NGFS Occasional Paper

Case Studies of Environmental Risk Analysis Methodologies

SEPTEMBER 2020

NGFS
Central Banks and Supervisors
Network for Greening the Financial System

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With the exception of chapter 1, the views and opinions expressed in this volume are those of the authors alone and do not reflect those of the Central Banks and Supervisors Network for Greening the Financial System (NGFS) or the editors.

Glossary[1]

Business-as-usual (BAU)	Also referred as Baseline or Reference, describing scenarios based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force or legislated or will be adopted.[2]
Collateral	An asset or third-party commitment used by a collateral provider to secure an obligation vis-à-vis a collateral taker.[3]
Credit risk	The potential that a bank borrower or counterparty will fail to meet its obligations in accordance with agreed terms.[4]
Environmentally unsustainable asset	Polluting or high carbon asset, according to the terminology commonly used in the financial industry.
ESG integration	An SRI strategy that aims at enhancing traditional financial (risk) analysis by systematically including ESG criteria in the investment analysis to enhance risk-adjusted returns.[5]
ESG scoring	The scoring methodologies assessing a company's performance in environmental, social and governance aspects based on different approaches, such as generating a final numeric score based on weighted scores of indicators in the three dimensions.[6]
Exposure	The inventory of elements/assets exposed to a hazard or risk.[7]
Green asset	Asset that provides environmental benefits in the broader context of environmentally sustainable development.[8]

[1] Definitions, unless otherwise indicated, are taken from the occasional papers or this report.

[2] Adapted from IPCC reports (Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Dubash, N. K. (2014). IPCC fifth assessment synthesis report-climate change 2014 synthesis report. Intergovernmental Panel on Climate Change, Geneva, Switzerland.). Note that BAU is defined at a general conceptual level here, thus the acute definition of it depends on the purposes of the studies and varies in terms of detailed assumptions.

[3] Adapted from glossary of online database of European Central Bank (2020), All Glossary Entries, retrieved April 2020 from https://www.ecb.europa.eu/home/glossary/html/glossc.en.html

[4] Adapted from BCBS. (2000). Principles for the Management of Credit Risk.

[5] Adapted from NGFS. (2019). A sustainable and responsible investment guide for central bank's portfolio management.

[6] Note that ESG scoring methodologies vary according to users and purposes, thus the definition here is a general conclusion based on some ESG scoring practices by institutions like AXA Investment Managers (2020), Our framework and scoring methodology. retrieved from https://www.axa-im.com/responsible-investing/framework-and-scoring-methodology

[7] Adapted from background papers commissioned by the Global Commission on Adaptation to inform its 2019 flagship report: Stadtmueller, D., Jarzabkowski, P., Iyahen, E., Chalkias, K., Clarke, D., & Zwick, A. (2019). Insurance for Climate Adaptation: Opportunities and Limitations.

[8] Adapted from the definition of "green finance" in the report by Green Finance Study Group (2016). Please note that the scope and definition of "green" now still varies across institutions according to different purposes (See OECD publication: Inderst, G., Kaminker, C., & Stewart, F. (2012). Defining and measuring green investments: Implications for Institutional Investors' Asset Allocations.).

Hazard Potential events with possibilities of occurrence and severity of any particular potential disaster, such as a tropical storm or flood, at a given location, within a specified time period.[9]

Legal risk The risk of a loss being incurred from unexpected application of a law or regulations or a contract that cannot be enforced.[10]

Liquidity risk The risk that the firm will not be able to meet efficiently both expected and unexpected current and future cash flow and collateral needs without affecting either daily operations or the financial condition of the firm.[11]

Market risk The risk of losses arising from movements in market prices of assets, including but not limited to equities, bonds, foreign exchanges, and commodities.[12]

Non-performing loans (NPLs) Loans that satisfy either or both of the following criteria: (a) material exposures which are more than 90 days past due; (b) the debtor is assessed as unlikely to pay its credit obligations in full without realization of collateral, regardless of the existence of any past-due amount or of the number of days past due.[13]

Operational risk The risk of losses resulting from inadequate or failed internal processes, people and systems or from events, including legal risks, but excluding strategic and reputational risks.[14]

Physical risks Economic costs and financial losses resulting from the increasing severity and frequency of extreme climate change-related weather events (such as heat waves, landslides, floods, wildfires and storms) as well as longer term progressive shifts of the climate (such as changes in precipitation, extreme weather variability, ocean acidification, and rising sea levels and average temperatures), and rises in sea levels. In addition, losses of ecosystem services (e.g., desertification, water shortage, degradation of soil quality or marine ecology), as well as environmental incidents (e.g., major chemical leakages or oil spills to air, soil and water/ocean) also fall into the category of physical risks.[15]

[9] Adapted from background papers commissioned by the Global Commission on Adaptation to inform its 2019 flagship report: Stadtmueller, D., Jarzabkowski, P., Iyahen, E., Chalkias, K., Clarke, D., & Zwick, A. (2019). Insurance for Climate Adaptation: Opportunities and Limitations.

[10] Adapted from glossary of online database of European Central Bank (2020). All Glossary Entries. Retrieved April 2020 https://www.ecb.europa.eu/home/glossary/html/glossc.en.html

[11] Adapted from BCBS. (2008). Principles for Sound Liquidity Risk Management and Supervision.

[12] Adapted from BCBS. (2016). Minimum capital requirements for market risk.

[13] Adapted from glossary of online database of European Central Bank (2020). All Glossary Entries. Retrieved April 2020 https://www.ecb.europa.eu/home/glossary/html/glossc.en.html

[14] Adapted from publication of BCBS. (2011). Principles for the Sound Management of Operational Risk.

[15] Partly adopted from NGFS. (2019). First comprehensive report: A call for action: Climate change as a source of financial risk. Note that the definitions of physical and transition risks in this work are slightly different from (i.e., broader than) the definitions provided in the NGFS first comprehensive report where physical and transition risks only focus on climate-related impacts, while in this report both environment and climate related risks/impacts are taken into account.

Representative Concentration Pathway (RCP) Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover. The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome.[16]

Stress test The evaluation of an FI's financial position under a severe but plausible scenario to assist in decision making within the FI. The term "stress testing" is also used to refer not only to the mechanics of applying specific individual tests, but also to the wider environment within which the tests are developed, evaluated and used within the decision-making process.[17]

Transition risks The risks relate to the process of adjustment towards a low-carbon economy. The process of reducing emissions is likely to have significant impact on all sectors of the economy affecting financial assets values.[18]

Underwriting risk The loss on underwriting activity in the insurance or securities industry[19]. For the insurance industry, is the risk that an insurance company will suffer losses because the economic situations or the occurring rate of incidents have changed contrary to the forecast made at the time when a premium rate was set.[20]

Vulnerability The level of damage which would be expected at different levels of intensity of a hazard. For example, when a storm surge hits an area with weak building regulations and few flood mitigation measures, it is more vulnerable to loss compared to an area with strong flood control infrastructure and strong building regulations. Vulnerability assessment may include secondary impacts such as business interruption.[21]

[16] Adapted by IPCC (2014), AR5 Climate Change 2014: Mitigation of Climate Change; TCFD (2017), Final Report: Recommendations of the Task Force on Climate-related Financial Disclosure.

[17] Adapted from BCBS. (2009). Principles for sound stress testing practices and supervision.

[18] Adapted from NGFS. (2019). First comprehensive report: A call for action: Climate change as a source of financial risk. In its work, the NGFS has incorporated the risk associated with emerging legal cases related to climate change for governments, firms and investors, e.g. liability risks, as a subset of physical and transition risks. See also footnote 15.

[19] Adapted from Kumar, R. (2014). Strategies of banks and other financial institutions: Theories and cases: Elsevier.

[20] Adapted from FSA Japan. (2020). Insurance Underwriting Risk Checklist and Manual.

[21] Adapted from background papers commissioned by the Global Commission on Adaptation to inform its 2019 flagship report: Stadtmueller, D., Jarzabkowski, P., Iyahen, E., Chalkias, K., Clarke, D., & Zwick, A. (2019). Insurance for Climate Adaptation: Opportunities and Limitations.

Preface

by

Frank Elderson, Chair of the NGFS

Dr. Ma Jun, Chair of NGFS Supervision Workstream

Over the last few years, the idea that environment-related risks can strand assets in different sectors of the global economy has become much more widely accepted. The threat of stranded assets, particularly from climate-related physical and transition risks, has spurred work by financial supervisors and central banks. NGFS members have announced new supervisory expectations and climate stress tests to help improve the solvency of individual financial institutions, as well as the resilience of the financial system as a whole.

We know we must act. But financial institutions and their supervisors are still at an early stage in developing and deploying suitable datasets, models, and tools. We urgently need better data and analysis in order to properly measure and manage exposures to environment-related risks.

There are barriers that need to be overcome and we know what these are: poor availability of consistent, comparable, and trusted data; costs of data and accessing resources to conduct analysis; missing standards and norms that hinder the use and flow of data; a lack of transparency into data and methods used, resulting in a trust deficit among users; and underdeveloped internal capabilities to analyse and interpret data and analysis to aid decision making.

The NGFS is committed to helping the entire global financial system quickly overcome these barriers, so environment-related risks can be properly measured and managed, and that is why I am excited to see the publication of our first NGFS Occasional Paper, Case Studies of Environmental Risk Analysis Methodologies.

This anthology contains dozens of examples of environmental risk analysis in practice, with chapters written by a wide range of different research providers and practitioners. The methods and tools they describe can be used by wide range of different financial institutions, including banks, asset managers and insurance companies. While we are not recommending any particular service or provider, the point of the paper is to showcase the scale and pace of innovation currently underway.

The Occasional Paper is relevant to all central banks, NGFS members, as well as non-members. It offers valuable insight into the state of environmental risk analysis and many technical details that will be helpful for financial institutions and supervisors. The fact that it showcases the adoption of environmental risk analysis by some financial institutions in the world will also serve as an important inspiration for many others to follow suit. The views expressed in the Occasional Paper are those of the individual authors, and do not necessarily reflect the views of the members and observers of the NGFS.

Finally, I would like to thank all those that contributed to this report, particularly the editors of this Occasional Paper—Prof. Ben Caldecott and Prof. Ulrich Volz—as well the NGFS

Secretariat and Dr. Ma's team including Dr. Sun Tianyin, Dr. Li Jing, and Zhu Yun for their great efforts in organizing the participating authors and editing this volume.

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Chapter 4 Assessing Forward-Looking Climate Risks in Financial Portfolios: A Science-Based Approach for Investors and Supervisors

By

Irene Monasterolo and Stefano Battiston[1]

Abstract

Climate risk is a new source of financial risk characterized by deep uncertainty, non-linearity, and endogeneity. Neglecting these characteristics leads to a severe underestimation of potential financial losses and gains. We present the CLIMAFIN methodology designed to help investors and financial institutions to address this challenge and to embed climate risk into pricing models and stress-tests. The method builds on the Climate Stress-test by Battiston et al. (2017), which has become over the years a reference tool for academics and practitioners. CLIMAFIN allows to translate forward-looking climate transition scenarios into financial shocks and to provide investors and financial supervisors with scenario-adjusted risk metrics and models (e.g. Climate Value at Risk, Climate Spread, Climate Stress-test). The chapter describes the technical details of the methodology and some recent policy applications carried out in collaboration with leading financial institutions.

Keywords: climate scenarios, climate transition risk, financial risk, risk management strategy, climate VaR, climate spread, climate stress-test, financial stability

1 Introduction

There is a growing consensus among scientists, central bank officials and financial supervisors that climate change is a new source of risks for the economy and financial stability, at both individual institution and system levels (Battiston et al., 2017). Climate-related financial losses can result from the misalignment of investments in the economy and finance with the climate and energy transition targets. It is broadly recognized that massively scaling up investments in low-carbon firms and sectors and phasing-out those in fossil-fuel power plants and carbon-intensive sectors are both needed to achieve climate targets laid out in the Paris Agreement (New Climate Economy, 2018).

In recent years, many central banks and academic institutions began to analyze climate-related financial risks that could stem from a disorderly transition to a low-carbon economy, consisting

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in the late and/or sudden introduction of climate policies (e.g., carbon pricing, Stiglitz et al., 2017) that cannot be fully anticipated by investors. In such a context, firms and investors are unable to timely adjust their business and portfolios' risk management strategies (Battiston et al., 2017). Mispricing of climate-related financial risks may reflect in the value of the financial contracts and securities issued by low-carbon and carbon-intensive activities, leading to asset price volatility. This, in turn, could have potential implications on financial stability at the system level if large and correlated asset classes are involved (Monasterolo et al., 2017). Given the interconnectedness of financial markets and the strong linkage between finance and the real economy, such losses could be amplified by network effects and cascade from the financial sector to the economy (Battiston et al., 2017), with destabilizing effects on countries' economic performance and social cohesion (Monasterolo, 2020).

A main barrier for investors, financial supervisors and regulators to embed climate-related financial risks in their decision making is the lack of science-based approaches to quantitatively assess the implications of future climate scenarios on the value of financial contracts and investors' portfolios. To fill this gap, we developed an operational framework, CLIMAFIN, to assess and manage forward-looking climate risks in investment and financial policy decisions under deep uncertainty (Battiston et al., 2019a). CLIMAFIN addressed to questions that are relevant to investors and financial supervisors in the low-carbon transition:

1. How to carry out a quantitative assessment of climate transition risks at the individual and systemic financial level that makes best use of the available scientific knowledge on climate change and financial risks?

2. How to price climate risk characteristics (forward-looking, deep uncertainty, non-linearity, endogeneity) in the probability of default of financial contracts and investors' portfolios, considering counterparty risks?

The major challenge in addressing these questions stands in the complex nature of climate change, which represents a new type of risk for financial actors and renders standard finance approaches to risk pricing and valuation inadequate. In particular, we need to consider that climate-related financial risks are endogenous (Battiston et al., 2017). This means that the today's perception of future climate risks held by policy makers and investors can impact on their action (or inaction) towards those risks and affect the realization of climate risks themselves. Indeed, if the introduction of stable climate policies is delayed by governments, firms and financial actors do not align their investments to sustainability. This, in turn, makes it impossible to limit global temperature increase below 2 degrees Celsius from pre-industrial levels, triggering the realization of climate risks in the economy and finance in the near future. Such endogeneity leads to multiple possible pathways (or equilibria, in the sense of strategic interaction of economic agents) that are very different based on the future prevalence of climate policies, or energy technology shocks, and on investors' anticipation and reaction to them. Moreover, it is very difficult to estimate the probability of such pathways given that we are in a context of deep uncertainty (Weitzman, 2009). This information is not contained in historical data, thus representing a poor proxy of the materiality of the climate-related financial risks we could face in the near future. However, traditional approaches to financial risk assessment and portfolio optimization are based on backward-looking benchmarks and short-term horizons, as well as assumptions of normal distributions, perfect markets and absence of arbitrage.

This chapter is structured as follows. Section 2 discusses why standard economic and financial risk models are inadequate to assess such risks. Section 3 presents the details of the CLIMAFIN methodology (Battiston et al., 2019a), introducing the workflow, the fundamental components, input metrics and data used. Section 4 illustrates the output of the CLIMAFIN methodology (Climate Spread, the Climate Value at Risk (VaR) and the Climate Stress-test) as applied to equity holdings, corporate and sovereign bond portfolios held by financial institutions, in collaboration with central banks (e.g., Austrian National Bank (OeNB), Banco de Mexico (BdM)) and financial regulators (e.g., European Insurance and Occupational Pension Funds Authority (EIOPA)). In section 5, we conclude by discussing the applicability of science-based climate-financial risk metrics and methods to inform investors' risk management strategies, and to support financial supervisors in identifying systemic climate-related financial risks and the designing prudential measures to mitigate them.

2 Climate change as a new type of risks for financial analysis

Climate change represents a new type of risk for financial actors and decision makers, because it is characterized by:

- **Deep uncertainty:** Due to the nature of the earth system, climate change is characterized by deep uncertainties in forecasting its realization and impact on humans and ecosystems. This is in part due to the presence of tail events (Weitzman, 2009) and tipping points after which the characteristics of the system change abruptly (Solomon et al., 2009). The more the system gets closer to such tipping points, the more the possibility of irreversible changes in the human-environmental system to occur, and with that the possibility of crossing of the planetary boundaries (Steffen et al. 2018) and of triggering domino effects (Lenton et al., 2019). Other sources of uncertainty refer to the assumptions on agents' utility function, future productivity growth rate, and intertemporal discount rate used in cost-benefit analyses of climate change.

- **Non-linearity**: Recent research showed that the distribution of extreme climate-related events (heat/cold waves) is highly non-linear (Ackerman, 2017). Fourteen of the 15 hottest years on record were since 2000, while 2015-2019 was the hottest five-year period on record (WMO, 2019).

- **Forward-looking nature of risk**: The impacts of climate change are on the time scale of two decades or longer, while the time horizon of financial markets is much shorter (few months).

- **Endogeneity**: Climate-change risks are endogenous and depend on the risk perceptions of the agents involved. Indeed, the achievement of the climate targets depends on governments' and firms' investment decisions. But both types of decisions depend on their perceptions of the risks involved, which differ across the possible transition scenarios and trajectories (Battiston, 2019). Thus, the endogeneity between policies choices and investors' expectations on the financial risks resulting from these policies generates the possibility of multiple equilibria. Green perception is likely to lead to green climate policy and green portfolio.

Climate change is expected to impact the economy and finance via physical and transition risks (Carney 2015). However, while climate physical risks will be more visible in the medium-to-long term, climate transition risks could happen earlier and be more financially relevant. Further, it is now well recognized that in assessing climate-related financial risks, one should not only consider the characteristics of climate risks, but also those of financial risks. Research developed following the Great Financial Crisis highlighted the **key role of financial complexity**

and financial actors' interconnectedness in amplifying shocks via the reverberation of losses within the financial network (Battiston et al. 2012, 2016) and in contributing to the building up of systemic risk (Battiston et al. 2012).

These elements challenge the traditional approaches to financial risk assessment used by investors and financial supervisors because they require a rethinking of the notion of **materiality** of risks and, connected to that, the notion of **time horizons, benchmarks and coordination problems** in investment decisions. Indeed, standard approaches to economic and financial risk assessment stand on the identification of the most likely scenarios, on the computation of expected values and on the calculation of risk metrics (e.g., volatility) based on the historical values of market prices. In addition, they rely on strong assumptions of market conditions and agents' behaviors, including perfect information, normal distributions, and a lack of arbitrage (Black & Scholes, 1973). These assumptions and characteristics are clearly at odds with the characteristics of climate risks (and financial risks) and could lead to underestimating the impact of climate change in risk assessment models, with relevant implications on policy recommendations (DeFries et al., 2019).

3 The CLIMAFIN framework

CLIMAFIN methodology is a transparent and science-based approach to quantitatively assessing and pricing forward-looking climate risks and their characteristics (i.e., deep uncertainty, non-linearity and endogeneity) in the value of individual financial contracts and investors' portfolio. More specifically, we can embed forward-looking climate transition scenarios provided by climate science and climate economic models (e.g., Integrated Assessment Models, IAMs) in:

- Probabilities of defaults of contracts and securities (i.e., introducing climate in financial pricing models for equity holdings, corporate and sovereign bonds)
- Quantitative metrics of financial risks used by investors, central banks and financial regulators (e.g., climate VaR, climate spread)
- A full-fledged Climate Stress-test rooted in financial network models.

Table 4-1 summarizes the purpose of CLIMAFIN and its characteristics along key dimensions such as coverage of scenarios, risk types and financial instrument types.

Table 4-1: Purpose and characteristics of CLIMAFIN

Purpose	To enable investors, central banks and financial regulators to assess forward-looking climate risks (transition, physical) and opportunities in financial portfolios and identify drivers at the individual and system level.
Target users	CLIMAFIN can be customized for both private and public financial institutions, portfolios and types of financial contracts (e.g. equity holdings, corporate and sovereign bonds, loans). Existing applications have involved development finance institutions (e.g. China Development Bank), national central banks (e.g. OeNB, BdM), financial regulators (EIOPA) and commercial banks (European and US banks).
Climate scenarios covered	CLIMAFIN covers 2°C-aligned climate transition scenarios, including those characterized by a disorderly low-carbon transition (e.g., late and sudden introduction of climate policies and lack of full anticipation by investors). CLIMAFIN builds on the IEA Technological Roadmap as well as scenarios of emissions targets, energy technology trajectories and national contributions produced by IAMs used by the IPCC (2014, 2018), and their scenario databases, such as LIMITS Database[2] and Socio-Economic Shared Pathways and the most recent CD-Links[3].
Risk types covered	The methodology allows users to compute the probability of default (PD) for individual financial contracts, the Climate Value at Risk (Climate VaR) and Expected Shortfall (ES), and the climate stress-test under forward-looking climate transition scenarios (including a disorderly transition) aligned to the 2°C target. The sectors covered, such as energy, utility, manufacturing and transportation, are those in the IEA technological roadmap and in the EU Reference Scenarios.
Risk transmission channels	CLIMAFIN has focused so far on transition risks arising from asset value adjustments according to the types of climate risks, the financial risk characteristics of the investors and their expectations of the impact of climate policies. Adjustments include economic and financial gains/losses (Gross Value Added (GVA), Probability of Default (PD)) due to i), exposures to high/low carbon activities (classified in Climate Policy Relevant Sectors (CPRS) and ii), delayed and disorderly alignment with climate targets that investors do not fully anticipate. If climate policies are credible, stable and anticipatable by investors, the portfolios will not experience large price volatilities that require asset revaluation. Our team is working to include physical risk transmissions. Recent application has focused on climate physical risk stemming from floods and sea-level rise.
Financial contracts covered	The methodology applies to loans, corporate and sovereign bonds and equity holdings, and cat bonds. Our team is working to integrate derivatives.
Granularity of the analysis	Risks at the firm level can be aggregated to the portfolio level and incorporated into standard financial risk metrics (see Climate VaR by Battiston et al., 2017). The level of granularity required depends on the depth of analysis and would normally include project and/or counterparty data.

[2] The LIMITS Scenario Database is operated by the International Institute for Applied Systems Analysis (IIASA) https://tntcat.iiasa.ac.at/LIMITSDB/dsd?Action=htmlpage&page=about

[3] https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/login?redirect=%2Fworkspaces

Country-specific risks	We elaborate a dataset of proprietary trajectories based on country and sector specific progress towards their Nationally Determined Contributions (NDCs) and climate targets in order to incorporate country-level transition risks into standard metrics of sovereign risks (see the Climate Spread in Battiston & Monasterolo, 2019). The team is working to incorporate country-specific exposures to climate physical risks.

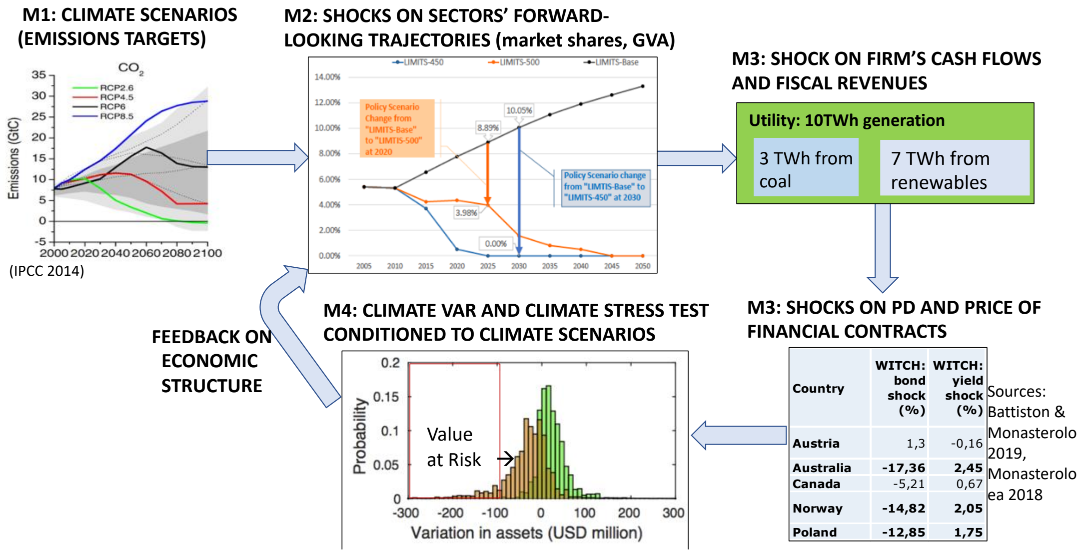
The CLIMAFIN framework provides a quantitative assessment arranged in a workflow of four modules. Figure 4-1 shows the interplay of the four modules in the CLIMAFIN workflow. **Module 1** gathers and consolidates a database of climate science scenarios and climate transition scenarios, e.g., those provided by the IPCC (2018) and the NGFS (2019).

Module 2 uses the information from Module 1 to generate a large set of forward-looking climate transition scenarios that imply a shock on the low-carbon and carbon-intensive economic activities (respectively positive and negative) based on their energy technologies (i.e., specific renewable energy or fossil fuels based). Depending on the assumptions on the climate economic model used (e.g. IAMs) and the introduction of the policy (e.g. the value of the carbon tax), the policy shock can be computed either as difference across trajectories (Monasterolo et al., 2018) or as difference along time steps in the same trajectory (Battiston et al., 2017). when moving from the initial state of the economy, i.e., the Business as Usual (B), to a specific policy scenario (P). Using climate economics models (e.g., the IAMs), we calculate economic shocks (market share, Gross Value Added (GVA)) by region and sector of economic activity (e.g., low-carbon or carbon-intensive), conditioned to each scenario. The core of the feedback mechanism is as follows: the forward-looking climate transition scenarios imply a shock to the low-carbon and carbon-intensive economic activities (respectively positive and negative) based on their energy technologies (i.e., renewable energy or fossil fuels based). To associate a climate financial risk profile to the sectors of economic activities, Battiston et al. (2017) introduced the Climate Policy Relevant Sectors (CPRS), i.e., fossil fuels, low/high-carbon utility, low/high-carbon transportation, energy intensive manufacturing, housing.

Module 3 provides the information set of a risk-averse investor and carries out a valuation adjustment and a risk adjustment of individual financial contracts, i.e., in their Probability of Default (PD) based on the scenarios of economic shocks (by activity and its energy technology) obtained from Module 2. In particular, Module 3 uses the outcome of the economic shock on each economic activity and assets, and prices it in the PD and value of the financial contracts (equity holdings, corporate and sovereign bonds) issued by the activity, or in the loans associated to that.

Module 4 uses information on repricing of the contracts and computes distributions that allow to consider non-linearity and deep uncertainty of climate change in climate financial risk metrics (e.g. Climate VaR) and the Climate Stress-test. Rooted on financial valuation in network models, the Climate Stress-test allows to assess the largest losses for individual portfolios conditioned to climate scenarios, considering risk amplification and reverberation driven by financial interconnectedness, considering losses generated by direct and indirect exposures (second round losses, Battiston et al., 2017, Roncoroni et al., 2019).

Figure 4-1 CLIMAFIN framework for climate financial risk assessment under deep uncertainty.



Module 1 provides the information set combining science-based knowledge and market data to be used by financial supervisors and investors. Module 2 provides information on the economic shocks (positive and negative) associated with climate transition scenarios, at the level of economic activity. Modules 3 and 4 provide metrics and methods of financial risks to support investment and policy decision making in the transition to a carbon-neutral economy. Source: Battiston et al. (2019a)

3.1 Module 1. Database of climate science scenarios and climate economics scenarios

Module 1 gathers and consolidates the following sets of information:

- Sets of future climate change scenarios, as from the IPCC reports (IPCC, 2014, IPCC 2018), forecasts of GHG emission concentrations, temperature changes and socioeconomic impacts of climate change conditioned to the scenarios.

- Sets of economic trajectories under climate policy scenarios as provided by well-established economic models of climate change, e.g., IAMs[4], partial or general economic equilibrium models that consider GHG emission targets and any physical damages resulting from climate change. For instance, the LIMITS database and the new CD-Links database provides scenarios of the evolution of different economic sectors' output under various policy scenarios as computed by IAMs developed by leading academic institutions such as IIASA, PIK, and CMCC.

For instance, in the climate risk assessment of the sovereign bond portfolios of insurance companies in the European Union (EU), Battiston et al. (2019a) used the climate policy scenarios aligned to the 2°C target developed by the international science community and reviewed by the IPCC. They considered the stabilization concentration of CO2 at the end of

[4] Note that IAMs consider only in very stylized way, if at all, the impact of climate change on the socioeconomic system. It can be argued that the convex damage function used in this literature cannot account for the essential characteristics of climate risks such as tail risk and climate tipping points. The approach presented here can be adapted to use trajectories from economic models that would also account for these effects.

century consistent with the 2°C pledge under the Paris Agreement (i.e., 450 and 500 parts per million (ppm)). These are associated with two different policy implementation scenarios, i.e., Reference Policy (RefPol) and Strong Policy (StrPol) in the exercise conducted by LIMITS IAMs (Kriegler et al., 2013). RefPol assumes a weak near-term target by 2020 with fragmented countries' actions to achieve emissions reduction by 2050, while StrPol assumes a stringent near-term target by 2020. The 500 and 450 ppm scenarios are associated with a probability of exceeding the 2°C target by 35-59% and 20-41% respectively. A change in climate policy (e.g. in the value of the carbon tax every five years) implies a change in the sectors' macroeconomic trajectory, thus a change in the market shares of primary and secondary energy sources. Currently, CLIMAFIN's new analyses use the CD-Links post-Paris Agreement Scenarios.

Table 4-2 provides an overview of the scenarios and their comparisons (See Battiston & Monasterolo, 2019).

Table 4-2 LIMITS scenarios' characteristics

Scenario class	Scenario name	Scenario type	Level of ambition (near term)	Level of ambition (long term)	Level of international cooperation
No policy	Base	Baseline	None	N/A	None
Fragmented action	RefPol	Reference	Weak	2100	None
	StrPol	Reference	Stringent	2100	None
Immediate action	450	Benchmark	None	N/A	450 ppm
	500	Benchmark	None	N/A	500 ppm
Delayed Policy	RefPol-450	Climate Policy	Weak	2020	450 ppm
Delayed Policy	StrPol-450	Climate Policy	Stringent	2020	500 ppm
Delayed Policy	RefPol-500	Climate Policy	Weak	2020	500 ppm
Delayed Policy	StrPol-500	Climate Policy	Stringent	2020	500 ppm
Delayed Action	RefPol2030-500	Climate Policy	Weak	2030	501 ppm

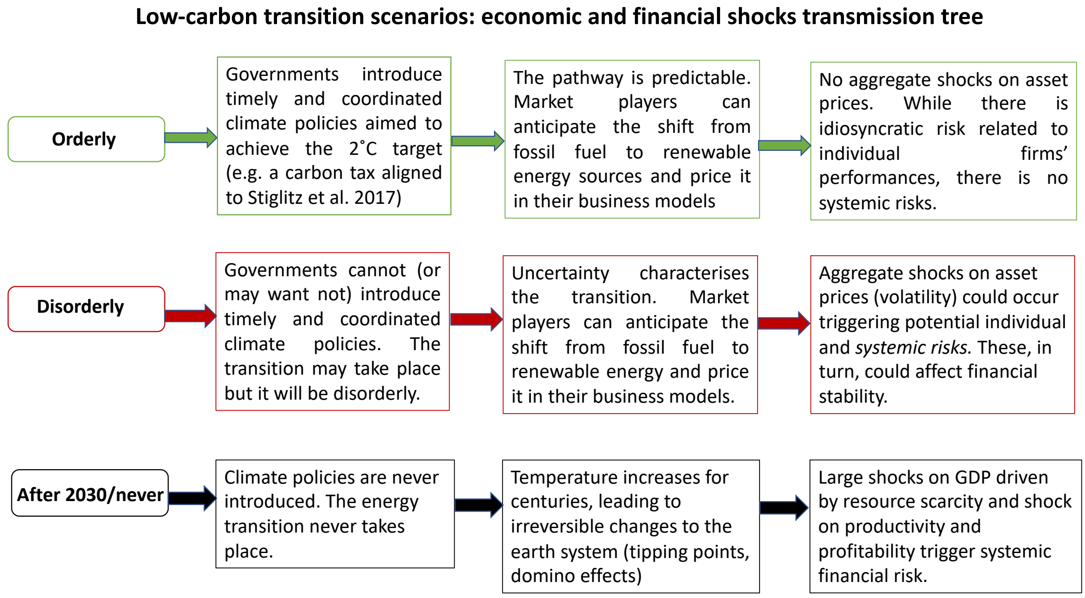
Source: Table based on Kriegler et al. (2013), adapted in Battiston and Monasterolo (2019)

3.2 Module 2. Climate transition shock scenarios

This module derives scenarios of economic shocks (positive or negative) at the level of economic activities, based on their energy technology and relevance for climate policy implementation from the information provided by Module 1.

First, based on climate science evidence from Module 1, we construct an event tree for the main possible scenarios relevant for climate transition risk, in a mid-term horizon of 2025-2030 or in a long-term horizon (2050), following the 5 years calculations of the IAMs. In particular, we provide an argument for how the current socioeconomic dynamics of opposing vested interests increases the likelihood of a disorderly low-carbon transition. This event tree can be defined for the zero-carbon energy transition needed to achieve the climate targets (IPCC, 2018) as in Figure 4-2:

Figure 4-2 Low-carbon transition's main transition scenarios: chain of events in the transmission of economic and financial shocks.



Second, based on the economic trajectories from Module 1, we derive a set of economic shocks (on output, market share and GVA) by region and sector of the economic activities (low-carbon and carbon-intensive). These shocks can be computed either across climate transition trajectories (Monasterolo et al. 2018), or within the same trajectory across years (Battiston et al. 2017). Since the current classifications of economic activities (e.g. NACE 4 digit) do not provide information on the sector's exposure to climate risks, we classify economic activities relevant to climate transition risks into CPRS. These include fossil fuel, utility, energy-intensive, transport, housing, infrastructure, identified based on: the direct and indirect contributions of economic activities (classified at the NACE 4-digit level) to GHG emissions (Scope 1, 2, 3); their sensitivities to climate policy implementation (e.g. the EU carbon leakage directive 2003/87/EC); the technology mix of the activities and their role in the energy value chain; their investment plans, particularly the climate relevant part (e.g. CAPEX in Battiston et al., 2017). Doing so allows us to identify activities and sectors that will have the most impact on achieving climate targets and will also be impacted by climate transition risks. The CPRS classification was used by the European Central Bank (2019[5]) and by EIOPA (2018[6]) to assess financial actors' exposure to climate transition risks in the EU.

Third, we consider the transition of the economy from a business-as-usual (BAU) trajectory to a given policy trajectory (P) compatible with a 1.5°C or a 2°C target:

- Shocks are obtained as differences in sectors' output between the BAU and the climate policy shock trajectories (P) for the same model (e.g., IAMs[7]) that can be calculated either across trajectories or across years (2020 to 2100) within the same trajectory;

[5] https://www.ecb.europa.eu/pub/financial-stability/fsr/special/html/ecb.fsrart201905_1~47cf778cc1.en.html#toc5

[6] https://register.eiopa.europa.eu/Publications/Reports/EIOPA%20FSR%20December%202018.pdf

[7] Note that other climate economic models could be used to provide shocks on output. We opted for IAMs because they are the models reviewed by the IPCC report and used to inform climate policy discussion.

- We need to depart from the idea of "most likely/feasible scenario" and consider sets of several scenarios (see Table 4-2) to be able to determine (in Module 4) how wrong could an investor be in computing the Climate VaR of her portfolio.

- The disorderly transition is thus intended as a temporary out-of-equilibrium shift of the economy between two separate equilibrium trajectories based on the energy technology that drives the transition. This formulation makes the exercise familiar to economists because they are consistent with traditional economic models' rationale.

3.3 Module 3. Shock scenario-adjusted financial pricing and risk valuation

This module integrates forward-looking climate transition risk scenarios in financial risk-pricing models and quantitative financial risk metrics used by investors and financial supervisors, such as Climate Spread (Battiston & Monasterolo, 2019) and Climate VaR (Battiston et al., 2017). The Climate Spread is defined as the change in the spread of a corporate or sovereign bond contract conditional on a given Climate Policy Shock Scenario, thus introducing future climate risks in the assessment of firms or countries' financial solvency. The Climate VaR can be defined as the "worst-case loss" conditioned to future climate shock scenarios given a certain confidence level.

From the sectorial economic shock trajectories based on climate transition scenarios (Module 2), we compute the financial shocks on the cashflows of individual economic activities comprising the sector. We then translate the shock on the cashflows in the adjustments of PDs of individual firms and sovereign governments, and in the adjustment of risks and values of the individual risky financial contracts (equity holdings, corporate and sovereign and bonds). In this step, we develop climate-based financial pricing models and financial risk metrics (e.g. Climate Spread, Climate VaR) embedded in the forward-looking climate shock trajectories, accounting for the deep uncertainties of climate risks.

Our approach stands on the definition of the Information Set of a risk-averse investor who aims to minimize the largest climate-related losses to her portfolio. We define an information set that can accommodate incomplete information and deep uncertainty (Greenwald & Stiglitz, 1986) and can cover a time horizon that is relevant both for investment strategies and for the low-carbon transition (e.g. from 2020 to 2050). The investor's information set comprises (Battiston et al., 2019a):

- **Climate policy scenarios** corresponding to Greenhouse Gases (GHG) emission reduction target across regions), provided e.g. by IPCC reports;

- Future **economic trajectories** for carbon-intensive and low-carbon activities conditioned to climate scenarios, provided by climate economic models (e.g., IAMs);

- Forward-looking **Climate Policy Shock Scenarios** intended as a disorderly transition from B (Business as Usual) to P (a given climate policy scenario). These can be computed either across trajectories or across years within the same trajectory;

- **Climate Policy Shocks on the economic output** of low-carbon/carbon-intensive activities, on their Gross Value Added (GVA) and their contribution to the fiscal revenues of the sovereign government. The policy shocks are under transition scenarios and in a specific climate economic model.

3.3.1 Pricing forward-looking climate risks into equity holdings

We introduce a valuation model where t_0 denotes the time at which valuation is carried out and *E* denotes a generic equity contract. In the absence of climate policies, we assume that all relevant information is captured by the expected future flow of dividends.

Following Gordon's formulation (Gordon 1959), we further consider that dividends grow at a constant rate $g(B)$ so that for all $t \geq t_0$; $div(t+1) = \big(1 + g(B)\big)div(t)$

Denoting by r the cost of risky capital, the value of equity is then determined as the net present value of future dividends equal to V_E^{B,t_0}:

$$V_E^{B,t_0} = \sum_{t=1}^{+\infty} \frac{(1+g(B))^t \mathrm{div}(t_0)}{(1+r)^t} = \frac{\mathrm{div}(B)(1+g(B))}{r-g(B)}$$

Where

$$div\ (\mathrm{B}) = div(t_0).$$

If we assume a climate policy shock to occur at time t^*, dividend is assumed to shift to $div(\mathrm{P})$ and the growth rate of dividends to $g(P)$ where *P* identifies a specific climate policy scenario. The value of equity is then determined as V_E^{P,t^*}

$$V_E^{P,t^*} = \sum_{t=1}^{t^*} \frac{(1+g_0)^t \mathrm{div}(B)}{(1+r)^t} + \sum_{t=t^*+1}^{+\infty} \frac{(1+g(P))^{t-t^*} \mathrm{div}(P)}{(1+r)^t}$$

If the climate policy shock occurs at valuation time, i.e., $t^* = t_0$, we have

$$V_E^{P,t_0} = \frac{\mathrm{div}(P)(1+g(P))}{r-g(P)}$$

In a climate policy scenario *P*, it is expected that $div(\mathrm{P})$ and $g(P)$ decrease for carbon-intensive economic activities and increase for low-carbon economic activities.

From the equity valuation under climate scenarios, we can then assess:

The change of valuation in the case of a disorderly transition occurring at time t^* given by

$$V_E^{B,t_0} - V_E^{P,t^*}$$

Given a probability distribution P on the time of occurrence and/or the impact of the policy scenarios, we can compute Climate VaR associated with an equity contract. Climate VaR is a quantile of loss distributions conditioned to climate policy shocks scenarios, which could be either characterized by physical or transition risks (Battiston et al., 2017), in a given time. The Climate VaR, then, defines the largest losses (usually in USD) in the value of a risky asset (e.g., equity holdings and bonds) or portfolio that the investor should withstand, conditioned to a given scenario, confidence level and time. Thus, the Climate VaR is a measure of risk of investment under forward-looking climate scenarios. The Climate VaR Management Strategy can be written as:

$$ClimVaRStr = min_{Portfolio}\{max_{Shock}\{VaR(Portfolio, Adj.PD|Policy\ Shock)\}\}$$

The VaR, despite being well known and used by investors, has two main limitations in this context. First, VaR is computed assuming knowing how the loss will be distributed, and this leads to *model risk*. Second, VaR depends linearly on the PD of underlying assets, thus implying that small errors have small consequences. However, the PD of leveraged investor depends non-linearly on PD of underlying assets, thus implying small errors can have big consequences. But, importantly, VaR does not consider leverage. This means that to assess the financial risk implications of climate change, we need to go beyond VaR and consider interconnected financial actors, leverage financial agents with overlapping portfolios, i.e., the conditions for systemic risk in financial networks (Battiston et al., 2016). This is a main feature of CLIMAFIN, as well as the possibility to be applied to other risk metrics, such as the Expected Shorfall (ES). This is the average of all the losses above the VaR (i.e., the largest losses), and gives us a measure of what we can expect in terms of losses on our portfolio.

For a complete explanation of the pricing of forward-looking climate transition risks in the value of equity holdings, see Battiston and Monasterolo (2019).

3.3.2 Pricing forward-looking climate risks into corporate and sovereign bonds

We consider a risky (defaultable) bond issued by a corporate issuer *j*, issued at t_0 with maturity T. The value of the defaultable bond at time *T*, with *R* being the Recovery Rate of the corporate bond (i.e., the percentage of notional recovered upon default), and LGD being the Loss-Given-Default (i.e., the percentage loss), can be written as:

$$v_j(T) = \begin{cases} R_j = \left(1 - LGD_j\right) & if\ j\ defaults\ (with\ probability\ Q_j) \\ 1 & else\ (with\ probability\ 1 - Q_j) \end{cases}$$

The unitary price $P_j(t)$ of the bond at time $t < T$ and $t > t_0$ follows the usual definition of discounted expected value at the maturity:

$$P_j(t) = \exp\left(-r_f(T-t)\right) E[v_j(T)] = \exp\left(-r_f(T-t)\right) (1 - Q\ LGD)$$

The bond price v_j^* is equal to the bond discounted expected value, with y_f risk-free rate, i.e., the yield of the bond facing no default risk (e.g. the German bond in the case of sovereign bonds, see Battiston & Monasterolo, 2019). The cumulative probability of default *Q* is related to the probability of default at *t* as follows: $\mathrm{Q} = 1 - (1-\mathrm{q})^{(T-t)}$. The formula can be used to determine, from the market price, the value of the annual default probability *q* (i.e., *q implied*) for a given risk-free rate and LGD. In the case of a multi-coupon bond, the formula gets more complicated since one must sum up the expected value of the coupons, but the logic remains the same. For each coupon k, the coupon amount is assumed to be paid only if *j* has not defaulted before.

The bond price is defined implicitly by the yield y_j of bond *j* (under risk neutral measure) as follows:

$$v_j^* = e^{-y_j T}$$

We can define the Probability of Default (PD) $q_j(P)$ of the corporate bonds' issuer *j* under Climate Policy Scenario *P* as:

$$q_j(P) = \mathcal{P}\ (\eta_j < \theta_j(P)) = \int_{\eta_{inf}}^{\theta_j(P)} \phi_{(P)}(\eta_j) d\eta_j$$

where $\phi_{(P)}(\eta_j)$ is the probability distribution of idiosyncratic shock η_j, and η_{inf} is the lower bound of the range of the value of η_j.

We report a result on the PD adjustment. In simple terms, conditioned to the climate policy shock, there is a shift Δq in the probability distribution of the small productivity shocks and thus in the default probability of issuer *j*:

$$\Delta q_j(P) = q_j(P) - q_j(B) = \int_{\eta_{inf}}^{\theta_j(P)} \phi_{(\eta_j)} d\eta_j, \text{ with } \theta_j(P) = \theta_j(B) - \xi_j(P)$$

Thus, assuming that the climate policy shock on the fiscal revenues of the firm (and thus of the sovereign) is proportional to the shock on the GVA of low-carbon and carbon-intensive sectors, i.e., $\xi_j = \chi_j u_{j,s}^{GVA}$(P), with elasticity χ_j, then the adjustment $\Delta q_j(P)$, the PD of j in a Climate Policy Shock Scenario:

- Increases with the GVA shock magnitude $|u_{j,s}^{GVA}$(P)| if $u_{j,s}^{GVA}$(P)<0, decreases vice versa;
- Is proportional to the GVA shocks on CPRS (in the limit of small Climate Policy Shocks).

The bond spread can be defined then as:

$$s_j = y_j - y_f, \text{ with } e^{-y_j T} = 1 - q_j \, LGD_j$$

The Climate Spread Δs_j is defined as the change in the spread of a bond contract conditional upon a Climate Policy Shock Scenario:

$$\Delta s_j = s_j(q_j(P) - s_j(q_j(B))$$

For a complete explanation of the pricing of forward-looking climate transition risks in the value of corporate and sovereign bonds, see Battiston and Monasterolo (2019).

3.4 Required input data

From the perspective of the user, the application of the CLIMAFIN methodology requires the following information on the portfolio of investments to be collected and analyzed:

- Financial securities (listed equities, corporate and sovereign bonds): identifier of the financial security, e.g. ISIN code, TICKER and LEI of the issuer;
- Financial securities (unlisted equities and loans): LEI of the firm, full legal name, location of incorporation. Same information for the parent company;
- The NACE sector of the economic activities of the firm that issue the contract (at 4-digit level, if possible);
- The composition of financial actors' investments in financial securities (i.e., their exposure);
- Information on the characteristics of the financial securities and time series data (e.g., duration, maturity, coupon, term, prices, etc.).

All financial information (except loans) can be collected using financial data providers (e.g., Bloomberg, Thomson Reuters Eikon, etc.).

In addition to the financial input data, the following climate and energy data are needed:

- Measures of economic shocks associated with climate scenarios and provided by IAMs (Kriegler et al., 2013; McCollum et al., 2018);
- Contributions from fossil fuels and renewable energy sectors to the individual countries' GVA (e.g. Eurostat, IEA);
- Data on country's macroeconomic and financial aggregates (e.g., debt/GDP, deficit, etc.) provided by national or international statistical offices (e.g., Eurostat, OECD).

4 Applications to portfolios of financial institutions

In this section, we present several applications of the CLIMAFIN approach to the risk analysis of investment portfolios.

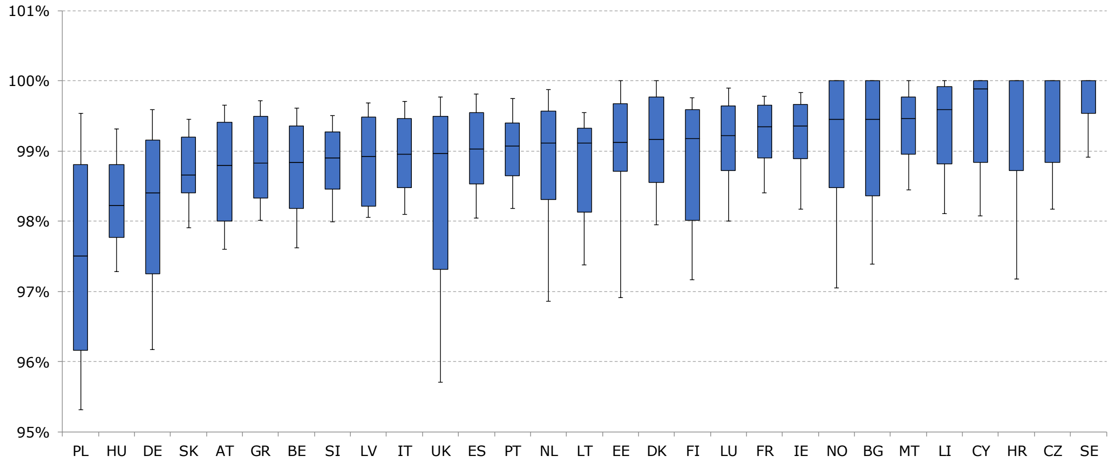
4.1 Climate risk assessment of insurance companies' sovereign bond portfolio

The CLIMAFIN framework was recently applied to a forward-looking climate transition risk assessment of sovereign bond portfolios of insurance companies in Europe, as a result of the first collaboration between climate economists, climate financial risk modelers and financial regulators (Battiston et al., 2019b). The analysis considers forward-looking scenarios characterized by a disorderly introduction of climate policies (i.e., carbon pricing) and lack of full anticipation and pricing by investors.

The authors first computed the shocks on market shares and profitability of carbon-intensive and low-carbon activities that contribute to the GVA and fiscal revenues of the EU countries, which in turn issue the sovereign bonds that are held in the portfolios of European insurers. The shocks are calculated with climate economic models that provide climate transition trajectories for fossil fuel and renewable energy and electricity sectors, conditioned to 2°C-aligned climate policy scenarios. After defining the climate risk management strategy under uncertainty for a risk averse investor (insurer) that aims to minimize the largest losses in her sovereign bonds' portfolio, the authors price the climate transition scenarios in the PD of the individual sovereign bonds and in the bonds' climate spread. The results (see e.g., Figure 4-3) show that the impact of a disorderly transition to the low-carbon economy on the sovereign bonds' portfolios of European insurers, under 2°C-aligned climate policy scenarios, are moderate but non-negligible. In particular, shocks on bonds' value are heterogeneous across countries and reflect the progress towards decarbonization of countries' economies. Most negative impacts affect the portfolios of insurance solos exposed to Polish sovereign bonds.

Two dimensions drive the magnitude of the impact of climate shocks on bonds' portfolios. First, for each sovereign bond, negative shocks (e.g., on primary energy fossil sector) can be possibly compensated by positive shocks (e.g., on secondary energy electricity based on renewable sources). Second, in a portfolio of sovereign bonds issued by several countries, negative aggregate shocks from a less climate-aligned sovereign can be possibly compensated by positive shocks from another more climate-aligned sovereign. These two dimensions contribute to limit the magnitude of the median value of the portfolio impact in the chart.

Figure 4-3 Distribution of impact on sovereign holdings of European insurers.



Note: The length of the bars represents the heterogeneity of impacts on insurers domiciled in the given country (wider distribution). Y-axis represents negative impact (percentage of the original value of government portfolios) of climate policy shocks on the value of sovereign bonds (e.g. 100% expresses 0% impact, 97% corresponds to drop of 3%). The estimated impact is based on the country of the holder (issuing country), across climate policy shock scenarios and under the scenario of adverse market conditions. Source: Battiston et al. (2019b)

This work aims to raise the awareness of climate risks to insurers as well as of regulators and financial supervisors, and provide an approach to include climate risks into their risk assessment frameworks. This requires moving from the backward-looking nature of traditional financial risk assessment to a forward-looking assessment that considers both climate uncertainty and financial complexity.

4.2 Climate risk assessment of sovereign bond portfolio of the Austrian National Bank (OeNB)

Battiston and Monasterolo (2019) assessed the climate risk exposure of OeNB's portfolio of sovereign bonds issued by OECD countries (10 years, zero coupon). They considered forward-looking climate transition trajectories produced by two climate economic models (used to calculate energy and electricity trajectories consistent with the 2°C targets and used by the IPCC report, i.e., GCAM and WITCH[8]), conditioned to several mild and tight climate policy scenarios characterized by carbon pricing (Kriegler et al., 2013). They then modelled the impact of the change in low-carbon and carbon-intensive sectors' profitability on the GVA and fiscal revenues of each individual OECD country. Finally, they priced the shock on the fiscal revenues in the PD of the sovereign bond of the issuing country, on the bond price and yield, i.e., the Climate Spread. Results show that the level of (mis)alignment of a country's economy with low-carbon transition, under feasible climate transition scenarios, can be priced in the sovereign bond and affect the country's financial risk position. In particular, as Table 4-3 shows, the largest negative shocks on the value of individual sovereign bonds are on countries where fossil fuel-based primary and secondary energy sources represent a large contribution to GVA and national GDP, e.g., Australia and Poland. In contrast, sovereign bonds of countries with

[8] The Global Change Assessment Model (GCAM) is the IAM developed by the Joint Global Change Research Institute in Maryland to explore the dynamics of the coupled human-Earth system and the response of this system to global change (http://www.globalchange.umd.edu/gcam/). WITCH is the IAM global dynamic model integrating the interactions between the economy, the technological options, and climate change. It is developed at the RFF-CMCC-EIEE European Institute on Economics and the Environment in Milan (IT): www.witchmodel.org

growing shares of renewable energy sources contributing to GVA, such as Austria, experience positive shocks. The largest negative shocks are associated with the 10-year sovereign bonds issued by Australia, equal to 17.36% decrease in value (under a tight climate policy scenario (StrPol450) characterized by carbon tax introduction) that translates in an increase in the Climate Spread. The negative shock on the sovereign bond is due to the negative shock on the fiscal revenues of the fossil fuel extraction and carbon-intensive sectors, which represent a relevant share of Australian GDP**.** In contrast, positive shocks on the sovereign bonds' value (and thus a decrease in the Climate Spread) are associated with the bonds of countries that are aligning their economies to the climate targets, e.g., Austria (due to the role of hydropower in electricity generation).

Table 4-3 Climate Spread of sovereign bonds.

Geo region	Models' region	WITCH: bond value shock (%)	WITCH: yield (spread) shock	GCAM: bond value shock (%)	GCAM: yield (spread) shock
AUSTRIA	EUROPE	1,3	-0,16	0,13	-0,02
AUSTRALIA	REST_WORLD	-17,36	2,45	n.a.	n.a.
BELGIUM	EUROPE	0,84	-0,1	0,03	0
CANADA	PAC_OECD	-5,21	0,67	-18,29	2,61
POLAND	EUROPE	-12,85	1,75	-2,49	0,32

Note: Climate policy shocks on selected OECD sovereign bond and Climate Spread conditioned to a tight climate policy scenario (StrPol450). Positive shocks on the yield correspond to negative shocks on the value of the sovereign bond. Climate Spread: 2,45=245 basis points. GCAM and WITCH IAMs were used to obtain the shocks on the energy technology trajectories conditioned to the StrPol450 2°C-aligned climate policy scenario. The shock on the bond is the shock on the value of the bond, while the shock on the bonds' yield is its Climate Spread. Source: Battiston and Monasterolo (2019)

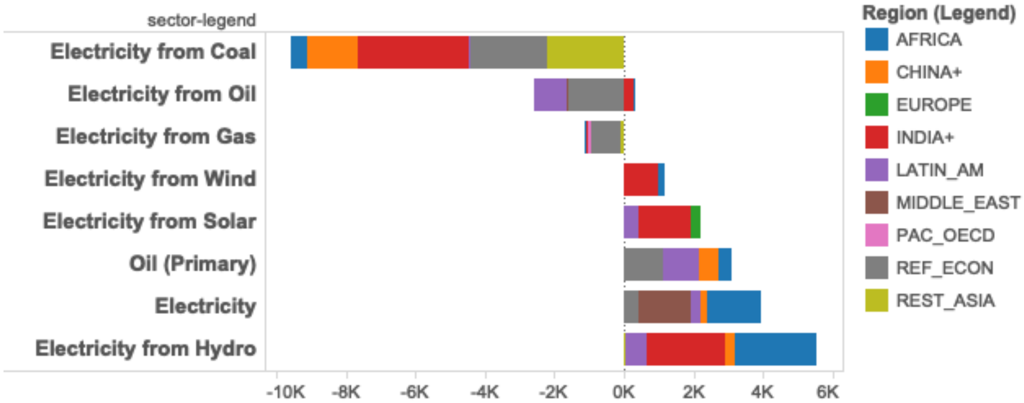
4.3 Climate risk assessment on energy infrastructure projects of Chinese development finance institutions

Monasterolo et al. (2018) used the CLIMAFIN methodology to assess the climate transition risk exposures of two main Chinese policy banks' (China Development Bank and Export-Import Bank of China) portfolios to overseas energy infrastructure projects. They analyzed 199 overseas energy investment loans (from oil-based primary energy to solar-based electricity production) in 63 low-income and mid-income countries in 2000-2018 with a combined value of US$228.105 billion. They found that the banks' exposures to losses induced by climate transition risk ranged between 4% and 22% of their portfolios.[9]

Figure 4-4 shows the results of the analysis under a stringent 2°C-aligned climate policy scenario (i.e., StrPol450, Kriegler et al., 2013) characterized by the introduction of a carbon tax and countries' fragmented action. The authors found that negative shocks on project loans' value affect coal power generation in the Chinese and bordering countries' region (i.e., CHINA+), and oil and gas power generation in former USSR and transition countries (i.e., the Reforming Economies). In contrast, positive shocks are associated with renewable energy projects, in hydropower in the African region and nuclear in Pakistan. The scenarios and shocks presented in Figure 4-4 are computed using the GCAM IAM and the LIMITS database, while the shocks are in USD million.

[9] Note that with an average 12-times leverage, even an average shock (10% circa) could lead the banks to financial distress.

Figure 4-4 Climate financial risk assessment of Chinese overseas energy projects.



Note: Projected gains and losses of China Development Bank and Export-Import Bank of China's overseas energy loans portfolio (project based) conditioned to stringent 2°C-aligned climate policy scenarios (in million USD). Source: Monasterolo et al. (2018)

4.4 Climate Stress-test of the financial system

In 2017, Battiston et al. (2017) published a Climate Stress-test exercise that provides an application of financial valuation in network models to the analysis of equity portfolios of banks exposed to climate transition risks. First, the authors assessed investors' exposure to climate transition risk using the CPRS classification. Then, with the climate stress-test, they assessed the first and second-round losses of investors' portfolios conditioned to climate transition scenarios, i.e., the indirect losses due to devaluation of counterparties' debt obligations on the interbank market, using the DebtRank[10]. They further calculated the Climate VaR, conditioned to different climate transition scenarios provided by IAMs and under low-carbon or high-carbon investment strategies, of the 20 most exposed banks in the EU and US (Figure 4-5).

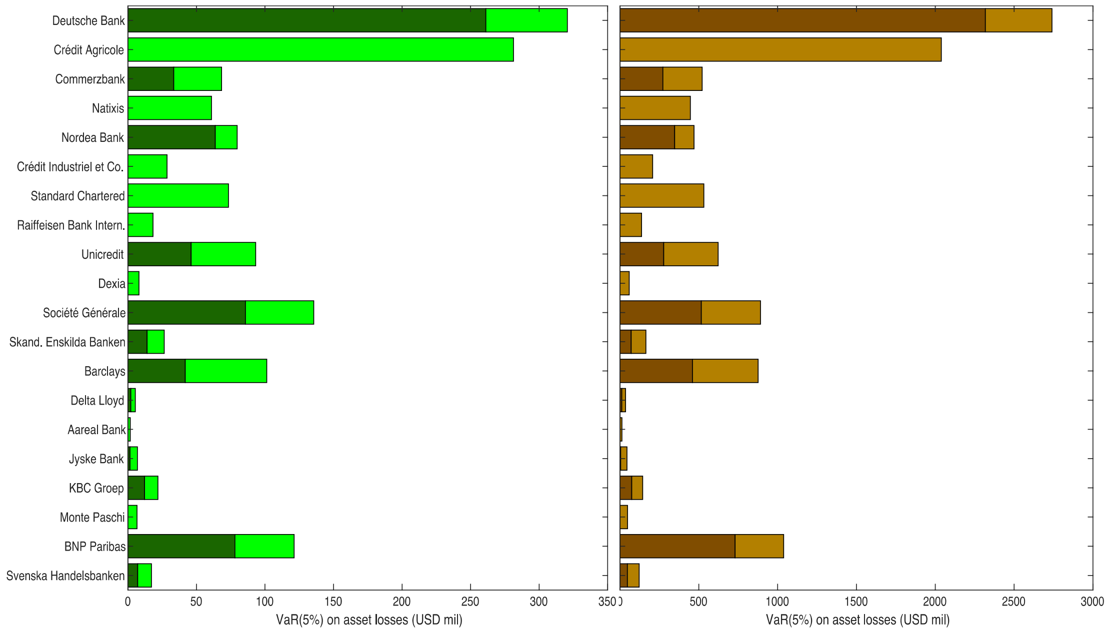
The authors found that the exposure of institutional investors to climate transition risk is largely heterogenous and amplified by network effects. In particular, the exposures of pension and investment funds to CPRS reached 43-45% of equity portfolios, and the potential losses could be amplified by the mutual exposures of financial actors (e.g., pension funds and investment funds). Roncoroni et al. (2019) further developed the climate stress-test applied to Banco de Mexico's portfolio using the Asset Network Valuation Framework (NEVA) approach (Barucca et al., 2019).

Battiston et al. (2017)'s Climate Stress-test considered micro-level climate transition risks, i.e., the exposures of individual banks to individual financial contracts (equity holdings) and computed the Climate VaR (VaR 95, i.e., 5%) on largest EU and US banks' portfolios, assessing the impact of a disorderly transition on banks' capital. They found that banks with a "environmentally unsustainable" investment strategy (i.e., those mostly exposed to fossil fuel and carbon intensive firms) incur large losses (Figure 4-5 left chart) in comparison to banks with a greener investment strategy (Figure 4-5 right chart). Moreover, the losses via first round (i.e., due to direct effects, dark colors) are amplified by risk reverberation and contagion of

[10] The DebtRank is a reference measure of systemic financial impact developed by Battiston et al. (2012).It is inspired by feedback-centrality and allows to determine the systemically important nodes in a network to assess drivers of systemic financial risk.

intra-financial contracts (i.e., the indirect effects, lighter colors). For instance, with regards to the two most exposed banks, Deutsche Bank's losses on capital are driven by direct effects, while Credit Agricole's losses are driven by indirect effects. This means that the largest banks are heterogeneously exposed to climate transition risk and the related losses could be amplified by financial interconnectedness, with implications on asset price volatility and financial stability (Monasterolo et al., 2017).

Figure 4-5 Climate Value at Risk (VaR) of EU largest banks conditioned to low-carbon or high-carbon investment strategy



Note: The Climate VaR (5%) analysis is conducted on the equity holdings of 20 most severely affected banks, under scenario of renewable (green, left chart) and fossil fuel and carbon intensive (brown, right chart) investment strategies, in USD million. Dark (light) color represents first (second) round losses. The analysis is based on the financial network model by Battiston et al. (2012) that introduced the DebtRank. Source: Battiston et al. (2017)

5 Conclusion

In this chapter, we presented CLIMAFIN, a transparent and science-based approach vetted by academics and practitioners. CLIMAFIN allows to translate forward-looking climate transition scenarios into financial shocks and to provide investors and financial supervisors with scenario-adjusted risk metrics and models (i.e., Climate Spread, Climate VaR and Climate Stress-testing).

The innovative approach of CLIMAFIN supports private and public financial institutions in their portfolio risk management strategies. It also provides financial supervisors with a methodology, independent from the ones developed by the industry, in order to inform the design of regulations to foster financial stability in the low-carbon transition.

Embedding climate risk into financial risk metrics requires to connect areas of knowledge which have remained separated so far and developed in parallel by climate scientists, climate economists, financial risk and network experts. Moreover, this interdisciplinary endeavor would not be possible without the long-term dedication of academic researchers.

The CLIMAFIN applications addresses three important elements of climate-financial risk assessment. First, **the temporal scale of the problem and its uncertainty** compel us to move from a stress-test approach based on a single type of scenarios to a set of scenarios, to be able to compute the Climate VaR conditioned to the uncertainty that characterizes the scenarios. Second, the **assumptions of the scenarios matter for their use in financial assessment**. New generation of climate scenarios assumes that countries are on track to deliver on their 2030 climate pledges, and do not consider the role of finance nor its complexity in achieving the scenarios, implying that funds for undertaking even massive investments in energy technology (and change the energy technology composition) are always available with no frictions. However, in reality, financing (in particular to low-carbon energy investments) is constrained and affects the likelihood of the transition scenarios. Third, **the information gaps at firm level** (e.g., the energy technology and emissions profile) mean imperfect information for investors about their exposure to climate risks via firms' contracts (e.g., stocks, bonds, or loans). Greenhouse gases (GHG) emissions accounting suffers from **limited availability, comparability and relevance for climate policy** (Monasterolo et al., 2017). In contrast, in the definition of the activities that are exposed to transition risk, i.e., the CPRS, CLIMAFIN considers not only GHG direct and indirect emissions of activities but also their relevance for climate policy implementation, their role in the energy value chain, and firms' future investment plan (e.g. CAPEX).

CLIMAFIN has been applied to several portfolios (e.g., equity holdings of EU and US largest banks, sovereign bonds' portfolios of European insurance firms and central banks, syndicated loans of US banks, etc.) and is supporting several central banks and financial regulators' climate financial risk assessment exercises. CLIMAFIN has been recently extended to the analysis of the exposure of US banks' loans to climate physical risks (storms and floods) impacting on firms and sectors' capital intensity, at a granular geographical level, and computing the Value-at-Risk (95 and 99 percentile by Battiston et al., 2020).

The result indicates that under several climate scenarios, the potential impact of a disorderly transition to a low-carbon economy on financial actors (e.g., pension funds, investment funds and insurers, development banks) is considerable. In addition, investors' exposures to climate risks are large and can be amplified by financial complexity, potentially creating new sources of risk for economic and financial stability.

Regarding climate transition risks, current CLIMAFIN's developments focus on the refinement of the disorderly transition scenarios in collaboration with the IAM community, including SSPs and Post-Paris Agreement scenarios, and the analysis of the feedbacks of the climate financial shocks Battiston et al., 2020. Regarding the climate physical risk scenarios, the CLIMAFIN team is working at the refinement of the shocks' transmission to the individual firms at a granular geo-localized level, in collaboration with development finance institutions (e.g., the World Bank), using microlevel data.

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