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Enhanced scenarios for climate stress-tests

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Summary

Central banks and financial supervisors recommend that financial institutions run climate stress-tests, and several have developed their own. Climate scenarios are central to climate financial risk assessments. Moreover, conditional to additional factors, such as leverage, interconnectedness and climate policy credibility, financial institutions can absorb or amplify climate risks. Thus, climate stress-tests are a powerful tool to quantify the exposure of financial institutions to climate financial risks, to support investors' climate risk management and central banks and financial supervisors on both micro and macroprudential measures.

Scenarios play a key role in stress-tests, including in climate stress-tests. The development of the scenarios of the Network for Greening the Financial System (NGFS) has been a pivotal development in the climate finance space. Going forward, we need to be aware that these scenarios are constructed without taking into account that the reaction of the financial system to the scenarios may impact, positively or negatively, on the realisation of this or that scenario. We refer to this circularity as the endogeneity of climate risks and it can cause a gap to emerge between the level of climate finance investments actually carried out and those assumed to be carried out in the scenario used in the climate stress-test.

Neglecting such endogeneity could lead to increased risks for financial stability. To address this challenge, central banks and financial supervisors can benefit from a recently developed methodological framework that connects process-based Integrated Assessment Models and the Climate Financial Risk model. This framework produces a new generation of climate mitigation scenarios that capture the key role of investors' expectations, policy credibility and risk assessment within the realisation of the scenarios, yielding more robust climate financial risk analysis. This framework can be applied to the NGFS scenarios, and to different internal credit and financial risk models, to improve the relevance of climate stress-testing for decision making.

This paper is part of a toolbox designed to support central bankers and financial supervisors in calibrating monetary, prudential and other instruments in accordance with sustainability goals, as they address the ramifications of climate change and other environmental challenges. The papers have been written and peer-reviewed by leading experts from academia, think tanks and central banks and are based on cutting-edge research, drawing from best practice in central banking and supervision.

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1. Introduction

Several central banks and financial supervisors across the world are in the process of assessing climate risks for the banks and financial institutions under their supervision. Depending on their regulatory purpose, these exercises may go under different names, such as 'climate stress-tests' or 'climate scenario analyses', but they share similar challenges and solutions. Central banks and financial supervisors typically carry out these assessments based on the climate scenarios co-developed by the Network of Central Banks and Financial Supervisors for Greening the Financial System (NGFS) with an expert group of climate scientists and economists. These scenarios are generated using a class of models known as 'process-based Integrated Assessment Models' (Weyant, 2017), referred to here as 'IAMs' for brevity.[1] The NGFS scenarios have been used by public financial institutions and central banks (e.g. European Central Bank [ECB]; see Alogoskoufis et al., 2021) and also by private financial institutions (e.g. banks and insurance firms) in their internal climate stress-test exercises.

To explore the rationale for using climate stress-tests and their recent developments, we can begin from the following question: where does climate-related financial risk come from? On the one hand, unmitigated climate change is projected to lead to both acute and chronic impacts, which can trigger adverse socioeconomic consequences (IPCC, 2022). These in turn can threaten financial stability. On the other hand, the mitigation of climate change means that countries can only meet the Paris Agreement objectives of limiting global temperature increase to well below 2°C above pre-industrial levels if the structure of their economies is steered away from current fossil fuel-based production, investment and consumption patterns to low-carbon alternatives. Therefore, the economy of the future should look very different from the past century's, in terms of both risks and opportunities. Such a transformation would eventually be reflected in adjustments in financial valuation and risk. For this reason, central banks, financial supervisors and investors need to conduct financial risk assessments, conditional on climate scenarios.

Central banks and financial supervisors have only relatively recently started to recognise that climate change represents a new type of financial risk, thanks in part to research and development into climate stress-tests (Battiston et al., 2017; NGFS, 2019; Basel Committee on Banking Supervision [BSCB], 2021; Brunetti et al., 2021). Moreover, it is now acknowledged that climate risk is characterised by specific features, i.e. deep uncertainty (Weitzman, 2009), non-linearities (Steffen et al., 2018), tipping points (Lenton et al., 2019) and endogeneity (Battiston et al., 2021), which in turn affect its assessment. Because of these features, risk premia calculated on past market data may be insufficiently informative on the potential losses (or gains) that firms and investors could incur in the future (Monasterolo, 2020). In particular, relying on market data alone can lead to the underestimation of climate-related financial risks and opportunities for investors. In contrast, the analysis of climate-related risks has to be truly forward-looking (Battiston, 2019). To this end, the NGFS scenarios and the recommendation to use climate stress tests – as opposed to traditional stress-tests – represent a pivotal step to support institutions, central banks and financial supervisors to conduct their climate-related financial risk assessments.

"Central banks and financial supervisors have only relatively recently started to recognise that climate change represents a new type of financial risk."

Yet, a challenge remains: current climate scenarios are constructed without accounting for the role of the financial system and, in particular, the interplay between investors' expectations, policy credibility and risk materialisation (Battiston et al., 2021). This is an important limitation for assessing and managing climate-related financial risk. For instance, consider the NGFS scenario that assumes that the below 2°C temperature target is met in an orderly way (i.e. supported by a gradual and predictable introduction of a carbon tax). If investors do not expect the policy to be

[1] 'Process-based Integrated Assessment Models' should not be confused with 'aggregate Integrated Assessment Models', e.g. DICE (see Nordhaus, 2018). These two classes of model differ greatly in their assumptions, granularity and policy relevance. In particular, the process-based IAMs are used to generate the Intergovernmental Panel on Climate Change (IPCC) scenarios, using a carbon budget approach. Aggregate IAMs are used for cost-benefit analysis, which has been widely criticised in terms of policy implications because the optimal warming is too sensitive to discount rates and damage function calibration (Pindyke, 2013; Keen et al., 2022; Stern et al., 2022).

carried forward (i.e. they do not see the policy as credible), they would not adjust their risk assessment for high-carbon and low-carbon activities, by increasing and decreasing the risk profile, and thus the cost of capital, respectively. As a consequence, a gap can emerge between the level of climate finance investments actually carried out by investors and those assumed to be carried out in the scenario used in the climate stress test. In other words, if the scenario does not consider the role of finance and investors' expectations, it could lead to a reallocation of capital from high-carbon to low-carbon activities that is not sufficient to meet the investment needs assumed in that scenario. There is a resulting danger of illusion of control over the low-carbon transition, which could lead to missed opportunities for climate change mitigation and the potential underestimation of risks. Therefore, a more coherent use of climate scenarios for financial risk assessment is crucial to strengthening climate stress-tests.

Scope and structure of the paper

Section 2 discusses the characteristics and limitations of traditional balance sheet stress-tests used by investors, central banks and financial supervisors. Section 3 introduces climate stress-tests and explains how they differ from traditional stress-tests. Section 4 presents a new generation of climate scenarios that account for the endogeneity of climate financial risks and explains why these scenarios are relevant for financial risk assessment and management. Section 5 concludes with insights for central banks and financial supervisors, explaining how the results of these enhanced climate stress-tests can be used to inform the design of prudential measures.

2. Stress-testing individual institutions and the financial system

2.1. Types of stress-test and information required

The 2008 financial crisis highlighted the important role of stress-tests for central banks and financial supervisors (Borio et al., 2014), while stirring up a debate on the adequacy of the way in which stress-tests had been conducted before (Haldane, 2009), and on the need to account for the complexity of the financial system in contagion analyses (Battiston et al., 2016).

Since then, balance sheet stress-tests (i.e. those that assess losses for financial institutions based on their current or projected balance sheets) have been used by central banks and financial supervisors to ensure the proper functioning and stability of financial markets, and to identify any need for supervisory intervention. Note that the use of econometric models based on past market data to calibrate financial institutions' equity valuation response to climate-related shocks such as news (Jung et al., 2021) suffers from the limitations highlighted earlier of neglecting the forward-looking nature of climate risk and the limited internalisation of these risks by market players. Thus, unless specified otherwise, by climate stress-tests we mean here the balance-sheet climate stress-tests.

Stress-tests quantify the 'largest' losses – where usually the notion of 'largest' is captured by financial risk measures such as the Value-at-Risk (VaR)[2] or the Expected Shortfall (ES) (McNeil et al., 2015) – that an individual investor, or the financial system as a whole, could incur if a certain scenario materialised in the future. Stress-test exercises usually contrast several scenarios, at least one of them being adverse (e.g. an economic recession).

Stress-tests can be conducted either on the balance sheet of individual financial institutions (e.g. individual banks, insurance firms, pension funds) or on the balance sheets of all the financial institutions that compose the financial system. The former contributes to informing microprudential regulation, while the latter contributes to informing macroprudential regulation.

"If a climate scenario does not consider the role of finance and investors' expectations, it could lead to an insufficient reallocation of capital from high- to low-carbon activities."

[2]The quantile-based Value-at-Risk (VaR) is the main risk measure used in industry to quantify regulatory capital (McNeil et al., 2015).

Three types of stress-test can be identified:

1. *Top-down stress-tests* are usually run by supervisory authorities or central banks, which develop a methodology (e.g. the ECB's BEAST model: Budnik et al., 2020), collect data and perform the risk assessment. Thus, the regulated financial institutions are not directly involved in this assessment.
2. *Constrained bottom-up stress-tests* are developed by the targeted financial institution, but the supervisory authority or referent central bank provides some inputs (e.g. which scenarios to use) and parameters with which to calibrate the exercise. Each targeted institution assesses the impact on its own portfolios, while the supervisory authority or central bank challenges the estimates provided by the institutions with the results of their top-down models (an example is the biannual EU-wide stress-test).
3. Finally, *bottom-up stress-tests* are led by the targeted financial institutions. The relevant supervisory authority or central bank provides some inputs and parameters to calibrate the exercise, and each targeted institution assesses the impact on its own portfolios.

To run a stress-test, the following information is usually considered:

- **Information about the individual investor's balance sheets:** breakdown of assets and liabilities by type of instrument (stocks, bonds, loans, derivatives), maturity, and type or sector of counterparty (e.g. firm, sovereign).
- **A set of economic scenarios,** usually a mild and an adverse one (e.g. an economic recession or double-digit inflation).
- The translation of economic losses, conditioned to the occurrence of a scenario, into adjustments in counterparties' **probability of default and financial performance**, and thus into adjustments in the value of the securities and financial contracts through which the investor is exposed to such counterparties.
- The estimation of the **distribution of losses**, conditioned to the occurrence of each scenario, and the calculation of financial risk measures such as the VaR or ES, to capture the tails of the loss distribution.
- When stress-tests aim to take into account the effects of financial contagion, then data on the **network of pairwise financial exposures** among financial institutions is also needed. If this information is only partially available, the financial network can also be estimated using techniques of network reconstruction. Data on the financial network enables the calculation of the direct and indirect losses for financial institutions but also for creditors and depositors (Battiston et al., 2012; Barucca et al., 2020; Roncoroni et al., 2021b), and the identification of the drivers of systemic risk.

2.2. Limitations in using traditional stress-tests to assess climate risk

A question naturally arises here: how well suited are traditional stress-tests to investigating the resilience of the financial system with respect to climate risks? In addressing this question, the following considerations are relevant:

- Traditional stress-tests do not make any use of information specific to the low-carbon transition, and in particular to climate policies and regulations, nor to climate physical risk. Therefore, using traditional stress-tests to assess climate risk would be tantamount to assuming that climate change and its impacts are already internalised into market prices and economic variables. However, this assumption is not supported by evidence in the literature. Moreover, there is consensus among economists and practitioners that climate change is an externality that is currently not internalised by market players (Stiglitz, 2019). A similar argument would hold for environmental risk more generally.

"Traditional stress-tests do not make any use of information specific to the low-carbon transition."

- Traditional stress-tests use a time horizon of three to five years for the estimation of loss distribution. This time horizon is still relevant for climate risks. However, the valuation of assets in a three-to-five-year horizon depends on the present value of assets computed on a longer time horizon (5–20 years and beyond). Hence, even performing short-term climate stress-tests requires the use of medium- to long-term scenarios.
- In traditional stress-tests, a specific exercise can be applied to test the resilience of the financial system to losses in specific sectors (e.g. the shipping sector was examined in the European Central Bank Asset Quality Review in 2014). However, in general the scenarios are usually macroeconomic and do not distinguish between different economic sectors. In particular, they are not designed to consider the technological or long-term factors related to the difference between high-carbon and low-carbon activities.

The points above imply that using traditional stress-testing for dealing with climate risks can lead to an assessment of risk that is inadequate, and to investments and policy implications that are not able to address the problem at hand.

3. From stress-test to climate stress-test

3.1. Climate stress-tests

Climate stress-tests are a recent development of the traditional stress-tests. Moving from stress-tests to climate stress-tests requires the integration of climate financial risk which takes the form of both physical risks (e.g. via damages to physical assets that lead to adjustment in firms' production and economic performance) and transition risks (e.g. via adjustments in relative costs of energy inputs as a result of sudden and late climate policies and environmental regulations, which can lead to large valuation adjustments for fossil fuels and high-carbon firms). Such risks need then to be translated into risks on securities and financial contracts on the balance sheets of the financial institutions that invested in the firms exposed to climate risks.

Concretely, climate stress-tests aim to quantify the financial losses that a financial actor could face on their balance sheet as a result of either physical or transition risk, conditional on the realisation of scenarios. Note that in addition to the financial actor's direct exposure to climate risks, the losses also depend on three additional factors: first, the financial actor's leverage; second, the actor's indirect exposures through the financial network; and third, the level of potential mispricing of collateral associated with financial contracts (Battiston et al., 2016; Barucca et al., 2020). The climate stress-tests that have been implemented to date vary in the extent to which these three elements are considered.

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The purpose of climate stress-tests is to help financial institutions to assess and manage climate-related financial risks. On the one hand, banks and insurance firms can use climate stress-tests to adjust their lending and investment strategies, with the aim of minimising their potential climate financial risks. On the other, central banks and financial supervisors can use climate stress-tests to:

- *Quantify potential losses*, especially in the tail of the distribution, e.g. by calculating a climate VaR or ES, that can affect financial stability of the individual institution and the financial system as a whole, including by considering potential contagion effects (see e.g. Battiston et al., 2017; Roncoroni et al., 2021a).
- *Design early warning risk indicators*, based on revisions of risk weights to account for climate tail risks.

- *Inform potential adjustments in prudential regulation* (d'Orazio and Popoyan, 2019; Dikau and Volz, 2021) *and systemic risk buffers* (Monnin, 2021; Hiebert and Monnin, 2023), with the aim of strengthening the balance sheet of financial institutions against climate scenarios and to mitigate potential climate-related systemic risk.

The framework for climate stress-tests based on climate scenarios (for transition risk) was first developed in academia (Battiston et al., 2017) while more recently, central banks and financial supervisors have been developing their own climate stress-test based on NGFS guidelines (NGFS, 2019) and – more specific guidelines in some jurisdictions such as in the EU (ECB, 2020).[3] An empirical assessment by Battiston et al. (2017) found that EU and US investors' exposures to fossil fuels and high-carbon activities on the equity market can be as large as around 40% of equity holdings for pension funds and investment funds. Such exposures can lead to direct or 'first round' losses. These losses, in turn, can reverberate and be amplified in the financial network, with implications for financial contagion and systemic financial risk, depending on the characteristics of the financial system.

Implementing climate stress-testing differs depending on whether we analyse physical risk or transition risk, as described below.

Climate stress-tests for transition risk

The following elements are required to implement a climate stress-test for transition risk:

- **A set of climate scenarios**, e.g. those provided by the Intergovernmental Panel on Climate Change (IPCC). The scenarios in the IPCC's Sixth Assessment Report (AR6) (IPCC, 2022) consider combinations of:
  - Shared Socioeconomic Pathways (SSPs), i.e. narratives of how the world would evolve from a socioeconomic and geopolitical point of view (Riahi et al., 2017); and
  - Representative Concentration Pathways (RCPs) of greenhouse gas emissions, with their associated remaining carbon budget, i.e. the emissions (measured in kg equivalent of CO_2) that can be released into the atmosphere before reaching a level of warming (e.g. 2°C above pre-industrial levels).
- **Climate economic models** to translate climate mitigation scenarios into economic shocks. Climate mitigation scenarios provide trajectories of carbon prices and the corresponding production output of high- and low-carbon energy technology sectors, which are consistent with a given target in terms of the targeted maximum global warming (e.g. below 2°C, or net zero by 2050). The use of process-based IAMs in climate mitigation scenarios for financial risk assessment, initially proposed in the climate stress-test by Battiston et al. (2017), is now recommended by the NGFS to investors as the first building block of a climate risk assessment (NGFS, 2020). The NGFS provides a reference set of scenarios, generated by large-scale IAMs, adapted from the set of scenarios reviewed by the IPCC (NGFS, 2022). These scenarios, which model forward-looking shocks in sector output trajectories depending on energy technology, can inform firms' calculation of net present value (NPV) and thus their investment strategies.
- **Asset-level or firm-level, data**. We refer to 'asset-level data' as information on firms' production plants and facilities. Eventually, information has to be aggregated at firm level (i.e. the legal entity that is the counterparty to a financial contract). Data comprise: (i) revenue shares across technologies, e.g. extraction of fossil fuel (coal vs. gas), or electricity generation from renewables vs. fossil sources; (ii) greenhouse gas emissions, i.e. Scope 1, 2 and 3; and (iii) forward-looking investment data (e.g. Capex) across technologies (this is not indispensable

"Climate mitigation scenarios provide trajectories of carbon prices and the corresponding production output of high- and low-carbon energy technology sectors."

[3] See Baudino and Svoronos (2021) for a review of central banks and financial supervisors' climate financial risk assessments.

at a first stage). Note that for firms engaged in economic activities relevant for climate mitigation in the EU, data for (i) and (ii) are closely related to data about alignment to the EU Taxonomy of sustainable activities. Moreover, physical risk climate stress-testing additionally requires information about the geolocation of production plants and their exposure to hazards.

- **Mapping of firms' economic activities** into: (i) standard classifications of economic activities, e.g. NACE Rev2 (used in the EU) or the NAICS classification (used in the USA); (ii) the sectors of economic activities used by the IAMs; and (iii) classification of economic activities in terms of exposure to transition risk, e.g. 'Climate Policy Relevant Sectors' or CPRS.[4] While IAMs do not provide information about the transition risk of different economic activities *per se*, CPRS enable counterparties' activities to be mapped into the relevant IAM variables (Battiston et al., 2022).
- **Adjustment of firms' risk metrics**, e.g. the probability of default (PD) or Loss Given Default (LGD) conditioned to the forward-looking trajectories of the climate mitigation scenarios.
- **Adjustment of the valuation of the financial contract** of the firm (e.g. stocks, bonds) and owned by the investor, conditioned to the forward-looking trajectories of the climate scenarios.
- Translation of adjustments in financial valuation of contracts and securities into the **adjustment in financial risk metrics (e.g. climate VaR, climate ES) of the investor** who holds firms' contracts and securities, conditioned to climate scenarios.
- Analysis of the reverberation of losses within **the financial network**, considering second, third and fourth round losses (e.g. in networks of banks and investment funds – see Roncoroni et al., 2021b).

"Physical risk climate stress-testing requires information about the geolocation of production plants and their exposure to hazards."

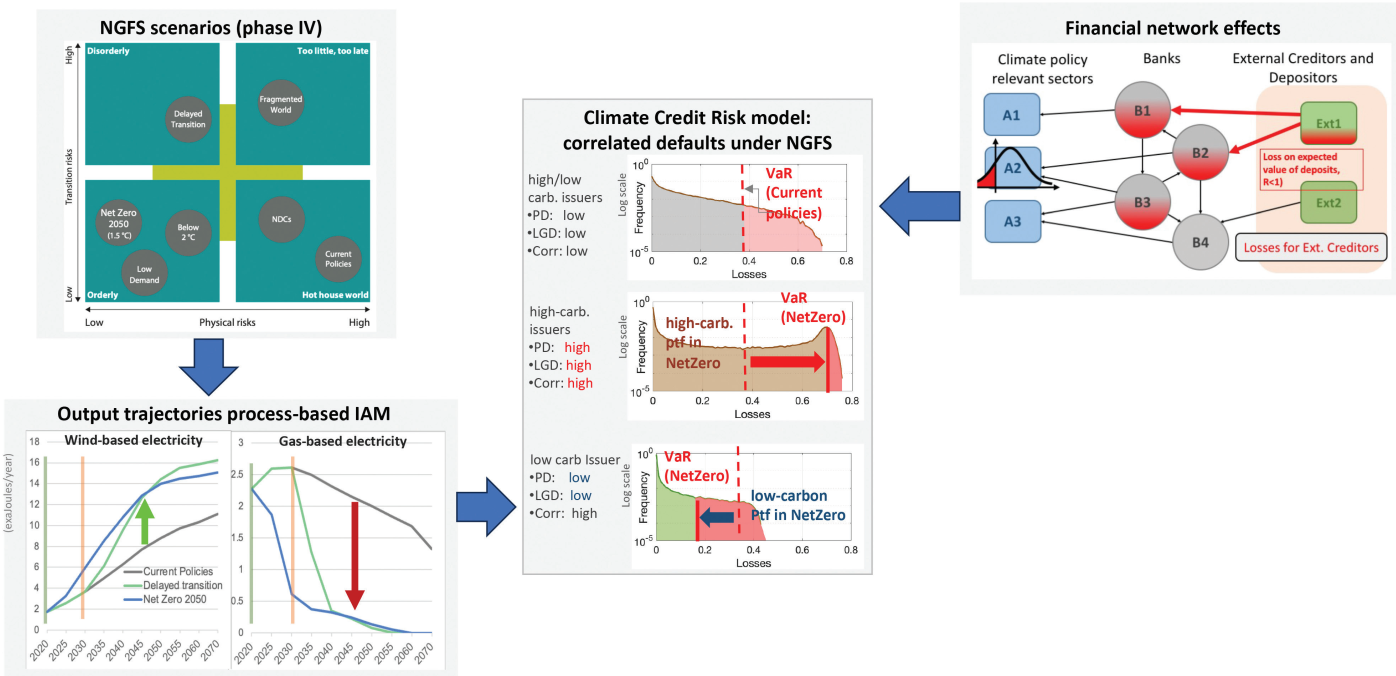
Figure 1 provides a visual illustration of the methodological framework of the science-based climate stress-test first developed by Battiston et al. (2017). This structure is currently being tailored by several central banks and financial supervisors in their jurisdictions, and by investors. The figure presents the main steps for conducting a climate stress-test for transition risk. It should be read moving in an anti-clockwise direction, from top left (climate scenarios) to the top mid-panel (climate financial network).

- **Step 1** (top left) includes a set of climate scenarios, displaying how the transition to a low-carbon economy, aimed at keeping global temperature rise to within 1.5 or 2°C, might be achieved (the figure shows the NGFS scenarios from 2021; CDR stands for Carbon Dioxide Removal).
- In **Step 2**, climate scenarios are translated into output trajectories of economic activities, by a process-based IAM reviewed by the IPCC.
- **Step 3** (centre) consists of calculating the scenario-contingent financial valuation of securities (e.g. equity or bond) and loans as from the CLIMACRED model (Battiston et al., 2023). The financial valuation is conditioned to the firm's revenue trajectory under each climate scenario. The calculation of the future production demand and revenue trajectories of the firms across scenarios is based on the individual technology profile of the firm. To this end, economic activities (at NACE 4-digit level) can be classified into CPRS[5] and into the variables of a process-based IAM. For bonds, an adjusted default probability (PD) and loss-given-default (LGD) is also computed. This typically leads to higher valuations of low-carbon firms under a transition scenario in comparison to their valuations under current policies scenarios. The relative difference in the value of a security going from a current policy to a transition scenario must be interpreted in terms of transition risk. It represents the adjustment

[4]Available at: https://www.finexus.uzh.ch/en/projects/CPRS.html.

[5]The mapping of economic activities from NACE 4-digit codes into CPRS Main (most aggregate) and CPRS-2 is available at: https://www.finexus.uzh.ch/en/projects/CPRS.html.

Figure 1. Methodological framework of a science-based climate stress-test for transition risk



Note: The figure illustrates the blocks of a framework for climate stress-testing. Step 1 (top left): select the relevant climate scenarios (e.g. NGFS 2023 phase IV). Step 2 (bottom left): extract output trajectories by type of energy technology from the NGFS scenarios. Step 3 (centre): adjust the financial valuation of securities and loans conditioned to the scenarios' trajectories (CLIMACRED [Battiston et al., 2023]) and compute the adjustments in financial risk measures (e.g. Value at Risk [VaR]) at portfolio level (Battiston and Monasterolo, 2020). Step 4 (top right): consider financial network effects (e.g. contagion and fire-sales [Roncoroni et al., 2021a]).
Source: Authors' own elaborations.

in the financial valuation following a change today in markets' expectations about the realisation of future mitigation scenarios. Finally, step 3 builds on the scenario-contingent financial valuation to calculate the adjustment in financial risk measures (e.g. the Climate VaR, or ES) at the level of the portfolio, in order to assess the potential losses in the tail (Battiston and Monasterolo, 2020).

- **Step 4** (top right) considers the financial network effects (e.g. contagion and fire-sales [Roncoroni et al., 2021a]), and feeds them back into the scenario-contingent financial valuation of step 3. It quantitatively assesses the direct losses for the portfolio of a leveraged investor who holds such financial contracts, accounting for the interconnectedness to other financial actors in the financial network in an interbank contagion model. This enables assessment of loss reverberation and thus the implications of climate scenarios on systemic financial risk.

"Multiple scenarios, especially the adverse ones, need to be included in the set of scenarios."

In the context of the ongoing policy discussions about climate scenarios, two questions arise:

1. Should climate-stress-tests include scenarios that seem unlikely?

The likelihood of the different scenarios remains intrinsically uncertain because of the endogeneity of risk, as pointed out in Battiston et al. (2021). This means that it is methodologically incorrect to exclude ex-ante from the climate stress-test scenarios that seem unlikely. Multiple scenarios, especially the adverse ones, need to be included in the set of scenarios. Ultimately, the purpose of a climate stress-test is to try to avoid the materialisation of the adverse scenarios. But this requires financial actors to be encouraged to assess the risks in such a scenario. To this end, scenarios such as those provided by the NGFS, which model forward-looking shocks in the trajectories of sectors' output depending on the energy technology at hand, can inform firms' calculation of net present value and thus their investment strategies. However, it should be noted that NGFS scenarios do not provide direct information on financial risk *per se*. Risk can be derived from the scenarios using, for instance, the six steps of the methodology described above.

2. Can climate stress tests include alternative scenarios, such as those developed by the International Energy Agency?
NGFS scenarios and IEA scenarios are obtained from models that differ in terms of their aim, characteristics and assumptions. However, both the NGFS and IEA scenarios are characterised in terms of warming levels reached in the year 2100 (e.g. 1.5°C, 2°C) and can thus be usefully compared. The framework presented here can be applied to conduct climate stress-tests also on IEA scenarios.

"There are examples of both voluntary and mandatory central bank and financial supervisor initiatives that invite financial institutions to assess climate-related financial risk."

Climate stress-tests for physical risk

To implement a climate stress-test for physical risk, the first steps of the climate stress-test described above for transition risk need to be adjusted as follows, to include:

- **A set of climate impact scenarios**, such as those provided by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), which can be used to derive future trajectories of climate impacts including both acute impacts (such as floods and hurricanes) or chronic impacts (such as sea-level rise). These scenarios are reviewed by the IPCC (e.g. see Working Group I of the *Sixth Assessment Report* [AR6]).
- **Probabilistic disaster risk assessment.** Climate related hazards are characterised in terms of their 'Return Period': for instance, a 100-year event identifies the magnitude of a hazard that is expected to occur at most every 100 years on average in a given location.[6] Damage functions (Emanuel, 2011) enable to translate the Return Period for variables such as wind speed or precipitation intensities into direct damages to capital stock of geolocalised assets, tailored by the type of hazard, intensity and frequency. Eventually these estimates of impacts can be used to compute estimates of VaR for losses on the valuation of firms that own physical assets exposed to the hazards considered (Bressan et al., 2022).
- **Geolocalised information about assets**, their climate, business and financial information, including on their capacity, residual life, sector, technology, prices, revenues and the current level of adaptation to climate change.
- **Reconstruction of the ownership chain** of the firm and contribution of the asset to the revenues of the firm, in order to assess the impact of climate physical risks at the asset level on a firm's performance and default probability.
- **The adjustment of firms' risk metrics**, e.g. the probability of default (PD) or Loss Given Default (LGD) conditioned to the forward-looking trajectories of the climate mitigation scenarios.
- **The adjustment of the valuation of the financial contract** of the firm (e.g. stocks, bonds) and that owned by the investor, conditioned to the forward-looking trajectories of the climate mitigation scenarios.
- The translation of adjustments in financial valuation of contracts and securities into the **adjustment in financial risk metrics (e.g. climate VaR, climate ES) of the investor** who holds firms' contracts and securities, conditioned to climate scenarios.

3.2. Climate stress-testing by central banks and financial supervisors

There are examples of both voluntary and mandatory central bank and financial supervisor initiatives around the world that invite financial institutions, starting with banks and insurance firms, to assess climate-related financial risk. For instance, the European Central Bank published guidelines in 2020 for banks to conduct a climate

[6] https://www.nhc.noaa.gov/climo

stress-test by 2022 (ECB, 2020). The European Insurance and Occupational Pension Authority (EIOPA) requires insurance companies to integrate climate change risk scenarios into their own risk and solvency assessments (EIOPA, 2021), while the Swiss financial authority, FINMA, now requires a quantitative climate risk assessment for large banks and insurance companies. Similar developments are ongoing in the United States after the current administration signed an Executive Order on climate-related financial risk in May 2021.

Several central banks and financial supervisors have already internally developed their climate stress-tests:

- **The first central bank to develop its climate stress-test was the Dutch National Bank (DNB)**, which aimed to quantify financial stability risks related to the energy transition for more than 80 Dutch financial institutions for €2.3 trillion-worth of assets (Vermeulen et al., 2021). This exercise did not rely on NGFS scenarios. It constructed tail-event scenarios that incorporate shocks into climate policies and energy technologies. It then derived the macroeconomic and industry-specific implications of these shocks. The study found portfolio losses of up to 11%, due to credit and market risk.
- **The French Prudential Control and Resolution Authority (ACPR) has identified climate change as an emerging risk for the financial system** and has developed the first pilot exercise with banking and insurance groups to assess the risks associated with climate change (Clerc et al., 2021). Results revealed a moderate exposure of French banks and insurers to climate risks, conditioned to the assumptions and the scenarios used (including two scenarios developed by the NGFS [2020]). Note that the scenarios did not include an adverse scenario in economic terms (e.g. an economic recession) in combination with the climate scenarios.
- **In 2020, Banque de France analysed the macroeconomic and financial impacts of a disorderly (delayed or sudden) transition**, building on the NGFS scenarios. The study found that shocks would be limited, but the impacts on the sectors exposed to transition risk could be large and heterogeneous (Allen et al., 2020). The authors acknowledge that the translation of climate scenarios into adjustments in financial variables is sensitive to some of the modelling assumptions.
- **The Austrian National Bank (OeNB) developed a transition risk stress-test focused on carbon pricing scenarios** (Guth et al., 2021). The climate stress-test builds on the OeNB's top-down stress-testing framework 'ARNIE' and enriches it with a multiregional input–output model for economic sectors and an expanded corporate insolvency model. Results show that a disorderly transition scenario would negatively affect agriculture and transport in particular, where default rates would rise sharply, affecting banks exposed to these sectors, leading to a 2.7 percentage point decrease in the aggregate CET1 (common equity tier one, widely used for capital requirements) ratio for the Austrian banking system.
- **The ECB published its economy-wide climate stress-test in 2021** (Alogoskoufis et al., 2021), finding that the short-term costs of the transition would be dwarfed by the costs of unmitigated climate change in the medium to long term. Moreover, while until 2050 climate impacts would increase moderately on average, they would also be concentrated in geographical areas and sectors where impacts can be much higher. The ECB also warned that the impact would potentially be very significant for companies and banks that are most exposed to climate risks.

"The first central bank to develop its climate stress-test was the Dutch National Bank (DNB)."

In emerging economies, climate stress-tests have been carried out for Colombia, Mexico and the Philippines:

- **For Colombia,** the analysis of the World Bank and International Monetary Fund (IMF) (Sever and Perez-Archila, 2021) focused on country-based transition risk scenarios and the impact of severe fluvial flooding, considering the effects of flood-related economic damages on the vulnerability of banks, in terms of their profitability and solvency. The analysis found that loan losses for individual banks ranged between 0.2% of total assets for the least vulnerable bank and 2.2% for the most vulnerable bank in the most severe flood scenario, while in a scenario in which there are high greenhouse gas reduction targets and delayed implementation of policies, aggregated loan losses for Colombian banks could range between 0.2% of total assets for the least vulnerable banks and 2.7% for the most vulnerable.
- Roncoroni et al. (2021a) developed a climate stress-test for **Mexico**, in collaboration with Banco de Mexico, using a unique supervisory dataset in a range of climate policy scenarios and market conditions. This climate stress-test considers ex-ante network valuation of assets and the dynamics of indirect contagion of banks and investment funds to analyse the effects on financial stability of the interplay between climate transition risk and market conditions (recovery rate and asset price volatility). The authors found that stronger market conditions enable the policymaker to reach more ambitious climate policies at the same level of financial risk.
- The IMF and World Bank-assessed climate stress-test for **the Philippines** (Hallegatte et al., 2022) considered the impact of severe typhoons on financial sector exposures, estimating the macrofinancial impacts of a one-in-25-year and one-in-500-year typhoon, using the high-end Representative Concentration Pathway (RCP) 8.5 (IMF-WB, 2022). The exercise found that annual losses from typhoons represent a loss to GDP ratio of 20%. In a follow-up climate stress-test, the World Bank showed that climate change may significantly worsen the impact of a severe typhoon on bank capital as well, especially in tail events.

The NGFS scenarios, which are used in many of the aforementioned climate stress-test exercises, are all generated by climate economic models, sometimes coupled with macroeconomic models (e.g. see the IAM-NIGEM coupling in NGFS, 2021; 2022). It is very important to note that these models do not contain a description of the financial system, nor include money, or financial institutions (e.g. a bank) that decide whether to finance firms' investments in, for example, high- or low-carbon technologies, based on their financial risk assessment (Battiston et al., 2021). This means that the models describe a world where a representative firm can make investments without being credit-constrained. In reality, credit constraints represent an important barrier to firms' investments, in particular for small- and medium-sized enterprises. Thus, current climate economic models do not enable the consideration of features that are key to the problem under examination, namely climate investments in the low-carbon transition. This is an important limitation to the policy relevance of the current climate stress-test exercises. For instance, currently, the NGFS scenarios include trajectories of sectors' output generated by three process-based IAMs (REMIND, developed by the Potsdam Institute for Climate Change; MESSAGE by the International Institute for Applied Systems Analysis; and the Global Change Assessment Model [GCAM] by the Pacific Northwest National Laboratory) and by the macro-econometric model NIGEM (Hantzsche et al., 2018).

"The NGFS scenarios, which are used in many climate stress-test exercises, are all generated by climate economic models."

As described in Section 3.1, these output trajectories of specific sectors can then be used to carry out a financial valuation, conditional to scenarios, of assets held by financial institutions. A change today in markets' expectations about the realisation of future mitigation scenarios implies an adjustment in the financial valuations across assets. As a result, gains and losses can be computed for a portfolio. In turn, the computation can inform investment decisions about possible adjustments in the portfolio. In this regard, it is worth mentioning the ongoing debate over whether policymakers should encourage divestment from high-carbon firms or rather engage more with shareholders in those firms to encourage their capital reallocation. On the one hand, a potential problem with the fact that regulated domestic financial actors divest from high-carbon firms is that their shares could be acquired by foreign, unregulated and more opaque financial actors (Alessi et al., 2023), de facto making the transition risk more difficult to assess and manage for authorities. On the other hand, a necessary condition for the low-carbon transition to occur is the reallocation by the investee non-financial firm of its capital expenditure from high-carbon activities to low-carbon activities. It remains unclear to what extent shareholder engagement alone, without any divestment, can elicit such reallocation of capital expenditure by the investee.

One challenge that remains outstanding is the fact that the scenarios used in the above analyses do not account for markets' expectations. As explained in Battiston et al. (2021), using scenarios as they are now can lead to substantial investment gaps compared with what is needed to achieve decarbonisation targets (Kreibiehl et al., 2022). These are gaps both in capital expenditure by non-financial firms and in financial investments by financial investors. A proposal to address this issue is described in Section 4.

4. The way forward: introducing the endogeneity of risk in climate stress-tests

How financial investors perceive the risk of high-carbon and low-carbon assets has an impact on the materialisation of transition risk itself, as their perception determines their investment decisions, which in turn impact on non-financial firms' decisions to expand low-carbon activities or not (by means of capital expenditure reallocation). This can make the difference between cases in which the low-carbon transition takes place in an orderly or disorderly fashion, or even the transition being missed entirely. However, investors' expectations are not accounted for in the current stage of development of climate mitigation scenarios and models.

To overcome this limitation, the NGFS climate mitigation scenarios used by central banks and financial supervisors can be enhanced to take into account the endogeneity of risk in the scenarios, following the framework recently developed in Battiston et al. (2021). This framework pairs a large-scale, process-based IAM (such as MESSAGE, REMINS or GCAM) with a Climate Financial Risk (CFR) model that captures financial investors' expectations based on the scenarios and feeds them back into the IAM. The CFR based on the CLIMAFIN tool for climate stress-tests has been used to date, but other CFRs could be used in its place. Figure 2 provides a visual illustration of the general framework of the IAM-CFR model.

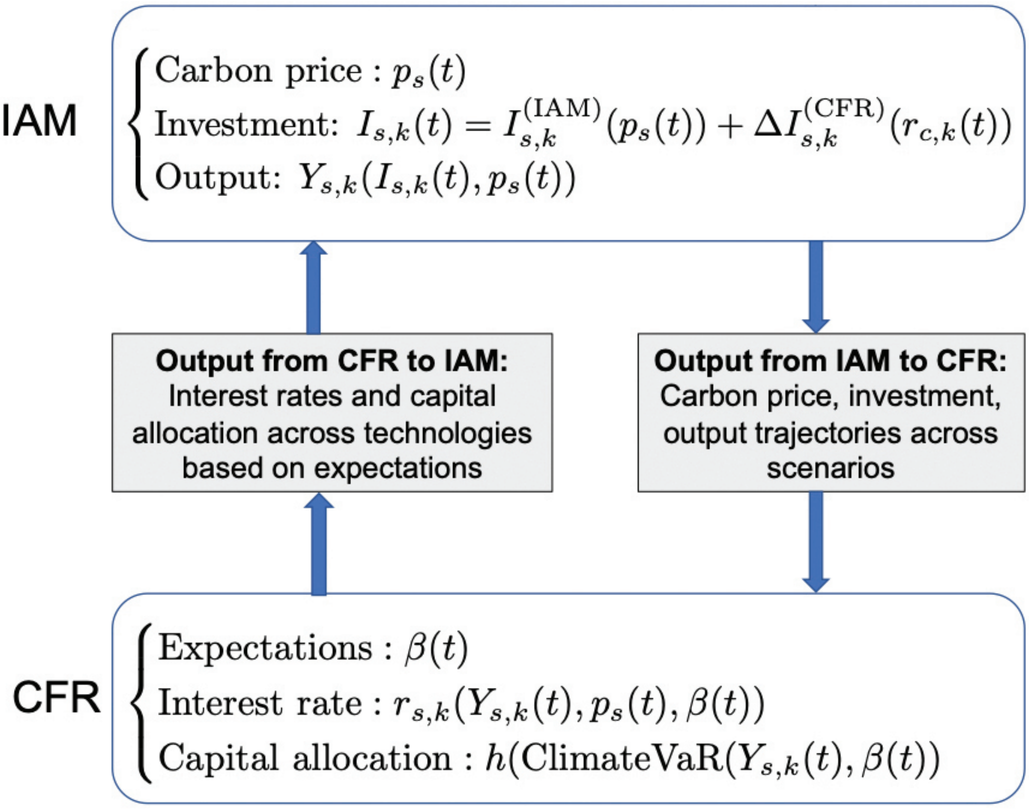
> "The NGFS climate mitigation scenarios used by central banks and financial supervisors can be enhanced to take into account the endogeneity of risk."

As explained in Section 3.1, translating scenarios into financial shocks involves several steps. In the CFR model (Figure 2), transition risk results from a change in markets' expectations β: for example, switching from the expectation that the structure of the economy continues on a carbon-intensive path (baseline) to the expectation that full-scale decarbonisation of the economy (i.e. a low-carbon transition) takes place. The interplay between the *time of the introduction* of the climate policy (e.g. carbon price *p*) and *the credibility of the policy* in investors' minds makes the transition orderly (e.g. if introduced early and credibly) or disorderly (e.g. if introduced late and not credibly enough and eventually takes place in a sudden way). This in turn results in different trajectories of output *Y*, by sector *s*, country *c*, and time *t*, as elaborated by a specific IAM (see the left-hand box in Figure 2). In the NGFS scenario database published in May 2021, the Current Policy could be taken as a baseline: this is characterised by a continued reliance on fossil fuel, although with a decline in coal use. The Net Zero 2050 scenario (1.5°C), or the Below 2°C scenario, could be taken as transition scenarios.

"Using the proposed approach the orderly or disorderly character of the transition can be obtained in the model."

In the CFR model (lower box in Figure 2), in both the baseline and transition scenarios, the financial valuation of equity can be estimated as the net present value of future cash flows under the future trajectories of production output. For debt, the valuation is made in terms of adjusted probability of default and adjusted loss given default (LGD). The change in expectations induces, potentially in a very short time span, a substantial re-valuation of financial securities, because for many sectors output trajectories differ starkly between the two scenarios. The adjustment in financial valuation by investors leads to an adjustment in the calculation of climate financial risk metrics (e.g. the *Climate VaR*), which leads, in turn, to adjusting the cost of capital *r* for the firm. This adjustment is related to the performance of the firm and sector within the climate mitigation scenarios, calculated by the IAM. The climate-adjusted cost of capital r calculated by the CFR feeds back into the investment decisions of the sector in the IAM, leading to an adjustment in the trajectory of the sector.

Figure 2. The process-based IAM–Climate Financial Risk (CFR) model framework



Note: The figure illustrates the feedback between the process-based IAM and the Climate Financial Risk (CFR) model. First, in the CFR, investors assess climate financial risk based on climate scenarios. The credibility of climate policies affects investors' expectations (denoted by β), which in turn concur to determine the adjustment of the cost of capital (denoted by r). The adjusted r is then fed back to the IAM, resulting in new investment decisions (denoted by I) of the firms and thus in new output scenarios.
Source: Battiston et al. (2021)

This framework enables users to take a climate-adjusted financial risk assessment that considers investors' expectations and to feed it back within the IAM into the investment decisions, according to sector and technology. The outcome is the production of a new generation of climate mitigation scenarios that can complement the current NGFS scenarios by capturing the key role of investors' expectations, which drive the endogeneity of risk. This makes the scenarios more relevant for climate stress-testing, by yielding more robust risk analysis.

The proposed approach can be implemented by using the adjusted NGFS scenarios, as well as different internal credit and financial risk models. For those central banks and financial supervisors that use scenarios obtained from internally developed macroeconomic models, this approach can be implemented by setting up a modelling framework to interface those macroeconomic models with the CFR model. This effort could contribute to strengthening the policy relevance of scenarios and address some of the challenges identified by central banks and financial supervisors, some of which have pointed out limitations of the currently used scenarios. For instance, trajectories of production output in the Net Zero 2050 and Divergent Net Zero 2050 scenarios appear very similar, even though the first is considered an orderly transition and the latter a disorderly one. In contrast, using the proposed approach the orderly or disorderly character of the transition can be obtained endogenously in the model, as a function of investors' expectations of the credibility of the policy.

5. Conclusions and policy recommendations

In this paper, we have discussed the role of climate stress-tests in climate-related financial risk assessment and management. We have presented some reasons why traditional stress-tests should be tailored to assess climate-related risks in the economy, the building blocks of climate stress-tests, and how they differ from traditional stress-tests.

Balance-sheet climate stress-tests can be a powerful tool for quantifying the qualitative notion of 'how bad it could get' for a financial actor in a given climate scenario. In this context, the result depends on the interplay between the climate scenario and the financial system's characteristics, i.e. its leverage, interconnectedness and potential mispricing of collateral. Accordingly, the design of scenarios plays a crucial role in the assessment of potential losses. We have highlighted the limitation that supervisory climate scenarios neglect the role of finance and investors' expectations. This aspect is very important for financial stability because whether the framework used by policymakers appropriately captures the feedback from investors' expectations to investment decisions can, in principle, make the difference between the economy achieving or failing on the low-carbon transition, with very different financial risks and opportunities associated with the two cases. Thus, we have described a recent approach to address this limitation and to generate climate scenarios that accounts for such expectations, and how this approach can contribute to strengthen central banks and financial supervisors' climate stress-tests.

"Balance-sheet climate stress-tests can be a powerful tool for quantifying the notion of 'how bad it could get' for a financial actor in a given climate scenario."

In a nutshell, the idea is that if investors find a climate policy such as the introduction of a carbon tax credible, they will more likely reallocate capital into low-carbon investments early and gradually. In contrast, if they do not find the policy credible, they could have a delayed or sudden reaction that would lead to large asset price adjustment, leading to financial instability. For instance, if the implementation of the EU Taxonomy of sustainable investments is not perceived as credible by investors, an insufficient reallocation of capital to low-carbon investments, compared to that which the decarbonisation scenarios assume, will occur.

Eventually, changes in investors' expectations can lead to sudden adjustments in values of high- and low-carbon assets and to market instability. Note that a sudden collective change in expectation regarding the value of an entire asset class is precisely what happened in the 2008 financial crisis. Importantly, this dynamic could result in reallocation of capital into low-carbon investments that would be insufficient to meet the Paris Agreement targets.

In conclusion, climate stress-tests can support a robust assessment of climate financial risks. This, in turn, is fundamental to informing financial supervisors about incorporating climate risks considerations into macroprudential regulations, including (but not limited to):

- *Changes in the weighting factors* used for the computation of risk-weighted assets, as a function of the technological and sectoral characteristics of the issuers of those assets (e.g. based on the Climate Policy Relevant Sector [CPRS] classification), to reflect financial actors' exposures that are associated with *particularly high risks*.[7]
- The introduction of concentration limits on banks and insurance firms to high-risk assets (Miller and Dikau, 2022).
- The introduction of lending limits to *high-risk* activities, e.g. via the introduction of upper/lower ceiling floors and large exposure limits (FSB, 2022), i.e. a maximum level of exposure to those activities that would suffer *particularly high risks* because their profitability would be negatively affected by the realisation of climate scenarios. In this regard, exposures to CPRS should be considered, rather than only activities directly involved in the extraction of fossil fuels.
- Revision of *minimum capital requirements*,[8] to enable financial institutions to withstand losses related to different climate scenarios.
- The introduction of *policies that increase the cost of capital* for firms at high climate risk (e.g. a dirty penalising factor) (Dafermos and Nikolaidi, 2021; Dunz et al., 2021; Dikau et al., 2020).
- The use of *systemic risk buffers* to address climate systemic risks: i.e. supervisors could apply a buffer on assets from sectors most exposed to climate risks and/or on financial institutions particularly exposed to them (Monnin, 2021). Sectoral exposure can be defined in terms of economic activity and geographical areas (EBA, 2020).

Whatever revision of prudential regulations is introduced, three points should be considered:

- First, the analysis of financial institutions' exposures to climate risk should extend well beyond the firms directly involved in fossil fuel extraction. Indeed, in a transition scenario, losses of profitability could occur for firms that use fossil fuels as an energy input (e.g. energy-intensive), or that contribute to the trading and commercialisation of fossil fuels (transport), as well as along the whole value chain of fossil fuels.
- Second, there are issues with coverage and comparability of disclosures of carbon emissions (Scopes 1, 2 and 3) that limit the ability to assess exposures to transition risk solely based on carbon emissions. Firm-level information on carbon emissions can be complemented with data on the firm's technology profile in terms of production plants, business model, input substitutability, and sensitivity of production costs to changes in climate and energy policies, in line with the CPRS framework.[9]
- Third, climate risk metrics and measures should be transparent and peer-reviewed (Bingler et al., 2020), to rule out the possibility that important sources of risk are neglected.

"A robust assessment of climate financial risks is fundamental to incorporating climate risk considerations into macroprudential regulations."

[7]See Art. 128 of the Capital Requirements Regulation. 4 Regulation (EU) no 575/2013 of the European Parliament and of the Council of 26 June 2013 on prudential requirements for credit institutions and investment firms and amending regulation (EU) no 648/2012.

[8]The minimum capital adequacy requirement (CAR) is the ratio required by the regulator of a bank or insurance capital over its risk-weighted assets. Basel III regulatory capital and liquidity regulations do not explicitly account for the risks stemming from climate change. An update of the principles for the effective management and supervision of climate-related financial risks by the Basel Committee on Banking Supervision is currently under consultation (BCBS, 2021).

[9]These additional characteristics are captured by the CPRS.

References

Allen T, Dees S, Boissinot J, Caicedo Graciano C M, Chouard V, Clerc L et al. (2020) *Climate-related scenarios for financial stability assessment: An application to France*. Working Paper Series no. 774. Paris: Banque de France.

Alessi L, Battiston S and Kvedaras V (2023) *Over with carbon? Investors' reaction to the Paris Agreement and the US withdrawal* (No. 2021/12). Forthcoming on Journal of Financial Stability. Earlier version at JRC Working Papers in Economics and Finance.

Alogoskoufis S, Dunz N, Emambakhsh T, Hennig T, Kaijser M et al. (2021) *ECB economy-wide climate stress-test Methodology and result*s. Occasional Paper Series 281. Frankfurt: European Central Bank.

Basel Committee on Banking Supervision [BCBS] (2021) *Climate-related financial risks – measurement methodologies*. Working paper. Bank for International Settlements.

Barucca P, Bardoscia M, Caccioli F, D'Errico M, Visentin G, Caldarelli G, Battiston S (2020). Network valuation in financial systems. *Mathematical Finance* 30(4): 1181–1204.

Battiston S, Puliga M, Kaushik R, Tasca P, Caldarelli G (2012) DebtRank: Too Central to Fail? Financial Networks, the FED and Systemic Risk. *Scientific Reports* (2): 1–6.

Battiston S, Caldarelli G, May R, Roukny T, Stiglitz J (2016). The price of complexity in financial networks. *Proceedings of the National Academy of Sciences* 113(36): 10031–10036.

Battiston S, Mandel A, Monasterolo I, Schütze F, Visentin G (2017) A climate stress-test of the financial system. *Nature Climate Change* 7(4): 283–288.

Battiston S (2019) The importance of being forward-looking: managing financial stability in the face of climate risk. *Financial Stability Review* (23) 39–48.

Battiston S and Monasterolo I (2020) *On the dependence of investor's probability of default on climate transition scenarios*. https://ssrn.com/abstract=3743647.

Battiston S, Monasterolo I, Riahi K, van Ruijven B (2021) Accounting for finance is key for climate mitigation. *Science* 372(6545): 918–920.

Battiston S, Monasterolo I, van Ruijven B, Krey V (2022) The NACE–CPRS–IAM mapping: A tool to support climate risk analysis of financial portfolio using NGFS scenarios. https://ssrn.com/abstract=4223606.

Battiston S, Mandel A, Monasterolo I, Roncoroni A (2023) Climate credit risk and corporate valuation. Working paper. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4124002.

Baudino P, Svoronos J (2021) *Stress-testing Banks for Climate Change – A Comparison of Practices*. FSI Insights on Policy Implementation No. 34. Basel: Financial Stability Institute, Bank for International Settlements.

Bingler J, Colesanti Senni C, Monnin P (2020) *Climate financial risks: Assessing convergence, exploring diversity*. CEP Discussion Note No. 6.

Borio C, Drehmann M, Tsatsaronis K (2014) Stress-testing macro stress testing: does it live up to expectations? *Journal of Financial Stability* 12: 3–15.

Bressan G, Duranovic A, Monasterolo I, Battiston S (2022) *Asset-level climate physical risk assessment and cascading financial losses*. Working paper. https://ssrn.com/abstract=4062275.

Brunetti C, Dennis B, Gates D, Hancock D, Ignell D et al. (2021) *Climate Change and Financial Stability*, FEDS Notes. Washington: Board of Governors of the Federal Reserve System.

Budnik K, Balatti M, Dimitrov I, Groß J, Kleemann M et al. (2020) *Banking euro area stress test model*. Working Paper Series 2469. Frankfurt: European Central Bank.

Chen Y, Ens E, Gervais O, Hosseini H, Johnston C et al. (2022) *Transition Scenarios for Analyzing Climate-Related Financial Risk*. Bank of Canada Working paper No. 2022-1.

Clerc L, Bontemps-Chanel A, Diot S, Overton G, Soares de Albergaria S et al. (2021) *A First assessment of financial risks stemming from climate change*: *The main results of the 2020 climate pilot exercise*. ACPR-Banque de France Analyses et synthèses No. 122–2021.

D'Orazio P, Popoyan L (2019) Fostering green investments and tackling climate-related financial risks: Which role for macroprudential policies? *Ecological Economics* 160: 25–37.

Dafermos Y, Nikolaidi (2021) How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis. *Journal of Financial Stability* 54: 100871.

Dikau S, Robins N, Volz U (2020) *A toolbox for sustainable crisis response measures for central banks and supervisors*. London: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science and SOAS Centre for Sustainable Finance.

Dikau S, Volz U (2021) Central bank mandates, sustainability objectives and the promotion of green finance. *Ecological Economics* 184: 107022.

Dunz N, Naqvi A, Monasterolo I (2021) Climate sentiments, transition risk, and financial stability in a stock-flow consistent model. *Journal of Financial Stability* 54: 100872.

Emanuel K (2011) Global warming effects on U.S. hurricane damage. *Weather, Climate, and Society* 3(4): 261–268.

European Banking Authority [EBA] (2020) *Risk Assessment of the European Banking System*. Luxembourg: Publications Office of the European Union.

European Central Bank [ECB] (2020) *Guide on climate-related and environmental risks. Supervisory expectations relating to risk management and disclosure*. Frankfurt: ECB.

European Insurance and Occupational Pension Authority [EIOPA] (2021) *Opinion on the supervision of the use of climate change risk scenarios in ORSA*. Frankfurt: EIOPA.

Financial Stability Board [FSB] (2022) *Supervisory and Regulatory Approaches to Climate-related Risk: Final report*.

Guth M, Hesse J, Königswieser C, Krenn G, Lipp C et al. (2021) *OeNB climate risk stress test – modeling a carbon price shock for the Austrian banking Sector*. Vienna: Oesterreichische Nationalbank [Austrian National Bank].

Haldane A (2009) Why banks failed the stress test. *BIS Review* 18.

Hallegatte S, Lipinsky M, Morales P, Oura M, Ranger N, Regelink M, Reinders H (2022) *Bank Stress Testing of Physical Risks under Climate Change Macro Scenarios: Typhoon Risks to the Philippines*. Washington D.C.: International Monetary Fund.

Hantzsche A, Lopresto M, Young G (2018) Using NiGEM in uncertain times: Introduction and overview of NiGEM. *National Institute Economic Review* 244: R1–R14.

Hiebert P, Monnin P (2023) *Climate-related systemic risks and macroprudential policy*. INSPIRE Sustainable Central Banking Toolbox – Policy Briefing No.14. Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.

Intergovernmental Panel on Climate Change [IPCC] (2021) Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

International Monetary Fund [IMF] and World Bank (2022) P*hilippines financial sector assessment program. Technical note on bank stress test for climate change risks*. IMF Country Report No. 22/154.

Jung H, Engle R, Berner R (2021) CRISK: Measuring the Climate Risk Exposure of the Financial System. Federal Reserve Bank of New York Staff Reports No. 977.

Keen S, Lenton T, Garrett T, Rae J, Hanley B, Grasselli M (2022) Estimates of economic and environmental damages from tipping points cannot be reconciled with the scientific literature. *Proceedings of the National Academy of Sciences* 119(21): 2117308119.

Kreibiehl S, Yong Jung T, Battiston S, Carvajal P, Clapp C et al. (2022) Investment and finance. In: Shukla P et al. (Eds.), *Climate change 2022: Mitigation of climate change. Contribution of Working Group iii to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.

Lenton T, Rockström J, Gaffney O, Rahmstorf S, Richardson K et al. (2019) Climate tipping points – too risky to bet against. *Nature* 575: 592–595.

McNeil A, Frey R, Embrechts P (2015) *Quantitative risk management: concepts, techniques and tools* – revised edition. Princeton University Press.

Miller H, Dikau S (2022) *Preventing a 'climate Minsky moment': environmental financial risks and prudential exposure limits.* Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.

Monasterolo I (2020) Embedding finance in the macroeconomics of climate change: research challenges and opportunities ahead. *CESifo Forum* 21(4): 25–32. Munich: ifo Institut-Leibniz-Institut für Wirtschaftsforschung an der Universität München [Ifo Institute for Economic Research].

Monnin P (2021) S*ystemic risk buffers – the missing piece in the prudential response to climate risks.* CEP Policy Brief. Zurich: Council on Economic Policies.

Network for Greening the Financial System [NGFS] (2022) *NGFS Climate Scenarios for central banks and supervisors. Technical report.* Paris: NGFS.

Network for Greening the Financial System [NGFS] (2021) *NGFS Climate Scenarios for central banks and supervisors. Technical report.* Paris: NGFS.

Network for Greening the Financial System [NGFS] (2019; 2020) *NGFS Climate Scenarios for central banks and supervisors. Technical report.* Paris: NGFS.

Network for Greening the Financial System [NGFS] (2019) *First Comprehensive Report: A Call for Action. Climate Change as a Source of Financial Risk.* Paris: NGFS.

Nordhaus W (2018) Evolution of modeling of the economics of global warming: changes in the DICE model, 1992–2017. *Climatic Change* 148(4): 623–640.

Pindyck R (2013) Climate change policy: what do the models tell us? *Journal of Economic Literature* 51(3): 860–872.

Riahi K, Van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC et al. (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change* 42: 153–168.

Roncoroni A, Battiston S, Escobar-Farfán L, Martinez-Jaramillo S (2021a) Climate risk and financial stability in the network of banks and investment funds. *Journal of Financial Stability* 54: 100870.

Roncoroni A, Battiston S, D'Errico M, Hałaj G and Kok C (2021b) Interconnected banks and systemically important exposures. *Journal of Economic Dynamics and Control* 133: 104266.

Sever C, Perez-Archila M (2021) *Climate-Related Stress Testing: Transition Risk in Colombia*. Washington D.C.: International Monetary Fund.

Steffen W, Rockström J, Richardson K, Lenton T et al. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences* 115(33): 8252–8259.

Stiglitz JE (2019) Addressing climate change through price and non-price interventions. *European Economic Review* 119: 594–612.

Stern N, Stiglitz J and Taylor C (2022) The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change. *Journal of Economic Methodology* 29(3): 181–216.

Vermeulen R, Schets E, Lohuis M, Kölbl B, Jansen D J, Heeringa W (2021) The heat is on: A framework for measuring financial stress under disruptive energy transition scenarios. *Ecological Economics* 190: 107205.

Weitzman M (2009) On modeling and interpreting the economics of catastrophic climate change. *The review of Economics and Statistics* 91(1): 1–19.

Weyant J (2017) Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy* 11(1): 115–137.

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