	Energy Supply	G	M	R
Emissions	CO_2	CO_2 (TOTAL)	G	M	R
Emissions	CO_2	AFOLU	G	M	R
Emissions	CO_2	Energy (TOTAL)	G	M	R
Emissions	CO_2	Energy and Industrial Processes (TOTAL)		M	R
Emissions	CO_2	Energy Demand (TOTAL)	G	M	R
Emissions	CO_2	Energy Demand Industry (TOTAL)	G	M	R
Emissions	CO_2	Energy Demand Industry Cement	G	M	R
Emissions	CO_2	Energy Demand Industry Chemicals (TOTAL)	G	M	R
Emissions	CO_2	Energy Demand Industry Chemicals Ammonia	G		

Sector	Subsector	Variable	IAM131		
Emissions	CO_2	Energy Demand Industry Non-ferrous metals	G	M	
Emissions	CO_2	Energy Demand Industry Other	G		R
Emissions	CO_2	Energy Demand Industry Steel	G	M	R
Emissions	CO_2	Energy Demand Residential and Commercial (TOTAL)	G	M	R
Emissions	CO_2	Energy Demand Residential and Commercial (Commercial)	G		
Emissions	CO_2	Energy Demand Residential and Commercial (Residential)	G		
Emissions	CO_2	Energy Demand Transportation (TOTAL)	G	M	R
Emissions	CO_2	Energy Demand Transportation Freight	G		
Emissions	CO_2	Energy Demand Transportation Passenger	G		
Emissions	CO_2	Energy Demand Transportation|Aviation|Passenger			
Emissions	CO_2	Energy Demand Maritime|Freight			
Emissions	CO_2	Energy Demand Transportation Rail Freight			R
Emissions	CO_2	Energy Demand Transportation Rail Passenger			R
Emissions	CO_2	Energy Demand Transportation Road			R
Emissions	CO_2	Energy Demand Transportation Road Freight			R
Emissions	CO_2	Energy Demand Transportation Road Passenger			R
Emissions	CO_2	Energy Demand Transportation Road Passenger Bus			R
Emissions	CO_2	Energy Demand Transportation Road Passenger LDV			R
Emissions	CO_2	Energy Demand Transportation Rail Freight			R
Emissions	CO_2	Energy Supply (TOTAL)	G	M	R
Emissions	CO_2	Energy Supply Electricity	G	M	R
Emissions	CO_2	Energy Supply Gases	G	M	R
Emissions	CO_2	Energy Supply Heat	G	M	R
Emissions	CO_2	Energy Supply Liquids	G	M	R
Emissions	CO_2	Energy Supply Other Sector			R
Emissions	CO_2	Energy Supply Solids	G	M	R
Emissions	CO_2	Energy and Industrial Processes	G		
Emissions	CO_2	Industrial Processes	G	M	R
Emissions		F-Gases	G	M	R
Emissions	HFC	HFC (TOTAL)	G	M	R
Emissions	HFC	HFC125	G	M	
Emissions	HFC	HFC134a	G	M	
Emissions	HFC	HFC143a	G	M	
Emissions	HFC	HFC227ea	G	M	
Emissions	HFC	HFC23	G	M	
Emissions	HFC	HFC245fa	G	M	

Sector	Subsector	Variable	IAM131		
Emissions	HFC	HFC32	G	M	
Emissions	Kyoto Gases	Kyoto Gases (TOTAL)	G	M	R
Emissions	Kyoto Gases	AFOLU	G	M	R
Emissions	Kyoto Gases	Cement	G		
Emissions	Kyoto Gases	Chemicals	G		
Emissions	Kyoto Gases	Electricity	G		
Emissions	Kyoto Gases	Industry	G		R
Emissions	Kyoto Gases	Other	G		
Emissions	Kyoto Gases	Other Energy Supply	G		
Emissions	Kyoto Gases	Other Industry	G		
Emissions	Kyoto Gases	Residential and Commercial	G		R
Emissions	Kyoto Gases	Steel	G		
Emissions	Kyoto Gases	Supply	G		R
Emissions	Kyoto Gases	Transportation	G		R
Emissions	N2O	N2O (TOTAL)	G	M	R
Emissions	N2O	AFOLU	G	M	R
Emissions	N2O	Energy	G	M	
Emissions	N2O	Other	G		
Emissions	NH3	NH3 (TOTAL)	G	M	R
Emissions	NH3	AFOLU	G	M	R
Emissions	NH3	Energy (TOTAL)	G	M	R
Emissions	NH3	Energy Demand Industry	G	M	R
Emissions	NH3	Energy Demand Residential and Commercial	G	M	R
Emissions	NH3	Energy Demand Transportation	G	M	R
Emissions	NH3	Energy Supply	G	M	R
Emissions	NH3	Other			R
Emissions	NH3	Waste			R
Emissions	NOx	NOx (TOTAL)	G	M	R
Emissions	NOx	AFOLU	G	M	R
Emissions	NOx	Energy (TOTAL)	G	M	R
Emissions	NOx	Energy Demand Industry	G	M	R
Emissions	NOx	Energy Demand Residential and Commercial	G	M	R
Emissions	NOx	Energy Demand Transportation	G	M	R
Emissions	NOx	Energy Supply	G	M	R
Emissions	NOx	Other			R
Emissions	NOx	Waste			R
Emissions	OC	OC (TOTAL)	G	M	R
Emissions	OC	AFOLU	G	M	R
Emissions	OC	Energy (TOTAL)	G	M	R

Sector	Subsector	Variable	IAM131		
Emissions	OC	Energy Demand Industry	G	M	R
Emissions	OC	Energy Demand Residential and Commercial	G	M	R
Emissions	OC	Energy Demand Transportation	G	M	R
Emissions	OC	Energy Supply	G	M	R
Emissions	OC	Other			R
Emissions	OC	Waste			R
Emissions		PFC	G		
Emissions		SF6	G	M	R
Emissions	Sulfur	Sulfur (TOTAL)	G	M	R
Emissions	Sulfur	AFOLU	G	M	R
Emissions	Sulfur	Energy (TOTAL)	G	M	R
Emissions	Sulfur	Energy Demand Industry	G	M	R
Emissions	Sulfur	Energy Demand Residential and Commercial	G	M	R
Emissions	Sulfur	Energy Demand Transportation	G	M	R
Emissions	Sulfur	Energy Supply	G	M	R
Emissions	Sulfur	Other			R
Emissions	Sulfur	Waste			R
Emissions	VOC	VOC (TOTAL)	G	M	R
Emissions	VOC	AFOLU	G	M	R
Emissions	VOC	Energy (TOTAL)	G	M	R
Emissions	VOC	Energy Demand Industry	G	M	R
Emissions	VOC	Energy Demand Residential and Commercial	G	M	R
Emissions	VOC	Energy Demand Transportation	G	M	R
Emissions	VOC	Energy Supply	G	M	R
Emissions	VOC	Other			R
Emissions	VOC	Waste			R
Fertilizer Use	Nitrogen	Nitrogen (TOTAL)		M	
Fertilizer Use	Phosphorus	Phosphorus (TOTAL)		M	
Energy Service	Residential and Commercial	Floor Space	G		
Energy Service	Residential and Commercial	Residential Floor Space	G		
Energy Service	Transportation	Aviation	G		
Energy Service	Transportation	Freight (TOTAL)	G		
Energy Service	Transportation	Freight International Shipping	G		
Energy Service	Transportation	Freight Road	G		
Energy Service	Transportation	Passenger (TOTAL)	G		
Energy Service	Transportation	Passenger Aviation	G		
Energy Service	Transportation	Passenger Bicycling and Walking	G		
Energy Service	Transportation	Rail	G		
Energy Service	Transportation	Road	G		

Sector	Subsector	Variable	IAM131		
Final Energy		Final Energy (TOTAL)	G	M	R
Final Energy		Electricity	G	M	R
Final Energy	Gases	Gases (TOTAL)	G	M	R
Final Energy		Heat	G	M	R
Final Energy		Hydrogen	G	M	R
Final Energy	Industry	Industry (TOTAL)	G	M	R
Final Energy	Industry	Cement (TOTAL)	G	M	R
Final Energy	Industry	Cement Electricity	G	M	R
Final Energy	Industry	Cement Gases		M	R
Final Energy	Industry	Cement Hydrogen		M	R
Final Energy	Industry	Cement Liquids		M	R
Final Energy	Industry	Cement Liquids Bioenergy		M	
Final Energy	Industry	Cement Liquids Fossil		M	
Final Energy	Industry	Cement Solids		M	R
Final Energy	Industry	Cement Solids Bioenergy		M	
Final Energy	Industry	Cement Solids Fossil		M	
Final Energy	Industry	Chemicals High value chemicals		M	
Final Energy	Industry	Chemicals High value chemicals Electricity		M	
Final Energy	Industry	Chemicals High value chemicals Gases		M	
Final Energy	Industry	Chemicals High value chemicals Heat		M	
Final Energy	Industry	Chemicals High value chemicals Hydrogen		M	
Final Energy	Industry	Chemicals High value chemicals Liquids		M	
Final Energy	Industry	Chemicals High value chemicals Liquids Bioenergy		M	
Final Energy	Industry	Chemicals High value chemicals Liquids Fossil		M	
Final Energy	Industry	Chemicals High value chemicals Solids		M	
Final Energy	Industry	Chemicals High value chemicals Solids Bioenergy		M	
Final Energy	Industry	Chemicals High value chemicals Solids Fossil		M	
Final Energy	Industry	Chemicals (TOTAL)	G		R
Final Energy	Industry	Chemicals Ammonia (TOTAL)	G		
Final Energy	Industry	Chemicals Ammonia Gases	G		R
Final Energy	Industry	Chemicals Ammonia Hydrogen	G		R
Final Energy	Industry	Chemicals Ammonia Liquids	G		R
Final Energy	Industry	Chemicals Ammonia Solids (TOTAL)	G		R
Final Energy	Industry	Chemicals Ammonia Solids Fossil	G		
Final Energy	Industry	Chemicals Electricity	G		
Final Energy	Industry	Chemicals Gases	G		
Final Energy	Industry	Chemicals Heat	G		
Final Energy	Industry	Chemicals Hydrogen	G		

Sector	Subsector	Variable	IAM131		
Final Energy	Industry	Chemicals Liquids	G		
Final Energy	Industry	Chemicals Solids (TOTAL)	G		
Final Energy	Industry	Chemicals Solids Bioenergy	G		
Final Energy	Industry	Chemicals Solids Fossil	G		
Final Energy	Industry	Electricity (TOTAL)	G	M	R
Final Energy	Industry	Electricity Share			R
Final Energy	Industry	Gases (TOTAL)	G	M	R
Final Energy	Industry	Gases Bioenergy			R
Final Energy	Industry	Heat	G	M	R
Final Energy	Industry	Hydrogen	G	M	R
Final Energy	Industry	Liquids (TOTAL)	G	M	R
Final Energy	Industry	Liquids Bioenergy		M	
Final Energy	Industry	Liquids Oil		M	
Final Energy	Industry	Non-ferrous metals (TOTAL)	G	M	
Final Energy	Industry	Non-ferrous metals Electricity	G	M	
Final Energy	Industry	Non-ferrous metals Gases	G	M	
Final Energy	Industry	Non-ferrous metals Liquids	G	M	
Final Energy	Industry	Non-ferrous metals Solids (TOTAL)	G	M	
Final Energy	Industry	Non-ferrous metals Solids Bioenergy	G	M	
Final Energy	Industry	Non-ferrous metals Solids Fossil	G	M	
Final Energy	Industry	Other (TOTAL)		M	
Final Energy	Industry	Other Electicity			R
Final Energy	Industry	Other Gases			R
Final Energy	Industry	Other Heat			R
Final Energy	Industry	Other Hydrogen			R
Final Energy	Industry	Other Liquids			R
Final Energy	Industry	Other Solids			R
Final Energy	Industry	Solids (TOTAL)	G	M	R
Final Energy	Industry	Solids Biomass	G	M	R
Final Energy	Industry	Solids Coal	G	M	R
Final Energy	Industry	Steel (TOTAL)	G	M	R
Final Energy	Industry	Steel Electricity	G	M	R
Final Energy	Industry	Steel Gases	G	M	R
Final Energy	Industry	Steel Hydrogen	G	M	R
Final Energy	Industry	Steel Liquids	G	M	R
Final Energy	Industry	Steel Solids (TOTAL)	G	M	R
Final Energy	Industry	Steel Solids Bioenergy	G	M	
Final Energy	Industry	Steel Solids Fossil	G	M	
Final Energy	Liquids	Liquids (TOTAL)	G	M	R

Sector	Subsector	Variable	IAM131		
Final Energy	Other Sector	Other Sector (TOTAL)			R
Final Energy	Other Sector	Electicity			R
Final Energy	Other Sector	Gases			R
Final Energy	Other Sector	Heat			R
Final Energy	Other Sector	Hydrogen			R
Final Energy	Other Sector	Liquids			R
Final Energy	Non-Energy Use	Non-Energy Use (TOTAL)	G	M	
Final Energy	Non-Energy Use	Biomass	G	M	
Final Energy	Non-Energy Use	Coal	G	M	
Final Energy	Non-Energy Use	Gas	G	M	
Final Energy	Non-Energy Use	Oil	G	M	
Final Energy	Residential and Commercial	Residential and Commercial (TOTAL)	G	M	R
Final Energy	Residential and Commercial	Commercial Cooling	G		
Final Energy	Residential and Commercial	Commercial Electricity	G		
Final Energy	Residential and Commercial	Commercial Gases	G		
Final Energy	Residential and Commercial	Commercial Heat	G		
Final Energy	Residential and Commercial	Commercial Heating Space	G		
Final Energy	Residential and Commercial	Commercial Hydrogen	G		
Final Energy	Residential and Commercial	Commercial Liquids	G		
Final Energy	Residential and Commercial	Commercial Solids (TOTAL)	G		
Final Energy	Residential and Commercial	Commercial Solids Biomass	G		
Final Energy	Residential and Commercial	Commercial Solids Coal	G		
Final Energy	Residential and Commercial	Cooling	G		
Final Energy	Residential and Commercial	Electricity	G	M	R
Final Energy	Residential and Commercial	Gases (TOTAL)	G	M	R
Final Energy	Residential and Commercial	Gases Biomass			R
Final Energy	Residential and Commercial	Gases Natural gas			R
Final Energy	Residential and Commercial	Heat	G	M	R
Final Energy	Residential and Commercial	Heating Space	G		
Final Energy	Residential and Commercial	Hydrogen	G	M	R
Final Energy	Residential and Commercial	Liquids (TOTAL)	G	M	R
Final Energy	Residential and Commercial	Liquids Biomass			R
Final Energy	Residential and Commercial	Liquids Oil			R
Final Energy	Residential and Commercial	Residential Cooling	G		
Final Energy	Residential and Commercial	Residential Electricity	G		R
Final Energy	Residential and Commercial	Residential Gases	G		R
Final Energy	Residential and Commercial	Gases Biomass			R
Final Energy	Residential and Commercial	Gases Natural Gas			R
Final Energy	Residential and Commercial	Residential Heat	G		R

Sector	Subsector	Variable	IAM131		
Final Energy	Residential and Commercial	Residential Heating Space	G		
Final Energy	Residential and Commercial	Residential Hydrogen	G		R
Final Energy	Residential and Commercial	Residential Liquids	G		R
Final Energy	Residential and Commercial	Solids (TOTAL)	G	M	R
Final Energy	Residential and Commercial	Solids Biomass (TOTAL)	G	M	R
Final Energy	Residential and Commercial	Solids Biomass Traditional	G	M	R
Final Energy	Residential and Commercial	Solids Coal	G	M	R
Final Energy	Solids	Solids (TOTAL)	G	M	R
Final Energy	Solids	Biomass (TOTAL)	G	M	R
Final Energy	Solids	Biomass Traditional	G	M	R
Final Energy	Solids	Coal	G	M	R
Final Energy	Transportation	Transportation (TOTAL)	G	M	R
Final Energy	Transportation	Aviation (TOTAL)	G		
Final Energy	Transportation	Aviation Passenger	G		R
Final Energy	Transportation	Electricity	G	M	R
Final Energy	Transportation	Freight (TOTAL)	G		R
Final Energy	Transportation	Freight Electricity	G		R
Final Energy	Transportation	Freight Gases	G		R
Final Energy	Transportation	Freight Hydrogen	G		R
Final Energy	Transportation	Freight Liquids	G		R
Final Energy	Transportation	Freight Other	G		
Final Energy	Transportation	Gases (TOTAL)	G	M	R
Final Energy	Transportation	Gases Bioenergy			R
Final Energy	Transportation	Gases Fossil			R
Final Energy	Transportation	Hydrogen	G	M	R
Final Energy	Transportation	Liquids (TOTAL)	G	M	R
Final Energy	Transportation	Liquids Bioenergy			R
Final Energy	Transportation	Liquids Coal			R
Final Energy	Transportation	Liquids Natural Gas			R
Final Energy	Transportation	Liquids Oil			R
Final Energy	Transportation	Maritime (TOTAL)	G		R
Final Energy	Transportation	Maritime Freight	G		R
Final Energy	Transportation	Other	G	M	R
Final Energy	Transportation	Passenger (TOTAL)	G		R
Final Energy	Transportation	Passenger Electricity	G		R
Final Energy	Transportation	Passenger Gases	G		R
Final Energy	Transportation	Passenger Hydrogen	G		R
Final Energy	Transportation	Passenger Liquids	G		R
Final Energy	Transportation	Rail (TOTAL)	G		R

Sector	Subsector	Variable	IAM131		
Final Energy	Transportation	Rail Freight	G		R
Final Energy	Transportation	Rail Passenger	G		R
Final Energy	Transportation	Road Freight (TOTAL)	G		R
Final Energy	Transportation	Road Freight Electric	G		R
Final Energy	Transportation	Road Freight FC	G		R
Final Energy	Transportation	Road Freight ICE	G		R
Final Energy	Transportation	Road Passenger (TOTAL)	G		R
Final Energy	Transportation	Road Passenger 2W&3W	G		
Final Energy	Transportation	Road Passenger Bus	G		R
Final Energy	Transportation	Road Passenger LDV	G		R
Food Demand		Food Demand (TOTAL)		M	R
Food Demand		Crops (TOTAL)		M	R
Food Demand		Livestock (TOTAL)		M	R
Forestry Demand	Roundwood	Roundwood (TOTAL)		M	
Forestry Demand	Roundwood	Industrial Roundwood		M	
Forestry Demand	Roundwood	Wood Fuel		M	
Forestry Production	Roundwood	Roundwood (TOTAL)		M	
Forestry Production	Roundwood	Industrial Roundwood		M	
Forestry Production	Roundwood	Wood Fuel		M	
GDP		MER	G		R
GDP		PPP	G		R
GDP		MER Counterfactual without damage		M	
GDP		PPP Counterfactual without damage		M	
GDP		PPP including high chronic physical risk damage estimate		M	
GDP		PPP including medium chronic physical risk damage estimate		M	
Investment	Energy Supply	Energy Supply (TOTAL)			R
Investment	Energy Supply	CO_2 Transport and Storage	G	M	R
Investment	Energy Supply	Electricity (TOTAL)	G	M	R
Investment	Energy Supply	Electricity Biomass (TOTAL)	G	M	R
Investment	Energy Supply	Electricity Biomass w/ CCS	G	M	R
Investment	Energy Supply	Electricity Biomass w/o CCS	G	M	R
Investment	Energy Supply	Electricity Coal (TOTAL)	G	M	R
Investment	Energy Supply	Electricity Coal w/ CCS	G	M	R
Investment	Energy Supply	Electricity Coal w/o CCS	G	M	R
Investment	Energy Supply	Electricity Gas (TOTAL)	G	M	R
Investment	Energy Supply	Electricity Gas w/ CCS	G	M	R
Investment	Energy Supply	Electricity Gas w/o CCS	G	M	R
Investment	Energy Supply	Electricity Geothermal	G	M	R

Sector	Subsector	Variable	IAM131		
Investment	Energy Supply	Electricity Hydro	G	M	R
Investment	Energy Supply	Electricity Non-Biomass Renewables	G	M	R
Investment	Energy Supply	Electricity Nuclear	G	M	R
Investment	Energy Supply	Electricity Oil (TOTAL)	G	M	R
Investment	Energy Supply	Electricity Oil w/o CCS	G	M	R
Investment	Energy Supply	Electricity Solar	G	M	R
Investment	Energy Supply	Electricity Transmission and Distribution	G	M	R
Investment	Energy Supply	Electricity Wind	G	M	
Investment	Energy Supply	Extraction Coal	G	M	
Investment	Energy Supply	Extraction Fossil	G	M	
Investment	Energy Supply	Extraction Gas	G	M	
Investment	Energy Supply	Extraction Oil	G	M	
Investment	Energy Supply	Extraction Uranium		M	
Investment	Energy Supply	Heat		M	R
Investment	Energy Supply	Hydrogen (TOTAL)		M	R
Investment	Energy Supply	Hydrogen Fossil		M	R
Investment	Energy Supply	Hydrogen Other		M	R
Investment	Energy Supply	Hydrogen Biomass			R
Investment	Energy Supply	Hydrogen Electricity			R
Investment	Energy Supply	Hydrogen Renewable		M	R
Investment	Energy Supply	Liquids (TOTAL)		M	R
Investment	Energy Supply	Liquids Biomass		M	R
Investment	Energy Supply	Liquids Coal and Gas		M	R
Investment	Energy Supply	Liquids Oil		M	R
Investment	Energy Supply	Other		M	R
Land Cover		Land Cover (TOTAL)	G	M	R
Land Cover		Built-up Area	G		R
Land Cover	Cropland	Cropland (TOTAL)	G	M	R
Land Cover	Cropland	Cereals		M	R
Land Cover	Cropland	Cropland Energy Crops	G	M	R
Land Cover	Forest	Forest (TOTAL)	G	M	R
Land Cover	Forest	Afforestation and Reforestation		M	r
Land Cover	Forest	Managed	G	M	R
Land Cover	Forest	Natural Forest	G	M	R
Land Cover	Forest	Secondary			R
Land Cover		Other Land	G	M	R
Land Cover		Pasture	G	M	R
Population		Population (TOTAL)	G	M	R
Population		Population Rural		M	

Sector	Subsector	Variable	IAM131		
Population		Population Urban		M	
Price	Agriculture	Corn Index	G		R
Price	Agriculture	Non-Energy Crops Index	G	M	R
Price	Agriculture	Soybean Index	G		R
Price	Agriculture	Wheat Index	G		R
Price	Carbon	Carbon (TOTAL)	G	M	R
Price	Carbon	Demand Industry	G		R
Price	Carbon	Demand Residential and Commercial	G		R
Price	Carbon	Demand Transportation	G		R
Price	Carbon	Supply	G		R
Price	Final Energy	Industry Electricity	G		R
Price	Final Energy	Industry Gases (TOTAL)	G		R
Price	Final Energy	Industry Gases Bioenergy			R
Price	Final Energy	Industry Gases Fossil			R
Price	Final Energy	Industry Hydrogen			R
Price	Final Energy	Industry Liquids (TOTAL)	G		R
Price	Final Energy	Industry Liquids Bioenergy			R
Price	Final Energy	Industry Liquids Fossil synfuel			R
Price	Final Energy	Industry Solids Bioenergy			R
Price	Final Energy	Industry Solids Coal			R
Price	Final Energy	Industry Electricity	G		
Price	Final Energy	Transportation Electricity	G		R
Price	Final Energy	Transportation Gases	G		R
Price	Final Energy	Transportation Liquids (TOTAL)	G		R
Price	Final Energy	Transportation Liquids Fossil synfuel			R
Price	Final Energy	Transportation Hydrogen			R
Price	Final Energy	Residential and Commercial Residential Electricity		M	R
Price	Final Energy	Residential and Commercial Residential Electricity Index		M	R
Price	Final Energy	Residential and Commercial Residential Gases Natural Gas		M	R
Price	Final Energy	Residential and Commercial Residential Gases Natural Gas Index		M	R
Price	Final Energy	Residential and Commercial Residential Liquids Biomass		M	R
Price	Final Energy	Residential and Commercial Residential Liquids Biomass Index		M	R
Price	Final Energy	Residential and Commercial Residential Liquids Oil		M	R
Price	Final Energy	Residential and Commercial Residential Liquids Oil Index		M	R

Sector	Subsector	Variable	IAM131		
Price	Final Energy	Residential and Commercial Residential Solids Biomass			R
Price	Final Energy	Residential and Commercial Residential Solids Biomass Index			R
Price	Final Energy	Residential and Commercial Residential Solids Coal			R
Price	Final Energy	Residential and Commercial Residential Solids Coal Index			R
Price	Industry	Cement		M	
Price	Primary Energy	Biomass (TOTAL)	G	M	R
Price	Primary Energy	Biomass Index	G	M	R
Price	Primary Energy	Coal (TOTAL)	G	M	R
Price	Primary Energy	Coal Index	G	M	R
Price	Primary Energy	Gas (TOTAL)	G	M	R
Price	Primary Energy	Gas Index	G	M	R
Price	Primary Energy	Oil (TOTAL)	G	M	R
Price	Primary Energy	Oil Index	G	M	R
Price	Secondary Energy	Electricity (TOTAL)	G	M	R
Price	Secondary Energy	Electricity Index	G	M	R
Price	Secondary Energy	Gases Natural Gas (TOTAL)	G	M	R
Price	Secondary Energy	Gases Natural Gas Index	G	M	R
Price	Secondary Energy	Hydrogen (TOTAL)	G	M	R
Price	Secondary Energy	Liquids (TOTAL)	G	M	R
Price	Secondary Energy	Liquids Biomass (TOTAL)	G	M	R
Price	Secondary Energy	Liquids Biomass Index	G	M	R
Price	Secondary Energy	Liquids Oil (TOTAL)	G	M	R
Price	Secondary Energy	Liquids Oil Index	G	M	R
Price	Secondary Energy	Solids Coal (TOTAL)	G	M	R
Price	Secondary Energy	Solids Coal Index	G	M	R
Primary Energy		Primary Energy (TOTAL)	G	M	R
Primary Energy	Biomass	Biomass (TOTAL)	G	M	R
Primary Energy	Biomass	1st Generation		M	R
Primary Energy	Biomass	Electricity (TOTAL)		M	R
Primary Energy	Biomass	Electricity w/CCS		M	R
Primary Energy	Biomass	Electricity w/o CCS		M	R
Primary Energy	Biomass	Energy Crops		M	R
Primary Energy	Biomass	Residues		M	R
Primary Energy	Biomass	Modern	G	M	R
Primary Energy	Biomass	Traditional	G	M	R
Primary Energy	Biomass	Gases			R

Sector	Subsector	Variable	IAM131		
Primary Energy	Biomass	Heat			R
Primary Energy	Biomass	Hydrogen			R
Primary Energy	Biomass	Liquids			R
Primary Energy	Biomass	Solids			R
Primary Energy	Coal	Coal (TOTAL)	G	M	R
Primary Energy	Coal	Coal Electricity		M	R
Primary Energy	Coal	Coal Electricity w/CCS		M	R
Primary Energy	Coal	Coal Electricity w/o CCS		M	R
Primary Energy	Coal	w/ CCS	G	M	R
Primary Energy	Coal	w/o CCS	G	M	R
Primary Energy	Coal	Gases			R
Primary Energy	Coal	Heat			R
Primary Energy	Coal	Hydrogen			R
Primary Energy	Coal	Liquids			R
Primary Energy	Coal	Solids			R
Primary Energy	Fossil	Fossil (TOTAL)	G	M	R
Primary Energy	Fossil	w/ CCS	G	M	R
Primary Energy	Fossil	w/o CCS	G	M	R
Primary Energy	Gas	Gas (TOTAL)	G	M	R
Primary Energy	Gas	Gas Electricity	G	M	R
Primary Energy	Gas	Gas Electricity w/CCS	G	M	R
Primary Energy	Gas	Gas Electricity w/o CCS	G	M	R
Primary Energy	Gas	w/ CCS	G	M	R
Primary Energy	Gas	w/o CCS	G	M	R
Primary Energy	Gas	Gases			R
Primary Energy	Gas	Heat			R
Primary Energy	Gas	Hydrogen			R
Primary Energy	Gas	Liquids			R
Primary Energy	Gas	Solids			R
Primary Energy		Geothermal	G		R
Primary Energy		Hydro	G		R
Primary Energy		Non-Biomass Renewables	G	M	R
Primary Energy		Non-Biomass Renewables Geothermal		M	R
Primary Energy		Non-Biomass Renewables Hydro		M	R
Primary Energy		Non-Biomass Renewables Ocean		M	
Primary Energy		Non-Biomass Renewables Solar		M	R
Primary Energy		Non-Biomass Renewables Wind		M	R
Primary Energy		Nuclear	G	M	R
Primary Energy	Oil	Oil (TOTAL)	G	M	R

Sector	Subsector	Variable	IAM131		
Primary Energy	Oil	Oil Electricity	M		
Primary Energy	Oil	Oil Electricity w/ CCS	M		
Primary Energy	Oil	Oil Electricity w/o CCS	M		
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
Production		Cement	G	M	R
Production		Chemicals		M	
Production		Non-ferrous metals	G	M	
Production		Steel	G	M	R
Revenue	Government	Tax Carbon (TOTAL)	G	M	R
Revenue	Government	Tax Carbon Demand Industry	G	M	R
Revenue	Government	Tax Carbon Demand Residential and Commercial	G	M	R
Revenue	Government	Tax Carbon Demand Transportation	G	M	R
Revenue	Government	Tax Carbon Supply	G	M	R
Secondary Energy		Secondary Energy (TOTAL)	G		R
Secondary Energy	Electricity	Electricity (TOTAL)	G	M	R
Secondary Energy	Electricity	Biomass (TOTAL)	G	M	R
Secondary Energy	Electricity	Biomass w/ CCS	G	M	R
Secondary Energy	Electricity	Biomass w/o CCS	G	M	R
Secondary Energy	Electricity	Coal (TOTAL)	G	M	R
Secondary Energy	Electricity	Coal w/ CCS	G	M	R
Secondary Energy	Electricity	Coal w/o CCS	G	M	R
Secondary Energy	Electricity	Fossil		M	
Secondary Energy	Electricity	Fossil w/ CCS		M	
Secondary Energy	Electricity	Fossil w/o CCS		M	
Secondary Energy	Electricity	Gas (TOTAL)	G	M	R
Secondary Energy	Electricity	Gas w/ CCS	G	M	R
Secondary Energy	Electricity	Gas w/o CCS	G	M	R
Secondary Energy	Electricity	Geothermal	G	M	R
Secondary Energy	Electricity	Hydro	G	M	R
Secondary Energy	Electricity	Non-Biomass Renewables	G	M	R
Secondary Energy	Electricity	Nuclear	G	M	R
Secondary Energy	Electricity	Oil (TOTAL)	G	M	R
Secondary Energy	Electricity	Oil w/o CCS	G	M	R
Secondary Energy	Electricity	Solar (TOTAL)	G	M	R
Secondary Energy	Electricity	Solar CSP	G	M	R

Sector	Subsector	Variable	IAM131		
Secondary Energy	Electricity	Solar PV	G	M	R
Secondary Energy	Electricity	Wind (TOTAL)	G	M	R
Secondary Energy	Electricity	Wind Offshore	G	M	R
Secondary Energy	Electricity	Wind Onshore	G	M	R
Secondary Energy	Gases	Gases (TOTAL)	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	Gases	Other		M	R
Secondary Energy	Heat	Heat (TOTAL)		M	R
Secondary Energy	Heat	Heat Biomass		M	R
Secondary Energy	Heat	Heat Coal		M	R
Secondary Energy	Heat	Heat Gas		M	R
Secondary Energy	Heat	Heat Geothermal		M	R
Secondary Energy	Heat	Heat Oil		M	
Secondary Energy	Heat	Heat Other		M	
Secondary Energy	Hydrogen	Hydrogen (TOTAL)	G	M	R
Secondary Energy	Hydrogen	Biomass (TOTAL)	G	M	R
Secondary Energy	Hydrogen	Biomass w/ CCS	G	M	R
Secondary Energy	Hydrogen	Biomass w/o CCS	G	M	R
Secondary Energy	Hydrogen	Coal (TOTAL)	G	M	R
Secondary Energy	Hydrogen	Coal w/o CCS	G	M	R
Secondary Energy	Hydrogen	Coal w/o CCS	G	M	R
Secondary Energy	Hydrogen	Electricity	G	M	R
Secondary Energy	Hydrogen	Fossil (TOTAL)	G	M	R
Secondary Energy	Hydrogen	Fossil w/ CCS	G	M	R
Secondary Energy	Hydrogen	Fossil w/o CCS	G	M	R
Secondary Energy	Hydrogen	Gas (TOTAL)	G	M	R
Secondary Energy	Hydrogen	Gas w/ CCS	G	M	R
Secondary Energy	Hydrogen	Gas w/o CCS	G	M	R
Secondary Energy	Liquids	Liquids (TOTAL)	G	M	R
Secondary Energy	Liquids	Biomass (TOTAL)	G	M	R
Secondary Energy	Liquids	Biomass w/ CCS	G	M	R
Secondary Energy	Liquids	Biomass w/o CCS	G	M	R
Secondary Energy	Liquids	Coal (TOTAL)	G	M	R
Secondary Energy	Liquids	Coal w/o CCS	G	M	R
Secondary Energy	Liquids	Fossil (TOTAL)	G	M	R
Secondary Energy	Liquids	Fossil w/o CCS	G	M	R
Secondary Energy	Liquids	Gas (TOTAL)	G	M	R

Sector	Subsector	Variable	IAM[131]		
Secondary Energy	Liquids	Gas w/ CCS			R
Secondary Energy	Liquids	Gas w/o CCS			R
Secondary Energy	Liquids	Oil	G	M	R
Secondary Energy	Solids	Solids (TOTAL)	G	M	R
Secondary Energy	Solids	Biomass	G	M	R
Secondary Energy	Solids	Coal	G	M	R
Trade	Primary Energy	Biomass Volume		M	R
Trade	Primary Energy	Coal Volume		M	R
Trade	Primary Energy	Gas Volume		M	R
Trade	Primary Energy	Oil Volume		M	R
Water Consumption		(TOTAL)		M	
Water Consumption		Irrigation		M	R
Water Withdrawal		Irrigation		M	
Yield		Cereal		M	R
Yield		Oil crops		M	R
Yield		Sugar crops		M	R

Table 35. Mapping of IAM regions and downscaled countries

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.2-4.6
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

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.2-4.6
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
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

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.2-4.6
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
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

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.2-4.6
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
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

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.2-4.6
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
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

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.2-4.6
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
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

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.2-4.6
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
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

ISO	MESSAGEix-GLOBIOM 1.1-R12	GCAM 6.0 NGFS	REMIND-MAgPIE 3.2-4.6
ZMB	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa
ZWE	Sub-Saharan Africa	Africa_Southern	Sub-Saharan Africa

Table 36. NGFS Phase IV Scenario Explorer downscaling output

Sector	Subsector	Variable	IAM[132]		
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

[132] G = GCAM, M = MESSAGE-GLOBIOM, R = REMIND-MAgPIE

Sector	Subsector	Variable	IAM132		
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
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

Table 37. Acronyms and meanings

Acronym	Term
AFOLU	Agriculture, forestry and other land use
AgLU	Agriculture and land use
BC	Black carbon
BECCS	Bioenergy with Carbone capture storage
C_2F_6	Hexafluoroethane

Acronym	Term
CCS	Carbon capture and storage
CCS	Carbone capture storage
CES	Constant Elasticity of Substitution
CF_4	Tetrafluoromethane
CH_4	Methane
CMIP5	Coupled Model Intercomparison Project – phase 5
CO	Carbon monoxide
CO_2	Carbon dioxide
DACCS	Direct air capture with Carbone capture storage
EJ	Exajoule
ETS	Emissions trading system
ETS	Emissions trading system
EW	Enhanced weathering of rocks
EW	Enhanced weathering of rocks
Gg	Gigagram
GHG	Greenhouse gases
GJ	Gigajoule
GLU	GLOBE Land Unit
HDV	Heavy-duty vehicles
HDV	Heavy-duty vehicles
HFC	Hydrofluorocarbon
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
HFC23	Fluorophore
HFC236fa	1,1,1,3,3,3-Hexafluoropropane
HFC245fa	1,1,1,3,3-Pentafluorpropan
HFC32	Difluoromethane
HFC365mfc	1,1,1,3,3-Pentafluorobutane
HFC43-10mee	1,1,1,2,3,4,4,5,5,5-Decafluoropentane
IPCC	Intergovernmental Panel on Climate Change
Kyoto gases	Basket of CO_2, CH_4, N_2O, HFC, PFC, SF_6
LDV	Light-duty vehicles
MAC	Marginal abatement cost

Acronym	Term
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
RCP	Representative Concentration Pathways
SSP	Socioeconomic Development Pathways
TC	technological change
Tg	Teragram
VOC	Volatile organic compounds
VRE	Variable renewable energy

Table 38. Regional net-zero targets implemented in the 3 IAMs.

Country	Net-zero year	GCAM	MESSAGE-GLOBIOM	REMIND-MAgPIE
Argentina	2050	GHG	GHG	GHG (as LAM)
Australia	2050	GHG (as AUS_NZ)	GHG	GHG (as CAZ)
Brazil	2050	GHG	GHG	GHG (as LAM)
Canada	2050	GHG	GHG	GHG (as CAZ)
China	2060	GHG	GHG	GHG
Colombia	2050	GHG	CO2‡	GHG (as LAM)
EU+UK	2050	GHG (for total EU12 and EU15)	GHG	GHG
India	2070	CO2	GHG	CO2
Indonesia	2060		GHG	
Japan	2050	GHG	GHG	GHG
New Zealand	2050	GHG (as AUS_NZ)	GHG	GHG (as CAZ)
Russia	2060		GHG	GHG (as REF)
South Africa	2050	GHG	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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