Network for Greening the Financial System

Note on key assumptions of NGFS long-term scenarios Phase V

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Central Banks and Supervisors
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Notice to readers on physical risk estimates in Phase V of NGFS long-term scenarios

The NGFS long-term climate scenarios are a set of forward-looking pathways designed to explore how the global economy and financial system might evolve under different levels of climate policy ambition and physical climate impacts over the rest of the 21st century. They were developed by the Network for Greening the Financial System (NGFS) to provide a consistent analytical basis for assessing climate-related financial risks and opportunities. The academic paper underpinning the physical risk estimates in Phase V of NGFS long-term scenarios (released in November 2024), Kotz *et al*. (2024), has received academic critiques (see first and second Matters Arising) as part of the post-publication review process at Nature.

Therefore, users should be aware of this and academic debate pertaining specifically to the Phase V physical risk methodology when interpreting and applying Phase V results, alongside the broader limitations of physical risk estimates already detailed in NGFS documentation.

It should be noted that the long-term scenarios outputs which do not incorporate physical loss estimates from Kotz *et al.* (2024) remain unaffected[1]. Also, the outputs of NGFS short-term scenarios are not impacted, as they do not rely on the Kotz *et al.* (2024) paper.

It cannot be excluded that the economic effects of climate change might turn out to be more severe than anticipated in the NGFS scenarios, for instance, if certain tipping points are reached. Thus, users should also take into account the tail risks of climate change, along with other risks such as nature-related ones, which are not necessarily captured by these scenarios.

The NGFS is constantly working to further improve the scenarios, including with regard to physical risks. Users are reminded that neither the NGFS, nor its member institutions, nor any person acting on their behalf, is responsible or liable for any reliance on, or for any use of the NGFS scenarios and/or supplementary documentation. This also applies to the use of the data produced under the scenarios – see section 5 in https://data.ene.iiasa.ac.at/ngfs/#/license. Thus, while the NGFS climate scenarios are certainly a helpful tool, they do not alleviate the responsibility of users, including banks and other (financial) organisations, to design and implement their own risk management frameworks.

1 The affected variables are those reflecting physical loss estimates from Kotz *et al.* (2024) in Phase V of NGFS long-term scenarios. This includes: all outputs of "Integrated Physical Damages" scenarios by REMIND-MAgPIE, all "physical" and "combined" (*i.e.* combined physical and transition damages) outputs by NiGEM, as well as post-processed or downscaled outputs for GDP damages from the damage function (*i.e.* GDP change and Net GDP variables referring to "Kotz-Wenz"). All other variables from Phase V, the physical risk estimates as presented in the Climate Impact Explorer, as well as outputs from previous phases of NGFS long-term scenarios, remain unaffected.

Summary

The Network for Greening the Financial System has developed **long-term climate scenarios** for financial institutions, aligned with the latest climate impact and climate transition science. The scenarios stem from an ensemble of models including three Integrated Assessment Models (IAMs), one macroeconomic model, and tools for climate impact projections. This note explains the key modelling assumptions driving the scenario results, in terms of transition risks, physical risks, and macroeconomic impacts.

Key assumption in transition pathways

Starting with NGFS transition pathways provided by IAMs, the key external drivers are **socioeconomic projections and assumptions on climate policies**. All NGFS scenarios are aligned with the **Shared Socioeconomic Pathway 2 (SSP2), the middle-of-the-road scenario.**[2] The NGFS scenario narratives are based on existing national policies[3] which have different levels of stringency, in particular:

- The **Current Policies scenario** follows only already implemented policies.
- The **Nationally Determined Contributions (NDC)** scenario includes all pledged policies, even if not yet backed with implemented effective policies, to achieve NDC 2030 targets.
- The **Net Zero 2050 scenario** follows national net zero targets[4] and assumes an additional global emission neutrality target by 2050.
- The **Low Demand scenario** follows national net zero targets, assumes an additional global emission neutrality target by 2050, as well as significant behavioural changes that reduce energy demand.
- The **Below 2 °C scenario** gradually increases the stringency of climate policies, until reaching 80% of national net zero targets. This gives a 67% chance of limiting global warming to below 2 °C.
- The **Delayed Transition scenario** follows implemented policies until 2030, and subsequently assumes that strong policies are implemented to limit warming to below 2 °C.
- The **Fragmented World scenario** follows implemented policies until 2030, subsequently only countries with national net zero commitments are assumed to introduce additional policies to reach their targets, while other countries keep following their implemented policies. Only 80% of national net zero targets are reached.

Three Integrated Assessment Models (IAMs) – REMIND-MAgPIE, MESSAGEix-GLOBIOM and GCAM – are used to generate **optimised transition pathways.** Key differences between the models lie in **anticipation of future developments and targets** (perfect or limited foresight) and **decision-making mechanism** (maximizing welfare or minimizing system cost): **REMIND-MAgPIE** maximizes welfare with perfect foresight, **MESSAGEix-GLOBIOM** minimizes system cost with perfect foresight, **GCAM** minimizes system cost with limited foresight.

In all three IAMs, **carbon prices** are shadow prices, representing the marginal abatement costs under the constraints imposed in the scenario, rather than actual market prices.

Energy prices reflect long-term equilibria derived from the marginal extraction costs of energy supply and economic fundamentals, and are not influenced by short-term market fluctuations. The price of fossil fuels is determined by their extraction costs, maximum potential energy resources, and depletion effects, following regional resource supply curves. This implies that fossil fuel prices increase over time if demand for these fuels keeps rising while marginal production costs increase (e.g. under the Current Policies scenario).

2 Under the latest SSP2, global population is expected to reach 9.5 billion by 2050 and 9.8 billion by 2100. Global GDP is projected to rise from $112 trillion in 2015 to $281 trillion in 2050 and $641 trillion in 2100. Average income per capita is anticipated to grow from $15,000 in 2015 to $65,000 by 2100, assuming moderate changes in global inequality. The fifth vintage of the NGFS scenarios uses the updated version 3.0 of the SSP scenarios.

3 The cut-off date for targets to be considered is March 2024.

4 Net zero targets as published by the UNFCCC as of March 2024 for the following countries: Argentina, Australia, Brazil, Canada, China, Colombia, EU + UK, India, Indonesia, Japan, New Zealand, Russia, South Africa, South Korea and USA.

Secondary energy prices in the NGFS scenarios account for carbon prices. Therefore, if electricity is produced mainly from fossil fuel, its price will increase with carbon pricing, until the technology mix shifts to lower emission technologies (e.g., under Net Zero 2050 scenario). The cost of renewable energy resources (solar, wind, hydro, bio-energy) is defined as a function of resource potential and land availability for the infrastructure (i.e., depending on landscape accessibility and authorised areas).

In IAMs, **energy technology** choices are a result of system cost optimization, determined by investment and operational costs, the assets' lifetime and capacity factor (exogenous), and fuel costs (endogenous), as well as deployment constraints. In addition to technology targets, an effective carbon pricing raises the fuel and emissions costs of CO_2-emitting technologies, which encourages a shift towards cleaner and cheaper technologies. A high and fast-increasing carbon price triggers a faster technological shift. Moreover, the use of carbon capture and storage (CCS) as mitigation technology highly depends on its costs and deployment assumptions. The deployment constraints include resource availability, growth constraints on capacity additions, grid integration challenges, land availability, as well as specific policies.

To overcome the limited geographical resolution of IAMs, an algorithm is used to **downscale regional results to the country level** by combining historical national trends with long-term scenario trajectories. The method relies on key assumptions including the time of convergence between short and long-term trends.

Key assumptions in physical impacts

The NGFS physical risks assessment has multiple components: the biophysical risk indicators provided in the Climate Impact Explorer (CIE), and the economic assessment of GDP effects for both bottom-up (acute) and top-down aggregate risks.

Climate change impacts with the Climate Impact Explorer (2025 update)

For all NGFS scenarios, the emissions computed by the IAMs are translated to Global Mean Temperature (GMT) projections using the MAGICC model. Based on this information, the Climate Impact Explorer (CIE), an open access webtool with global coverage, derives the severity of climate change impacts until 2100.

The CIE methodology is based on the well-established assumption that most climate impacts primarily depend on the global warming level and not on the timing when this warming level is reached. To focus on climate effects only, the CIE keeps other factors (e.g. economy, infrastructure, population) at constant levels. Uncertainty ranges stem from (i) the translation of emission trajectories into global warming projections, and (ii) translating these into the respective physical risk indicators on the local scale.

Acute physical risks indicators[5]

In NGFS Phase IV (2023), four physical risks indicators have been used to estimate acute risks economic impacts with the macroeconomic model NiGEM. These indicators cover four types of extreme events, and their key assumptions are:

- **Extreme droughts**: Focuses only on *very extreme, long-term* drought using a drought indicator (SPEI-12) that takes both rainfall and evaporation into account. Applying a local threshold for assessing drought exposure, it estimates crop losses assuming an idealized relationship where more drought months lead to more crop losses.
- **Heat extremes**: Focuses only on population exposed to very high heat stress from humid heat, using a combined threshold for wetbulb temperature to assess exposure. Less densely populated areas are weighted less.
- **Tropical Cyclones (hurricanes/typhoons)**: Focuses only on asset damages from *extreme winds*, damages from heavy rainfall are not included, storm surge-related damages only indirectly. Historical storm track data is used to project future exposure and changes in frequency and intensity. Potential non-linearities in future changes for TCs are not accounted for. Asset data is proxied, and vulnerability is modelled based on region-specific damage functions. Both are assumed to be constant for the projections.

5 Important note: In NGFS Phase V (2024), the acute risks estimates were reported based on the Phase IV (2023) climate scenarios. The drought and heat risk indicators have been substantially improved in 2025, and the updated results can be explored on the CIE. The macroeconomic estimates have however not been updated with NiGEM accordingly.

- **Floods**: Focuses only on asset damages from *river* floods. Applies a chain of models with partly very high resolution, which is then aggregated. Modelling assumes fixed flood protection standards, i.e. no further adaptation. Asset values, infrastructure distribution and water withdrawal patterns are kept fixed.

Aggregate economic impacts from a damage function

Aggregate GDP changes due to climate change risks are derived from aggregate econometric damage functions. Econometric approaches estimate the effects of climate and weather on GDP and GDP growth using historical data. They capture climate impacts related to the climate drivers in the estimate, usually mean annual temperature and precipitation, affecting GDP and having occurred in the period and countries included in the analysis. This means they do not capture high-end extremes not seen in the past, nor non-market impacts or effects of sea-level rise. They also do not account for future adaptation to climate change. While they do not distinguish the channels through which climate change affects GDP they do provide a more comprehensive assessment than specific channel-based approaches. Their magnitude is strongly affected by assumptions on the persistence of the impacts on growth, which is an unresolved question.

The NGFS informs users that the academic paper underpinning the economic damage estimates from physical risks in Phase V, Kotz *et al*. (2024), has received critiques post-publication in Nature (for more detail, please refer to the notice at the start of this document).

Key macroeconomic assumptions

In addition to the three IAMs and physical risk models, the NGFS uses the National Institute Global Econometric Model (NiGEM) to simulate the **macroeconomic implications** of transition and physical risks (both from acute and aggregate impacts). NiGEM establishes a climate-neutral baseline to ensure consistency with IAMs and expresses results as deviations from this baseline, using selected IAM and climate model results as inputs. Specifically, to derive transition impacts, NiGEM uses the following IAM results: **primary energy consumption, carbon revenues and useful energy**.

Key macroeconomic assumptions include:

- **Recycling of carbon tax revenues**: In orderly scenarios (i.e., Net Zero 2050, Low Demand, Below 2 °C), 50% of carbon tax revenue goes to government investment, and the rest to debt repayment. Other scenarios recycle revenues through tax reductions.
- **Confidence shocks in the Fragmented World and Delayed Transition scenarios**: a one percentage point increase in the investment premium is applied in 2031-2032 to simulate a drop in business confidence due to sudden climate policy shifts.
- **Monetary Policy**: The monetary policy follows a 'two-pillar rule', where the short-term interest rate is set as a function of the deviation of nominal GDP target to nominal GDP (a proxy for the money stock) and the difference between expected inflation and the inflation target.

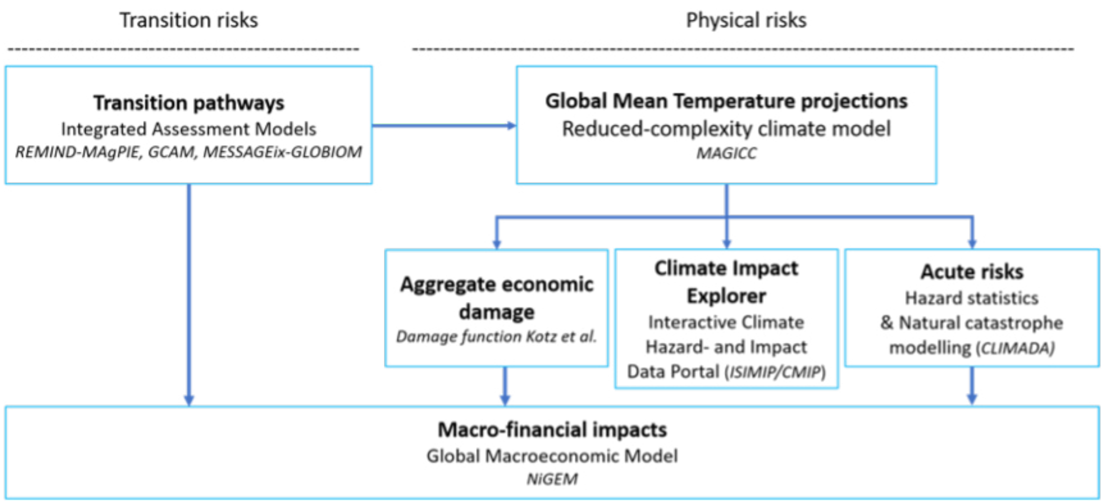
Macroeconomic impacts from acute physical risks are assessed for three scenarios only: Current Policies, Delayed Transition, and Net Zero 2050. NiGEM simulates these hazard-specific impacts as economic shocks[6] using a stochastic approach (i.e., a random draw from climate variables distributions), except in the case of floods where a deterministic approach is used (i.e. a single shock, rather than a stochastic trial). The model treats both acute risks at the national level: it captures direct local supply and demand impacts, while taking exogeneous assumptions on global trade and policy reactions (e.g., monetary and fiscal responses).

6 NiGEM shocks population and productivity for heatwaves, crops yields for droughts, and physical assets for cyclones and floods. See the Stochastic Implementation chapter in the NGFS Phase V Technical documentation (2024) for detailed information about the transmission channels per hazard.

1. Purpose of this note

The Network for Greening the Financial System has developed long-term climate scenarios for financial institutions, aligned with latest climate impact and climate transition science. The scenarios stem from an ensemble of models including three Integrated Assessment Models, one macroeconomic model, and tools for climate impact projections (Figure 1). This note explains the key modelling assumptions driving the scenario results, in terms of transition risks, physical risks, and macroeconomic impacts. More detailed information is available in the NGFS Phase V scenarios documentation.

Figure 1 **NGFS suite-of-models approach**



2. Transition risks assumptions

This section clarifies key assumptions of NGFS scenarios (Phase V) to help users understand what underlies the different pathways and the assessed transition risks – including assumptions on GDP and population, policy and emission targets, model characteristics, price mechanisms, and technology, as well as physical risks, and macroeconomic impacts.

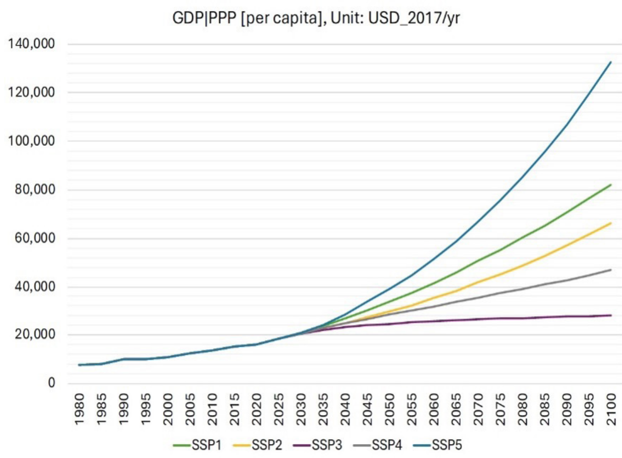
2.1 Socioeconomic projections

The initial assumption for all NGFS scenarios is to align economic development and population with the latest release of the Shared Socioeconomic Pathways, specifically the SSP2, middle-of-the-road scenario. This pathway is based on the OECD Economic Outlook (2023) and the IMF World Economic Outlook (2023) for the near-term (OECD, 2024[7]). In the longer term, this pathway assumes **medium global GDP growth and moderate convergence** between rich and poor countries, with medium fertility and aging trends for the population.

Numerically, under the latest SSP2, the global population will reach 9.5 billion in 2050 and 9.8 billion in 2100. Global GDP will increase from $112 trillion in 2015 to $281 trillion in 2050 and $641 trillion in 2100. The global average income would grow from approximately 15,000 USD/capita in 2015 and reach about 65,000 USD/capita by the end of the century (all monetary units use USD2017 and purchasing-power-parity).[8]

This pathway also assumes **moderate changes in global inequality**, neither extreme divergence nor rapid convergence. In the IAMs, GDP and population are important upstream assumptions that drive projections of energy demand and technology development. Figure 2 shows how SSP2 GDP relates to the other pathways.

Figure 2 **World GDP per capita of Shared Socioeconomic Pathways**



The Integrated Assessment Models also include the substitution between factors of production (e.g., energy, and non-energy factors such as labor, capital), which is applied as the feedback between the energy prices (production factor energy) and the demand (labor, capital, and all non-energy production factors). With this feedback, the impacts on energy demand are semi-endogenously modelled[9].

The country-level macroeconomic losses due to the integrated damages are post-assessed (see Section on "Aggregate economic impacts from physical risks" below, and "Macro-economic damage estimates" Section in the NGFS Phase V Technical documentation (2024)).

2.2 Policies and emission targets

The NGFS scenario narratives reflect various level of climate policy ambition and timings:

- The Current Policies scenario follows only **already implemented policies** and current trends.
- The Nationally Determined Contributions (NDC) scenario includes all pledged policies, even if not yet backed with implemented effective policies, to achieve **NDC 2030 targets**.

7 OECD, 2024. Updating the economic projections of the SSPs: Integrating observed history with original storylines. Dellink *et al.* Available at: https://www.iamconsortium.org/wp-content/uploads/2024/01/Dellink-presentation.pdf.

8 The fifth vintage of the NGFS scenarios uses the updated version 3.0 of the SSP scenarios.

9 For a model that currently does not include an energy-GDP feedback mechanism, it mimics the dynamics of models with such a feedback mechanism and post-processes the GDP trajectories (see the NGFS Technical documentation Phase V, p 98).

- The Net Zero 2050 scenario follows national net zero targets and assumes an **additional global emission neutrality target** by 2050.
- The Low Demand scenario follows national net zero targets, assumes an additional global emission neutrality target by 2050, as well as **significant behavioural changes** that reduce energy demand.
- The Below 2 °C scenario gradually increases the stringency of climate policies, until reaching 80% of national net zero targets. This gives a 67% chance of limiting global warming to below 2 °C.
- The Delayed Transition scenario follows **implemented policies until 2030**, and subsequently assumes that strong policies are implemented to **limit warming to below 2 °C**.
- The Fragmented World scenario follows **implemented policies until 2030**, subsequently only countries with national net zero commitments are assumed to introduce additional policies to reach their targets, while other countries keep following their implemented policies. **Only 80% of national net zero targets** are reached.

The NGFS scenario narratives consider announced national policy which have different level of stringency:

- **Current implemented policies**: National climate policies which were legislated and backed with instruments as of March 2024. These policies are implemented in GCAM and REMIND-MAgPIE based on a bottom-up assessment of resulting emission reductions, which is subsequently achieved in the model by imposing a carbon price that achieves such reductions. In MESSAGEix-GLOBIOM, policy targets on the energy system are imposed directly in the model.
- **NDC 2030 targets**: National Determined Contribution targets for 2030, as published by the UNFCCC by the end of March 2024. Country level NDCs are aggregated to IAM model regions (12 regions in REMIND-MAgPIE, 12 in MESSAGEix-GLOBIOM, 32 in GCAM). The NDC targets are imposed similarly as described above for Current Policies.
- **Net Zero targets**: Countries with a political commitment to net zero targets[10] as published by the UNFCCC in March 2024, are assumed to at least meet their targets around the committed target year, which are set between 2050 and 2070. Reaching the net zero targets by 2050 may exceed the ambition levels of the NDCs for 2030. When combined with a global goal (e.g., Net Zero 2050, Low Demand), the regional net zero targets may be exceeded to reach the global target.

It is important to note that the revenue recycling mechanism of carbon tax, as well as policy backsliding, are beyond the narratives represented by the IAMs.

2.3 Model characteristics

Integrated Assessment Models: REMIND-MAgPIE, MESSAGEix-GLOBIOM, GCAM

The transition pathways of NGFS scenarios are quantified with three different Integrated Assessment Models. Key foundational differences between the three IAMs participating in the NGFS scenarios are the **anticipation of future developments and targets** (perfect foresight or limited short-term foresight) and the **decision-making mechanism or objective function** (maximizing welfare or minimizing system cost). The **REMIND-MAgPIE** model maximizes welfare with perfect foresight, the **MESSAGEix-GLOBIOM** model minimizes system cost with perfect foresight, while the **GCAM** model minimizing cost with limited short-term foresight. Perfect foresight models can still include unanticipated future shocks by optimizing the period before and after the shock separately. For example, in the Delayed Transition scenario, the period with limited climate policies before 2030 does not anticipate the stringent climate policies that are imposed after 2030.

In order to reflect the structural uncertainty of IAMs, the NGFS framework includes three well-recognized IAMs in the scientific literature, which represent an adequate range and variety of assumptions. The scientific IAM community has a long-standing tradition of multi-model studies to derive robust insights across the different methods, and which allows for quantification of long-term future uncertainties. The three IAMs cover different tendencies for demand-versus-supply responses to greenhouse gas mitigation, fossil fuel reduction, and mitigation costs, as shown in two scientific studies on

10 Net zero targets as published by the UNFCCC as of March 2024 for the following countries: Argentina, Australia, Brazil, Canada, China, Colombia, EU + UK, India, Indonesia, Japan, New Zealand, Russia, South Africa, South Korea and USA.

models fingerprints and diagnostics (Dekker *et al.*, 2023[11], Harmsen *et al.*, 2021[12]).

Country-level downscaling algorithm

To stay within the limits of computational feasibility, IAMs aggregate countries into a few regions and only provide results at the regional level. However, the NGFS scenario framework is able to provide **country-level results using a downscaling algorithm** called DSCALE (Sferra *et al.* 2025[13]). DSCALE balances historical trends at the country level with future scenario trajectories at the regional level, thus preserving short-term plausibility while aligning with long-term climate objectives.

To estimate the energy use of a given country, DSCALE fixes the base year values to current national data and slowly converges to the regional average of IAM scenarios. **The date of convergence is a key parameter of the downscaling algorithm: a slower convergence means that country-level characteristics have a stronger influence in the near term.** This parameter is therefore tailored to the scenario narrative, with final energy demand converging in:

- 2100, for scenarios Net Zero 2050 and Low Demand (fast convergence time),
- 2150, for scenarios Current Policies, NDCs and Below 2 °C (medium convergence time),
- 2200, for scenarios Fragmented World and Delayed Transition (slow convergence time).

For all scenarios, primary and secondary energy use converge hundred years after final energy. The choice of these parameters derives from experiments with the downscaling method; more information can be found in the NGFS Phase V Technical documentation (2024).

Based on this interpolated energy mix, DSCALE computes emissions of energy-related CO_2, industrial processes, and non-CO_2 gases. It also reports direct and indirect land-use emissions in line with the national inventory accounting schemes (Grassi *et al.*, 2021[14]). Assuming that national prices follow regional IAM prices, DSCALE also calculates carbon revenues based on carbon prices and national emissions trajectories. Other parameters can influence the downscaled results; please refer to Sferra *et al.* (2025) for more details.

The downscaled outputs for primary energy consumption, carbon tax, carbon revenue, useful energy and socio-economic projections are then used as inputs for NiGEM. This enables the assessment of the macroeconomic implications associated with transition risks, in line with the narratives and assumptions of the original IAM scenarios (see section 4: Macroeconomic impacts assumptions (NiGEM)).

2.4 Price mechanisms

The **carbon prices** in NGFS scenarios are **shadow prices**, which differ from actual market prices. These shadow prices emerge from the models as the pricing that is needed to achieve imposed emissions reduction targets. The shadow prices reflect **marginal abatement costs** under the constraints imposed in the scenario. These values are different from the observed market prices, as the latter are rather driven by market supply, demand, and regulatory factors. The carbon prices should be interpreted as model-derived signals of the **stringency of climate policy** rather than predictions of future market or policy conditions.

The **price of primary energy** in IAMs reflect the equilibrium prices driven by long-term economic fundamentals. For both fossil and renewable sources, their primary energy price depends on their **extraction costs**, **maximum potential or reserves, and depletion effects**. These long-term equilibrium prices do not include short-term fluctuations due to market conditions or tightness between supply

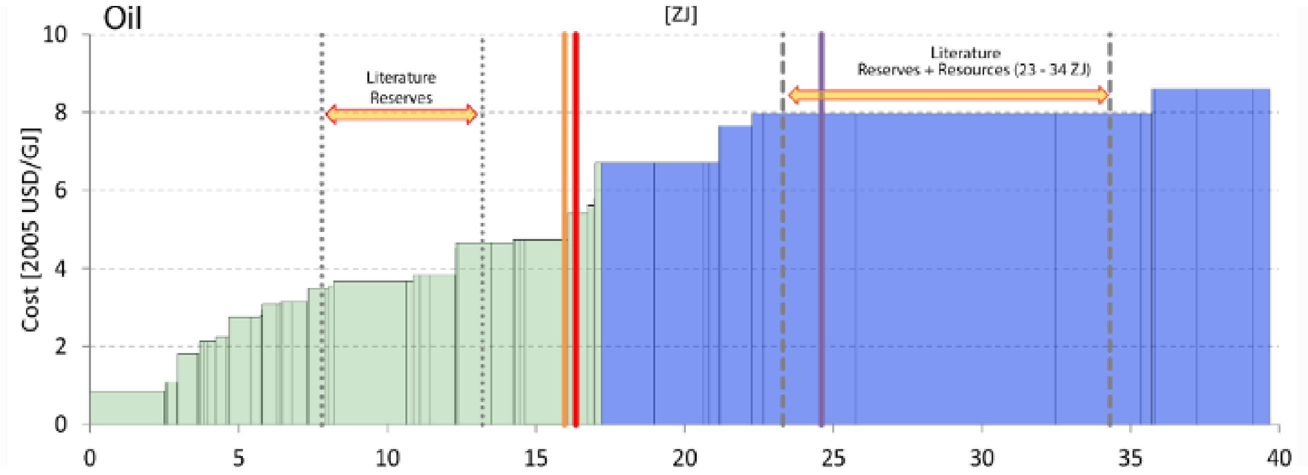
11 Dekker, Mark M., Vassilis Daioglou, Robert Pietzcker, Renato Rodrigues, Harmen-Sytze De Boer, Francesco Dalla Longa, Laurent Drouet, *et al.* "Identifying Energy Model Fingerprints in Mitigation Scenarios." Nature Energy 8, no. 12 (November 6, 2023): 1395–1404. https://doi.org/10.1038/s41560-023-01399-1.

12 Harmsen, Mathijs, Elmar Kriegler, Detlef P Van Vuuren, Kaj-Ivar Van Der Wijst, Gunnar Luderer, Ryna Cui, Olivier Dessens, *et al.* "Integrated Assessment Model Diagnostics: Key Indicators and Model Evolution." Environmental Research Letters 16, no. 5 (May 1, 2021): 054046. https://iopscience.iop.org/article/10.1088/1748-9326/abf964.

13 Sferra, F., van Ruijven, B., Riahi, K., Hackstock, P., Maczek, F., Kikstra, J., and Haas, R.: DSCALE v0.1 – an open-source algorithm for downscaling regional and global mitigation pathways to the country level, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-121, 2025.

14 Grassi, G., Stehfest, E., Rogelj, J., van Vuuren, D., Cescatti, A., House, J., Nabuurs, G.-J., Rossi, S., Alkama, R., Viñas, R. A.,Calvin, K ., Ceccherini, G., Federici, S., Fujimori, S., Gusti, M., Hasegawa, T., Havlik, P., Humpenöder, F., Korosuo, A.,1065 Perugini, L., Tubiello, F. N., and Popp, A.: Critical adjustment of land mitigation pathways for assessing countries' climate progress, Nat. Clim. Change, 11, 425–434, https://doi.org/10.1038/s41558-021-01033-6, 2021.

Figure 3 **Cumulative global resource supply curves (oil, MESSAGEix-GLOBIOM, Fricko *et al.*, 2017[15])**



and demand. However, demand responds dynamically to higher energy prices and changes in cumulative demand lead to different extraction-costs. In IAMs, primary energy prices do not include carbon prices. They can differ between scenarios due to scenario-specific differences in demand, scarcity and depletion.

The **resource supply curve** is an upward-sloping function in which the cost of extraction increases as the quantity of resource extracted increases (Figure 3). The **cost of primary energy commodities** depends on the level of extraction that has been reached in the region (however does not account for carbon price). If a resource has a steep supply curve (e.g., oil in deepwater fields), its marginal price will rise sharply as the demand increases. This implies that fossil fuel prices increase over time if demand for these fuels keeps rising while marginal production costs increase (e.g. under the Current Policies scenario). The supply curve for renewable energy resources (solar, wind, hydro, bio-energy) is defined as a function of resource potential and land availability for the infrastructure (i.e., depending on landscape accessibility and authorised areas).

Similarly, the **price of secondary energy**, such as electricity and synthetic fuels, emerges from the marginal cost of supplying the secondary energy, and depends on the energy **technology mix** and **conversion costs**. In IAMs, secondary energy prices **account for carbon price**, in case the energy conversion process emits CO_2. Therefore, if electricity is produced mainly from fossil fuel, its price will increase with carbon pricing, until the technology mix shifts to lower emission technologies (e.g., under Net Zero 2050 scenario).

2.5 Technology

While the primary driver of technology change in IAMs is the change in relative costs of technologies, the constraints on deployment or integration of technologies also affects the uptake and growth of specific technologies in the scenario results. We here elaborate on the power sector technologies, but dynamics are similar for upstream mining, other secondary fuels, and final energy sectors, as documented in the NGFS Phase V Technical documentation (2024).

The technology choice in IAMs generally follows from a form of cost optimality, including factors such as investment costs, operational costs, fuel costs (endogenous), emission costs, capacity factors and lifetimes (exogenous).

- **REMIND-MAgPIE** assumes perfect substitution at the energy goods level and imperfect substitution at the sectoral demand level, incorporating learning curves. It also features a feedback mechanism between energy costs and macroeconomic variables.

15 Fricko, Oliver, Petr Havlik, Joeri Rogelj, Zbigniew Klimont, Mykola Gusti, Nils Johnson, Peter Kolp, *et al*. "The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century." Global Environmental Change 42 (January 2017): 251–67. https://doi.org/10.1016/j.gloenvcha.2016.06.004.

- **MESSAGEix-GLOBIOM** employs detailed process-based modeling and includes dynamic constraints on technology diffusion.
- **GCAM** is a global, dynamic, market equilibrium model. Agents in GCAM are assumed to act to maximize their own self-interest, but the model does not perform an overall optimization calculation and instead uses logit functions to determine market shares of technologies.

Model assumptions on investment costs for power generation technologies can, to some extent, explain the difference in technological transition across models. IAMs cover an **adequate range of investment costs** that are observed in the scientific literature (see Table 1). In particular, the use of carbon capture and storage (CCS) as mitigation technology highly depends on its costs and deployment assumptions.

For emitting technologies, technology targets and carbon price drive the technological shifts. The carbon price raises the operational costs of a given emitting technology by raising the cost of fuel and emissions. An effective carbon price raises the fuel and emissions costs of CO_2-emitting technologies, which encourages a shift towards cleaner and cheaper technologies. A high and fast-increasing carbon price triggers a faster technological shift.

The deployment constraints (Table 2) include resource availability, growth constraints on capacity additions, grid integration challenges, land availability, as well as specific policies. These constraints vary regionally and represent the challenges to technological change in different economies.

Table 1 **IAMs assumptions on investment costs per technology in 2030 and 2050**

Investment cost (US$2010/kW)[16]	Year	REMIND-MAgPIE	MESSAGEix-GLOBIOM	GCAM
Coal power plant	2025	[2551, 2840]	[567, 1944]	~2946
	2050	[2551, 2840]	[651, 1494]	~2595
Coal power plant with CCS	2025	[3623, 5818]	[2811, 3953]	~4793
	2050	[3399, 4374]	[2012, 2836]	~4131
Gas power plant	2025	[606, 1086]	[454, 891]	~755
	2050	[815, 1028]	[427, 698]	~657
Gas power plant with CCS	2025	[2033, 2788]	[1342, 1982]	~1736
	2050	[1679, 2015]	[1201, 1851]	~1433
Solar (PV)	2025	[487, 900]	[472, 1455]	~1979
	2050	[353, 355]	[228, 570]	~1021
Solar (CSP)	2025	[4189, 5256]	[3297, 9932]	~3329
	2050	[2811, 2901]	[2736, 7885]	~2626
Wind (onshore)	2025	[1001, 4048]	[1126, 3775]	~2304
	2050	[1131, 1141]	[687, 1882]	~1321
Wind (offshore)	2025	[3656, 4075]	[1363, 3208]	~2104
	2050	[1633, 1749]	[895, 1729]	~1272
Nuclear	2025	[3901, 7205]	[3722, 8773]	~5279
	2050	[5200, 6667]	[3711, 7592]	~4830

Note: The ranges for REMIND-MAgPIE and MESSAGEix-GLOBIOM represent the minimum and maximum of regional variation in investment costs.

16 Notes: The cost of supporting battery storage facilities is not included in the investment cost of the solar and wind power generation technologies listed above for REMIND-MAgPIE and MESSAGEix-GLOBIOM; in the case of GCAM, the reported costs for solar and wind onshore represent the average of investment costs for technologies with and without battery storage, and are thus higher than in the other two models (this also explains the higher costs for onshore compared to offshore). All models adopt the same set of investment cost assumptions across all NGFS scenarios.

Table 2 **IAMs assumptions on deployment constraints per technology**

Deployment constraints	REMIND-MAgPIE	MESSAGEix-GLOBIOM	GCAM
Coal and Gas power plant	Follow policy constraints and growth constraints; endogenous choice for early retirement of vintages or reduction in load factors		
	With fixed lifetime and capacity factors	With max lifetime and capacity factors	With max lifetime and capacity factors
Solar PV and wind power	Constrained by resource availability modelled with spatial and temporal variability, constraints of curtailment and intermittency, growth constraints on capacity addition		
Nuclear	Some constraints based on regional context, but effectively endogenously limited by high upfront investment costs and long construction times		

2.6 Land use

The land use assumptions affect deforestation, reforestation, bioenergy production, and agricultural land expansion in IAMs. The land use change and biomass production (i.e., the biomass available to produce electricity, heat, ethanol, diesel, and hydrogen energy sources) are also responding to the carbon price, and thus differentiated across the NGFS scenarios. The overall potential of land use follows the SSP2 assumptions (i.e, moderate availability, where the share of land that can be used for biomass energy is relatively limited, considering a range of ecological and socioeconomic constraints).

All three IAMs are coupled between energy-economy and land-use components, allowing bioenergy markets and land-use emissions to equilibrate iteratively under the carbon price trajectory of each NGFS scenario.

The land-use modules (MAgPIE, GLOBIOM, and GCAM-Land) are recursive dynamic partial-equilibrium frameworks, with agricultural demand driven by GDP, population, dietary patterns, and food waste. This demand is met primarily through increases in land productivity – endogenously modelled in MAgPIE and exogenously specified in GLOBIOM and GCAM – as well as through cropland expansion or relocation (e.g., *via* trade). In each model, land-based GHG emissions (CO_2 from land-use change and CH_4 and nitrogen-related emissions from agricultural practices, such as fertilizer use) and biomass potentials are priced alongside emissions from the rest of the economy. This pricing mechanism limits deforestation and promotes afforestation or natural vegetation regrowth. More information in the NGFS Phase V Technical documentation (2024) (p 52, p 79, p 90).

3. Physical risks assumptions

The NGFS long-term scenarios offer a framework to estimate physical risks from climate change and their relative macroeconomic impacts. The NGFS physical risks assessment has multiple components: the biophysical risk indicators provided in the Climate Impact Explorer (CIE) (Section 3.1), and the economic assessment of GDP effects for both bottom-up acute (Section 3.2) and top-down aggregate risks (Section 3.3). The acute risk approach assesses GDP impacts of specific hazards (extreme heat, extreme droughts, tropical cyclones and river floods) through specific impact channels in NiGEM, while the Kotz *et al.* (2024) damage function approach focuses on aggregate GDP impacts.

3.1 Climate Impact Explorer tool (2025 update)

The Climate Impact Explorer (CIE) is an open access webtool with global coverage showing how the severity of climate change impacts (both chronic and acute risks) will increase over time for different levels of global warming for over 40 different indicators.

Methodology for NGFS physical risks impact chain

The emissions computed by the IAMs' transition scenarios are translated to Global Mean Temperature (GMT) projections using the MAGICC model. Following established approaches in the scientific literature, we assume that a given GMT level will on average lead to the same shift in the distribution of the respective climate indicators covered in the CIE – even if it is reached at two different moments in time, in two different emission scenarios. By exploiting all available impact data from ISIMIP3 by warming level, we estimate how specific impacts evolve with temperature. Projections are calculated assuming that **socio-economic conditions** (e.g., population, land-use, management practices) **remain constant at current levels**, therefore the CIE **isolates the sole effect of climate change** on the indicators it provides information on. However, it should be noted that actual future climate impacts will crucially be driven by socio-economic changes (e.g. population growth, urbanization) affecting vulnerability and exposure to changing climate hazards, which could not be captured within the context of the NGFS physical risk assessment. Aggregation from grid-cell level to the continental, national and sub-national levels uses weighted averages by either area, GDP, or population.

Uncertainty ranges shown in the CIE cover both the global climate response to emissions (i.e. how GHG emissions translate into global mean temperature increases) and the response of local impacts to global warming (i.e. the uncertainties stemming from the modeling of the impacts of climate change). Uncertainty increases for more complex modelling chains. There is higher scientific confidence in indicators from bias-adjusted Earth System Models ('level I indicators') compared to indicators based on sectoral impact models ('level II indicators') due to the additional level of complexity in the modeling chain (see 'report on physical risks in the updated Climate Impact Explorer'[17] (2025), for an overview).

Applicability note

The benefit of globally consistent data in the CIE comes with the downside that not all impact indicators can be validated on the local level. Only indicators from Earth System models are locally bias-corrected (see report on physical risks in the updated Climate Impact Explorer) on differentiation between "level I' and 'level II' indicators). Thus, the CIE indicators could show deviations from other datasets used in risk assessments focused on the regional, national or sub-national level. The findings from the CIE should be used to **supplement rather than replace national or regional risk assessments**.

Moreover, several types of physical risks from climate change are currently not covered in the CIE (for example sea level rise, permafrost melting, coastal flooding, winter storms or tipping points – see also "Tipping Points in the Earth System in the

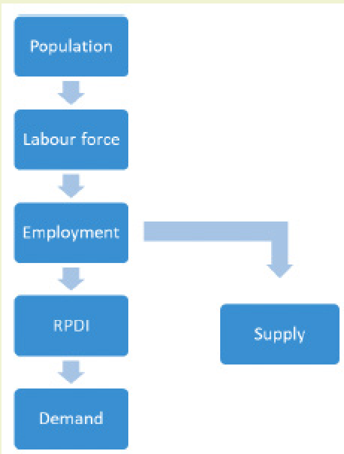
17 Zimmer, A., Anz, J., Byers, E., Hwong, Y., Kornhuber, K., Langer, R., Perette, M., Quante, Q., Schleussner, C., Hoegner, A., Moeller, T., Zimmer A., Kornhuber, K. (2025) Tipping Points in the Earth System in the context of the NGFS physical risk assessment – A short note. Network of Greening the Financial System. https://www.ngfs.net/en/publications-and-statistics/publications/explanatory-notes-ngfs-long-term-climate-scenarios.

context of the NGFS physical risk assessment – A short note[18]". Finally, given scope limitations, the CIE indicators for direct damages from Tropical Cyclones and from (river) floods have not been updated in this iteration.

3.2 Acute physical risk indicators as input to NiGEM (Phase IV, 2023)

In NGFS Phase IV (2023), four physical risk indicators have been used to estimate acute risks economic impacts with the macroeconomic model (NiGEM). This follows a bottom-up approach, as each indicator addresses one type of impact through one economic entry point in NiGEM. These have not been updated in Phase V. This section provides an overview of the acute physical risk indicators considered in the NGFS scenarios (Table 3), and a summary on the key methodological assumptions and caveats. Further assumptions related to NiGEM can be found in Section 4 on "Macroeconomic impacts assumptions".

Table 3 **Overview of acute physical risks indicators – More information in NGFS Phase V Technical documentation (2024) (Chapter 3 and 4)**

Acute risk	Drought	Heat	Flood	Tropical cyclones
What is measured?	Projected annual crop-land exposure to *extreme long-term* drought conditions and related agricultural yield losses estimations for different climate scenarios. Impacts from less severe droughts are not accounted for.	Projected annual exposed population to heat stress from humid heat (threshold-based definition) for different climate scenarios, as country-level Weibull distribution.	Projected annual average of direct damages due to river floods on proxied assets (based on gridded GDP data) exceeding flood protection standards (of the time of the modeling) for different climate scenarios. Only *river* floods are considered.	Projected direct damages on proxied (satellite derived) assets due to extreme winds for different climate scenarios. Damages from heavy rainfall are not included, storm surge damages only implicitly through wind driven waves.
Impact channels in NiGEM	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. 3. Prices: a fall in supply generates an increase in prices leading to a fall in demand.		Capital stock damages: investment premia variables (IPREM) are used by NiGEM to impact housing and business (as well as prices).	
Note	The drought and heat risk indicators have been substantially improved for the 2025 CIE update, however, NiGEM has not been run with the updated acute risk estimates. While Phase IV (2023) estimates remain reported, these are based on the Phase IV climate scenarios and not the latest vintage (Phase V).		The (river) flood and tropical cyclone modelling and the direct damage estimates have not been revised in the 2025 CIE update.	

18 Schleussner, C., Hoegner, A., Moeller, T., Zimmer A., Kornhuber, K. (2025) Tipping Points in the Earth System in the context of the NGFS physical risk assessment – A short note. Network of Greening the Financial System. https://www.ngfs.net/en/publications-and-statistics/publications/explanatory-notes-ngfs-long-term-climate-scenarios.

Key methodological assumptions and caveats for 2023 acute risk estimates (bottom-up approach)

Extreme Droughts:

- The drought indicator was chosen to reflect **crop-land exposure** to **extreme long-term drought conditions** and their impacts under different global warming levels. The underlying drought index (SPEI12) assesses dryness not just based on rainfall, but also accounting for loss through evapotranspiration from e.g. soil and plants. SPEI12 accounts for long-term droughts conditions lasting for a period of 12 months (SPEI12). A threshold of SPEI12 <-3 was used to test **extreme drought conditions** on a monthly basis, while the annual impact on yields was estimated to decline linearly with the number of months for which the threshold was breached. Consequently, **drought conditions less severe than the chosen threshold for extreme droughts are not covered**, even if they may also affect yields already. A 100% exposure to extreme drought is considered to lead to a 100% yield loss, non-exposure is assumed to lead to 0% yield loss. We assume that the impact of a drought on yields scale linearly with the number of months of extreme drought conditions within a year. Note that the applied linear drought impact model is based on several simplifications which could affect its accuracy on the national level (see more information on "Drought impacts" in the NGFS Phase V Technical documentation (2024)).
- Inputs into the NiGEM macroeconomic model: country-level distributions of projected yield losses (%) due to extreme drought risk (aggregated over a year) per global warming level to reflect the physically plausible spread of year to year exposure variations.

Extreme Heat

- We use a measure of **humid heat** (wet bulb temperature) which is particularly harmful for human health. We estimate the annual exposed population to heat stress by applying a combination of a relative location-specific threshold and an absolute threshold of 29.1 °C (which is considered harmful to outdoor workers, irrespective of the region) combined with gridded (2005) population data. Thus, regions in which humid heat is projected to dramatically increase but that are currently not as densely populated are assumed to be economically affected to a lesser degree. Individuals can be affected multiple times per year.
- Inputs into the NiGEM macroeconomic model: country-level (Weibull) distributions of projected people affected by heat stress (aggregated over a year) for different global warming levels to reflect the physically plausible spread of year to year exposure variations for different climate models from ISIMIP.

Tropical Cyclones (TC, also called *Hurricanes* or *Typhoons* depending on the region)

- Only **damages from extreme winds** are considered. Damages from heavy rainfall are not included, storm surge-related damages only implicitly through wind creating strong waves. The CLIMADA natural catastrophe modelling framework was applied. Data from observed historical tropical cyclones between 1950 and 2020 is used to project future TC exposure by generating a set of probabilistic storm tracks accounting for predicted changes in frequencies and intensities. Exposure is modelled at the country level for global coverage proxying asset data by disaggregating macro-economic data (e.g. on GDP) based on night light intensity data and population data. Thus, the proxy asset data **may not represent actual asset values** since it is a modelled estimation based on satellite images (LitPop). Vulnerability is modelled by applying damage functions (for 9 distinct regions) which have been calibrated based on empirical data. While these regions can be considered fairly homogeneous, **single country vulnerabilities may not be reflected**. By running the model by country and at various time steps for a specific scenario, countries' loss distributions at various levels of global warming are derived assuming linear relationships. **Potential non-linearities in future changes for TCs are not accounted for.** More importantly, **neither the exposure** (such as asset value changes) **nor the vulnerabilities are evolving in time** (since there is no generally accepted, spatially explicit projection of the sort to date at global scale). Only **impacts** of future climate cyclones **on current assets** are reported. Estimates represent **annual expected damages**.
- Inputs into the NiGEM macroeconomic model: asset damage estimates (in USD) for each GMT level for all modelled countries, and for a range of output samples along with the probability of that damage occurring in a country.

Floods

- Only **river floods** are considered. Flood protection standards at the time of the modelling at the subnational scale have been accounted for based on the information available in the FLOPROS database, thus **no further adaptation** is assumed. A **threshold-based approach** is applied assuming that flooding occurs when the amount of water in a river channel is exceeding the protection level. For quantifying the damages from flood height and flooded area as economic losses, historical (2005) gridded GDP data has been converted to capital stock estimates. Grid level damage from river floods is estimated by multiplying the exposed assets by the flooded area fraction and by a flood-depth damage function. Assumptions on **asset values** as well as **other socio-economic conditions** such as urbanisation patterns, river engineering and water withdrawal have been **kept fixed** at 2005 levels. Results were derived by aggregating a number of **global flood models**. Despite the partly high spatial resolution of the underlying modelling, local models tailored to certain regions likely represent local patterns better than global models. Estimates represent **expected annual damages**.
- Inputs into the NiGEM macro-economic model: Annual expected economic losses (direct damages) from river floods for each GMT level for all modelled countries or regions. These economic losses have been used as input to NiGEM in the form of discrete shocks to the NiGEM regions.

More information on the methodology can be found in the NGFS Phase V Technical documentation (2024) section on "acute risks". Note that with the 2025 CIE Update, the physical risk indicators for heat and drought have been considerably updated and improved compared to the estimates provided in 2023 (NGFS Phase IV), however these have *not* yet been implemented in NiGEM for updated acute risk estimates. Therefore the 2023 NiGEM acute risk estimates remain reported. However, note that these are still based on the Phase IV (2023) climate scenarios.

3.3 Aggregate GDP impacts from physical risks (top-down approach)

Throughout all phases of NGFS scenario releases aggregate economic impacts on GDP have been calculated using damage functions, reduced form relations quantifying the effect of mean temperature change on GDP. Different methods are used to estimate these relations and the uncertainty in the literature is high (see also the explanatory note 'Damage functions, NGFS scenarios, and the economic commitment of climate change' (2024). This was still reflected in Phase 1, where three different damage functions where used, spanning a range of outcomes and methodologies. Since Phase 2 this was reduced to one econometric damage function (Kalkuhl & Wenz 2020), given the already large uncertainty from the combination of climate uncertainty, inherent uncertainty in the damage estimate and multiple integrated assessment models. Econometric approaches estimate the effects of climate and weather on GDP and GDP growth using historical data. They capture climate impacts related to the climate drivers in the estimate, usually mean annual temperature and precipitation, affecting GDP and having occurred in the period and countries included in the analysis. This means they do not capture high-end extremes not seen in the past, nor non-market impacts or effects of sea-level rise. They also do not account for future adaptation to climate change. While they do not distinguish the channels through which climate change affects GDP they do provide a more comprehensive assessment than specific channel-based approaches. Their magnitude is strongly affected by assumptions on the persistence of the impacts on growth, which is an unresolved question.

The NGFS informs users that the academic paper underpinning the economic damage estimates from physical risks in Phase V, Kotz *et al.* (2024), has received critiques post-publication in Nature (for more detail, please refer to the notice at the start of this document).

4. Macroeconomic impacts assumptions (NiGEM)

In addition to the three IAMs, the NGFS uses the National Institute Global Econometric Model (NiGEM) to simulate the macroeconomic implications of transition and physical risk. To ensure consistency with the IAMs, NiGEM first creates a climate neutral baseline based on its own forecast and IAMs' Current Policies scenario trend. **Scenario-specific results are expressed as deviations from this baseline**, using selected IAM and climate model results as inputs.

4.1 Assumptions on transition impacts

The specific IAMs variables that NiGEM takes as inputs to derive transition impacts are **primary energy consumption, carbon revenues and useful energy**. Other key assumptions include:

- **Useful energy** is the primary driver of the productivity shock where the IAM useful energy is used to provide the change in the energy intensity of production within the NiGEM production function. The use of Useful energy was instigated in NGFS Phase III (2022) in order to capture technological improvements in the use of energy implicit in the IAM models. This supersedes the previous use of primary energy consumption.
- **Primary energy consumption** is used within NiGEM in the following manner:
  - The importance of fossil fuels within the energy mix is used in order to affect the impact of world energy prices on a country's import prices. Essentially, we are changing the importance of fossil fuels in the import basket based on their usage.
  - The export share of fossil fuel producing countries and regions is affected by changes in global fossil fuel consumption to represent the importance of fossil fuels to their export market.
- **Recycling of carbon tax revenues:**
  - In orderly scenarios (Net Zero 2050, Low Demand, Below 2 °C), 50% of the carbon tax revenue is allocated to government investment, while the remaining 50% is used for debt repayment.
  - In the other scenarios, revenues are recycled entirely through tax reductions.[19]
- **Confidence shocks in disorderly scenarios (Fragmented World, Delayed Transition)**: a one percentage point increase in the investment premium is applied in 2031-2032 to simulate a drop in business confidence due to sudden climate policy shifts.
- **Monetary Policy**: the monetary policy follows a 'two-pillar rule', where the short-term interest rate is set as a function of the deviations of the nominal GDP target to nominal GDP and the difference between expected inflation and the inflation target.

4.2 Assumptions on physical impacts

Acute physical risks[20]:

- Damages from acute physical risks are derived for four different types of hazards (drought, heat, flood and tropical cyclones – as defined in Section 3.2), for three of the NGFS scenarios: Current Policies, Delayed Transition, and Net Zero 2050.
- NiGEM simulates hazard-specific impacts using stochastic economic shocks[21], which are implemented *via* a random draw from climate variables distributions as calibrated by Climate Analytics. Only in the case of floods, a deterministic approach (given the annual average estimate provided by the CIE), i.e. a single shock rather than a stochastic trial, is used to impact NiGEM.
- The model treats acute risks at the national level: it only captures direct local supply and demand impacts, while taking exogeneous assumptions on global trade and policy reactions (e.g., monetary and fiscal responses).

19 For further documentation on the specific methods of recycling and their macroeconomic implications, see NGFS Sensitivity Analysis (2022).

20 Acute physical risks are applied only in 4th vintage (2023) of the long-term NGFS scenarios and results did not change in Phase V.

21 NiGEM shocks labour productivity for heatwaves, crops yields for droughts, and physical assets for cyclones and floods. See the Stochastic Implementation chapter in the NGFS Technical Documentation for detailed information about the transmission channels per hazard.

Aggregate economic damages from physical risks (top-down approach):

- To derive wider macroeconomic impact based on the aggregate damage function, NiGEM applied the GDP impacts derived with chosen aggregate damage function[22].
- The damage distribution is based on the median estimates of the future global temperature paths.
- To isolate domestic impacts, the model treats the corresponding GDP impacts as local shocks, without global economic reaction (i.e. trade and monetary policy channels are exogenised).

22 NGFS Phase V scenarios rely on the work of Kotz *et al.* (2024). More details about the NGFS approach damage function can be found in the explanatory note 'Damage functions, NGFS scenarios, and the economic commitment of climate change'. "See also disclaimer at the start of this document".

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