NGFS Short-Term Climate Scenarios Technical Documentation

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Central Banks and Supervisors Network for Greening the Financial System

Contents

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Executive Summary

The Network for Greening the Financial System (NGFS) is a group of 144 central banks and supervisors and 21 observers (as of 11 March, 2025) 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.

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.[1]

This document provides technical information on the first vintage of the NGFS short-term climate scenarios and the underlying modelling infrastructure. It outlines the main modelling and calibration assumptions used in the implementation of short-term scenarios.

This document offers both a non-technical overview and in-depth technical explanations of the scenarios, ensuring accessibility for readers with varying levels of technical expertise. The document is organised as follows: Firstly, the structure and objectives of the modelling framework is presented, followed by the key features of each model. Secondly, the approach to modelling transition and physical risk is explained, and the calibration of the baseline scenario is detailed. All subsequent sections are organised by scenario. Each scenario section presents the high-level narrative, followed by the implementation of the associated shocks, which sheds light upon how the narratives have been translated into the simulation specifications.

[1] The results do not assess the impacts on individual financial institutions, rather, the scenarios provide sector-specific financial outcomes that can serve as input, for example, for firm-specific balance sheet analysis.

Structure and objective of the modelling framework

The NGFS short-term scenarios aim to provide policymakers, regulators and financial institutions with a quantitative assessment of the potential short-term impacts of climate change and mitigation policies on the real economy, financial institutions, and the broader financial system.[2]

To achieve these objectives, the modelling framework covers multiple dimensions and macro-financial feedback loops. Both transition and physical risks are covered. To model transition risks, the modelling framework considers: (i) the direction, timing and scale of technological dynamics needed to achieve climate objectives; (ii) the resulting short-term macro-economic and financial dynamics; (iii) the interplay between these dimensions (macro-financial feedback) and (iv) how they feed back to technological dynamics.

To model physical risks the modelling framework considers: (i) the granular geographical (i.e. asset-level, georeferenced) exposures and sectoral characteristics of the distribution of impacts, (ii) their potential compounding effects, (iii) their propagation through production and financial networks, and (iv) the resulting macro-economic and financial impacts.

In terms of the interplay between transition and physical risks in the short-term time horizon, it is important to note that transition risk has little to no impact on physical risk over the short-term scenario forecast horizon of five years. This is as climate change impacts experienced now are the result of past GHG emissions and concentration in the atmosphere. To assess the trade-off between conducting ambitious transition policies and the policy-contingent future impacts from unmitigated climate change, a longer-term analysis is required (such as the one provided by the NGFS long-term scenarios).

In order to provide actionable insights for different stakeholders and reflecting the multidimensional characteristics of climate impacts and policies an assessment should cover multiple spheres: from global macro-economic dynamics to micro-level economic and financial impacts at a high level of sectoral and geographical granularity.

The short-term scenario modelling framework combines, in a logically consistent way, highly granular models for the representation of climate and transition impacts on the technological and financial risk dynamics, with a stock-flow consistent macro-financial model designed to capture the non-linear and complex features of the green transition and climate impacts (including expectations). Thus, the modelling structure accommodates these different requirements, while representing the key economic and financial mechanisms and transmission channels that characterise transition and physical risks associated with climate change.

[2] The data is available in the IIASA portal and via the EnTry python script. Please see the annex for more details on data access and tools.

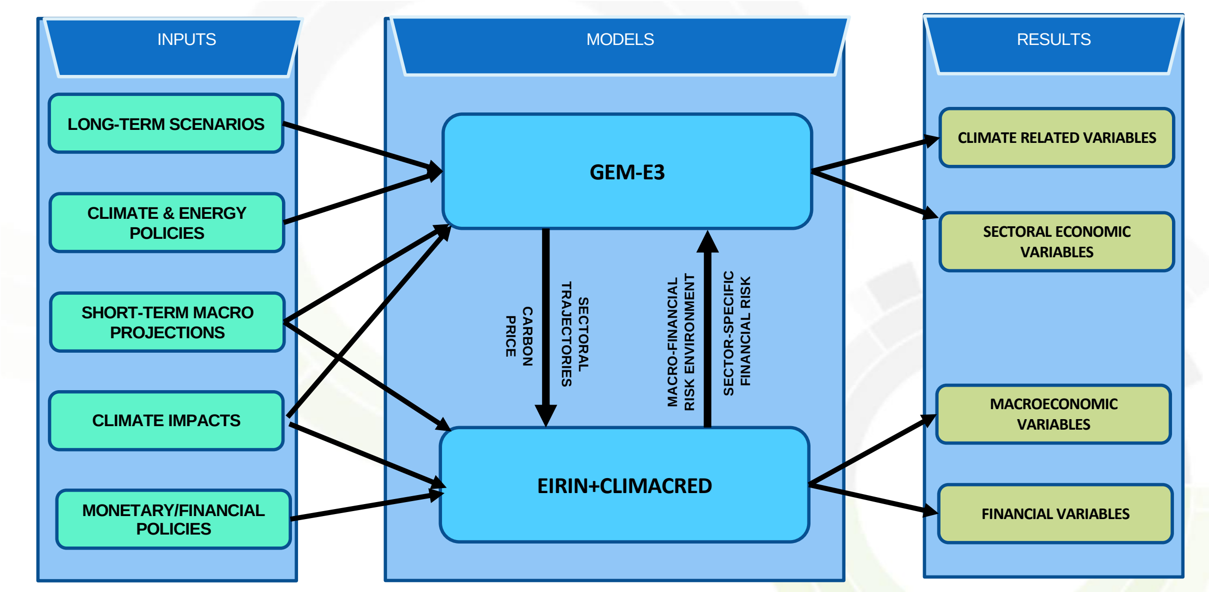


Figure 1: General structure of the GEM-E3-CLIMACRED-EIRIN modelling framework.

Technological dynamics and supply-chain propagation mechanisms are captured by the large scale macroeconomic CGE GEM-E3 model.

In the context of **transition risks**, GEM-E3 takes as input climate objectives and key features of climate policies and provides detailed economic and technological projections at a high-level of sectoral and geographical granularity (50 sectors and 46 regions, see Appendix E and F) taking not account the interdependencies of the global economic system.

In the context of **physical risks**, GEM-E3 takes as input sector and country specific distributions of climate exposures and determines their direct economic impacts as well as the extent of their propagation through global supply chains for each country and economic activity (aggregated to 50 sectors and 46 regions).

Financial dynamics (i.e. probability of default, financial valuation adjustment, Value at Risk) are captured by the CLIMACRED credit risk model.

In the context of **transition risks**, CLIMACRED takes as inputs firms' business and financial characteristics, and GEM-E3 scenario-contingent projections of sectoral economic trajectories. It thus derives the dynamic evolution of the balance-sheet of representative sectoral firms and therefrom determines scenario-contingent changes in asset values, interest rates, cost of capital and financial risk characteristics (in particular default probabilities).

As for **physical risks**, CLIMACRED takes as inputs the country and sector level distribution of impacts in terms of capital destruction, business interruption and productivity losses. It models the induced changes in the evolution of the balance-sheet of sectoral firms and quantify therefrom scenario-contingent changes in asset values (equity, corporate and sovereign bonds), interest rates, sectoral cost of capital and financial risk characteristics.

Macro-financial dynamics are simulated by the EIRIN model at the level of global regions (North America, South America, Asia, Europe, Oceania).

In the context of **transition risks**, the EIRIN model takes as input carbon price projections from the GEM-E3 model. EIRIN then simulates the resulting macroeconomic and financial dynamics, accounting for the substitution between high- and low-carbon capital, its macro-financial consequences, and their interplay with fiscal and monetary policies. Notably, EIRIN derives dynamic trajectories for GDP, inflation and policy rates that are consistent with the technological and financial dimensions of transition scenarios.

In the context of **physical risks**, EIRIN takes as inputs the country and sector level distribution of impacts in terms of capital destruction, business interruption and productivity losses. Then, EIRIN derives dynamic trajectories of GDP, inflation, and policy rates that account for both direct macroeconomic impacts and their potential macro-financial amplification.

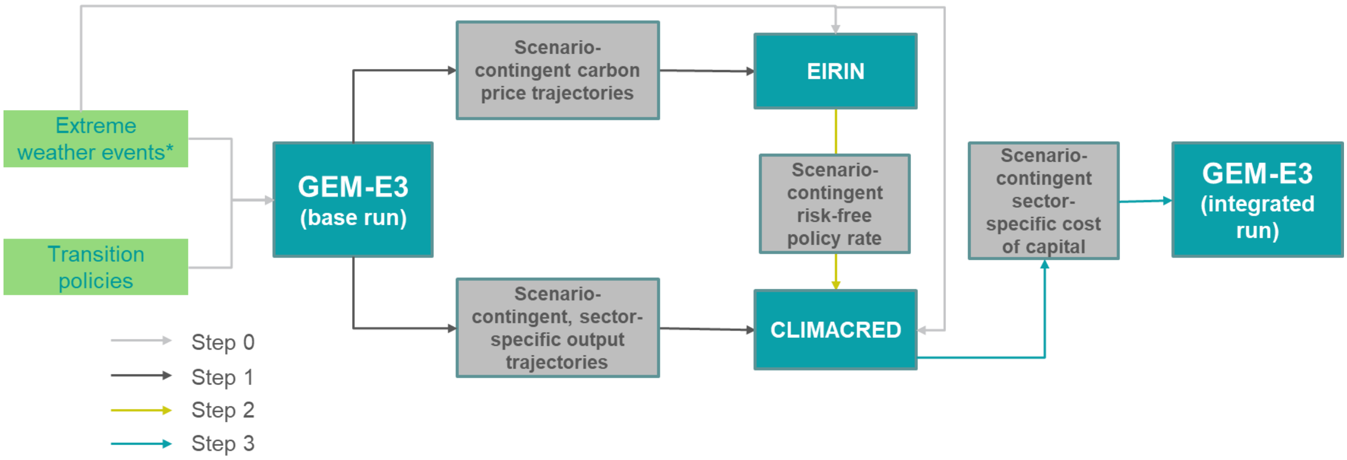


Figure 2: Logical and temporal flow of the coupling of GEM-E3, CLIMACRED and EIRIN models. The figure should be read from left to right. Step 0 (grey arrows): Scenario-contingent direct physical impacts (see section 'Representation of physical risks') passed to GEM-E3 and EIRIN. Scenario-contingent transition policies passed to GEM-E3. Step 1 (black arrows): GEM-E3 calculates and provides the scenario-relevant carbon price to EIRIN, and the sectoral output trajectories to CLIMACRED. Step 2 (green arrows): EIRIN calculates and provides the risk-free policy rate to CLIMACRED. Step 3 (teal arrows): CLIMACRED calculates and provides the scenario-adjusted sectoral cost of capital to GEM-E3. Step 4 (final/integrated run): GEM-E3 provides scenario-contingent output trajectories disaggregated by sector and country, considering the monetary and financial valuation dynamics provided by EIRIN and CLIMACRED, respectively. For the implementation of physical risk, the direct physical effects on GEME3 sectors are applied to all three models, and combined in the GEM-E3 integrated run

The three models (GEM-E3, EIRIN and CLIMACRED) have different characteristics and cover different aspects of the economy. Nevertheless, interfacing these provides an integrated assessment, as illustrated in Figure 2. The initiating run is performed by GEM-E3. The carbon price is determined by GEM-E3, as a function of climate policies, energy prices and technological characteristics/dynamics, which is then used as an input in EIRIN to represent the stringency of the energy system transition. EIRIN produces macro-financial dynamics contingent to the climate scenarios. Variables include, among the others, the evolution of the inflation and risk-free rate. CLIMACRED takes the risk-free rate from EIRIN and the sectoral trajectories from GEM-E3 to calculate adjustments in the sectoral probability of default, valuation of equity, corporate and sovereign bonds, and resulting changes in cost of capital. These updated costs of capital are then fed into GEM-E3. The second run of GEM-E3 then produces updated macro-economic dynamics that account for macro-financial feedbacks and financial risk assessment. The variables produced by each of the models can be found in the appendixes G, H and I.

Macro-financial developments in the short-terms scenarios can have substantial feedback effects on sectoral and geographical dynamics. To account for these second-round effects, the evolution of (i) scenario-contingent risk-free rates determined by EIRIN is fed into CLIMACRED, and (ii) sector specific evolution of the risks and costs of debt and equity determined by CLIMACRED is fed into GEM-E3. This allows to determine: i) the evolution of sectoral costs of capital, ii) the sectoral investments, iii) the impact on GDP components and iv) impact on sectoral production. [3]

Overall, the modelling framework provides (i) a granular representation of technological, economic and financial dynamics (at the sectoral level), (ii) a granular representation of the evolution of financial risk (at the sectoral level), and (iii) a representation of macro-financial and monetary policy dynamics at the aggregate level. The framework also considers the key transmission channels between physical and transition risks (see Figure 3 below) and across these three dimensions: the impact of technological dynamics on financial risk, the impact of structural change on macro-economic dynamics, the impact of macro-financial, monetary policy and credit risk dynamics on technological change and economic development.

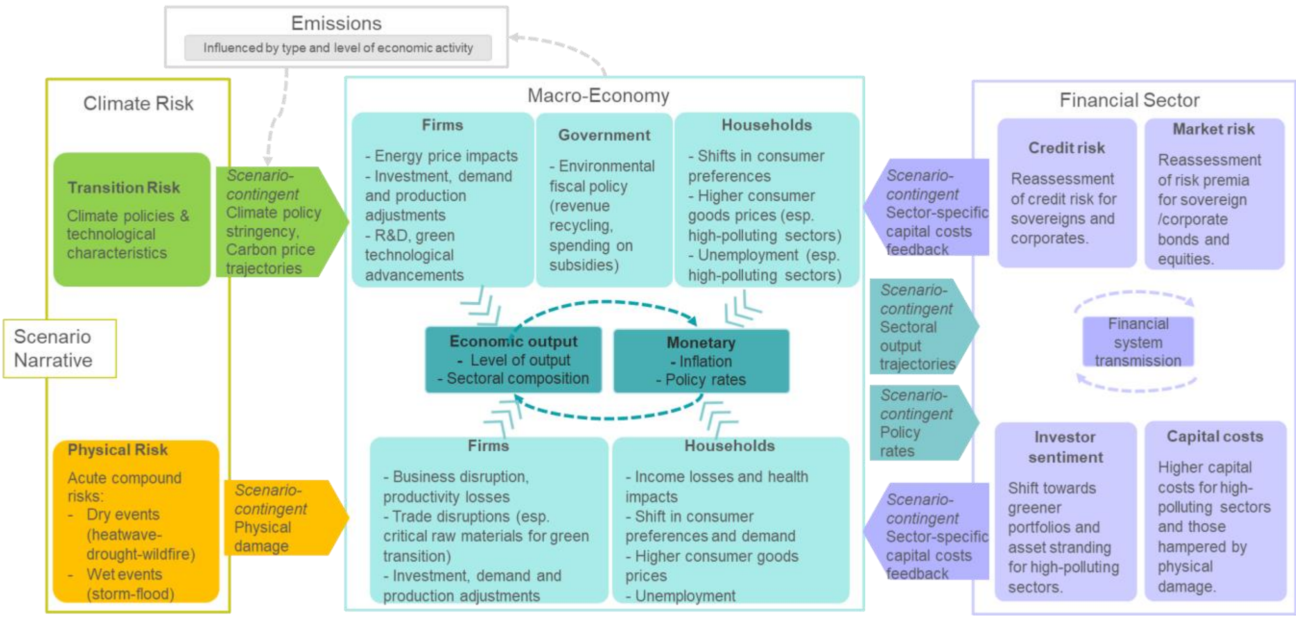


Figure 3: Transmission channels and feedback mechanisms in the NGFS short-term scenario modelling framework

[3] Note: The initial first run data is also available in the IIASA portal. This is labelled as _run1 for the given scenario and allows users to explore the magnitude of the additional impact from the monetary and financial sector on final outcomes.

Model features

This section presents the key features of the modelling framework implemented in the NGFS short-term scenarios.

GEM-E3

GEM-E3[4] is a global, multi-regional, multi-sectoral, recursive dynamic CGE model which provides details on the macroeconomy and its interaction with the environment and the energy system.

Box 1: General characteristics of Computable General Equilibrium (CGE) models

A Computable (solvable numerically), General (covering the wider economy), Equilibrium (optimising agents leading to balances) model, or CGE, describes a whole economy by a set of equations representing the behaviour and interdependencies of all economic agents and is calibrated on empirical data. Agents behaviour and economic system operation is in line with neoclassical theory, where firms seek to maximise their profits and households to maximise their welfare (Dudu & Kabir, 2020). Models are founded on rigorous microeconomic theory and are solved numerically. Their full coverage of the economy and its interdependencies, the large set of agents, variables and equations, might make the results hard to interpret, entailing a "black box" phenomenon (Sue Wing, 2004) when they are not accompanied by explanatory documentation. The complexity of the ensuing interpretation is however the other side of the coin of the ability of these models to capture and shed light over the inter-dependencies among sectors, agents, countries, and markets (The Scottish Government, 2016). Essentially these models allow to trace any impact back to its fundamental drivers and map the channels through which they affect the economic system. CGE models are calibrated on large and wide datasets, covering all economic and energy system transactions to correctly reflect the starting point for the economy. The building block of the model calibration is the Social Accounting Matrix (SAM), which a statistical framework used to capture all economic relationships across households, firms, government and the public sector. Each sector or agent has an optimisation behaviour. The approximation of production and consumption takes place through a variety of functions, including Constant Elasticity of Substitution CES (and its sub cases which are the Leontief (constant production factors) or a Cobb-Douglas), trans-log, Linear Expenditures System, Constant Elasticity of Transformation, etc (Lofgren, Harris, & Robinson, 2001). The CGE models capture both the capital and the functioning of the labour markets allowing for frictions and disequilibria.

Benefits of CGE models (including for application in climate modelling)

Thanks to their ability to represent complexity and their detailed/granular representation of the economy, these models are apt to assess the impact of a wide variety of policies, from fiscal to energy policies. CGE models are hence particularly suitable for the assessment

[4] The technical documentation of the model can be found in the https://e3modelling.com/modelling-tools/gem-e3/

of climate policies, which can affect each sector differently, *e.g.* on the basis of their carbon intensity, trade exposure, technology dynamics, financial constraints and the limitations imposed by governments. Additionally, the geographical and sectoral granularity of a CGE, if combined with the representation of the interactions between the economy, the energy system and the environment, can offer a good outlet for the implementation of climate events and the analysis of their effects across the economy. For example, the World Bank uses a CGE model to assess the impact of changes in temperature and precipitation and related crop yields losses on Zimbabwe's (Benitez-Ponce et al., 2018), and the European Commission performs impact assessment of climate policies (Joint Research Centre, 2025).[5]

The world version of the GEM-E3 model simultaneously represents 50 sectors (see Annex E) and 46 countries/regions linked through endogenous bilateral trade flows. The model features perfect competition market regimes, discrete representation of power producing technologies, semi-endogenous learning by doing effects, unemployment, an option to introduce energy efficiency standards, and formulates emission permits for GHG and atmospheric pollutants. The environmental module includes flexibility instruments allowing for a variety of options when simulating emission abatement policies, including different allocation schemes (grandfathering, auctioning, etc.), user-defined clubs for emission trading, various systems of exemptions, various systems for revenue recycling, etc.

The GEM-E3 model includes all simultaneously interrelated markets and represents the system at the appropriate level with respect to geography, the sub-system (energy, environment, economy) and the dynamic mechanisms of agent's behaviour. The model has discrete but interconnected modules representing the energy, economic and environmental systems.

The model formulates separately the supply or demand behaviour of the economic agents which are considered to optimise individually their objective (firms' profits and consumers welfare) while market derived prices guarantee that demand meets supply. The representation of multiple countries, economic agents, sectors, labour skills and households[6] allows the consistent evaluation of distributional effects of policies. The model considers explicitly the market clearing mechanism and the related price formation in the energy, environment and economy markets: prices are computed by the model as a result of supply and demand interactions in the markets and different market clearing mechanisms, in addition to perfect competition. For example, in the labour market an empirically estimated labour supply function is used allowing for unemployment per occupation.

The model formulates production technologies in an endogenous manner allowing for price-driven derivation of all intermediate consumption and the services from capital and labour. In the electricity sector a bottom-up approach is adopted for the representation of the different power-producing technologies. For the demand-side, the model formulates consumer behaviour and distinguishes between durable (equipment) and consumable goods and services.

[5] Other relevant studies: Feyen et al. (2020); Karkatsoulis, P. et al. (2017); Paroussos, L. et al. (2015); Elberry, A. M. (2024); Polzin, F. et al. (2021).

[6] Multiple households module is available only for the EU MS.

The model is dynamic, recursive over time and driven by accumulation of capital and equipment. Hence the model properties are mainly manifested through stock/flow relationships, technical progress, capital accumulation and agents' (myopic) expectations. Agents are myopic making investment and saving decisions considering that current period (annual) prices and demand will last in the long term. In the next period prices and demand changes leading to revised decisions. The implication of this approach is that agents are not adopting optimal inter-temporal investment decisions – increasing the potential for stranded assets and short-term capacity constraints.
Technological progress is explicitly represented in the production function, either exogenously or endogenously, depending on R&D expenditure by private and public sector and taking into account spillovers effects.

The design of the GEM-E3 model has been based on four main guidelines:

1. A model design around a basic general equilibrium core in a modular way so that different modelling options, market regimes and closure rules are supported by the same model specification.
2. Fully flexible (endogenous) coefficients in production and in consumer's demand.
3. Calibration to a base year data set, incorporating detailed Social Accounting Matrices as statistically observed.
4. Dynamic mechanisms, through the accumulation of capital stock.

The GEM-E3 model starts from the same basic structure as the standard World Bank models[7]. Following the tradition of these models, GEM-E3 is built on the basis of a Social Accounting Matrix (SAM). Technical coefficients in production and demand are flexible in the sense that producers can alternate the mix of production not only regarding the primary production factors but also the intermediate goods. Production is modelled through KLEM (capital, labour, energy and materials) production functions involving many factors (all intermediate products and three primary factors –capital, natural resources and labour). At the same time, consumers can also endogenously decide the structure of their demand for goods and services. Their consumption mix is decided through a flexible expenditure system involving durable and non-durable goods. The specification of production and consumption follows the generalised Leontief type of models as initiated in the work of Jorgenson (1984).

The GEM-E3 model is built in a modular way around its central CGE core. It supports defining several alternative regimes and closure rules without having to re-specify or re-calibrate the model. The most important of these options are presented below:

- Capital mobility across sectors and/or countries
- Flexible or fixed current account (with respect to the foreign sector)
- Flexible or fixed labour supply
- Market for pollution permits national/international, environmental constraints

[7] The World Bank type of models constitutes the major bulk of equilibrium modelling experiences. This type of model was usually used for comparative statics exercises. The World Bank and associated universities and scientists have animated a large number of such modelling projects, usually applied to developing countries. Main authors in this group are J. De Melo, S. Robinson, R. Eckaus, S. Devarajan, R. Decaluwe, R. Taylor, S. Lusy and others. These models however do not use full scale production functions but rather work on value added and their components to which they directly relate final demand.

- Fixed or flexible public deficit
- Perfect competition or Nash-Cournot competition assumptions for market competition regimes

The model is calibrated to a base year data set that comprises a full Social Accounting Matrices for each country/region represented in the model. Bilateral trade flows are also calibrated for each sector represented in the model, taking into account trade margins and transport costs. Consumption and investment are built around transition matrices linking consumption by purpose to demand for goods and investment by origin to investment by destination. The initial starting point of the model includes a detailed treatment of taxation and trade.

Total demand (final and intermediate) in each country is optimally allocated between domestic and imported goods, under the hypothesis that these are considered as imperfect substitutes (the “Armington” assumption (Armington, 1969)).

Institutional regimes, that affect agent behaviour and market clearing, are explicitly represented, including public finance, taxation and social policy. The model represents goods that are external to the economy as for example damages to the environment. Figure 4 illustrates the overall structure of the GEM-E3 model.

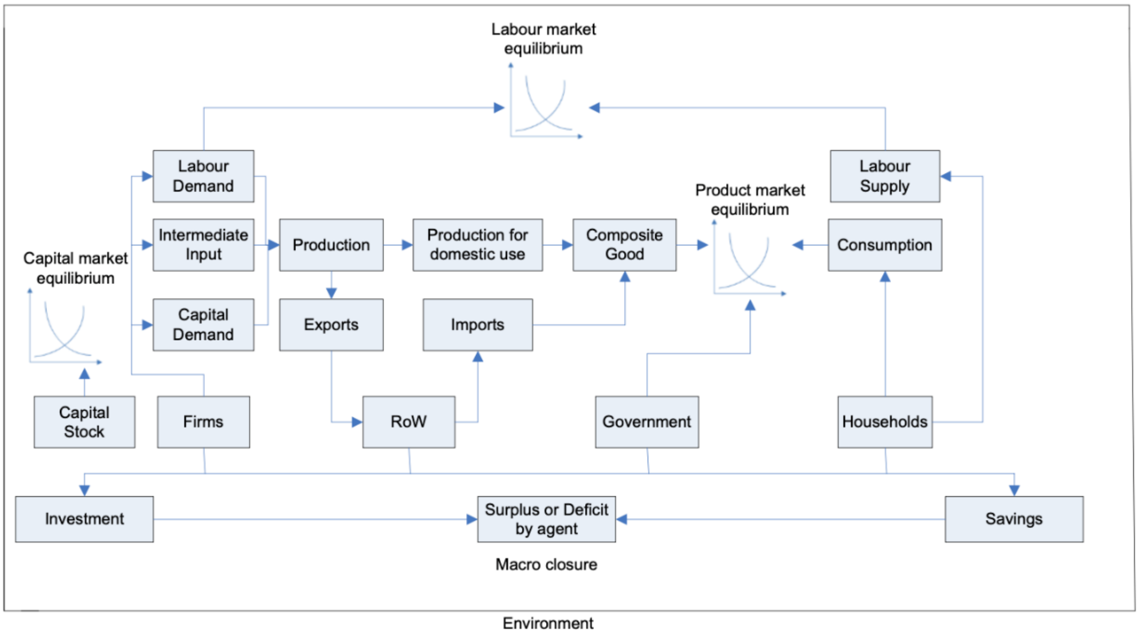


Figure 4: GEM-E3 economic circuit.

Climate-relevant modelling features

The internalisation of environmental externalities is achieved either through taxation (e.g. carbon pricing)or global system constraints, the shadow costs of which affect the decision of the economic agents (e.g. carbon value). In the GEM-E3 model, global/regional/sectoral constraints are linked to environmental emissions, changes in consumption or production patterns, external costs/benefits, taxation, pollution abatement investments and pollution permits. The model evaluates the impact of policy changes on the environment by calculating the change in emissions and damages; then determines costs and benefits through an equivalent variation measurement of global welfare (inclusive of the environmental impact).

Key features for the implementation of the short-term scenarios are the representation of technological change and investment choices. The speed of technological change is a key determinant of the economic impacts of climate policies. Following the modelling structure used in Paroussos et al. (2019), technological change is primarily driven by **learning-by-doing** on the one hand and **investment in R&D** on the other hand. Furthermore, GEM-E3 models the effects of technological spillovers through their impact on total factor productivity. More precisely, total factor productivity in the model is decomposed into three main components: i) a part related to learning-by-doing, ii) a part related to investment in R&D and iii) a part due to spillover, i.e. one has:

$$TFP_t = TFP_{t-1} \cdot GTFP_t^{lbd} \cdot GTFP_t^{R\&D} + GTFP_t^{spillover}$$

where $GTFP^{lbd}$, $GTFP^{R\&D}$ and $GTFP^{spillover}$ denote respectively the growth factor of productivity related to learning-by-doing, investment in R&D and spillover effects.

In line with the theoretical literature, **learning-by-doing** is assumed to be increasing with cumulative production, so that its growth factor is of the form:

$$GTFP_t^{lbd} = \left(\frac{Q_t}{Q_{t-1}}\right)^{1+l1}$$

where Q_t denotes cumulative production up to period t and *l1* is the elasticity that captures the percentage reduction in costs associated with an increase in cumulative production given by the learning rate LR. Namely:

$$l1 = -\frac{log(1 - LR)}{log\ (2)}$$

The learning rates have been determined through a comprehensive literature review (Capros et al. 2017, Karkatsoulis et al. 2O14) and are reported in supplementary Figure 34 on the Appendix J

Investment in R&D is determined in the model's R&D module in Capros et al. (2017) where firms choose to invest to increase productivity and hence, based on myopic demand expectations, maximise their intertemporal revenue. The growth in total factor productivity induced by R&D investment is then given by:

$$GTFP_t^{R\&D} = \left(\frac{CR\&D_t}{CR\&D_{t-1}}\right)^{1+l2}$$

where $CR\&D_t$ denoted the cumulative investment in R&D and $l2$ is the elasticity that captures the percentage reduction in costs associated with an increase in cumulative R&D expenditures. Namely $l2 = -\frac{log(1-LRRD)}{log\ (2)}$ where LRRD is a parametric learning rate (see supplementary tables).

Finally, total factor productivity growth can be induced by **spillover effects from R&D performed in other regions** as in Fragkiadakis et al. (2020). The literature, see Matthieu et al. (2013), emphasises trade, foreign direct investment, and more broadly transfers of intellectual property as potential drivers of technological spillovers. Their impact on total factor productivity is estimated according to the following equations (the time index is omitted here for the sake of simplicity):

$$GTFP_{i,r,t}{}^{spillover} = \sum_{j,s} TFP^{spillover}_{i,j,r,s,t}$$

$$TFP^{spillover}_{i,j,r,s,t} = absorption_{i,r} \cdot spillover_{i,j,r,s} \cdot \left(GTFP^{R\&D}_{j,s,t} - GTFP^{R\&D}_{j,s,t-1}\right)$$

where $absorption_{i,r}$ denotes the absorption capacity of sector i in region r and $spillover_{i,j,r,s}$ denotes the rate of spillover from sector j in region s to sector i in region r. These spillover rates are estimated in Paroussos et al. (2017) using the patent citation methodology of Verspagen (1997).

The investment decisions of firms are another key determinant of the dynamics of the energy transition. In GEM-E3, the investment decision is mainly determined by the ratio between investment costs and the rental price of capital. Namely, one has

$$A\_INV_{pr,er,t} = A\_KAV^{*}_{pr,er,t} \cdot a0_{pr,er,t}\left[\left(\frac{P\_KAV_{pr,er,t}}{P\_INV_{pr,er,t} \cdot \left(rr_{er,t} + d_{pr,er,t}\right)}\right)^{a1_{pr,er,t} \cdot sinv_{pr,er,t}} \cdot \left(1 + stgr_{pr,er,t}\right) - 1 + d_{pr,er,t}\right]$$

where:

- $A\_KAVC_{pr,\,er,\,t}$ is the capital stock of firms
- $A\_KAV^{*}_{pr,er,t}$ is the optimal level of capital
- $d_{pr,\,er,\,t}$: is the depreciation rate
- $A\_INV_{pr,\,er,\,t}$: is the investment of firms in volume
- $P\_KAV_{pr,\,er,\,t}$: is the user cost of capital
- $P\_INV_{pr,\,er,\,t}$: is the price of investment
- $stgr_{pr,\,er,\,t}$: is the exogenously specified expected growth rate of the sector
- rr: is the interest rate
- $a0_{pr,\,er,\,t}$: is the scale parameter in investment function
- $a1_{pr,\,er,\,t}$: is the speed of adjustment parameter
- $sinv_{pr,\,er,\,t}$: is the elasticity parameter

Overall, investment depends on the factor

$$\frac{P\_KAV_{pr,er,t}}{P\_INV_{pr,er,t} \cdot \left(rr_{er,t} + d_{pr,er,t} + cr_{pr,er,t}\right)}$$

which can be influenced by climate-related financial risks through an additional climate-risk factor $cr_{pr,er,t}$ affecting the cost of investment.

Sectors mapping

The mapping of GEM-E3 sectors to NACE 2 Sectors is available in appendix E. CLIMACRED and GEM-E3 sectors correspond one to one. To implement correctly the shocks, a mapping between EIRIN and GEM-E3 sectors is implemented by EIRIN within the model (Annex L).

Additional details on GEM-E3 implementation
Carbon pricing

- In the sectors belonging to ETS (international) the GHG emission allowances are auctioned.
- In the non-ETS sectors allowances are distributed for free. [8]
- Oil and Gas prices decline[9] as a result of the decarbonisation of the energy system (lower demand).
- There are no trade restrictions and exchange of clean energy technologies is driven by changes in relative costs.

Other

- Explicit financing schemes for agents in deficit are made explicit in the modelling. Interest rate and payback period set exogenously.
- Additional costs increase production costs of firms – marginal cost pricing is adopted in all firms.
- No modelling of alternative cost pass through rates.

CLIMACRED

The CLIMACRED model (see Battiston et al., 2023) is a climate credit risk model that allows for climate scenario-contingent financial valuation of firms' bonds and equity. In particular, with CLIMACRED we can carry out an analysis of scenarios-contingent adjustments in firms' probability of default (PD), the firms' costs of capital, and in the valuation of firms' financial instruments.

Credit risk stems from the adjustment of market expectations about the materialization of a given scenario (it can be physical or transition risk), and its impact on firm's cash flows and profitability. Thus, climate credit risk can emerge in the short term as a result of the change in the valuation of the firm, based on market expectations' adjustment.

Credit risk is then quantified starting from the analysis of firm's exposure to climate transition risk and physical risks, and then translating it into adjustment of firm's output and cash flows, contingent to the NGFS scenarios trajectories by sector and country.

Firms' exposure to transition risk is considered via the classification of firms' activities (plants) and revenues into Climate Policy Relevant Sectors (CPRS granular mapping to NGFS sectors for transition risk (Battiston et al., 2022))[10]. In contrast, firms' exposure to physical risks is

[8] Carbon value drives substitutions in agents' decisions - agents take decisions as if they had to pay the carbon price.
[9] Taken from the corresponding IEA scenario projections
[10] The mapping of NACE 4digit sectors into CPRS and into NGFS scenarios variables is freely available here: https://www.df.uzh.ch/en/people/professor/battiston/projects/CPRS.html

considered via the geolocation of assets (i.e. productive plants) and their climate risk (e.g. adaptation), business and financial characteristics (Mandel et al., 2025).

The CLIMACRED model builds upon a structural representation of firms' balance sheet where the evolution of debt is driven by investment needs and retained earnings[11]:

$$D_{t+1} = (1+r)D_t + I_t - (1-d)\Pi_t$$

where D_t is the debt at the beginning of period t, r the interest rate on the firm's debt, I_t the investment in period t, and $(1-d)\Pi_t$ are the retained earnings in period t, which consists in the share of profits Π_t not distributed as dividends in period t (where d is the dividend rate).

In turn, firms' assets A_t consist of the fixed capital they hold. A_t is built up of depreciated cumulative investment:

$$A_t = \sum_{s=0}^{t} (1-\delta)^{t-s} I_s$$

The default condition at a date T is then given by $A_T \leq D_t$. The default probability PD_T is determined by the profit rate distribution so that:

$$PD_T = P(A_T \leq D_t) = P\left(\pi \leq \frac{\bar{I}_T - A_T - \bar{W}_T}{(1-d)\bar{X}_T}\right) \quad \text{(CLIMACRED1)}$$

where $\bar{I}_T$ is the cumulative value of investment compounded at interest rate r, $\bar{W}_T$ is the value of (initial) equity compounded at rate r up to period T, $\bar{X}_T$ is the cumulative (future) value of output up to period T compounded at rate r, and π is the time-average of the profit rate (see Battiston and al. 2023 for details).

From here, one can derive the value of a zero-coupon bond with maturity T as

$$B_T = (1+r_0)^{-T}(1 - PD_T + r * PD_T) \quad \text{(CLIMACRED2)}$$

where r_0 is the risk-free rate and R the recovery rate given default, with R being endogenous.

Likewise, the value of equity (with default being evaluated at maturity T) is given by:

$$E_T = \mathbb{E}\left(d\, \underline{X}_T \pi_T + max(A_T - D_T, 0)\right) \quad \text{(CLIMACRED3)}$$

Where $d\underline{X}_T$ is the discounted sum of revenues up to T, π_T the associated profit rate and $max(A_T - D_T)$ the residual value of assets at maturity.

In the NGFS short term scenarios project, the CLIMACRED model is calibrated to ensure consistency with the baseline scenario. In particular:

[11] The initial capital of then firm is constituted with a mix of debt and equity, but no new equity is issued over time.

- The risk-free interest rate is derived from the policy rate in EIRIN
- The interest rate on firm's debt r is initialised using the market interest-rate in GEM-E3
- Using the zero-coupon fair valuation $B_T = (1+r)^{-T}$, one then infers the baseline probability of default PD_T by fixing the recovery ratio parametrically.
- Given the profit-rate distribution, one can infer the value of the default threshold $\bar{\pi} = \frac{\bar{I}_T - A_T - \bar{W}_T}{(1-d)\bar{X}_T}$.
- Among the components of $\bar{\pi}$, the values of cumulative output $\bar{X}_T$ and residual capital value A_T are inferred from the sectoral output trajectory in GEM-E3.
- Thus, one can infer the value of the net liabilities $\bar{I}_T - \bar{W}_T$.

After its calibration in the baseline scenario, the model is used to perform climate scenario contingent valuation of credit risk (e.g. sectoral PDs, spreads), corporate and sovereign bonds, equity values. Namely, for a climate scenario P:

- Risk-free rate is set equal to the scenario policy rate in EIRIN.
- Sectoral output trajectories provided by GEM-E3 for a climate scenario P are used to update the values of the cumulative output $\bar{X}_T^P$, of the discounted sum of revenues $\underline{X}_T^P$, and of the residual capital value A_T^P.
- The value of net liabilities $\bar{I}_T^P - \bar{W}_T^P$, and the related value of debt at maturity D_T^P are determined under the assumption that a share of the investment in the baseline scenario can become stranded, depending on the type of economic activity (i.e. fossil fuels and high-carbon) so that $\bar{I}_T^P - \bar{W}_T^P = \gamma(\bar{I}_T - \bar{W}_T)$, where γ is a stranding coefficient.

Using Equations (CLIMACRED1) to (CLIMACRED3), one can determine the scenario-contingent values of probabilities of default PD_T^P, bond value B_T^P, and equity value E_T^P and of the associated financial risk metrics, such as yield to maturity. A similar approach is used to derive scenario-contingent valuation for sovereign debt (see appendix B for details).

To infer the scenario-contingent weighted-average cost of capital (WACC) used as an input in the second-round run of GEM-E3, one can use the standard definition of WACC:

$$WACC = \sigma_E \, c_E + \sigma_B \, r$$

where σ_E and σ_B are the share of debt and equity, respectively, while c_E and r are the cost of debt and the cost of equity.

In our setting, the baseline WACC is obtained as an output of GEM-E3. The scenario-contingent WACC is obtained as follows:

- The share of debt and equity is inferred from the Damadoran debt ratios dataset[12] .

[12] https://pages.stern.nyu.edu/~adamodar/New_Home_Page/data.html and more specifically https://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/dbtfund.html

- From the baseline WACC and interest-rate given in GEM-E3, the implied baseline cost of equity is determined by inverting the WACC formula above.
- The cost of debt in the policy scenario is then given by the scenario-contingent interest rate r^P, while the scenario-contingent value of equity is determined by scaling up the baseline cost proportionally to the equity value ratio, i.e. one has $c_E^P = \frac{E_T}{E_T^P} c_E$. One then has:

$$WACC^P = \sigma_E \, c_E^P + \sigma_B r^P$$

It should be noted, for the goals of analysing the policies of a specific jurisdiction, that CLIMACRED does not account for ad-hoc government guarantees, financial schemes that could be introduced to support/de-risk specific sectors in some countries, nor economic and industrial policy that might be available in a jurisdiction as response to an economic shock. Users are advised to account for such country-specific schemes in their analysis.

The following additional assumptions are implemented in CLIMACRED in the context of the NGFS STS transition-risk scenarios:

(i) PD-adjustments (and related changes in bond and equity values) are assumed to be non-negative for some sectors. This assumption covers the cases of sectors that might grow in the short-term utility for which it is deemed unlikely that the market will consider this trend sufficiently sustainable to factor it in its risk-assessment (e.g. gas-fired power).

(ii) PD-adjustments in sectors with revenues lower than 25 million US$/year within a country are assumed to be zero for the non-materiality of those sectors. This assumption covers in particular the cases of certain sectors (e.g. oil fired and coal-fired power) that are being phased out in specific countries.

(iii) PD-adjustments associated to a given year Y refer to a zero-coupon bond issued on January 1st of Year Y with a maturity of one year.

EIRIN

EIRIN is a macro-financial Stock Flow Consistent (SFC) model of an open economy, calibrated at the country or regional level.

Box 2: General characteristics of Stock-Flow Consistent (SFC) models

A Stock-Flow Consistent (SFC) model connects a limited number of heterogeneous and interacting agents of the real economy and financial system. Agents are represented as a network of interconnected balance sheet items and calibrated on real data, making it possible to trace a direct correspondence between stocks and flows. Agents are characterised by bounded rationality and imperfect information and coordination. In a nutshell, SFC models employ specific accounting matrices (balance sheet matrix and transaction flow matrix) to ensure that every flow of payments has an origin and a destination and that every financial stock is recorded as a liability for someone and an asset for someone else.

General benefits and shortcomings of SFC models

The main advantages of SFC models include their ability to (i) account for endogenous money creation, (ii) consider rich behavioural features, including adaptive expectations of heterogeneous agents, (iii) treat real and financial side in an integrated way. The modelling structure provides a fundamental check of the model logical consistency. This enables users to trace out the direct and indirect impacts of a shock at the level of balance sheet entry, and to aggregate them up at the macroeconomic level, and to calculate effects on financial risk variables. Financial dynamics, in turn, can act as amplifiers of the original shock.

By design, SFC models make it possible to trace a direct correspondence between stocks and flows in the economy and finance, thus increasing the transparency of shocks' transmission channels.
On the limitation side, typically there is no full analytic solution. This, in turn, implies that the models do not support standard equilibrium analyses, and standard welfare optimization analyses. In comparison to a Computable General Equilibrium model, there is a lower level of disaggregation in terms of number of sectors and technologies, and few examples of multi-country models (as SFC models are usually calibrated at the country level).

Structural characteristics:

EIRIN includes a limited number of heterogeneous agents and sectors of the economy and financial system that are modelled as a network of interconnected balance-sheet items (Monasterolo & Raberto, 2018; Dunz et al., 2023; Gourdel et al., 2024, Mazzocchetti et al. 2025). EIRIN's agents and sectors are heterogeneous - in terms of source of income and wealth, skills, access to finance, high/low-carbon capital and preferences (Figure 5). They interact between a set of markets, and with the rest of the world (Figure 6). Markets include financial markets (bonds, stock shares, and credit market) and real markets, such as the consumption goods and service markets, the labour market, the energy market, and the capital goods market.

The model is calibrated to reproduce historical data, the official projections of the economy (e.g. from the International Monetary Fund) and the real policy response.

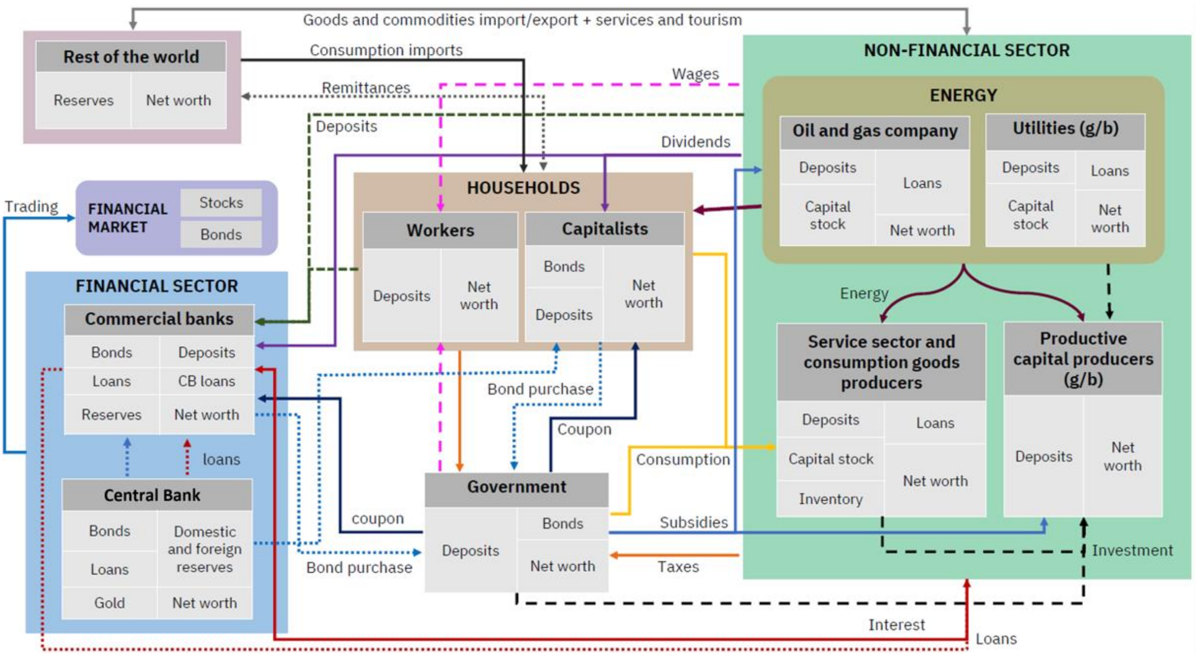
Advantages of the SFC structure include the possibility to capture:

- The entry point of a shock in the economy, the shock transmission channels to agents and sectors of the economy and finance, as well as the indirect or cascading impacts.
- Rich behavioural rule of the agents, including the departure from rational expectations.
- Financial sector dynamics and financial-macro feedback via risk assessment.
- Differentiated impacts across high and low-carbon investments, high and low-resilience investments.
- Endogenous money creation (banks create money through lending).

These features enable us to analyse the shock persistency on the levels of macroeconomic variables in the short to mid-term;[13] to understand the dynamics of the shock recovery given the characteristics of the economy (e.g. distribution of wealth and income, fiscal policies and monetary regimes), and to analyse the role of fiscal, monetary and prudential policies in the climate shock recovery. Shocks' impacts are traceable, increasing the transparency and accountability of results while retaining heterogeneity and rich behavioural features of the model.

EIRIN's agents and sectors:

- A wage-earning household (HW) and a capital income-earning household (HK)
- The consumption goods (FC) and the services sector (FS) that produce for final consumption
- A high-carbon capital goods producer (FKB) and a low-carbon capital goods producer (FKG)
- A utility company that produces electricity from fossil fuels (high-carbon, (UB)) and one that produces electricity from renewables (low-carbon, (UG))
- A mining and fossil fuel extraction company (MO)
- A commercial bank sector (BA) that lends to firms, households and the government, and invests in the financial market
- A government (G) in charge of fiscal policy and regulation (e.g. carbon tax), public debt issuance and management
- A central bank (CB) that sets the policy rate according to a Taylor rule based on Coenen et al. (2023).
- The rest of the world (ROW), with which the economy trades commodities (e.g. raw materials), goods and services (e.g. tourism, remittances).



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[13] Shock persistency could occur *on the levels* of macroeconomic variables, such as GDP and prices, *not on the growth rates* of variables, which return to the baseline value in the mid-term.

Figure 5: The EIRIN model framework: capital and current account flows of the EIRIN economy. For each sector and agent of the economy and finance, a representation in terms of their balance sheet entries (i.e. assets and liabilities) and their connections, is provided. The dotted lines represent the capital account flows, while the solid lines represent the current account flows.

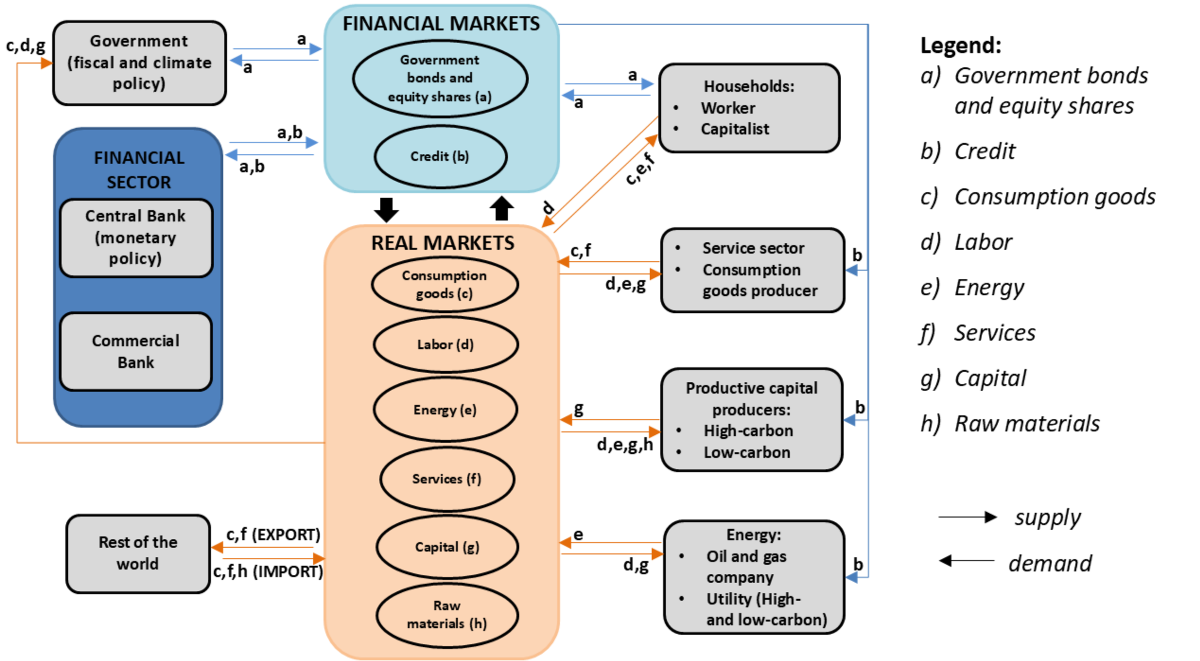

Figure 6: Agents, sectors and markets of the EIRIN economy. Grey box: agents and sectors. Light blue box: financial markets. Light orange box: real markets. Blue box: financial sector. Agents and sectors interact through real and financial markets. The outgoing arrows represent supply, while incoming arrows represent demand.

Behavioural characteristics:

EIRIN's agents are characterised by bounded rationality and adaptive expectations and are subject to incomplete information. Adaptive expectations enable to capture decision-making under uncertainty, which is a key feature of future climate risks, being either climate transition or physical risks. In this context, shocks such as sudden changes in the carbon price are not fully anticipated by agents. In presence of heterogeneity, adaptive expectations can lead to time-delayed, uncoordinated responses to shocks, with implications on the size and persistency of the economic shock. In particular, the impact of climate risks in the economy (e.g. on inflation or GDP) may be larger than in presence of rational expectations, they can show degrees of persistency in the short-term and trigger monetary policy response. However, the impact of shocks is tamed by delays in price and wage adjustments.

Firms' investment decisions are based on expected production plan and the Internal Rate of Return (IRR), and are subject – as all other agents – to adaptive expectations. This means that firms may not internalise the whole future carbon price trajectory and demand, thus delaying the return to pre-shock conditions. Differently from supply-led models (for example Solow 1956), in EIRIN, firms' investment decisions are fully endogenous.

The service FS (labour intensive) and consumption goods FC (capital intensive) sectors produce their respective outputs by means of a Leontief production technology.[14]
At time t, the firms set the prices for goods and services as a mark-up (m_j) on unit costs $(UC_{j,t})$:

$$p_{j,t} = m_j * UC_{j,t} \quad \text{(EIRIN 1)}$$

for $j \in \{FC, FS\}$.
The unit costs are computed by the sectors at each time step and include:

- Wages
- Energy and material costs
- Carbon taxes
- Depreciation costs

where wages, energy prices and carbon taxes are the main drivers of price dynamics. Higher prices of consumption goods and services constrain households' consumption budgets, which in turn lower aggregate demand. This represents a counterbalancing mechanism on aggregate demand. The minimum between real demand and the real supply determines the transaction amount that is exchanged in the goods and services market. This means markets may not perfectly clear due to excess demand or supply.

FC, FS, FKG, FKB, UG, UB and MO make investment decisions at time t based on the expected production plans $\hat{q}_{i,t}$, which determine a target capital stock level $\widehat{K}_{i,t}$. In general, the target investment amount $\hat{I}_{i,t}$ is set by the target capital level $\widehat{K}_{i,t}$ and the previous capital endowment $K_{i,t-1}$ subject to depreciation at a rate δ_i, hence:

$$\hat{I}_{i,t} = \max\{\widehat{K}_{i,t} - K_{i,t-1}(1-\delta_i), 0\} \quad \text{(EIRIN 2)}$$

with $i \in \{FC, FS, FKG, FKB, UG, UB, MO\}$.

Focusing on FC and FS, the decision to invest in low- versus high-carbon capital is endogenous and based on a comparison the sector-specific Internal Rate of Return (IRR) that would result from an investment in low- or high-carbon capital, thus naturally favouring the capital type with higher IRR. For the IRR, it is distinguished between the following cash flows:

- A positive cash flow given by the additional sales following from increased production capacity
- The additional labour, raw material, and energy costs

[14] Labour productivity in EIRIN evolves endogenously with real GDP growth, employment, and a baseline growth rate. Capital productivity remains constant, as the model abstracts from long-term technological change, consistent with the short-term focus.

- The additional tax on GHG emissions that follows the introduction of government's environmental regulation and/or climate policies and affect firms' use of high-carbon capital and the consumption of fossil energy.

In EIRIN, the expected IRR from an investment is calculated using the same discounted cash flow information involved in the Net Present Value (NPV) calculation. In particular, the IRR is the value that verifies:

$$PK_t^c = \sum_{q=1}^{\infty} \frac{CF_{j,t+q}^c}{\left(1+IRR_{j,t}^c\right)^q} \quad \text{(EIRIN 3)}$$

for $j \in \{FC, FS\}$, and where c represents the type of capital (low- or high-carbon) and PK_t^c is the price of the c type of capital (low- or high-carbon) at time t. Following the decision of how much to invest in low- vis-à-vis high-carbon capital, the final realised investment is thus $I_{j,t}=I_{j,t}^{low}+I_{j,t}^{high}$, which is potentially constrained by the credit conditions of the sector and the supply capacity of the producers.

Households' consumption plans are modelled based on Deaton's Buffer-Stock Theory of Savings (Deaton, 1991; Carroll, 2001), according to which, households adjust their consumption path around their net income, considering a target level of liquid wealth to income ratio. Therefore, households spend more (less) than their net income if their actual liquid wealth to income ratio is higher (lower) than the target. Inflation does not directly enter the formulation of consumption decisions, but rather indirectly through prices[15].

In the **banking sector**, the commercial bank provides loans, keeps deposits and invests in the financial market, including via sovereign bonds' purchase. BA endogenously creates money (Jakab & Kumhof, 2015), i.e. it increases its balance sheet with every new lending activity (McLeay et al., 2014).

The credit market is characterised by two elements, i.e., *the level* of credit and *the cost* of credit. The maximum credit supply of the bank is set by its equity level E_{BA} divided by the Capital Adequacy Ratio(CAR) to comply with the relevant banking regulation, potentially affecting the supply of new credit. The additional credit that the bank provides at each time step is given by the minimum between the credit demanded, $D_{BA,t}$, and the maximum supply of credit, which is given by the additional quantity of loans possible while complying with CAR regulation. That is:

$$\Delta^+ L_t = \min\left\{D_{BA,t}, \frac{E_{BA,t-1}}{CAR} - L_{t-1}\right\} \quad \text{(EIRIN 4)}$$

[15] For the formal explanation see Monasterolo & Raberto (2018).

Where L_{t-1} is the credit level at $t-1$. In this case, credit can be constrained depending on bank's lending capacity, which is affected by returns to sectoral investments.[16]
The sector-specific interest rate for credit takers, their cost of credit, is based on the policy rate, the bank's net interest margin and an adjustment for the sector-specific PD.

The central bank sets the policy rate according to a Taylor rule, coherently with the ECB's New Area-Wide Model II (NAWM) based on Coenen et al. (2023):

$$\begin{aligned} R_t^4 \quad &= \omega \cdot R_{t-1}^4 \\ &+(1-\omega) \cdot \left[R_{Base} + \psi \cdot \left(\frac{CPI_t}{CPI_{t-4}} - \Pi\right)\right] \\ &+\gamma \cdot \left(\frac{GDP_t}{GDP_{t-1}} - \Delta\right) \end{aligned} \quad \text{(EIRIN 5)}$$

where

- R_t^4 is the annualised short-term nominal interest rate in quarter t.
- ω is the weight of persistency in the policy rate.
- R_{Base} is the annualised nominal interest rate in absence of inflation or GDP growth deviations.
- ψ is the weighting of the inflation deviation (see Annex J).
- Π is the monetary authority's inflation target.
- CPI_t/CPI_{t-4} is the year-on-year headline inflation, based on region-specific CPI basket weights.
- γ is the weight of the output gap in the monetary authority's response.
- Δ is the quarterly GDP growth rate target[17].

Moreover, the central bank could provide liquidity to banks in case of shortage of liquid assets, can engage in non-ordinary monetary policy operations (e.g., quantitative easing) and in asset purchase programs in general (this mechanism is not activated within the NGFS Short Term Scenarios).

A monetary policy tightening can affect the low-carbon transition through the several channels, including: i) an increase of the interest rate on loans, which impact on firms' costs and ultimately their prices charged; ii) a decrease in investment.

A structural change of the policy rate can occur when shock-driven effects have some degree of persistency (e.g., on the GDP level because of a shock, such as COVID-19).

[16] When credit constraints occur, credit is rationed, and firms must scale down their investment plan. The bank reacts by retaining part of its earnings to increase the equity base and, thus, the CAR and the lending capacity. Thus, the lending activity in EIRIN is endogenously affected by the performance of the borrowers, which pay interest on loans, impacting the bank's profits and equity.
[17] As the EIRIN framework does not computes potential GDP, we instead base the target on the long-term GDP growth rates of the IMF projections used in the model's calibration process.

The government implements the fiscal policy via tax collection and public spending, including welfare expenditures, green subsidies, public workers' salaries, public consumption and investment. To cover running expenses, the government uses taxes and issues sovereign bonds. Taxes are applied to labour income (wage), capital income (dividends), profits of firms.

Prices and wages do not adjust immediately but are subject to stickiness. Prices are set by the supply side and are based on a mark-up on unit production costs (Blanchard 2017). Each unit cost evolves endogenously in the model, because agents and sectors adapt their decisions to costs. Price stickiness can arise due to endogenous adjustments in response to a shock or a policy (e.g. introduction or increase of a carbon price, which leads to increases in the mark-up on unit costs) and can be further amplified by supply-side constraints. Regarding wages, the speed of adjustment accounts for the level of employment and inflation at the previous time step[18].

In the EIRIN model, the **monetary policy transmission channel**, in the case of a positive monetary policy shock, involves higher interest rates leading to lower credit and investment, higher unemployment, lower wages and consumption, and ultimately lower inflation and GDP. The primary transmission mechanism of monetary policy in the EIRIN model operates through the credit channel. When the central bank raises the policy rate in response to macroeconomic conditions, commercial banks increase the interest rates they charge on loans to firms. As borrowing becomes more expensive, firms reduce their demand for credit, which is used to finance new investments. Lower credit demand leads to lower investments, negatively affecting the supply side of the economy. Lower investments lead to lower production and thus lower output, lower labour demand and higher unemployment. The increase in unemployment reduces wages and the disposable income of worker households, which in turn dampens consumption and aggregate demand. The combined effects of lower investment (supply-side) and lower consumption (demand-side) lead to a slowdown in economic activity, resulting in lower inflation and GDP.

Figure 7: Transmission channels of a positive interest rate shock. Green arrow: direct impacts of policy rate on bank rates. Red arrows: indirect impacts. Source: authors' own elaboration.

[18] The adjustment of w_{min} in response to a change in inflation can be moderated by a parameter whose value can be tailored and calibrated.

Representation of physical risks

To deliver to the objectives of the NGFS short-term scenarios as described in the NGFS conceptual note, low-probability-high-impact events are included in the analysis that can have relevance for systemic risk and financial stability. This type of events can arise in particular from the compounding of two or more climate-related hazards (e.g. flooding occurring after prolonged droughts could lead to damages to infrastructure as well as breadbasket crop failure), or from the compounding of climate-related hazards with geopolitical shocks (e.g. drought-driven breadbasket crop failure could occur in the same year as a supply chain shock and/or an energy price shock driven by geopolitics).

As for the compounding of several climate-related events, the recent scientific literature (e.g. Zscheischler et al. 2018, 2020; IPCC 2022) emphasizes their key role in the assessment of climate-related risks. More specifically, because they can lead to systemic economic and financial impacts, such compound events appear as a natural and necessary focus in a stress-testing exercise. The literature (see e.g. Ridder et al., 2020) notably puts forward (i) the potential occurrence of multivariate events driven by dry conditions, i.e. heatwaves, droughts and wildfires, and (ii) the compounding of storms and flood risks. The literature also emphasises the spatial and temporal clustering of extremes, in particular temporal compounding of storms and spatially concurrent precipitation extremes/floods at regional scale (see Mumby et al. (2011) for tropical cyclones, Dacre & Pinto (2020) for extra-tropical cyclones and Zscheischler et al. (2020) for a general review). The heatwave-drought-wildfire compound is of particular concern because of the manifold channels through which it can impact economic activity and well-being: food security, human health, water and energy supply, and more broadly the economy/environment interface. Also, the interaction of global climate phenomena such as El Niño/Southern Oscillation with regional climate extremes such as Indian heatwaves or flood events could lead to simultaneous crop failure in different regions, thus posing a risk to the global food system (Gaupp et al., 2020). The storm-flood compound is particularly relevant because it combines extremes that trigger large direct losses of capital and infrastructure[19].

As for the compounding of climate-related events with geopolitical shocks, the experience of the recent years has shown how extreme weather events can trigger social unrest or exacerbate the effects of conflicts on health and the broader economy. Moreover, waves of extreme weather events could precede or follow shocks on global supply chains leading to impacts that are more than the sum of the events in isolation (see e.g. Zscheischler et al., 2018; Ranger et al., 2022; Dunz et al., 2023). Risk experts and business practitioners perceive the relevance of these risks and their potential impact for price stability as increasing (WEF Global Risk Report, 2024).

The main challenge for the quantitative assessment of these compound events is the limited knowledge of their statistical properties. The current state of the science lacks statistical models of the joint distribution of hazards that could be used to simulate directly compound events in catastrophe risk models, even in the context of scenario-contingent projections. The

[19] see e.g. archived tables at iii.org

estimation of tail risk (e.g. return period or quantiles) for multivariate sources of risk requires empirical samples of size that are simply not available, especially in a context of changing climate.

While a quantitative characterization of the dependence structure between hazards is not available at the global scale, ignoring the role of compound risk would be a major oversight from a risk-management point of view.

To address this challenge, the physical risk scenarios are developed by using the notion of physical climate storylines. Physical climate storylines are defined *as physically self-consistent unfolding of past events, or of plausible future events or pathways* (see Shepherd et al. 2018). Their development stems from the remark that "*the high levels of uncertainty concerning the climate response of remote drivers of regional change and of the dynamical conditions leading to extreme events inevitably leads to general or weak statements [when one attempts to aggregate over that uncertainty]"* (see Sheperd 2019). Against this background, storylines provide *spatially and temporally coherent scenarios at the regional scale that are conditioned on those uncertain aspects of the climate response* (Caviedes-Voullième & Shepherd, 2023). This approach is particularly useful for exploring low-likelihood, high-impact outcomes (Caviedes-Voullième & Shepherd, 2023) in a stress-testing context.

Accordingly, the physical risk scenarios are modelled based on climate storylines describing compound events of the **heatwave-drought-wildfire** and of the **storm-flood types** occurring at the continental scale. The continental scale is particularly relevant in the context of systemic risk because it corresponds to the footprints of the largest events (as illustrated in table 1).

Myriad Event Id	Type of hazard	Continental Region	Start Date	% regionally exposed GDP
Hw61374	Heatwave	Africa	01/2010	47.8
Hw43535	Heatwave	Asia	01/2009	26.1
hw129835	Heatwave	North America	06/2015	63.9
hw134637	Heatwave	South America	03/2016	39.6
hw65352	Heatwave	Europe	06/2010	52.7
hw52537	Heatwave	Oceania	11/2009	31.1
ew31287	Extreme wind	Africa	02/2015	18.9
tc497	Tropical cyclone	Asia	09/2007	14.4
tc449	Tropical cyclone	North America	10/2012	26.7
tc483	Tropical cyclone	South America	10/2010	5.4
ew8696	Extreme wind	Europe	01/2007	47.1
ew24725	Extreme wind	Oceania	09/2012	41.0

Table 1 : Examples of continental scale events with large underlying exposure (in terms of percentage of GDP) by continent and hazards type (for heatwave and extreme wind). Data from the MYRIAD database (Claassen and al. 2023)

More precisely, for each continental region (Africa, Asia, North America, South America, Europe and Oceania), the climate physical storylines correspond to the following combination of hazards (at a return period 50 in the Disasters & Policy Stagnation (DaPS) scenario and 20 in the Diverging Realities (DiRe) scenario). The choice of the return period determines the magnitude of hazards and can be chosen in a scenario-specific manner.

- For the heatwave-drought-wildfire (HDW) storyline, it is assumed that a continent scale mega-event consists of, in the joint realization in each country, an x year return period drought (in terms of area affected), an x year return period wildfire season (in terms of burnt area), and an x year return period heatwaves (in terms of people affected).
- For the storm-flood (SF) storyline, it is assumed that a continent scale mega-event consists of the joint realization in each country of an x year return period event in terms of annual storm damage, annual river flood damage and annual coastal flood damage (in terms of economic capital affected).

Remark: the likelihood of the joint occurrence of hazards increases rapidly with correlation as illustrated in Figure 1. For example, assuming a Gaussian copula, the joint occurrence of three events with a 100-year return periods each, is a 1000-year return event if the level of correlation is of the order of 0.65 (see Figure 8, left panel).

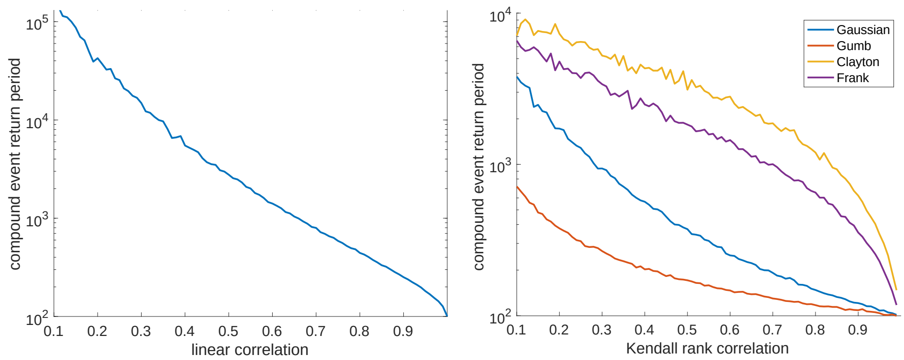

Figure 8: simulated return period of a compound event corresponding to the occurrence of three events with a return period of 100 years under a Gaussian copula as a function of the coefficient of linear correlation (left panel) and simulated return period of a compound event corresponding to the occurrence of two events with a return period of 100 years as a function of the rank correlation for Gaussian and Archimedean (Gumb, Clayton, and Frank) copulas. The y-axis is in logarithmic scale.

In order to estimate the magnitude of the direct impacts corresponding to each storyline, first the direct impact of each hazard is estimated in terms of share of capital stock damaged, output loss and productivity loss. In this perspective, an important caveat must be made: The joint assessment of such a large ensemble of impacts at the country level and sectoral granularity is unprecedented in the scientific literature. It requires combing a large array of datasets and projections with different spatial and temporal scales, different impact metrics, different treatments of uncertainty and correlation, and major variance remaining across models for certain hazards. In this context, simplifications and assumptions have to be made in order to provide impact metrics that are comparable across hazards and countries and that can be used for climate stress-testing. Our guiding principles in this context have been to rely exclusively on publicly available sources and to use empirical observations to bound the uncertainty stemming from model-based projections. From a methodological point of view, it was tried to remain as close as possible, given data and modelling constraints, to a catastrophe risk modelling approach that decomposes risk into hazard, vulnerability and exposure components.

Below a detailed description of the data and methodology used is provided. The focus lies on three output metrics for direct impacts:

- **Damaged capital** that represents the share of fixed capital destroyed per sector and country. Storms, floods and wildfires entail capital destruction in our framework.
- **Output loss**, that is the share of yearly production lost per sector and country. Output loss is induced by storms, floods and wildfires through business interruptions following destruction of capital. Output loss is induced by droughts through reduction of agricultural yields and decreasing output in water-dependent sectors (see below).
- **Labour productivity loss** is the yearly reduction in supply of productive labour units. In our framework, labour productivity loss is induced by heatwaves.

These direct impacts are determined as follows.

- To assess capital destruction from wildfires, the magnitude of hazard are represented as country-level distributions of burnt area. To estimate these distributions, simulations from the fire module of CLASSIC are used (see Melton et al., 2020) provided through ISIMIP. CLASSIC is the land surface component of the Canadian Earth System Model. It is a process-based ecosystem and land surface model designed for use at scales ranging from site-level to global. CLASSIC provides simulations of burnt area per grid cell (at the 0.5° resolution) for historical and scenario-based climate related forcing. It also considers a range of human-based forcing. In order to estimate country scale distributions, the time-series corresponding to observed and historical climatologies are pooled. This represents approximately thousand years of realisations at the grid cell level. The data is aggregated at the country level to generate a sample of burnt area at the country level and estimate on this basis lognormal distributions of burnt area per country. Quantiles of this country level distribution are considered as the realisation of the wildfire event. As for exposure, it is assumed that wildfires only affect sectors whose production is dispersed in the geographical space[20]. Indeed, economic sectors with localised production facilities (e.g. industrial facilities) are generally not located in burnable areas[21] and are better protected against wildfire. More specifically, the GEM-E3 sectors that are considered exposed are: agriculture, biomass solid, biofuels, power supply, construction, land transport, warehousing, market and non-market services. Furthermore, it is considered that only tangible capital (as opposed to intangible) is exposed. To estimate the share of tangible capital per country and sector, sector-level estimates are used from the EU KLEMS database (O'Mahony et al., 2009). As for vulnerability, a binary setting is considered where burnt areas are fully damaged. Overall, the share of capital equal to the share of burnt area is destroyed in the sectors is considered as exposed.

- To assess the capital destruction from tropical storms, first hazards are represented using, as in the long-term NGFS scenarios, an ensemble of synthetic storm tracks generated through CLIMADA (Aznar-Siguan et al., 2019). For exposure, downscaled

[20] The "exposed" sectors are evenly distributed in the areas affected by wildfires.

[21] Burnable areas exclude water bodies, permanent snow and ice, urban areas and bare areas, see Pettinari & Chuvieco (2018).

GDP data is used from ISIMIP following the LitPop approach of Wang and Sun (2022) to estimate the distribution of exposed economic capital within countries. The geographical distribution is assumed to be similar for each sector. Furthermore, it is considered that only tangible capital (as opposed to intangible) is exposed and sector-level estimates are used from the EU KLEMS database (O'Mahony et al. 2009, 2021 release) to estimate the share of tangible capital per country and sector. As for vulnerability, a cubic damage function is used as in Emanuel (2011) to assess the share of capital destroyed in each grid cell as a function of maximum wind speed observed in the grid cell. Damages are then aggregated at the country and sector level and thus realisations of country and sector level shares of capital destroyed are obtained for each synthetic storm. Finally, independent realisations of each synthetic storm are assumed to obtain a distribution of share of capital destroyed yearly per tropical storms per sector and country. Impact realisations in the storyline are based on the quantile of this distribution.

- For winter storms, a similar approach is used to that for tropical storms using the Copernicus synthetic windstorm events for Europe[22] (Copernicus 2022) as hazard data.

- For floods, the following elements were used: Exposure is derived using a similar approach than in the case of storms. Downscaled GDP data at 0.25°x 0.25° granularity was used from Wang and Sun (2022) to estimate the distribution of exposed economic capital within countries. The geographical distribution is assumed to be similar for each sector. Furthermore, only tangible capital (as opposed to intangible) is assumed to exposed and sector-level estimates are used from the EU KLEMS database (O'Mahony et al. 2009) to estimate the share of tangible capital per country and sector. As for hazards, aqueduct flood maps are used (see Ward et al. 2020) for both coastal and river floods. Realisations of floods are generated at the country scale assuming full correlation below grid-cell granularity (0.25°x 0.25°, i.e. approximately 25x 25km2 at the equator) and independence across cells. This is a first-order approximation that neglects correlation beyond the grid scale and can thus potentially underestimate impacts. As for vulnerability metrics, the global flood depth-damage functions of Huizinga et al. (2017) is used. Impacts are aggregated at the country and sector level and thus derive from an ensemble of realisations a distribution of capital destroyed per floods (coastal and river) per country and sector. Impact realisations in the storyline are based on the quantile of this distribution.

- In order to infer production lost following capital destruction for storms, floods and wildfires, first business interruption days are inferred using the table developed by FEMA (tables 15.10 and 15.1 in FEMA 2013). More precisely, it is assumed that the number of business interruption days is proportional to the share of capital destroyed according to

$$days\_interrupted_i = share\_destroyed_i \times days\_full_i$$

[22] Coverage is limited to Europe in the synthetic windstorm database of Copernicus (2022). This restriction implies that the impacts of wet events might be underestimated for other regions prone to winter storms such as North America.

where $days\_full_i$ is the number of business days interruption in case of full destruction of the capital stock, $share\_destroyed_i$ is the share of tangible capital destroyed in a given country and sector pair i, and $days\_interrupted_i$ is the associated the number of business day interruptions. It is then assumed that the yearly share of production lost is equal to the share of days in the year during which business was interrupted.

- In order to infer production lost from droughts, a similar approach to that in the long-term NGFS scenarios is followed, whereby impact is deemed proportional to the share of area multiplied by the months under drought condition. Drought conditions are defined by an SPEI (Standardised Precipitation-Evapotranspiration Index) below -2. As for the estimation of the magnitude of drought hazards, data provided by the CMCC SPEI dataset (Santini and al. 2023) is used. Yearly projections are considered over forty years[23] from six Global Climate Models (GCMs) provided at the grid cell level. These projections are aggregated at the country level to obtain two hundred forty observations of (area x month) affected by drought. Therefrom the parameters of a lognormal distribution for total (area x month) affected are estimated. Impact realisations in the storyline are based on the quantile of this distribution. As for exposure, exposed sectors are defined as those labelled as facing high water risk according to CDP water watch index. These correspond to (parts of) the following GEM-E3 sectors: agriculture, biofuels, biomass solid, hydroelectric power generation, nuclear power generation, basic pharmaceutical products, batteries, chemical Products, computer, electronic and optical products, ferrous metals, non-ferrous metals and advanced Electric Appliances. The share of GEM-E3 sector exposed is approximated based on the index of water risk exposure and the share of exposed activities in the sector. As for vulnerability, it is assumed that output lost (or equivalently reduction in yield) is proportional to the share of (area x month) subject to drought conditions as in the long-term scenarios (see NGFS, 2024).

- In order to infer labour productivity loss from heatwaves, the following elements are used: An approach similar to that of the long-term NGFS scenarios is followed, in which a forty year period (around the current year) of temperature and humidity data is considered at grid-cell level from the four bias-corrected GCMs available from ISIMIP. Therefrom grid-cell level observations are inferred of wet-bulb globe temperature following the approximation of Stull (2011). As for exposure, gridded population data is considered from ISIMIP and it is assumed that workers in the following GEM-E3 sectors are exposed: agriculture, biomass solid, coal, construction, crude oil, market services. Vulnerability curves are used linking wet-bulb globe temperature (WBGT) and labour productivity (Dasgupta et al. 2021; Dunne et al. 2013) to infer the loss in labour productivity per grid cell. Those are aggregated at the country level and a distribution of labour productivity loss is estimated at the country scale. The quantiles of this country level distribution is then considered as the realisation of the heatwave event in the storyline.

[23] RCP 4.5 2040-2079

- In order to benchmark impact estimates obtained from model-based projections, historical data was used on yearly economic damages by type of hazards (for floods, storms, wildfires and droughts) derived from a range of external sources including EM-DAT[24], the World Bank (PCRAFI Risk Reports[25], WB - Country Disaster Risk Profile, WB Latin America and Caribbean Risk Viewer[26], Financial Risk and Opportunities to Build Resilience in Europe Report[27], Strengthening Financial Resilience and Accelerating Risk Reduction in Central Asia Program[28]), United Nations Office for Disaster Risk Reduction (Disaster Risk Profile, Global assessment report on disaster risk reduction[29]), the Coalition for Disaster Resilient Infrastructure[30], and country-level estimates of flood risks from DIVA (for coastal floods) and GLOFRIS (for river floods) used for financial risk assessment in Mandel et al. (2021). These databases either provide direct estimates of the magnitude of country-level impacts at different return periods or allow the estimation of such country-level return-period events (in particular, for countries and hazards for which it provides sufficient data, estimates from EM-DAT were derived of the quantiles of the distributions of yearly country-level impacts). The estimates are then benchmarked against those obtained from model-based projections with these of external sources by constraining our estimates to be at least equal to these of the corresponding return period events from external sources and no more than twice the estimates from these external sources.

Looking beyond the direct effects, the propagation of impacts is considered through global supply chains using GEM-E3 models, macro-economic impacts of shocks through EIRIN and financial impacts of shocks through CLIMACRED.

Modelling physical risk in GEM-E3.

To assess the economic impacts stemming from the physical compound events, the resulting climate impacts (from CLIMACRED-PHYS) are used as an input to the macroeconomic model GEM-E3. The input data have been rearranged to match the sectoral detail of GEM-E3 – as in the underlying assumptions mentioned in the climate model analysis above.

[24] The full history of EM-DAT is used, the length of which can be country dependent EM-DAT is the only comprehensive, free-access disaster loss database with effective global coverage. However, it has limitations due to the limited number of sources and limitations related to how effectively disasters are reported worldwide.
[25] See https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099070523101026535
[26] See https://openknowledge.worldbank.org/entities/publication/85cfd5d4-d990-5e26-aa45-3c61bd68b8aa
[27] See https://documents1.worldbank.org/curated/en/231121622437102944/pdf/Economics-for-Disaster-Prevention-and-Preparedness-Financial-Risk-and-Opportunities-to-Build-Resilience-in-Europe.pdf
[28] See https://www.gfdrr.org/en/program/SFRARR-Central-Asia
[29] See https://www.undrr.org/publication/global-assessment-report-disaster-risk-reduction-2015
[30] See https://www.cdri.world/

For the Disaster and Policy Stagnation scenario six different scenarios are considered, one for each continent area – in each area the physical shocks take place separately. All hazards' impacts are considered to be linked with the following variables of the model:

- Capital stock (destruction)
- Labour productivity (loss)
- TFP (loss)

Given that the interest lies in the aggregated weather impacts on the above variables, aggregating them essentially takes into account the full effect from all hazards. This could be extended to analyse the effect of each hazard separately on each component. This can be considered at a future vintage of the results.

The acute nature of the shocks is represented by considering that impacts on capital stock are short-lived (capital is reconstructed after a year) and impacts on productivity decay at a 50% rate. Additional persistence arises endogenously through general equilibrium effects.

The following describes how the three different inputs are introduced in GEM-E3.

Labour productivity is a model parameter in the GEM-E3 model – explicit in the production function. Thus, the parameter according to the effect from the climatic events is changed according to its deviation from the baseline. Given that labour productivity is affected by heatwaves only, the change in labour productivity is applied to the "Agricultural and Unskilled" labour skill type of GEM-E3.

TFP loss relates to output loss originating from the business interruptions from the hazards. TFP is a model parameter explicit in firms' production function. The exogenous TFP component (the endogenous relates to the learning effects) of the model is adjusted so as to give the TFP reduction due to the extreme weather events.

Capital destruction is introduced in the model by reducing the amount of available capital per sector and per country as implied by the weather impacts.

Modelling physical risks in EIRIN

To model the physical risk scenarios, EIRIN takes following the direct impacts as an input: i) capital stock destruction, ii) productivity shock, iii) labour productivity shock, and iv) production loss. The natural hazards considered include floods, storms, heatwave, wildfire and drought.

The direct impacts from physical risks are computed at the sectoral level, after matching EIRIN's sectors with GEM-E3 sectors (Appendix K). Specifically, the EIRIN sectors include: a consumption goods sector; a services sector; a high-carbon capital goods producer; a low-carbon capital goods producer; a high-carbon utility company; a low-carbon utility company; and a mining and fossil fuel extraction company.

The direct impacts of physical risk at EIRIN sectoral level[31] are computed according to the following steps:

- Summing across hazards: for each year, the impacts are summed separately, respectively for wet hazards and dry hazards.
- Sectoral aggregation: the aggregated impacts are computed using a weighted average of the physical risk shock, and the weighting is based on the initial GEM-E3 sectoral outcomes:
    - For capital stock destruction, the weighted average is based on the initial capital stock of each GEM-E3 sector.
    - For other direct impacts, the weighted average is based on the initial production of each GEM-E3 sector.

EIRIN models four direct impacts of physical risks, in the following way:

- Capital stock destruction: Direct impact on sector-specific capital stock on Q1 in which the natural hazard occurs.
- Labour productivity shock: Direct impact on sector-specific labour productivity applied equally to all quarters of the year in which the natural hazard occurs.
- Productivity shock: Direct impact on sector-specific TFP applied equally to all quarters of the year in which the natural hazard occurs.
- Production loss: Direct impact on sector-specific output applied equally to all quarters of the year in which the natural hazard occurs.

Modelling physical risk in CLIMACRED

CLIMACRED-PHYS is used to model the direct financial impacts induced by physical risk. CLIMACRED-PHYS is a structural credit risk model that simulates climate impacts on the capital stock and the production operations of firms to estimate shocks on corporate asset and debt (see Mandel and al 2025). A Merton-like approach is then applied for the valuation of corporate securities (Merton, 1974). For the project, the model is applied to a representative firm in each country and sector of interest to estimate sector-level shocks on credit risk. As for sovereign debt, an index of fiscal revenues is built on the basis of sectoral economic trajectories and the Merton-like approach à la Bodie and al. (2006) is then used to evaluate sovereign securities.

More precisely, the structural climate credit risk model, CLIMACRED-PHYS (see Mandel et al. 2025 for details) allows us to perform the climate scenario-conditioned valuation of financial assets issued by a firm as follows. The firm is characterised by its set of production facilities I and the initial level of capital stock at each of these facilities $K_{0,i}$ (for the representative sectoral firm considered in this application, it is assumed that there is one production facility per grid cell and that the initial level of capital stock is proportional to downscaled GDP in the corresponding cell). A simplified representation of the production process is used whereby output is produced from capital in facility i according to a linear production technology of the form:

$$f_i(K) = \lambda_i K$$

[31] For regions represented by a single country, the physical impacts are based on the data for the representative country itself

Furthermore, the firm has a target growth rate for its capital stock at facility $i, \rho_i \in [0,1]$, which is assumed to be determined exogenously by market and technological factors. Existing capital is assumed to depreciate at rate $\delta_i \in [0,1]$. Thus, the target trajectory of capital is such that for all i:

$$K_{t+1,i} = (1+\rho_i)^t K_{0,i}$$

and gross investment (in absence of climate impacts) in productive facility i in period t is given by:

$$G_{t,i} = (\delta_i + \rho_i)K_{t,i}$$

In this setting, climate impacts are accounted for by inferring from our direct impact database the volume of capital damaged $\sigma_{i,t}^S K_{t,i}$ and the volume of production lost $\tau_{i,t}^S \lambda K_{t,i}$, in scenario S and period t at facility i. Residual economic uncertainty about the performance of facility i is captured through a random and time-dependent profit rate $\pi_{i,t}$ so that the profits of the firm in period t are given by

$$\Pi_{i,t}^S = \sum_i \pi_{i,t}(1 - \tau_{i,t}^S)\ \lambda_i K_{i,t}$$

The financial structure of the firm is then determined as follows. The initial capital is assumed to be financed through amounts D_0 of debt and $E_0 0$ of equity, i.e. one has:

$$K_0 = D_0 + E_0.$$

Required firm investments, i.e. growth and replacement of capital destroyed by climate impacts or depreciated, are then financed through increasing debt and self-financing. In the latter respect, it is assumed that a share $\mu \in [0,1]$ of profit is distributed as dividend each period and the remaining is used for self-financing. On the basis of these assumptions, one can derive the probability of default of the firm adjusted for climate risk as:

$$PD^S = \mathbb{P}((1+r)^T D_0 \leq K_T(\pi) + \sum_{t=0}^{T-1}(1+r)^{T-1-t}(1+\rho)^t \sum_i \gamma_{i,t} K_{0,i})$$

where $\gamma_{i,t}$ is the excess cash-flow in period t, i.e. the random variable corresponding to retained earnings minus gross investments:

$$\gamma_{i,t} = [(1-\mu)\pi_{i,t}(1-\tau_{i,t}^S)\lambda_i - \rho_i - \delta_i - \sigma_{i,t}^S]$$

Default probability and excess cash-flows are thus determined by two risk-drivers: baseline profitability (through the realisations of profit margins $\pi_{i,t}$) and climate impacts through business interruptions $\tau_{i,t}^{S}$, and capital destructions $\sigma_{i,t.}^{S}$. Capital destruction entails increased investment costs, and business interruption entails reduced revenues.

The characterisation of the default probability enables us to provide scenario-contingent valuation of the financial assets issued by the firm. As for the value of bonds, the value of a zero-coupon bond with maturity *T* is given by expected payment at maturity, that is

$$B^S = (1 + r_0)^{-T}[(1 - PD^S) + PD^S \kappa \mathbb{E}\left(\frac{K_T}{D_T^S}\middle| K_T < D_T^S\right)]$$

where r_0 is the risk-free rate, $\kappa \in [0,1]$ is the bankruptcy cost coefficient and $\mathbb{E}(\frac{K_T}{D_T^S} | K_T < D_T^S)$ the asset to debt ratio. Hence, the value of bonds is impacted by climate shocks through two channels: (i) the probability of default that increases with cumulative destruction of productive capital and reduced cashflow through business interruptions and (ii) the net worth at maturity that decreases with cumulative destruction of productive capital and reduced cashflow through business interruptions.

As for the value of equity, this is given by the expected discounted value of the dividends plus the net worth at maturity in absence of default, i.e.

$$E^S = \mathbb{E}[\sum_{t=0}^{T-1} \mu \Pi_t^S (1 + r_0)^{-t} + (K_T(\pi) - D_T^S)_+]$$

Hence, the value of equity is impacted by climate shocks through three channels: (i) the value of dividends that is decreased by business interruption, (ii) the probability of default that increases with cumulative destruction of productive capital and reduced cashflow through business interruptions, (iii) the net worth at maturity that decreases with cumulative destruction of productive capital and reduced cashflow through business interruptions.

The adjustment in asset value in a climate scenario is then determined by computing the relative adjustment between asset value in the scenario and asset value in a benchmark scenario without climate impacts.

Calibration of the models for the Baseline scenario

GEM-E3 calibration

The GEM-E3 baseline scenario is calibrated using the IMF's October 2023 World Economic Outlook following the methodology below.

GDP. The GDP projections as well as the GDP components (if available[32]) if each country follow the update of the IMF's World Economic Outlook database, dated October 2023 (in this section , we show the projections at global level and of the five biggest economies, namely: EU27, USA, China, Japan, and India). Government spending for all countries is assumed to follow the GDP growth with an elasticity of 0.9. This reflects a fiscal tightening at an international level that is projected after the fiscal loosening in the years of pandemic.

Sectoral Value Added. GEM-E3 models 50 economic activities, but the baseline main assumptions are made for the following aggregates: agriculture, services, energy, construction, transport, and manufacturing. The contribution of each sector to total value added is determined by the historical trends (namely the rate of sectoral value-added change to the overall GDP growth rate) at country level. Data exists for agriculture, services, and manufacturing. For sectors lacking time series data such as energy, construction, and transport, and for which it is infeasible to determine the sectoral-output elasticities an ad-hoc approach is used: construction is expected to mirror the investment growth rate and partially that of GDP. The transportation sector is projected to align equally with the growth rates of trade and GDP. Energy projections consider the growth rate of energy intensity in relation to GDP projections.

GEM-E3 Quantification of Baseline Assumptions. The quantification of the global economic outlook is based on assumptions regarding both supply and demand. The main instrument-exogenous variables used in GEM-E3 to calibrate it to exogenous projections are: i) Technical Progress[33], ii) Sectoral growth expectations – affecting investment decisions, iii) Population, iv) Consumption patterns.

Emissions. In the baseline scenario "current policies" GHG emissions follow the legislated GHG emission reduction targets (see the "current climate policies" section).

Global Macroeconomic Outlook and country outlook

In this section the key features of the IMF's World Economic Outlook for 2023 , used to calibrate the GEM-E3 baseline, are outlined.

[32] If projections for GDP components are not available, then a sustainable growth approach is adopted where excessive trade balances/deficits are reduced over time.
[33] Technical progress is composed of four parts: i) Exogenous - Autonomous, ii) R&D, iii) Learning by doing, iv) Level - State of infrastructure.

Global economic expansion is forecasted to be modest, with an annual growth rate of 2.67 percent from 2022 to 2030. This rate is lower than the average growth rate of 3.8 percent seen between 2000 and 2019. The reduction, following IMF's World Economic Outlook, can be attributed to the implementation of restrictive monetary policies, reduced fiscal support, and moderate productivity improvements.

Advanced economies are projected to grow at a rate of 1.9 percent annually from 2021 to 2030. This growth will be marked by a moderate recovery in the euro area between 2024 and 2025, as well as a stable growth path for the United States from 2024 to 2030.
Emerging markets and developing economies are anticipated to see an annual growth of 3.8 percent from 2023 to 2030, with variations across regions.

World trade is expected to increase by 3.4 percent annually from 2023 to 2030, falling below its historical average growth rate of 4.9 percent. The ongoing rise in trade distortions and fragmentation are likely to continue impacting global trade levels.

United States

The United States is expected to experience a stable and moderate annual growth of 1.9 percent from 2023 to 2030. There will be a slight downward trend in growth, with a projected decrease from 2.09 in 2023 to 1.47 in 2024. This decline is attributed to the effects of monetary policy tightening, gradual fiscal tightening, and a softening in labour markets, which will result in a slowdown in aggregate demand.[34] Additionally, government expenditures, according to the Congressional Budget Office, are anticipated to slightly decrease as a share of GDP during the same period due to gradual fiscal tightening. Balance of trade, as a share of GDP, is expected to marginally reduce from 4.5% in 2023 to 4.1% in 2030, driven by a higher growth in exports relative to imports.

Focusing on the US sectoral components, manufacturing is anticipated to decrease slightly as a share of GDP from 19 percent in 2023 to 18.7 in 2030. Conversely, the service sector is expected to see an increase, rising from 68.6 to 69.2 percent. Its overall elasticity to GDP for the years 2021-2030 is calculated to average at 1.07. The rest of the sectors will stay close to the 2023 values expressed as GDP shares therefore growing closely to the GDP trajectory path.

EU27

The EU27 is anticipated to experience an increase in growth rates, rising from 0.6 percent in 2023 to 1.3 percent in 2024 and further to 1.9 percent in 2025. The recovery is expected to be driven by stronger household consumption as the impact of energy price shocks diminishes and inflation decreases, thereby supporting real income growth.
The manufacturing, construction, transport, and services sectors are projected to experience consistent growth in tandem with GDP prospects. Agriculture is forecasted to have an elasticity of 0.2 from 2021 to 2030, indicating a diminishing impact as a share of GDP. Moreover, energy sectoral output is set to decline, reflecting efficiency improvements.

China

[34] See IMF World Economic Outlook, October 2023.

China's GDP is forecasted to grow at 3.9 percent from 2023 to 2030, primarily due to the resurgence of private consumption. Private consumption, as a percentage of GDP, is anticipated to rise from 41% in 2023 to 42.3% in 2030. Geoeconomic fragmentation is predicted to continue impacting global trade levels. Trade is expected to grow by 3 percent annually from 2023 to 2030, which is lower than the historical average of 10.8 percent from 2000 to 2019 or the short-term pre-COVID average of 4.1 percent from 2015 to 2019.

China's agricultural sector is projected to witness a decline in its contribution to the GDP, dropping from 4.2 percent in 2023 to 3.6 percent in 2030. Simultaneously, the services sector is expected to experience growth, with its share of the GDP increasing from 33.7 percent to 35.9 percent during the same period. Notably, there is an elasticity of 1.16 between these years, indicating the strong responsiveness of the services sector to changes in the economy.

Japan

The growth in Japan is anticipated to decelerate from 1.9 percent in 2023 to 1 percent in 2024 and 0.7 percent in 2025. This slowdown is attributed to the diminishing impact of temporary factors that boosted economic activity in 2023, such as a weakened yen, pent-up demand, and a rebound in business investment after project delays.

The trajectories for sectoral output growth appear to be steady for most sectors, showing elasticities with GDP of close to 1. The agriculture's gross value added is expected to decline with an average elasticity to GDP of -0.38 from 2021 to 2030, whereas the energy sector is forecasted to maintain stability at the 2021 levels, attributed to energy efficiency improvements.

India

India is expected to experience a robust GDP growth of 6.3 percent in both 2024 and 6.2 percent 2025. This growth is attributed to the resilience in domestic demand. Over the period from 2021 to 2030, private consumption and investment are anticipated to rise both in nominal terms and as shares of GDP, increasing their contribution to GDP by 1 percentage points and 2 percentage points respectively. The average annual growth rate of the economy during from 2023 to 2030 is estimated to be 6.38%.

On the sectoral decomposition, the agricultural sector is expected to see a decline of one percentage point as a share of GDP from 2021 to 2030, while the GDP share of services is projected to experience a strong increase of 3.8 percentage points, with an overall elasticity of the sector to GDP to be estimated at 1.21. On the other hand, manufacturing is likely to experience a slight decline in its share of GDP in the coming years.

Current Climate Policies

The current policies are implemented into the baseline based on the list of policies developed by Dafnomilis et al. (2023), which outlines the current climate and energy policies for major economies, including the specific sector, target, and the target and base year. The specific policies used can be tracked by the policy code.

Only implemented policies are included in the Current Policies assumptions (or baseline), which are defined as policies adopted by the government through legislation or executive orders, and non-binding targets backed by effective policy instruments. The overview of the policies and related targets implemented in all countries/regions can be found in Appendix C.

These types of policies can be divided in three different sets:

- **Horizontal policies**, including overall country-specific GHG emissions reductions targets and/or specific carbon price targets;
- **Focused policies: electricity and heat policies,** including shares of power generation and/or capacity by different sources (e.g. renewable electricity share in %, or hydro/wind/photovoltaics capacity in GW);
- **Fuel or RES Targets** (e.g. biofuel share in transport).

For the economy-wide ("horizontal") policies, the GHG emissions targets are achieved through a carbon price or via a carbon price target implemented directly into the model. For electricity-related and other policies, the policy targets are either achieved through increase in the carbon price (e.g. by imposing a carbon tax on brown technologies) or the targets are achieved by introducing additional exogenous investments into the relevant technologies.

Some country policies are outlined below:

For the **United States**, the policies related to the following targets are implemented into the GEM-E3 model:

- GHG emissions reductions (4,772 MtCO_2e by 2030),
- Capacity addition of PV and Wind (700 GW in total for these technologies by 2030). (USA total energy production 2023: 4178 KWh, of which 21.4% renewable, up to 40%, which is 794 KWh additional capacity)

For the **EU**, the policies related to the following targets are implemented:

- GHG emissions reductions (-55%, translating into 2,351 MtCO_2e by 2030),
- Renewable electricity share (45% by 2030).

For **China**, the policies related to the following targets are implemented:

- Renewable electricity share (35% by 2030),
- Capacity of nuclear energy (70 GW by 2025).

For **Japan**, the policies related to the following targets are implemented:

- Electricity shares for renewables, nuclear, coal, gas and oil (37%, 21%, 19%, 20% and 2%, respectively, by 2030),
- Capacity of wind energy (10 GW by 2030).

For **India**, the policies related to the following targets are implemented:

- Wind and hydro electricity shares target for 2030 at 6.9% and 2.8% respectively
- 40 GW renewable capacity at 2026
- 20.1 % renewable share in electricity generation for 2022
- 24.4 % renewable share in electricity generation for 2027

CLIMACRED calibration

CLIMACRED uses GEM-E3 sectoral economic trajectories to calibrate the investment and output trajectories in the baseline scenarios. It then uses sectoral averages for key financial metrics from the Damadoran database to calibrate the financial parameters of the model.

- We use data from the Damadoran database to determine sector-specific debt to capital ratio and thus express the initial debt as a function of the initial capital stock.
- We further use data on EBITDA (earnings before interest, taxes, depreciation, and amortisation), EBIT (Earnings before interest and taxes) and return on capital from the Damadoran database to calibrate, at the sectoral level, the profit margin and the depreciation rate. More precisely, depreciation is calibrated using the difference between EBITDA and EBIT and (the mean) return on capital using the EBITDA-to-capital ratio.
- Finally, we use the dividend payouts from Damadoran to calibrate the dividend share at the sectoral level.

As for the calibration of risk:

- The baseline probability of default and loss given default ratio are set to ensure consistency with the market interest rate in GEM-E3.
- We infer the interest rate on firm's debt by assuming that the bond assumes its risk-adjusted equilibrium price.
- Finally, we assume that the profit margin π follows a lognormal distribution whose parameters we determine by taking as given the mean profit margin and the probability of default, i.e. we assume that the standard deviation parameter of the lognormal distribution is such that the probability of default in absence of climate shocks is the baseline probability of default.

EIRIN Model calibration

The EIRIN baseline is dynamically calibrated to match data from the IMF's World Economic Outlook (retrieved as of April 2024).[35] We use IMF's historical data until 2023, and IMF's projections for the period 2024-2029.

We produce the baseline trajectories for a time span of 13 years, considering the period between 2018 up to 2030. This solution enables us to reproduce the economic impact of two major recent shocks, i.e. the COVID-19 pandemic shock in 2020, and the energy price shock in 2022, and to display the dynamics of their recovery phases.

We provide five calibration of EIRIN that represent the dynamics of five world regions: North America, South America, Europe, Asia and Oceania. For South America and Asia, the

[35] The IMF projections of April 2024 are not significantly different from those of October 2023 used in GEM-E3.
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calibration is based on the choice of a representative country in the region, i.e. Brazil for South America and China for Asia.[36]

The calibration strategy involves two steps:

1. The model is calibrated in a steady state where the growth rates of output match the IMF's projections.
2. The COVID-19 and energy price shocks are applied respectively in 2020 (as a demand shock) and 2022 (as an energy price shock).

Once we have reproduced the economic impacts of the shocks, we can use model simulations to endogenously produce trajectories that include the dynamics of the recovery phase.

[36] For the rest of the World, CLIMACRED takes the US policy rate as an input (several national currencies are pegged to the US dollar, and several enterprises and multinational companies are listed on the US stock exchange).

Highway to Paris scenario

High Level Narrative

The highway to Paris scenario is assumed to be ***consistent with net-zero in 2050*** *(and thus à priori with the corresponding long-term scenarios). It reflects an immediate and* ***technology-driven transition****, in which the* ***private sector develops and adopts green technologies faster than expected****, inducing a rapid shift on the supply side. Elevated levels of uncertainty related to fossil energy supply leads governments to implement carbon prices to reach net zero by 2050 in a widely anticipated fashion. The resulting fossil-fuel demand reductions are in line with reaching the Paris goals.* ***Revenues from carbon policies are partially recycled in the form of green public investments****, which induces a rapid re-allocation of private capital away from emission-intensive activities, both across sectors and internationally.* ***The speed of the transition may lead to initial demand-supply mismatches*** *in some sectors. Cross-country capital flows and lending patterns adjust accordingly****. On the regulatory side, green prudential policies reinforce the credibility of transition paths laid out by governments and, as a result, the financial disruption is contained.*** *This scenario captures one of many possible short-term pathways around the NGFS net zero by 2050 long-term scenario,* ***additionally including transition-related business cycle fluctuations.***

Outline of the Implementation

The scenario is implemented through a series of shocks and constraints that modify the trajectories calibrated in the baseline scenario. First, a constraint on global emissions is implemented to ensure that global carbon emissions are in line with the NGFS long term Net Zero scenario by 2050. This is achieved by implementing countries' NDC targets under regional carbon pricing (shown momentarily), and an additional global carbon tax, to the level necessary to reach emissions in line with NZ 2050. Second, a positive technology shock is implemented on the technological learning rates and their spillovers. This technology shock is implemented by the use of carbon revenues for supporting green investments and by the re-evaluation of financial risks in low and high carbon sectors. Carbon revenues are distributed as follows: 20% are given as capital subsidization and 80% as R&D in clean technologies. See World Bank. 2023. State and Trends of Carbon Pricing 2023.

Table of implemented shocks

Shock	Model	Implementation
Policy stringency shock + international coordination	GEM-E3	Global emissions by 2030 in line with NGFS long term Net Zero scenario. To achieve that, firstly, regional carbon pricing is aligned to NDCs and, secondly, additional carbon tax is applied to reach the NZ targets, implemented uniformly and globally (full cooperation). The carbon price hence is such that countries will meet their commitment targets in 2030 with respect to carbon emissions. This results in a globally coordinated increase in carbon prices yet characterized by regional heterogeneity where each jurisdiction achieves the respective level of emissions. This is on top of the NDC targets' resulting carbon price.
	EIRIN	Takes the trajectory of carbon price from GEM-E3 as input to represent the policy stringency shock
Technology shock	GEM-E3	Learning rates ($l1$ and $l2$) at the high-end of the parameter range and technological spillovers fully enabled at the global scale (see Annex J).
Government subsidies and investments	GEM-E3	Governments fully recycle carbon revenues for i) R&D in clean energy technologies and (80%) ii) Capital subsidisation of clean energy technologies (20%)
	EIRIN	Revenues from the carbon tax are fully recycled in green capital subsidies
Households' preferences	GEM-E3	Change in the utility coefficients of the households according to the carbon price trajectories moving from brown consumption purposes to green.[37]

[37] GEM-E3 reports consumption by purpose. Every purpose is then related to the corresponding sectors by the consumption matrix of the model. Sectors then can be classified as brown or green. The consumption patterns mainly relates to purposes like mobility, recreation, education, housing etc. The change is not necessarily on the purposes / pattern (e.g. less mobility more recreation) but in the composition of the goods and services required to meet the purpose. In other words needs for mobility (passenger km) will be more or less the same but households will engage in shared mobility options (e.g. busses/metro etc). Hence we can present two changes i) change in purpose/pattern, ii) change of consumption matrix / structure of consumption by purpose.

Other: low demand for carbon fuels	GEM-E3	Demand for fossil fuels is endogenous in GEM-E3 – carbon pricing drives lower demand for fuels
Uncertainty shock	CLIMACRED	Assumption that expectations of investors shift to the net-zero 2050 scenarios and that future revenue projections are updated accordingly. This yields an update of the costs of equity and debt and thus of the weighted average cost of capital (decrease in low-carbon sectors, increase in high-carbon sectors)
Energy price shock	GEM-E3	(Exogenous) Aligned with IEA

Sudden wake-up call scenario

High level narrative

The sudden wake-up call scenario reflects a world of widespread climate unawareness, which is challenged by a sudden change in policy preferences. Markets do not price in climate risks and the energy sector relies heavily on fossil fuels. A sudden change in policy preferences, triggered by for instance a surprise election result favouring green parties or a natural disaster (e.g. nuclear disaster in Fukushima triggering a 180-degree turnaround in German nuclear policy), leads governments to hastily implementing a stringent mitigation pathway, leading to a speedy re-allocation of capital from polluting to green sectors. The sudden and unanticipated nature of climate policies means that this re-allocation process leads to a climate Minsky moment in the most unprepared jurisdictions and asset stranding in polluting sectors. The ensuing financial turmoil leads to a crisis of confidence. The emission levels ultimately reach levels in line with reaching net zero by 2050 globally.

Energy prices rise sharply because of the sudden implementation of climate policy. Differences in producer and consumer prices of fossil fuel could lead to sharp terms-of-trade adjustments for exporters and importers. Risk-free rates drop in response to financial turmoil and depressed demand. The risk premium spikes reflecting the confidence crisis. In especially fossil-fuel reliant economies, sudden stops might trigger sharp exchange rate and terms- of-trade adjustments.

The real economy is severely affected. Household consumption drops due to higher precautionary savings following the confidence crisis. Corporates reduce their investments, and, in polluting sectors, stock values deteriorate and loans become non-performing. As a result, financial institutions face elevated credit, market and liquidity risks. Moreover, highly indebted governments might face sovereign debt crises.

Outline of the implementation

Table of implemented shocks

Shock	Model	Implementation
Policy stringency shock + international coordination	GEM-E3	Carbon tax bringing emissions in line with the HW2P carbon budget in 2030, but phasing in of Carbon tax policies only starting in 2027 ("sudden"). For the previous years, baseline "current policies" are implemented. No international cooperation: regionally-differentiated carbon prices in order to achieve the HW2P carbon budget values
	EIRIN	Takes the trajectory of carbon price from GEM-E3 as input to represent the policy stringency shock
Technology shock	GEM-E3	On the productive side of the economy, the industrial sectors are assumed to be caught unprepared by the abrupt transition and thus the speed of technological innovation remains aligned with that in the baseline scenario.
Government subsidies and investments	GEM-E3	Government spending from the carbon revenues recycling equals to this of the baseline in *nominal amount* terms (in baseline, 100% of carbon revenues are recycled). The rest are distributed to households for private consumption.
	EIRIN	Revenues from the carbon tax are fully recycled in green capital subsidies in line with baseline
Households preferences	GEM-E3	Households' preferences (endogenously) switching to green goods according to the carbon price trajectories. The utility coefficients of the households are modified according to the carbon price trajectories moving from brown consumption purposes to green. In the SWUC this is exponential as the increase in the carbon price from the first year of action (2027), which is higher than in HW2P (linear).
Other: low demand for carbon fuels	GEM-E3	Demand for fossil fuels is (endogenously) lower demand for fuels

Uncertainty shock	CLIMACRED	Instantaneous shift of expectation towards a net-zero 2050 scenario in 2027 and higher level of stranding than in the "highway to Paris" scenario. Only negative impacts (in high-carbon sectors) are considered.
Energy price shock	GEM-E3	(Exogenous) Aligned with IEA: They are exogenously[38] induced by carbon prices and can lead to a lower energy demand from households and corporates. Energy prices are assumed to follow **the stated policies scenario from the IEA's World Energy Outlook.**

[38] From IEA projections

Disaster and Policy Stagnation

High level narrative

*The **Disaster and Policy Stagnation scenario** (corresponding to the 'Low Policy Ambition and Disasters' scenario of the NGFS conceptual note) reflects the short-run repercussions of the past global reliance on fossil fuels. Severe and acute disasters hit a region of the world and lead to destruction of assets and lower productivity, spreading globally through trade and financial linkages.*

Outline of the implementation

The key framing conditions for this scenario are climate policy aligned with the baseline scenario and the occurrence of a sequence of compound physical risk events affecting each region. The modelling of physical risk follows a storyline approach, where it is assumed that dry events (i.e. the combination of droughts, heatwaves and wildfires) occur in 2026 and wet events (i.e. the combination of floods and storms) occur in 2027. There are six instances of this scenario corresponding to the occurrence of physical risk in the six continental regions (Africa, Asia, North America, South America, Europe and Oceania) according to the climate physical storylines. In each instance, or variant, the rest of the world is only affected indirectly, via trade and financial linkages, by the extreme events happening in the target region.

Natural disaster shocks:
Direct impacts are described in detail in the section on physical risk. In summary, the **HDW compound event** induces the following impacts in an affected region:

- Droughts induce a reduction of output proportional to the number of drought months in the agricultural sector and in GEM-E3 sectors that are identified as highly exposed to water risk: *agriculture, biofuels, biomass solid, hydroelectric power generation, nuclear power generation, basic pharmaceutical products, batteries, chemical products, computer, electronic and optical products, ferrous metals, non-ferrous metals and advanced electric appliances*.
- Heatwaves induce a reduction in labour supply and productivity for sectors with outdoor and physically intensive activities: *agriculture, biomass solid, coal, construction, crude oil, market services/ non-market services*.
- Wildfires induce destruction of capital stocks and business interruptions in the market and non-market service sectors proportional to the area affected.

The **SF compound event** (storms-floods) induces capital destruction proportional to hazard intensity and, in turn, business interruption proportional to the extent of capital destruction. Sector-specific exposure and vulnerability are accounted for through:

- The localisation and the concentration of sectoral activities,
- The sectoral composition of the capital stock (tangible vs intangible).

As described in detail in the section on physical risk, these direct impacts directly affect the capital stock and the output in GEM-E3 and then propagate across sectors and regions through global supply chains as modelled by general-equilibrium linkages. For each variant of the scenario, one considers the direct impact hitting a single continental region (Africa, Asia, North America, South America, Europe, or Oceania) and the propagation to the other, not directly impacted, regions via trade and financial linkages.

Table of implemented shocks

Shock	Model	Implementation
Policy stringency shock + international coordination	GEM-E3/ EIRIN	Aligned with baseline scenario.
Technology shock	GEM-E3	Not considered in this scenario.
Households' preferences	NA	Not considered in this scenario.
Natural disaster shocks	Direct impact models	Occurrence of the HDW in 2026 and of the SW compound events in 2027 at the magnitude of a 50 years return period. One variant of the scenario per continent where the direct impacts hit in the corresponding continent.
Uncertainty shock	CLIMACRED	Frontloading of future physical risk in financial risk assessment on a region-by-region basis. Physical risks of the magnitude of the compound events of the scenario are integrated in credit risk assessment leading to an increase in risk premia and the cost of capital across the board, with effects proportional to the exposure of sectors and countries.
Energy price shock	GEM-E3	Endogenously computed by the model following induced shocks on supply and demand

Diverging Realities

High Level Narrative

*The **Diverging Realities scenario** reflects how a lack of financing to drive the green transition outside of advanced economies can lead to global divergences. Emerging markets and developing economies, as well as low-income countries, experience repeated severe natural disasters and get trapped in perpetual states of recovery. This not only leads to severe local disruptions in the form of lives lost, capital destruction, migration and labour productivity declines, but also to global knock-on effects on food and commodity prices and on the supply of critical minerals. Short of external support from advanced economies, this renders the global transition ineffective.*

***In advanced economies**, emission pathways are aligned with a net-zero transition target. Energy prices rise initially due to ambitious climate policies being implemented and reflecting a shift from clean fossil fuels to more expensive renewables.*

***In EMDEs and LICs**, GDP losses are elevated due to the repeated disasters. Households are hit hard by the loss of (the value of) housing, while corporates suffer from loss of labour supply and productive capital destruction, which takes time to rebuild.*

Outline of the implementation

The key framing conditions for this scenario is a divide in climate policy implementation between advanced economies (AE[39]) on the one hand and Emerging Market and Developing Economies (EMDE) and Low-Income countries (LICs) on the other hand. In this context, we assume compound events affect EMDE and LIC countries (and some advanced economies as well) only in Africa, Asia and South America. This leads to direct economic impacts in the corresponding countries. These impacts cause interruption of global supply chains of materials critical for the green transition in advanced economies. In the financial realm, climate shocks induce a reassessment of credit risk due to the extreme weather events, leading to increased risk premia, notably on EMDE and LIC.

Natural disaster shocks:
The modelling of physical risk follows a storyline approach. We consider the occurrence of a sequence of compound events in EMDEs and LICs, with an HDW (heatwave-drought-wildfire) event occurring in 2025 in Asia, 2026 in South America, and 2027 in Africa and a SF (storms-floods) event occurring in 2028 in Asia, in 2029 in South America, and in 2030 in Africa at the magnitude of a 20 years return period[40].

[39] Advances economies is proxied by OECD membership.
[40] The characteristic of the scenario is the occurrence of a sequence of events in different regions, not the order per se.

Direct impacts are described in detail in the section on physical risk. Physical shocks are transmitted through the economy in the way already described in the “Disasters and Policy Stagnation” scenario.

As described in detail in the section on physical risk, these direct impacts affect directly the capital stock and the output in GEM-E3 and then propagate across sectors and regions through global supply chains as modelled by general-equilibrium linkages.

Table of implemented shocks

Shock	Model	Implementation AE (OECD and EU countries)	Implementation EMDE and LIC
Policy stringency shock + international coordination	GEM-E3/EIRIN	Consistent with NZ50 objectives (with backstop technology).	Aligned with baseline scenario.
Technology shock	GEM-E3	Same as Highway to Paris in AE.	Not considered in this scenario.
Government subsidies and investments	GEM-E3/EIRIN	Same as HW2: Government fully recycle carbon revenues for i) R&D in clean energy technologies and ii) Capital subsidisation of clean energy technologies	In line with Baseline.
Households preferences	GEM-E3	Shift in consumption patterns with a decrease in the consumption of high-carbon goods and of consumer durables.	Not considered in this scenario.
Natural disaster shocks	Direct impact models	Not considered in this scenario.	20 year return-period HDW event occurring in 2025 in Asia, 2026 in South America, and 2027 in Africa and 20 year return-period SF event occurring in 2028 in Asia, in 2029 in South America, and in 2030 in Africa.
Uncertainty shock	CLIMACRED	Financial risk is assumed to follow the Highway to Paris trajectories.	Frontloading of future physical risk in financial risk assessment. Physical risks of the magnitude of the compound events are integrated in credit risk assessment leading to an increase in risk premia and the cost of capital across the board, with effects proportional to the exposure of sectors and countries.

Energy price shock	GEM-E3	Endogenously computed by the model following induced shocks on supply and demand.
Supply restrictions for critical raw materials	Direct impact models	Propagation of shocks through global supply chains through price adjustments and the associated general equilibrium effects. Disruptions of imports and exports (through changes in Armington elasticities) are considered, more specifically for critical inputs for the low-carbon transition. Changes in trade/elasticity matrix of specific commodities to simulate lower availability of critical material. In detail: 1. Reduction in the total import share for RES technologies (Wind, PV, EV equipment, Batteries, CCS equipment) for the OECD and EU countries. Leading to reduction in total imports for those technologies. Namely, 1% reduction per year from 2025 and 0.5% from 2028. 2. Changes in the import share by partner. Applies to imports from China, Indonesia, Oceania as these have the highest proportion of critical materials. The reduced share from those countries leads to an increase to the rest of the world economies. This change is done by adjusting the trade share parameters in GEM-E3 of the model accordingly. The trade assumptions implemented are: - OECD countries reduce by 2% batteries imports from China, Indonesia, Oceania. Increase them by 6% from the Rest of the World - OECD countries reduce by 2% EV Transport Equipment, Equipment for wind power technology, Equipment for PV panels, Equipment for CCS power technology imports from China. Increase them by 2% per good from the Rest of the World.

Data access & tools

There are several ways to access the data, which serve different users' needs and analytical requirements.
All scenario data can be accessed in the **NGFS IIASA Scenario Explorer**, an online interface to visualise and explore the data. Here users can explore and compare scenarios, regions, variables, and models. Data can be downloaded in bulk as .csv or .xlsx data frames.

The NGFS IIASA Scenario Explorer provides a direct API to access the data in coding scripts directly. To facilitate users' access to this method, the **NGFS EnTry Tool** is also available – a browser-based python script in Google Collab, which allows users to access, query, visualise and export the data via the IIASA pyam package.

The NGFS short-term scenario database is structured as follows:

Models	Variables	Scenarios	Regions	Timeframes
GEM-E3	Macro (GDP, unemployment, energy, sectoral production…)	- Baseline - HWTP - SWUC - DAPS - DIRE Note: there is also run 1 data (labelled _*run1*), showing initial impacts before monetary and financial effects.	Full range of GEME3 countries & aggregates	Annual
EIRIN	Monetary (CPI, policy rates)	- Baseline - HWTP - SWUC - DAPS - DIRE	EIRIN-specific macro regions (Europe, North America, South America, Asia, Oceania)	Quarterly
CLIMACRED	Financial (WACC, PDs, Sovereigns…)	- HWTP - SWUC - DAPS - DIRE Note: baseline PDs are included, but as variables are shown as deltas there is no explicit baseline scenario included.	Full range of GEME3 countries & aggregates	Annual
Direct Impacts	Losses from extreme weather events (capital destruction, production and productivity loss)	- DAPS - DIRE (only physical risk scenarios)	Full range of GEME3 countries & aggregates	Annual

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ANNEX

A - Baseline Projections for GEM-E3

GDP Components as % shares of GDP

USA

% of GDP	2023	2025	2030
Private Consumption	69.4%	69.4%	69.0%
Public Consumption	14.0%	13.9%	13.8%
Investment	21.1%	20.9%	21.4%
Imports	15.9%	15.7%	15.8%
Exports	11.5%	11.4%	11.6%
Balance of Trade	-4.5%	-4.3%	-4.1%

EU27

% of GDP	2023	2025	2030
Private Consumption	52.7%	52.6%	52.6%
Public Consumption	21.1%	21.0%	20.8%
Investment	22.1%	22.2%	22.4%
Imports	49.8%	51.8%	54.6%
Exports	53.9%	55.9%	58.7%
Balance of Trade	4.1%	4.2%	4.2%

China

% of GDP	2023	2025	2030
Private Consumption	40.7%	41.6%	42.3%
Public Consumption	14.4%	14.5%	14.5%
Investment	40.6%	40.1%	39.8%
Imports	13.9%	13.7%	13.8%
Exports	18.2%	17.5%	17.1%
Balance of Trade	4.3%	3.8%	3.3%

Japan

% of GDP	2023	2025	2030
Private Consumption	52.7%	53.1%	53.6%
Public Consumption	21.4%	21.5%	21.6%
Investment	25.6%	25.2%	24.9%
Imports	19.2%	20.0%	21.1%
Exports	19.6%	20.2%	21.0%

Balance of Trade	0.3%	0.2%	-0.1%

India

% of GDP	2023	2025	2030
Private Consumption	59.7%	60.1%	61.3%
Public Consumption	10.4%	10.3%	10.2%
Investment	34.5%	34.8%	34.9%
Imports	25.1%	24.9%	25.1%
Exports	20.4%	19.8%	18.7%
Balance of Trade	-4.6%	-5.2%	-6.4%

Main Production Sectors: Annual Growth

USA

	2023	2025	2030
Agriculture	1.4%	1.2%	1.2%
Energy	0.2%	0.0%	0.1%
Manufacturing	1.8%	1.6%	1.6%
Construction	-1.7%	1.9%	1.8%
Transport	0.5%	1.9%	1.8%
Services	2.6%	2.0%	1.9%

EU27

	2023	2025	2030
Agriculture	0.4%	0.9%	0.3%
Energy	0.2%	1.1%	0.7%
Manufacturing	0.0%	1.3%	1.1%
Construction	0.6%	2.4%	1.1%
Transport	0.7%	1.8%	1.2%
Services	1.0%	2.3%	1.3%

China

	2023	2025	2030
Agriculture	2.4%	2.0%	1.7%
Energy	3.1%	2.2%	1.8%
Manufacturing	4.7%	3.9%	3.4%
Construction	7.6%	4.8%	3.5%
Transport	1.9%	3.8%	3.5%
Services	5.5%	4.7%	4.2%

Japan

	2023	2025	2030
Agriculture	-0.7%	-0.2%	-0.4%
Energy	0.9%	-0.4%	0.0%
Manufacturing	2.2%	0.7%	1.2%
Construction	0.9%	0.7%	0.7%
Transport	0.7%	1.7%	1.8%
Services	2.2%	0.6%	1.0%

India

	2023	2025	2030
Agriculture	4.3%	4.3%	2.5%
Energy	4.4%	4.4%	1.8%
Manufacturing	5.5%	5.5%	3.1%
Construction	8.2%	6.6%	3.6%
Transport	3.6%	5.8%	3.6%
Services	7.8%	7.9%	4.5%

B - Derivation of scenario-contingent sovereign bond valuation

Model structure

The assessment of the impact of alternative climate scenarios on sovereign risk is based on the methodology developed in Battiston et al. (2019) and Battiston and Monasterolo (2020) whereby default is evaluated at maturity T and occurs if fiscal sovereign assets $A(T)$ are less than sovereign liabilities $L(T)$, i.e.

$$A(T) \leq L(T)$$

In the baseline (B) scenario, the value of sovereign assets at maturity is a random variable determined by a deterministic initial value $A(0)$ and a random (cumulative) growth rate μ_T that is assumed to capture relevant economic and fiscal uncertainty on the sovereign. The default condition can thus be rewritten as:

$$(1 + \mu_T)A(0) \leq L(T)$$

and the probability of default in the baseline is given by

$$P_B = P[(1 + \mu_T)A(0) \leq L(T)] = P\left[\mu_T \leq \frac{L(T)}{A(0)} - 1\right] \quad (1)$$

More specifically, the aggregate growth rate of fiscal assets μ_T is assumed to be determined by a weighted average of sectoral growth rates, that is

$$\mu_T = \sum_{s=1}^{S} \alpha_s \mu_{s,T}$$

where S corresponds to the set of sectors considered, the weights α_s are proportional to the share of each sector s in the Gross Value Added (GVA) (and thus $\sum_{s=1}^{S} \alpha_s = 1$) and the $\mu_{s,T}$ are the sectoral growth rates.

Accordingly, the probability of default in B can equivalently be written as

$$P_B = P[(1 + \mu_T)A(0) \leq L(T)] = P\left[\sum_{s=1}^{S} \alpha_s \mu_{s,T} \leq \frac{L(T)}{A(0)} - 1\right] \quad (2)$$

The present value in the B scenario of a zero-coupon sovereign bond with maturity T is then given by

$$V_B = (1 + r_f)^{-T}\big[(1 - P_B) + P_B(1 - LGD)\big) = \left(1 + r_f\right)^{-T}(1 - P_B * LGD) \quad (3)$$

where r_f is the risk-free rate used for discounting and LGD the (parametric) loss given default ratio.

The change in market expectations from the materialization of the scenario B to the materialization of the climate policy scenario P leads to an adjustment in the valuation of the sovereign bond, given the sectoral characteristics of the economy (sectoral GVAs).

In the scenario P, the cumulative growth rate of sector s is assumed to be of the form $\mu_{s,T} + \rho_{s,T}$ where $\rho_{s,T}$ is the cumulative shock on (fiscal) assets linked to sector s up to maturity T.

Accordingly, fiscal assets at maturity in the P scenario are given by $[1+\sum_{s=1}^{S} \alpha_s(\mu_{s,T}+\rho_{s,T})]A(0)$, while the scenario adjusted probability of default P_P and zero-coupon valuation V_P are given, respectively, by

$$P_P = P[(1+\mu_T)A(0) \le L(T)] = P\left[\sum_{s=1}^{S} \alpha_s(\mu_{s,T} + \rho_{s,T}) \le \frac{L(T)}{A(0)} - 1\right] \quad (4)$$

and

$$V_P = \left(1 + r_f\right)^{-T}(1 - P_P * LGD) \ (5)$$

Computation and Calibration

Assuming an exogenously given probability of default in the scenario B, and the probability distribution of μ_T, then the calibration of the model is completely determined.
Indeed, by using an index value $A(0) = 1$ and by inverting Equation (1) we can determine the value of $L(T)$. Let us define the function $f(x)$ as follows

$$f(x) = P\left[\mu_T + x \le \frac{L(T)}{A(0)} - 1\right]$$

The value of $f(0)$ corresponds to the probability of default in the scenario B while the value $f(x)$ with $x > 0$ represents the probability of default in the climate policy scenario P, when an additional shock x is applied to the cumulative growth rate.
Note that f is completely determined by the cumulative growth rate in B and by the probability of default in B. In particular, f can represent both the probability of default of a sovereign entity and the probability of default of a firm in a given sector (once the cumulative growth rate and the probability of default in B are given).

Note that it holds

$$P_P = f(\sum_{s=1}^{S} \alpha_s \rho_{s,T})$$

Thus, for sufficiently small shocks, we can take the following first-order approximation

$$P_P = f(0) + f'(0) \sum_{s=1}^{S} \alpha_s \rho_{s,T} = P_B + f'(0) \sum_{s=1}^{S} \alpha_s \rho_{s,T} \ (6)$$

Now, in absence of further information, we assume that in the baseline scenario, the sectoral growth rates are uniformly distributed so that for all s, $\mu_{s,T} = \mu_T$. This implies that the probability of default in sector s in the climate policy scenario P is determined similarly to Equation (6) and thus given by

$$P_{P,s} = f(0) + f'(0)\,\rho_{s,T} = P_B + f'(0)\,\rho_{s,T} \quad (7)$$

Using the fact that $\sum_{s=1}^{S} \alpha_s = 1$, we can substitute Equation (7) in Equation (6) to get

$$P_P = \sum_{s=1}^{S} \alpha_s P_{P,s} \quad (8)$$

Hence, the sovereign probability of default can be approximated by a linear combination of sectoral probabilities of default (if the latter ones are calibrated on the same exogenous default probability of the former ones). Accordingly, the scenario-contingent sovereign zero-coupon valuation in the climate policy scenario P can be written as a linear combination of the sectoral zero-coupon valuation:

$$V_P = \left(1 - \sum_{s=1}^{S} \alpha_s P_{P,s} * LGD\right) = \sum_{s=1}^{S} \alpha_s V_{P,s} \quad (9)$$

where $V_{P,s} = 1 - P_{P,s} * LGD$.

C - List of current policies

The list of current policies implemented to the baseline is shown below.

Country	Policy code	Target description	Target year	Base year	Target
Argentina					
	2a-ARG-ENE-REN-25	Renewable electricity share	2025	-	20 %
	10a-ARG-GEN-TAX-17	Carbon tax	-	2017	10 USD/tCO2
Australia					
	1a-AUS-ENE-REN-30	Renewable electricity share	2030	-	50 %
	9a-AUS-GEN-FIN-30	GHG Emissions reduction	2030	2019	-100 MtCO2e
Brazil					
	4a-BRA-TRA-BIO-23	Biofuel share in transport	2023	-	15 %
Canada					
	1b-CAN-ENE-CPO-30	Transitional Capacity coal for electricity	2030	-	0 MW
	11b-CAN-GEN-TAX-22	Carbon tax	2022	2018	39 USD/tCO2e
China					
	2a-CHN-ENE-REN-30	Renewable electricity share	2030	2020	35 %
	2b-CHN-ENE-REN-25	Capacity nuclear	2025	-	70 GW
EU					
	27a-EUR-GEN-GHG-30	Renewable electricity share	2030	2023	45 %
	32a-EUR-GEN-GHG-30	GHG emissions (incl. LULUCF) - 55%	2030	1990	2351 MtCO2e

India					
	1e-IND-ENE-REN-26	Renewable capacity	2026	2016	40 GW
	2a-IND-ENE-REN-22	Renewable electricity share	2022	-	20.1%
	2b-IND-ENE-REN-27	Renewable electricity share	2027	-	24.4%
	3a-IND-ENE-REN-30	Wind electricity share	2030	2022	6.9 %
	3b-IND-ENE-REN-30	Hydro electricity share	2030	2022	2.8 %
Indonesia					
	4a-IDN-ENE-REN-30	Capacity addition Hydro	2030	2021	10.5 GW
	4b-IDN-ENE-REN-30	Capacity addition Geothermal	2030	2021	3.2 GW
	4c-IDN-ENE-REN-30	Capacity addition wind	2030	2021	0.4 GW
	4d-IDN-ENE-REN-30	Capacity addition solar	2030	2021	4.9 GW
	10a-IDN-GEN-TAX-60	Carbon tax	2060	2021	2 USD/tCO2
Japan					
	5a-JPN-ENE-REN-30	Capacity wind	2030	2020	10 GW
	11a-JPN-ENE-REN-30	Nuclear share in power generation	2030	-	21 %
	11b-JPN-ENE-REN-30	Renewable electricity share	2030	-	37 %
	11c-JPN-ENE-FOS-30	Coal share in power generation	2030	-	19 %
	11d-JPN-ENE-FOS-30	Gas share in power generation	2030	-	20 %
	11e-JPN-ENE-FOS-30	Oil share in power generation	2030	-	2 %
Korea					
	1a-KOR-GEN-ETS-30	GHG emissions	2030	BAU	504 MtCO2
Mexico					
	6a-MEX-GEN-ETS-30	GHG emissions (Excl. LULUCF)	2030	BAU	759 MtCO2e
	10c-MEX-ENE-REN-24	Renewable electricity share	2024	-	35 %
Russia					
	7a-RUS-TRA-GHG-30	CO2 emissions Road transport	2030	2017	1.2 %
Saudi Arabia					
	3a-SAU-ENE-REN-30	Renewable electricity share	2030	2023	50 %
	3b-SAU-ENE-FOS-30	Gas power generation share	2030	2023	50 %
South Africa					
	1a-SAF-ENE-REN-30	Renewable electricity share (excluding/including hydro)	2030	-	26.5/36.5 %
	1b-SAF-ENE-REN-30	Capacity hydro	2030	2010	4.7 GW
	1c-SAF-ENE-REN-30	Capacity wind	2030	2010	17.742 GW
	1d-SAF-ENE-REN-30	Capacity Solar CSP	2030	2010	0.6 GW
	1e-SAF-ENE-REN-30	Capacity PV	2030	2010	8.3 GW
	1f-SAF-ENE-REN-30	Capacity nuclear	2030	2010	1.86 GW
	1g-SAF-ENE-CPO-30	Coal share in power generation	2030	-	44.6 %
	6a-SAF-GEN-TAX-25	Carbon price	2025	2019	6 USD 2010/tCO2e
Turkey					
	1b-TUR-ENE-REN-23	Capacity hydro	2023	-	32 GW
	1c-TUR-ENE-REN-23	Capacity wind	2023	-	11.9 GW
	1d-TUR-ENE-REN-23	Capacity PV	2023	-	10 GW
	1e-TUR-ENE-REN-23	Capacity Geothermal	2023	2019	2.9 GW
	2a-TUR-ENE-ELE-23	Renewable electricity share	2023	-	30 %
USA					
	4a-USA-GEN-GHG-30	GHG emissions (-33 to 40%)	2030	2005	4772 MtCO2e
	4c-USA-ENE-REN-30	Capacity addition PV and Wind	2030	2023	70 - 693 GW

D - List of NDC targets

The list of the NDC targets implemented into the Highway to Paris scenario is shown below.

Country	NDC Target description	NDC emissions reduction target without LULUCF, MtCO2e
Argentina		
	Not exceeding the net emission of 349 million tons of carbon dioxide equivalent in 2030	258
Brazil		
	Unconditional 2030 target in the latest update to 50% below 2005	885
Canada		
	Reduction below 2005 levels by 2030 to at least 40-45%	435
China		
	CO2 emissions peak before 2030 and achieve carbon neutrality before 2060; to lower CO2 emissions per unit of GDP by over 65% from the 2005 level, to increase the share of non-fossil fuels in primary energy consumption to around 25%, to increase the forest stock volume by 6 billion cubic meters from the 2005 level, and to bring its total installed capacity of wind and solar power to over 1.2 billion kilowatts by 2030	11,265
EU		
	At least 55% in greenhouse gas emissions by 2030 compared to 1990	2,325
India		
	Emissions intensity of 45% below 2005 levels by 2030	4,145
Indonesia		
	Reduce emissions by 32% against the 2030 BAU	1,130
Japan		
	46% reduction in 2030 from 2013 levels including LULUCF credits, Japan intends to use LULUCF sink credits up to 47.7 MtCO2e/year	776
Korea		
	40% reduction in emissions compared to 2018 levels, including emissions reductions from LULUCF and international credits	453
Mexico		
	35% reduction from 2030 BAU	612
Oceania		
		439
Australia	Transitional Capacity coal for electricity	
New Zealand	50% reduction in GHG emissions from 2005 level of emissions in 2030 including LULUCF	
Russia		
	Reduction in greenhouse gas emissions by 2030 to 70 percent relative to the 1990 level	1,433
Rest of energy producing countries		
		2,377
United Arab Emirates	Reduction 31% compared to business as usual (BAU) for the year 2030	
Iran	4% (unconditional reduction) below business as usual (BAU) by 2030	
Nigeria	reduce GHG emissions in 2030 by 20% below business-as-usual emissions	
Venezuela	reduce its GHG emissions by 20% by 2030 in relation to the inertial scenario	
Algeria	A greenhouse gas emission reduction of 7% by 2030 compared to business as usual (BAU) levels	

Rest of Europe		
		540
Belarus	Reduce greenhouse gas emissions by at least 35 per cent from the 1990 level by 2030, inclusive of the LULUCF sector	
Switzerland	Reduce greenhouse gas emissions by at least 50% by 2030 compared to 1990 level	
Norway	Norway is committed to a target by at least 55 per cent reduction in greenhouse gas emission compared to 1990 levels	
Ukraine	Economy-wide net domestic reduction of 65 % in GHG emissions by 2030 compared to 1990	
Iceland	55% emission reduction from 1990	
Saudi Arabia		
	Reduce and avoid emissions by 278 million tons of CO2eq annually by 2030, with the year 2019 designated as the base year for this NDC	454
South Africa		
	In 2025, South Africa's annual GHG emissions will be in a range from 398-510 Mt CO2- eq. In 2030, South Africa's annual GHG emissions will be in a range from 350-420 Mt CO2-eq.	404
Turkey		
	41% reduction from BAU scenario in NDC	740
UK		
	Reduce economy-wide greenhouse gas emissions by at least 68% by 2030 compared to 1990 levels	260
USA		
	Reduce emissions by 50%–52% below 2005 levels by 2030 (including LULUCF)	4,035

E - GEM-E3 sectors and mapping to NACE 2 sectors

Table E.1: Sectoral dimension of the GEM-E3 model

GEM-E3 SECTORS					
Industry		**Industry (continued)**		**Agriculture**	
IND01	Ferrous metals	**IND19**	Equipment for PV panels	**AGR01**	Agriculture
IND02	Non-ferrous metals	**IND20**	Equipment for CCS power technology	**Services**	
IND03	Fabricated Metal products	**IND21**	CO2 Capture	**SRV01**	Market Services
IND04	Chemical Products	**Energy**		**SRV02**	Non Market Services
IND05	Basic pharmaceutical products	**ENE01**	Coal	**SRV03**	R&D
IND06	Rubber and plastic products	**ENE02**	Crude Oil	**Power Generation**	
IND07	Paper products, publishing	**ENE03**	Oil	**PGT01**	Coal fired
IND08	Non-metallic minerals	**ENE04**	Gas	**PGT02**	Oil fired
IND09	Computer, electronic and optical products	**ENE05**	Power Supply	**PGT03**	Gas fired
IND10	Other Equipment Goods	**ENE06**	Biomass Solid	**PGT04**	Nuclear
IND11	Transport equipment (excluding EV)	**ENE07**	Biofuels	**PGT05**	Biomass
IND12	Consumer Goods Industries	**ENE08**	Hydrogen	**PGT06**	Hydro electric
IND13	Construction	**ENE09**	Clean Gas	**PGT07**	Wind
IND14	Batteries	**Transport**		**PGT08**	PV
IND15	EV Transport Equipment	**TRA01**	Warehousing and support activities	**PGT09**	Geothermal
IND16	Advanced Electric Appliances	**TRA02**	Air transport	**PGT10**	CCS coal
IND17	Advanced Heating and Cooking Appliances	**TRA03**	Land transport	**PGT11**	CCS Gas
IND18	Equipment for wind power technology	**TRA04**	Water transport	**PGT12**	CCS Bio

Table E.2: Mapping of GEM-E3 sectors to NACE 2 sectors

GEM-E3 Sectors	NACE 2-digit
Agriculture	A01: Crop and animal production, hunting and related service activities A03: Fishing and aquaculture
Biomass Solid	A02: Forestry and logging
Coal Crude Oil	B05: Mining of coal and lignite B06: Extraction of crude petroleum and natural gas B07: Mining of metal ores B08: Other mining and quarrying B09: Mining support service activities
Consumer Goods Industries	C10: Manufacture of food products C11: Manufacture of beverages C12: Manufacture of tobacco products C13: Manufacture of textiles C14: Manufacture of wearing apparel C15: Manufacture of leather and related products C16: Manufacture of wood and of products of wood and cork, except furniture manufacture of articles of straw and plaiting materials
Paper products, publishing	C17: Manufacture of paper and paper products C18: Printing and reproduction of recorded media
Oil	C19: Manufacture of coke and refined petroleum products
Chemical Products Biofuels	C20: Manufacture of chemicals and chemical products
Basic pharmaceutical products	C21: Manufacture of basic pharmaceutical products and pharmaceutical preparations

Rubber and plastic products	C22: Manufacture of rubber and plastic products
Non-metallic minerals	C23: Manufacture of other non-metallic mineral products
Ferrous metals Non-ferrous metals	C24: Manufacture of basic metals
Fabricated Metal products	C25: Manufacture of fabricated metal products, except machinery and equipment
Computer, electronic and optical products	C26: Manufacture of computer, electronic and optical products
Advanced Electric Appliances Advanced Heating and Cooking Appliances	C27: Manufacture of electrical equipment
Equipment for wind power technology Equipment for PV panels Equipment for CCS power technology CO2 Capture	C28: Manufacture of machinery and equipment n.e.c.
Transport equipment (excluding EV) Batteries EV Transport Equipment	C29: Manufacture of motor vehicles, trailers and semi-trailers C30: Manufacture of other transport equipment
Other Equipment Goods	C31: Manufacture of furniture C32: Other manufacturing C33: Repair and installation of machinery and equipment
Gas Power Supply Hydrogen	D35: Electricity, gas, steam and air conditioning supply

Clean Gas Coal fired Oil fired Gas fired Nuclear Biomass Hydro electric Wind PV Geothermal CCS coal CCS Gas CCS Bio	
Construction	F41: Construction of buildings F42: Civil engineering F43: Specialised construction activities
Land Transport	H49: Land transport and transport via pipelines
Water transport	H50: Water transport
Air transport	H51: Air transport
Warehousing and support activities	H52: Warehousing and support activities for transportation H53: Postal and courier activities
Market Services	I55: Accommodation I56: Food and beverage service activities K64: Financial service activities, except insurance and pension funding K66: Activities auxiliary to financial services and insurance activities

		K65: Insurance, reinsurance and pension funding, except compulsory social security R90: Creative, arts and entertainment activities R91: Libraries, archives, museums and other cultural activities R92: Gambling and betting activities R93: Sports activities and amusement and recreation activities E36: Water collection, treatment and supply E37: Sewerage E38: Waste collection, treatment and disposal activities materials recovery E39: Remediation activities and other waste management services J58: Publishing activities J59: Motion picture, video and television programme production, sound recording and music publishing activities J60: Programming and broadcasting activities J61: Telecommunications J62: Computer programming, consultancy and related activities J63: Information service activities L68: Real estate activities M69: Legal and accounting activities M70: Activities of head offices management consultancy activities M71: Architectural and engineering activities technical testing and analysis M73: Advertising and market research M74: Other professional, scientific and technical activities M75: Veterinary activities N77: Rental and leasing activities N78: Employment activities N79: Travel agency, tour operator and other reservation service and related activities

	N80: Security and investigation activities N81: Services to buildings and landscape activities N82: Office administrative, office support and other business support activities S94: Activities of membership organisations S95: Repair of computers and personal and household goods S96: Other personal service activities T97: Activities of households as employers of domestic personnel T98: Undifferentiated goods- and services-producing activities of private households for own use U99: Activities of extraterritorial organisations and bodies G45: Wholesale and retail trade and repair of motor vehicles and motorcycles G46: Wholesale trade, except of motor vehicles and motorcycles G47: Retail trade, except of motor vehicles and motorcycles
Non Market Services	P85: Education O84: Public administration and defence compulsory social security Q86: Human health activities Q87: Residential care activities Q88: Social work activities without accommodation
R&D	M72: Scientific research and development

F - Geographical coverage by models

CLIMACRED / GEME3	GEME3 Continental Aggregation	GEME3 European Aggregation	GEME3 R5 Aggregation	EIRIN
Argentina - ARG	South America		Latin America (R5)	
Austria - AUT	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Belgium - BEL	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Brazil - BRA	South America		Latin America (R5)	South America (representative country)
Bulgaria - BGR	Europe	EU27, EU28	OECD & EU (R5)	Europe
Canada - CAN	North America		OECD & EU (R5)	North America
China - CHN	ASIA		Asia (R5)	Asia (representative country)
Croatia - HRV	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Cyprus - CYP	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Czechia - CZE	Europe	EU27, EU28	OECD & EU (R5)	Europe
Denmark - DNK	Europe	EU27, EU28	OECD & EU (R5)	Europe
Estonia - EST	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Finland - FIN	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
France - FRA	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Germany - DEU	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Greece - GRC	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Hungary - HUN	Europe	EU27, EU28	OECD & EU (R5)	Europe
India - IND	Asia		Asia (R5)	
Indonesia - IDN	Asia		Asia (R5)	
Ireland - IRL	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Italy - ITA	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Japan - JPN	Asia		OECD & EU (R5)	
Latvia - LVA	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe

Lithuania - LTU	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Luxembourg - LUX	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Malta - MLT	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Mexico - MEX	North America		Latin America (R5)	North America
Netherlands - NLD	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Poland - POL	Europe	EU27, EU28	OECD & EU (R5)	Europe
Portugal - PRT	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Romania - ROU	Europe	EU27, EU28	OECD & EU (R5)	Europe
Russia - RUS			Reforming Economies (R5)	
Saudi Arabia - SAU	Asia		Middle East & Africa (R5)	
Slovakia - SVK	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Slovenia - SVN	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
South Africa - ZAF	Africa		Middle East & Africa (R5)	No Africa region
South Korea - KOR	Asia		Asia (R5)	
Spain - ESP	Europe	EU27, EU28, Euro Area	OECD & EU (R5)	Europe
Sweden - SWE	Europe	EU27, EU28	OECD & EU (R5)	Europe
Turkey - TUR	Asia		OECD & EU (R5)	
USA - USA	North America		OECD & EU (R5)	North America
United Kingdom - GBR	Europe	EU28	OECD & EU (R5)	
Oceania	Oceania		OECD & EU (R5)	Oceania (Australia, New Zealand)
Rest of Europe			OECD & EU (R5)	Europe
Rest of Energy Producing Countries			Middle East & Africa (R5)	
Rest of World			Other (R5)	

G - CLIMACRED Variable Definitions

Variable	Granularity	Units	Definition
baseline_pd|sector	by country and sector	value/level in percentage points	The baseline pd is inferred from the country-level baseline interest rate prevailing in GEM-E3 to ensure consistency of the modelling framework. Please note: this however implies that a similar baseline pd is used in all sectors of a given country
corporate_bond_price_rel_adjustment|sector	by country and sector	relative change with respect to baseline in percents (i.e. share of baseline value)	Relative change in value of the bond with respect to the baseline
equity_relative_adjustment|sector	by country and sector	relative change with respect to baseline in percents (i.e. share of baseline value)	Relative change in value of the equity with respect to the baseline
pd_adjustment|sector	by country and sector	abs. change in value with respect to baseline in percentage points	Absolute change in pd with respect to the baseline. Sector and country specific probability of default
scenario_wacc|sector	by country and sector	value/level in percentage points	Weighted Cost of Capital (average cost of financing from debt and equity) in the scenario in levels
wacc_adjustment|sector	by country and sector	abs. change in value with respect to baseline in percentage points	Absolute change in Weighted Cost of Capital (average cost of financing from debt and equity) with respect to the baseline
sovereign_bond_price_rel_adjustment|country	by country	relative change with respect to baseline in percents (i.e. share of baseline value)	Sovereign bond price. Relative change in value of the bond with respect to the baseline
sovereign_pd_adjustment|country	by country	abs. change in value with respect to baseline in percentage points	Sovereign Probability of Default. Absolute change in pd with respect to the baseline
sovereign_spread_adjustment_incl_policy|country	by country	abs. change in value with respect to baseline in percentage points	Change in yield of the sovereign bond relative to the baseline (considering contribution of scenario-specific risk-free/policy rates)
sovereign_spread_adjustment|country	by country	abs. change in value with respect to baseline in percentage points	Change in yield of the sovereign bond relative to the baseline (not considering contribution of scenario-specific risk-free/policy rates)
corporate_bond_spread_adjustment_incl_policy |sector	by country and sector	abs. change in value with respect to baseline in percentage points	Sector and country specific bond prices. Change in yield of the bond relative to the baseline (considering contribution of scenario-specific risk-free/policy rates)
corporate_bond_spread_adjustment|sector	by country and sector	abs. change in value with respect to baseline in percentage points	Sector and country specific bond prices. Change in yield of the bond relative to the baseline (not considering contribution of scenario-specific risk-free/policy rates)

H - GEME3 Variable Definitions

Variable	Granularity	Units	Definition
GDP	by country	Billion US$2017/yr	Gross domestic product
Population	by country	Million persons	Population by country
Employment	by country and skill type	Number of employed inhabitants	Total employment and employment per skill type
Unemployment	by country	Number of unemployed inhabitants and unemployment rate	Total level of unemployment and unemployment rate
Production	by country and sector	billion US$2017	Production by sector
Investment	by country and sector	billion US$2017	Total investment and investment by sector
Exports	by country and sector	billion US$2017	Total exports and exports by sector
Imports	by country and sector	billion US$2017	Total imports and imports by sector
Household Expenditures	by country and expenditure type	billion US$2017	Total expenditure and expenditures by type
Wages and Salaries	by country	billion US$2017	Total level of countries' wages value
Carbon prices	by country	US$2017/t CO2	Carbon prices per country
Gross emissions	by country and type	Mt CO2/yr	Total GHG emissions and emissions per type of emissions
Power Generation Technologies	by country and type	% Shares in Power Generation	Share of technology in total power generation
Labour Force	by country	Number of inhabitants in the labour force	Number of labour force per country
Interest rate	by country	%	Interest rate per country
Cost of capital	by country	%	Cost of capital by country

I - EIRIN Variable Definitions

Variable	Units	Additional Detail
Policy rate	%	
Policy rate QoQ Growth	Growth Rate (%)	Quarter-on-quarter growth is calculated as the percentage change over 1 quarter
Policy rate YoY Growth	Growth Rate (%)	Year-on-year growth is calculated as the percentage change over 4 quarters
Price Level|Index	Index (2019 = 1)	Based on region-specific CPI basket weights for headline inflation.
Price Level|Index QoQ Growth	Growth Rate (%)	Quarter-on-quarter growth is calculated as the percentage change over 1 quarter
Price Level|Index YoY Growth	Growth Rate (%)	Year-on-year growth is calculated as the percentage change over 4 quarters

J - GEM-E3 Technology

In the Highway to Paris scenario the private sector develops and adopts green technologies faster than expected. This is reflected, in GEM-E3, by values of $l1$ and $l2$ at the high-end of the parameter range. Additionally, we consider that technological spillovers are fully enabled at the global scale.

Wind	
LCOE ($/MWh)	Learning by Research rate:
40	17%
PV	
LCOE ($/MWh)	Learning by Research rate:
37	12%
Batteries	
LCOE ($/MWh)	Learning by Research rate:
320-340	27%
Biodiesel	
LCOE ($/MWh)	Learning by Research rate:
4.77-7.37	13%

Figure 3Capital Costs of Clean Energy Technologies and Learning by Research Rates. LCOE for the RES technologies refer to the base year, which is common to all scenarios. Learning by research rate, similarly, is the same across scenarios. What changes is the cumulative R&D investments per scenario which has an increasing impact on the LCOE reduction. R&D in green technologies increases according to the carbon revenues. Therefore, LCOEs change across scenario as a result of different R&D expenditures

Sources: LCOE: Lazard Financial Services | Learning rates: Schoots et. al. (2008), Handayani et.al. (2019), European Commission (2018), Louwen et al. (2018), IEA 2019, Emmerling et al. (2016), Verdolini et al. (2018).

This materializes in a total factor productivity which increases faster for green technologies compared to emitting ones.

K - Mapping between EIRIN and GEM-E3 sectors

GEM-E3 Sectors	EIRIN Sectors
Advanced Electric Appliances	Consumer Goods Producer
Advanced Heating and Cooking Appliances	Consumer Goods Producer
Agriculture	Consumer Goods Producer
Air transport	Service Sector
Basic pharmaceutical products	Consumer Goods Producer
Batteries	Low-carbon Capital Producer
Biofuels	Mining and Oil Sector
Biomass	Mining and Oil Sector
Biomass Solid	Mining and Oil Sector
CCS Bio	Low-carbon Capital Producer
CCS coal	Low-carbon Capital Producer
CCS Gas	Low-carbon Capital Producer
Chemical Products	Mining and Oil Sector
Clean Gas	Mining and Oil Sector
CO2 Capture	Low-carbon Capital Producer
Coal	Mining and Oil Sector
Coal fired	Brown Utility Sector
Computer, electronic and optical products	Consumer Goods Producer
Construction	High-carbon Capital Producer
Consumer Goods Industries	Consumer Goods Producer
Crude Oil	Mining and Oil Sector
Equipment for CCS power technology	Low-carbon Capital Producer
Equipment for PV panels	Low-carbon Capital Producer
Equipment for wind power technology	Low-carbon Capital Producer
EV Transport Equipment	Low-carbon Capital Producer
Fabricated Metal products	Consumer Goods Producer
Ferrous metals	Consumer Goods Producer
Gas	Brown Utility Sector
Gas fired	Brown Utility Sector
Geothermal	Green Utility sector
Hydro electric	Green Utility sector
Hydrogen	Green Utility sector
Land Transport	Service Sector
Market Services	Service Sector
Non Market Services	Service Sector
Non-ferrous metals	Consumer Goods Producer
Non-metallic minerals	Consumer Goods Producer
Nuclear	Green Utility sector

Oil	Mining and Oil Sector
Oil fired	Brown Utility Sector
Other Equipment Goods	High-carbon Capital Producer
Paper products, publishing	Consumer Goods Producer
Power Supply	Brown Utility sector
PV	Green Utility sector
R&D	Service Sector
Rubber and plastic products	Consumer Goods Producer
Transport equipment (excluding EV)	High-carbon Capital Producer
Warehousing	Service Sector
Water transport	Service Sector
Wind	Green Utility sector

L - EIRIN Taylor rule parameters

Parameter	Region	Value
ω: weight of persistency in the policy rate	Europe	0.9
	North America	0.9
	Oceania	0.9
	Asia	0.95
	South America	0.85
ψ: weight of the inflation deviation	Europe	1.1
	North America	1.2
	Oceania	1.5
	Asia	1.1
	South America	2
γ: weight of the output gap	Europe	0.1
	North America	0.11
	Oceania	0.1
	Asia	0.04
	South America	0.075