Basel Committee
on Banking Supervision

Climate-related financial risks – measurement methodologies

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Contents

Glossary

Acute physical risk	See physical risks
Basel Framework	The Basel Framework is the full set of standards of the Basel Committee on Banking Supervision (BCBS). As at March 2021 the framework consists of 14 standards as set out at https://www.bis.org/basel_framework/
Carbon taxation (carbon tax)	A carbon tax (or energy tax) generally refers to a tax levied on the carbon content of some goods and services, typically in the transport and/or energy sectors. The purpose is to reduce CO_2 emissions by increasing the price of these goods and services. It is one of the main types of tools used in climate change policies around the world.
Chronic physical risk	See physical risks
Climate	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
Climate-related financial risks	The potential risks that may arise from climate change or from efforts to mitigate climate change, their related impacts and their economic and financial consequences.
Climate sensitivity	The change in the annual global mean surface temperature in response to a change in the atmospheric CO_2 concentration or other radiative forcing.
Climate vulnerability	Vulnerability is the propensity or predisposition to be adversely affected. It encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. In the context of climate risk drivers, vulnerability refers to the level of damage which can 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 that has strong flood control infrastructure and strong building regulations. Vulnerability assessments may include secondary impacts such as business interruption.
Damage functions	Relationships translating the effect of a specific hazard or change in global mean temperature affecting a building structure or the real economy into a damage ratio, which is the ratio of the repair cost to its replacement value.
Energy label	Energy labels describe various levels of energy efficiency, eg of buildings. Energy efficiency refers to the amount of energy required to provide a specific function, product or service (eg heating a building), with the idea that the lower the needed amount happens to be, the more efficiently the function, product or service is provided.
ESG	ESG (environmental, social and governance) refers to a set of criteria that play a role in the investment decision-making process or in a company's operations. Environmental factors consider how an investment or a company contributes to environmental issues such as climate change and sustainability. Social factors examine the social impacts of an investment or a company on communities. Governance relates to transparency and legal compliance of an investment or a company's operations, for instance in terms of accounting and shareholders' rights.
Feedback loop	An interaction in which a perturbation in one climate quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback loop is one in which the initial perturbation is weakened by the changes it causes; a positive feedback loop is one in which the initial perturbation is enhanced. The initial perturbation can either be externally forced or arise as part of internal variability.
Global mean surface temperature	Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in global mean surface temperature, near-surface air temperatures over both land and oceans are also used.

Global warming	The estimated increase in global mean surface temperature averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue.
Greenhouse gases (GHGs)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere.
Physical hazard (or hazard)	The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In TFCR (Task Force on Climate-related Financial Risks) reports, the term hazard refers to climate-related physical events or trends or their physical impacts.
Physical risks	Economic costs and financial losses resulting from the increasing severity and frequency of: • extreme climate change-related weather events (or extreme weather events) such as heatwaves, landslides, floods, wildfires and storms (ie acute physical risks); • longer-term gradual shifts of the climate such as changes in precipitation, extreme weather variability, ocean acidification, and rising sea levels and average temperatures (ie chronic physical risks or chronic risks); and • indirect effects of climate change such as loss of ecosystem services (eg desertification, water shortage, degradation of soil quality or marine ecology).
Physical risk driver	Physical risk drivers are the changes in weather and climate mentioned above that lead to physical risks and impacts on economies and banks (eg a flood).
Projection	A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised. A climate projection, different from climate predication, is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using climate models.
Representative Concentration Pathway (RCP)	Scenarios that include time series of emissions and concentrations of the full suite of 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 emphasises that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome.
Scenario	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (eg rate of technological change, prices) and relationships. Scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.
Scenario analysis	Scenario analysis is a tool that is used to enhance critical strategic thinking. A key feature of the scenarios analysed is to explore alternatives that may significantly alter the basis for "business-as-usual" assumptions. Accordingly, they need to challenge conventional wisdom about the future.
Stranded asset	Asset that at some time prior to the end of its economic life is no longer able to earn an economic return as a result of changes associated with the transition to a low-carbon economy (adapted from Carbon Tracker).
Stress test	The evaluation of a financial institution's financial position under a severe but plausible scenario. The term "stress testing" is also used to refer to the mechanics of applying specific individual tests and to the wider environment within which the tests are developed, evaluated and used within the decision-making process.
Tipping point	A level of change in system properties beyond which a system reorganises, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the climate system, it refers to a critical threshold when the global or regional climate changes from one stable state to another stable state.

Transition risks	The risks related to the process of adjustment towards a low-carbon economy.
Transition risk drivers	These drivers represent climate-related changes that could generate, increase or reduce transition risks. They include changes in public sector (generally government) policies, legislation and regulation, changes in technology and changes in market and customer sentiment, each of which has the potential to generate, accelerate, slow or disrupt the transition towards a low-carbon economy.
Transmission channels	The causal chains that explain how climate risk drivers give rise to financial risks that impact banks directly or indirectly through their counterparties, the assets they hold and the economy in which they operate.

Executive summary

This report provides an overview of conceptual issues related to climate-related financial risk measurement and methodologies, as well as practical implementation by banks and supervisors. Building on a companion report which identifies climate risk drivers and describes their transmission channels to the financial system, this report is structured in three parts. It first outlines general issues in measuring climate-related financial risks, along with the translation of underlying concepts to concrete climate risk measurement (including an inventory of candidate forward-looking methodologies). Second, it takes stock of how banks and supervisors are currently employing or developing methodologies for measuring climate-related financial risks. This is informed by a supervisory survey conducted among members of the Basel Committee's Task Force on Climate-related Financial Risks (TFCR), and workshops with the banking industry in 2020. Third, it provides a high-level overview of strengths and weaknesses of the main types of measurement approaches and assesses gaps and challenges in their execution and implementation.

The report contains five key findings:

First, climate-related financial risks have unique features, necessitating granular and forward-looking measurement methodologies. While conventional risk management tools may serve as a springboard for climate-related financial risk measurement, the impacts from climate risk drivers contain unique features that could challenge the incorporation of these risks into existing processes. A particularly high exposure granularity may be needed to assess both physical risks (geolocational data given spatially varying characteristics of climate impacts) and transition risk (counterparty- and industry-level data capturing risk resulting from a shift from a high- to a low-carbon economy). This need arises from heterogeneities at different levels (eg sectoral, jurisdictional or geographic). Further key conditioning elements relate to uncertainty stemming from data, models or the limited ability of the past to act as a guide for future developments. In addition, effective measurement should consider the availability and adoption of any risk mitigation or reduction techniques by banks or their counterparties.

Second, to date, measurement of climate-related financial risks by banks and supervisors has centred on mapping near-term transition risk drivers into counterparty and portfolio exposures. Areas of particular focus include capturing the carbon intensity of portfolios and sectoral exposures, devising internal climate risk ratings or scores, or estimating the prospect of more stringent climate regulation. Progress has been less tangible in empirically capturing banks' exposures to physical risks. This may be at least partly attributable to considerable additional non-standard data requirements associated with quantifying physical climate impacts, or confidence in the ability to insure against prospective losses.

Third, banks and supervisors have predominantly focused on assessing credit risk, as they advance in applying methods to translate climate-related exposures into categories of financial risk. A considerable focus on credit risk modelling has contrasted with a lesser focus on market risk, and a very limited focus on liquidity and operational risk. Credit risk quantification efforts are mainly focused on addressing risks to corporate lending and real estate exposures, whereas other risk assessments, including on reputational risk, have remained predominantly qualitative. Moreover, the adoption of climate-related metrics has also been instrumental in allowing banks to communicate more actively with their stakeholders, as they seek to manage reputational risks. Methodological efforts have built upon exposure mapping, with use of a varied set of candidate methodologies. Available methods specifying the paths of the main economic variables that underpin the performance of assets have run along a spectrum between bridging high-level features of climate modelling with economic and financial modelling, to methods which account for complex feedback and amplification effects inherent to associated systems.

Fourth, while banks and supervisors remain at an early stage of translating climate-related risks into robustly quantifiable financial risk, work continues to gather pace. Initial efforts have focused mainly on identifying climate-related risks and related exposures. Methods linking these to traditional risk parameters (such as probability of default or loss-given-default) remain, in contrast, often in early stages. In general, the retooling of in-house systems for risk assessment purposes appears to face limitations, evidenced by banks' extensive use of external providers. As pilot analyses have concluded, the need for forward-looking methodologies and multiple scenarios is increasingly recognised by banks and supervisors – but frameworks to systematically translate climate change scenarios into standard financial risk are not in place and currently require a mix of approaches. Initial scenario analyses and stress tests have in many cases focused on selected portfolios or exposures (for transition risks), and selected hazards (for physical risks). Supervisory survey results and industry outreach also indicate that banks and supervisors often base their scenario analyses or stress tests on scenarios developed by third parties, and tend to include scenarios for both transition and physical risks – though here also a stronger focus has been put on transition risk to date. In both cases, efforts are ongoing to improve the translation of scenarios into financial risk parameters over typical risk management horizons. Challenges include the range of impact uncertainties, limitations in the availability and relevance of historical data describing the relationship of climate to traditional financial risks, and questions around the time horizon. On the latter, forward-looking methods tend to span a longer time frame than traditional macroeconomic exercises, therefore requiring conditioning assumptions about balance sheet adjustment options.

Fifth, key areas for future analytical exploration relate to measurement gaps in data and risk classification methods, as well as methodologies suitable for assessing long-term climate phenomena not always of a standard nature. On the side of measurement, assessing climate-related financial risks will require new and unique types of data – not necessarily the same as those banks have traditionally used in financial risk analyses – spanning three areas: data translating climate risk drivers into economic risk factors; data linking climate-adjusted economic risk factors to exposures; and data to translate climate-adjusted economic risk into financial risk. The mapping of climate risk drivers to financial exposures also requires classifying and differentiating risks across exposures. These two features of measurement – data and risk classification – warrant further investment. First, new and more granular data collections will probably be needed for both physical and transition risk assessments. Such needs range from geolocational data capturing risks of physical damage associated with acute or chronic physical risks, to transition risks associated with climate adaptation actions at the level of industrial sectors and their constituent firms. Needs also exist on the side of financial data, notably for highly granular data collections to capture exposures of small and large financial institutions alike. Gaps include the quantity and quality of data reported by banks' counterparties (particularly by smaller firms), as well as issues related to the consistency of risk assessments at both the portfolio and exposure level. Second, banks and supervisors also face challenges applying consistent risk differentiation between individual exposures at a sufficient level of granularity across jurisdictions, as well as a lack of convergence in data standards limiting exposure comparability for internationally active banks.

On the side of methodologies, approaches suitable for capturing climate-related financial risks will require further investment, notably to account for uncertainty spanning three areas: intrinsic future uncertainty inherent to projections of physical and transition risk drivers and ensuring standardised scenarios; measurement uncertainty related to data gaps, which may limit the suitability of backtesting to calibrate loss or damage functions; and model-based uncertainty, with more work needed for a robust quantitative assessment of identified climate risk drivers and their impacts on banks – including risks to counterparties, assets, liquidity and operations. The systemic nature of climate change might imply many interconnections and feedback loops, non-linearities and tipping points. Areas of methodological work warranting further investment include granular climate risk exposure analysis, as well as enhanced scenario analysis capabilities bridging climate science with financial modelling. In particular, a forward-looking assessment of climate-related financial risks may require augmenting the standard risk scenarios used by banks to include both the prospect of climate-related hazards and possible policy and technological shocks and shifts in both market and customer sentiment – evaluating a suite of shocks which might only be material beyond the risk management horizons typically used by banks and supervisors.

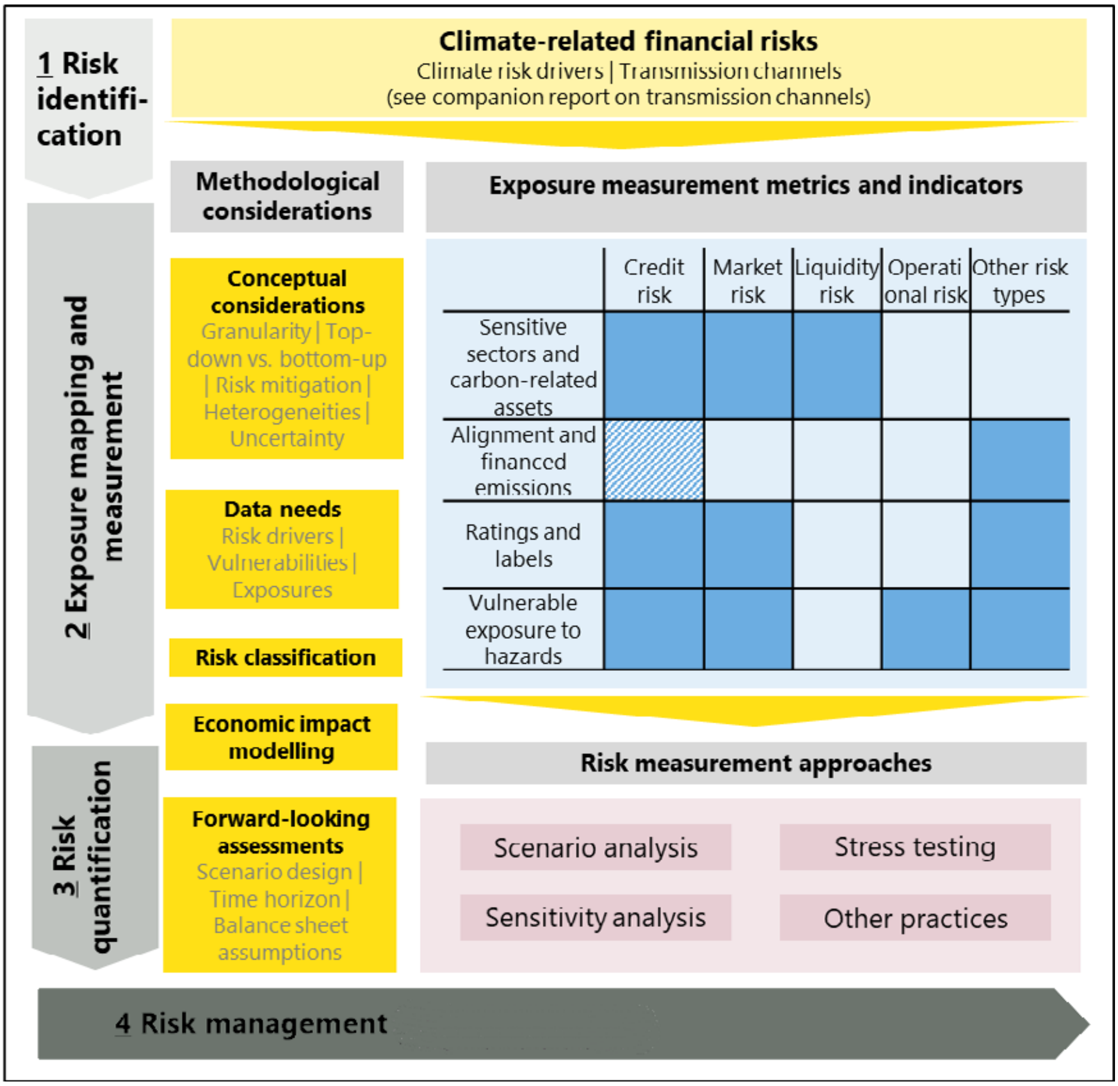
Notwithstanding the ongoing progress of supervisors and banks alike in coming to grips with climate-related financial risks, continued efforts are needed to enhance their measurement, monitoring and management. Initiatives under way within the stakeholder community to address all of these gaps are encouraged, to strengthen the basis for estimating climate risk impacts, and provide the foundation for efforts to mitigate climate-related financial risks.

1. Introduction

The combined economic and financial impacts associated with climate change may give rise to considerable future losses for banking institutions. Against this background, an effective risk management framework for banks and supervisors should have three goals: first, to identify material climate risk drivers and their transmission channels;[1] second, to map and measure climate-related exposures and any area of risk concentration; and third, to translate climate-related risks into quantifiable financial risk metrics.

Building on a discussion of conceptual issues related to climate-related financial risk measurement, this report provides an overview of measurement methodologies that banks and supervisors are currently employing or developing. Figure 1 presents an illustrative overview of this work, and how it fits into the broader risk management process.

A conceptual climate risk assessment framework for banks and supervisors — Figure 1



The infographic summarises key issues contained in this report; darker cells under "Exposure measurement metrics and indicators" denote a qualitative assessment of current risk categories where listed metrics are generally applied. "Other risk types" refer to reputational risks, for instance.

[1] See the companion report, *Climate-related risk drivers and their transmission channels.*

The report is organised as follows. Section 2 examines general issues in measuring climate-related financial risks, exploring the translation of underlying concepts to concrete climate risk measurement, and including an inventory of candidate forward-looking methodologies. Section 3 takes stock of how banks and supervisors are currently employing or developing methodologies for measuring climate-related financial risks. Section 4 identifies areas for future analytical exploration, discussing strengths and weaknesses of the main types of measurement approaches and assessing gaps and challenges in their execution and implementation. Section 5 concludes.

2. Methodological considerations

Mapping and measuring risk exposures constitute fundamental components of an effective risk governance framework (BCBS (2015)). The incorporation of climate-related financial risks into risk management frameworks may follow risk assessment processes similar to those used for managing any significant risk; however, climate-related financial risks have unique properties that challenge traditional risk measurement. This section reviews the methodological concepts that financial institutions and supervisors face when conducting exposure mapping and measurement of climate-related financial risks. It is structured as follows: Section 2.1 opens with a discussion of foundational concepts that factor into both the mapping of exposures and the measurement of climate-related financial risks; Section 2.2 discusses the unique data requirements of mapping exposures and measuring climate-related financial risks; Section 2.3 discusses the role and characteristics of climate risk classifications as an initial input into mapping climate-related risk exposures; Section 2.4 catalogues various approaches that estimate climate-related financial risks; and Section 2.5 concludes by presenting conceptual considerations for scenario analyses and stress testing.

2.1. Conceptual considerations in measuring climate-related financial risks

The assessment of climate-related financial risks introduces new concepts to risk managers. These concepts feature prominently in both the mapping of exposure to climate risk and the measurement of climate-related financial risks. The following section outlines several of the more pertinent concepts for banks and supervisors.

2.1.1 Physical and transition risk measurement considerations

Exposure mapping and risk measurement methodologies for climate-related financial risks can be differentiated according to physical risk and transition risk drivers (see the companion report on transmission channels for a description of each risk driver), with each risk type having unique characteristics that drive measurement approach decisions.

In general, physical risk drivers (physical hazards) can be linked to financial exposures using damage functions that define the impacts of specific hazards on the real assets and activities that generate financial flows. The disruptions to assets, activities and their corresponding financial flows can then be integrated, in principle, into established risk models that dimension financial risk parameters. The particular damage functions used within a specific risk model will often be informed by a bank's technological and resource capacity, the availability of relevant data, and the intended purpose of the estimation. Additionally, specific damage functions will be informed by sectors, severity of hazards, time horizon factors and geospatial idiosyncrasies. A challenge when using damage functions is the degree to which empirical functions are available or complete for all sectors, exposures and hazards. Similarly, the impacts of the shift from a high- to a low-carbon economy (transition risk) can be estimated through the use of models linking specific transition risk drivers to the economic factors that generate financial flows. Similarly to physical risks, projected disruptions to financial flows could, in theory, be integrated into conventional models of financial risk measurement.

Given their distinct features, physical and transition risks are often viewed and assessed separately; however, several features relating to climate change are increasing the likelihood that these risks may be dependent on each other, which may necessitate their being considered jointly. Due to past increases in greenhouse gas (GHG) concentrations in the atmosphere,[2] certain future hazards arising from climate change are likely to be inevitable. In addition, the climate system is potentially subject to environmental tipping points[3] that could be exceeded with continued increases in GHG concentrations. The changes in climate that are already locked in with existing GHG concentrations and the non-linear acceleration of impacts that could occur if tipping points are surpassed could both perpetuate and compound climate-related damages in spite of current actions to reduce GHG emissions – therefore, transition risk scenarios may still require assessment of physical risks. Similarly, the increased frequency and severity of physical risks[4] is likely to put pressure on policymakers to take decisive actions with the aim of mitigating physical risk impacts in the future, thereby increasing the probability that transition risks could manifest concomitantly to physical risks – which in turn would necessitate incorporating an increased probability of transition risk alongside physical risk assessments.

2.1.2 Exposure granularity

Banks are exposed to climate-related financial risks through their transactions with clients and counterparties: corporates, households, sovereigns and other financial institutions.[5] In estimating the implications of climate risk drivers for these transactions, banks and supervisors will need to determine the level of exposure granularity most relevant for their respective risk assessments. This may be influenced by several factors, including but not limited to:

- specific physical or transition risk drivers;
- availability of relevant data;
- risk management decision being supported; and
- increasing computational complexity with increasing granularity.

These decisions will influence the selection of available approaches, which will in turn affect the utility of model outputs for risk management. Methodologies reliant on a higher degree of granularity may be more useful for underwriting, valuation, or pricing, but may suffer from high computational intensity and a paucity of clean, standardised input data. Conversely, methodologies that are less complex and more tolerant of sparse data may be more useful for strategic planning or portfolio allocation. Banks, and to a lesser extent supervisors, face a trade-off on these methodological decisions.

2.1.3 Top-down and bottom-up approaches

One particular conceptual consideration that applies to both exposure mapping and risk estimation is the selection of top-down versus bottom-up approaches.[6] In general, top-down approaches start by dimensioning risk at the general, or aggregated, level and then "push down" or attribute the aggregated measure of risk to component parts. For instance, a top-down approach to exposure mapping may use sector or industry averages (eg carbon emissions intensity) and apply these averages to individual exposures – this simplifying approach assumes that the performance of the sector is reasonably representative of its constituent activities, with differences among exposures within a particular sector

[2] The IPCC projects with high confidence that the removal of all human-emitted CO_2 from the atmosphere by natural processes will take a few hundred thousand years (IPCC (2013a)).

[3] For literature on tipping points see, for instance, IPCC (2018a).

[4] IPCC (ibid) notes that the increase in global mean surface temperature, which reached 0.87°C in 2006–15 relative to 1850–1900, has increased the frequency and magnitude of impacts on organisms and ecosystems, and projects with high confidence that risks will be larger as this global mean increases.

[5] See the companion BCBS TFCR report, *Climate-related risk drivers and their transmission channels*.

[6] It should be noted that different supervisors, banks or third parties may present different definitions of top-down versus bottom-up approaches.

providing less meaningful information. In risk measurement, top-down modelling approaches usually try to estimate risk at the consolidated level (eg a consolidated portfolio, consolidated bank, or aggregated banking system) and proportionally allocate risk to the component parts. However, apportioning aggregate measures of risk to constituent parts may overlook the contribution of individual risk exposures in the presence of interactions among those parts.

Conversely, bottom-up approaches dimension risk at the component level, aggregating these individual measures of risk up to provide a consolidated view of risk. For instance, a bottom-up approach to exposure mapping might assess relative risk exposure at the asset (eg loan) or counterparty level (or along groups of assets or counterparties that exhibit substantively similar properties) and sum up the risk exposures to provide a combined portfolio-level (or banking sector) view of exposure to risk. Similarly, bottom-up modelling approaches usually begin by assessing the impact of physical and/or transition risks on an asset, counterparty, or portfolio level, making it possible to first differentiate financial impacts based on specific exposure characteristics then aggregate up to a consolidated measure of (eg credit or market) risk. From the perspective of the supervisor, a bottom-up approach might assess climate-related financial risks at the individual bank level and aggregate the results up to approximate the risk to the banking system. However, aggregating individual risk exposures to a consolidated view of risk may require understanding potential correlations among risk exposures that could amplify or diversify risk within a portfolio or bank.

2.1.4 Incorporating risk mitigation and risk reduction

As banks consider how to measure climate-related financial risks, they may need to estimate the effect of potential risk mitigation and to what extent mitigants could moderate or offset risk-taking. Similar to typical proactive financial risk offsetting practices (eg hedging, netting), climate risk exposure that includes the benefits of offsetting strategies (eg insurance, weather derivative hedging, catastrophe bonds) can be viewed as net exposure, while approaches that estimate climate risk impacts without incorporating offsetting strategies are viewed as showing gross exposure. Distinguishing between net and gross exposures can allow banks to disaggregate the impact of risks and of mitigating actions.

In addition to proactive measures a bank can take to reduce its risk exposure, climate-related financial risks can also be offset through counterparty measures to adapt to, or mitigate the effects of, climate change;[7] these measures may modify the relationship of exposures to risk drivers within banks' risk models. For example, the presence of strong building regulations and flood mitigation measures[8] may minimise an area's vulnerability to specific physical hazards, and therefore reduce potential losses on an asset exposed to the location, compared to an area without such regulations and measures (NGFS (2020a)). Moreover, counterparties can take measures to moderate disruptions to their own income sources arising from hazard events through insurance coverage. For example, estimating the gross flood risk exposure of a coastal mortgage portfolio may involve calculating the financial outflows and impairment resulting from reductions of cash flows and in collateral values arising from flood damage, in the absence of any insurance offset; when insurance coverage is included, however, the ultimate loss to the portfolio would also consider the inflows from insurance proceeds, the level of coverage (insurance protection gap), and any timing mismatch between outflows and inflows.

[7] Mitigation approaches target reducing the sources and stabilising the levels of GHGs in the atmosphere; adaptation approaches target adjusting to actual or expected climate and its effects, particularly to moderate or avoid harm from these effects. See, for example, IPCC (2014c).

[8] For more information on adaptive options, See IPCC (2014d).

Calculating the gross exposure of an asset or portfolio is important for two main reasons: (i) understanding exposure without incorporating risk offsetting practice can help inform the risk decision-maker about the present magnitude of climate-related risks and how these risks might evolve over time; and (ii) mitigants may lapse, change, fail to materialise, or become obsolete, reducing their reliability to effectively offset risk. For example, insurance and reinsurance firms often react in two main ways when insurance claims increase materially: they tend to increase insurance premiums or reduce coverage, such as through the introduction of policy caveats[9] or the decision not to insure a specific risk or region altogether (UNEP FI et al (2018)). Because the risk reduction benefits of mitigants are not certain (particularly as some strategies, such as hedging, remain underdeveloped), measuring the effects of gross risk exposure and risk mitigants separately may be an important consideration for banks and supervisors seeking to understand the full set of costs, benefits and efficacies associated with different courses of action.

2.1.5 Heterogeneities

Heterogeneities play a key role in selecting measurement approaches, as each bank faces idiosyncratic climate-related financial risks within its portfolio, according to the geographies, markets, sectors, political environment and technological frontiers to which its clients and counterparties are exposed. These considerations may drive the selection criteria for variables or model types by individual banking institutions and their supervisors. Several of these (non-exhaustive) heterogeneities are listed below:

- Geographical heterogeneity: Climate hazards manifest regionally or locally according to geographical diversity.[10]
- Sectoral heterogeneity: Corporate counterparties tend to exhibit risk exposure commonalities along sectoral classification, typically for transition risk but also for physical risk (IPCC (2014b)). However, sectoral classification can mask heterogeneity within a given sector, as individual clients may demonstrate differing carbon intensities (ESRB (2020)), energy mixes, or adaptive capabilities. Furthermore, existing sectoral classifications may ignore commonalities in climate sensitivity across sectors that factor into risk concentration.
- Jurisdictional heterogeneity: As national (and subnational) borders define the limits of legal jurisdiction, exposures within jurisdictional boundaries may face differing policy and regulatory regimes that influence vulnerability to climate risks. Such regimes may include permissions or restrictions on specific energy types that limit comparability of transition risks for similarly classified exposures in different countries or regions, or differing probabilities of adopting a globally calculated carbon policy at the national, state, or local level.

2.1.6 Sources of uncertainty

Measuring climate-related financial risks involves uncertainty that may lead to misestimation of risks, although estimates of climate sensitivity have generally trended higher as new information is incorporated into climate models, suggesting that estimates of climate-related financial risks may skew towards underestimation. Given that future climate-related financial risks will probably differ from observed

[9] The introduction of caveats can take multiple forms, such as deductibles, where only losses above a predetermined threshold will be covered by the insurance firm, and franchises, where losses must exceed a predetermined threshold for the insurer to cover the entire liability.

[10] “The climate system may be global in extent, but its manifestations – through atmospheric processes, ocean circulation, bioclimatic zones, daily weather, and longer-term climate trends – are regional or local in their occurrence, character, and implications” (IPCC (2014a)).

patterns, recourse to historical data in risk estimation or model calibration is limited.[11] Instead, quantifying climate-related risks to banks necessitates applying a suite of assumptions about the interactions among the climate, anthropogenic activity, and economic activity that will impart considerable uncertainty to the estimation process. These assumptions involve forecasting the behaviour of economic actors and policymakers and the future of technological advancement, and resulting projections of future emissions pathways, modelling the impact of emissions on climate, and quantifying the economic consequences of climate impacts. Potential non-linearity in impacts resulting from climate tipping points, interconnections among natural systems (feedback loops) that can amplify climate impacts, and spatial heterogeneity in the frequency and severity of impacts are sources of model uncertainty when quantifying climate risk.[12] In addition, the long time horizons over which these climate impacts are expected to manifest require assumptions about discounting and timing of occurrence. In particular, the path of technological innovations introduces a high level of uncertainty that can render the optimal response by policymakers even more ambiguous. Methodological approaches to take these different drivers of uncertainty into account often involve evaluating a number of scenarios in a forward-looking manner. Some researchers argue that advances in modelling, data and technical alternatives (Barnett et al (2020)) could help reduce uncertainty, although other researchers argue that residual uncertainty may remain even with such advances (eg Pindyck (2020)).

2.2. Data needs

Assessment of climate-related financial risks will require new and unique types of data, different to the data banks have traditionally used in financial risk analyses. The data needed to map risk exposures and translate climate-related risks into financial risk estimates may be only partially available and may not adequately meet traditional data quality standards, such as the length of history, completeness, and granularity needed to support the risk decision-maker.[13] Moreover, data describing the historical relationship between climate-related impacts and their economic and financial consequences may not be representative of future climate-economy or climate-financial relationships.

Focusing on the types of data needed to assess climate-related financial risk, three broad data categories can be observed:

- data describing physical and transition risk drivers, needed to translate climate risk drivers into economic risk factors (ie climate-adjusted economic risk factors);
- data describing the vulnerability of exposures, linking climate-adjusted economic risk factors to exposures;
- financial exposure data, needed to translate climate-adjusted economic risk into financial risk.

2.2.1 Data describing physical and transition risk drivers

Data describing physical and transition risk drivers are the starting point for assessing how climate-related risks can impact banking exposures. These data include climate information or information about current and projected hazard events. They may be used as explanatory variables to influence economic outcomes

[11] In particular, parameter uncertainty induced through the use of historical data implies that extreme values, and as a consequence catastrophic outcomes, cannot be ruled out; see Weitzman (2009).

[12] Barnett et al (2020) also present a useful differentiation regarding climate models between (i) *risk* (uncertainty within a given model – addressed by probabilistic analysis), (ii) *ambiguity* (uncertainty across models – addressed by subjective probability assignment), and (iii) *misspecification* (uncertainty about models – addressed by model combination).

[13] Several reports have highlighted the need to identify and address data gaps in climate risk measurement, eg NGFS (2019), ESRB (2020). Additionally, some multilateral organisations are exploring data gaps in the climate risk space in the near term, including the Financial Stability Board (FSB) and the Network for Greening the Financial System (NGFS).

and alter existing economic relationships, or to identify at-risk locations with other geographical data (eg topographical data including coastal elevation models, satellite data, etc), or cost and performance data for energy substitutes that can be used in estimating energy price relationships. Many types of climate risk driver data are supplied by government agencies and academic organisations. Some are increasingly provided by commercial third parties that compile readily available and formatted data sets for use in financial risk assessment.

Several climatological and geological survey agencies provide "off-the-shelf" data sets that identify geographical areas exposed to individual physical hazards. These include forecasts for fluvial and coastal flooding or wildfires, and in some cases provide probability distributions for the hazard event. These products distil many disparate climate data sets into a more manageable format and may be based on past data (eg catastrophe databases) or include forward-looking projections based on climate models.[14] In addition, physical risk measurement approaches may also include the vulnerability of a location to physical hazards, which requires combining information on past hazards or forward-looking hazard projections with information on location-specific characteristics such as land, elevation, soil composition, land cover, etc. Several third-party data providers have started aggregating such data and building proprietary data services (eg "climate analytics") that synthesise climate information for use by specific industries, but also aim at calculating aggregate physical risk indices.[15]

Various climate data may feature in models (see Section 2.4.1) that generate "optimal" carbon prices aiming to internalise the external costs of GHG emissions, energy demand preferences, governmental subsidies, or anticipated technological disruptions. Furthermore, these data, for both physical and transition risks, might then be used in projections of economic activity, such as macroeconomic variables (eg GDP growth, unemployment rate, or interest rates) or microeconomic variables (eg local economic conditions and market prices) for different scenarios. Institutions having sufficient expertise and modelling capabilities can use these climate data themselves to estimate economic risk factors arising from physical and transition risk drivers, including disruptions to cash flows and supply and demand dynamics. However, only some institutions have sufficient expertise and resources to estimate these climate-derived economic risk factors in-house. Those lacking such a capacity may choose to source these risk factors directly from external third parties.

2.2.2 Data describing the vulnerability of exposures

In addition to climate-adjusted economic risk factors, banks and supervisors require information about the vulnerability of bank exposures to those risk factors. These data tend to include features specific to those exposures, such as geospatial data for corporates (including their value chains), location data for mortgage collateral, or data on counterparties' sensitivity to energy prices or carbon emissions in the production and distribution processes. Used in measurement approaches, these exposure vulnerability data facilitate the translation of the risk defined by climate-adjusted economic risk factors to financial exposures. Generally, the relevant characteristics of these data differ according to the climate risk driver under consideration. For physical risk, vulnerability of bank exposures will mainly be determined by the geospatial location of counterparties, whereas for transition risk, the vulnerability of bank exposures often depends on the counterparties' economic activity within particular jurisdictions.

Physical risks can impact the economy via damage to or destruction of property and inventory, disruptions to corporate value chains, and depression of regional economic or sectoral activity, among other effects (see the companion report on transmission channels). Consequently, to assess exposures' vulnerability to physical risks, a comprehensive matching of physical hazards with the location of relevant

[14] Such as the publicly available output from climate models contributing to the Coupled Model Intercomparison Project, also used in the IPCC reports; see, for example, Taylor et al (2012); Eyring et al (2016).

[15] See also Fiedler et al (2021) and references therein, for a discussion of methodological challenges and suggested solutions when using climate model data for financial risk assessments.

physical touchpoints can facilitate the estimation of potential economic impacts and, ultimately, of the potential disruption to the contractual cash flows of a bank's lending exposure. Such geospatial information often necessitates documenting granular geospatial details that go beyond the location of legal jurisdiction. For example, knowing the location of a manufacturer's headquarters may not be sufficient to assess the risk of a shock to its full value chain arising from physical hazards. Factories and inventory might be distributed across different regions and, hence, various nodes along the value chain might be exposed to completely different physical risks. This risk is not just limited to the borrower's in-house production channels and storage, but also covers its suppliers' processing, production and storage facilities (both raw and intermediate goods), the mode and route of transportation between various facilities, and their downstream distribution channels. In a similar vein for retail portfolios, location of collateral is important to estimate potential impairment to properties collateralising bank lending.

Furthermore, information about interconnections among retail, corporate and municipal borrowers may be required to assess impacts from deterioration in local economic conditions arising from severe or chronic weather events. For example, a retail borrower's connection to an adversely impacted location might have a compounding impact on local employment prospects and disaster recovery expenses, which could in turn weigh on the borrower's repayment ability. Information on the interconnectedness of counterparties (eg corporates, municipalities) to surrounding regions and demand markets may be needed to assess the impact of physical risk events on revenue forecasts or labour productivity. Municipal governments may come under pressure as local economic stress and impaired property depress the taxable base. Data that link exposures to regional economy effects may be more elusive to source than data on direct physical impacts as these regional ties can be less tangible than physical presence, although the losses and revenue declines from these effects could be quite large.

Assessing the vulnerability of exposures to transition risk often requires data about the sectors and subsectors in which corporate counterparties operate and their respective carbon sensitivities. Carbon sensitivity measures may include a corporation's current GHG emissions, the relation between productive capacity and these emissions, and the corporation's capability to mitigate or moderate its emissions intensity through innovation. In the technological disruption space, the price elasticity of energy demand, the sensitivity of price substitution, and structural supply constraints may feature prominently in assessments of certain economic sectors and their profitability.

2.2.3 Data to translate climate-adjusted economic risk factors into financial risk

Additional data is needed to translate the vulnerability of exposures into financial loss estimates. Here, banks and supervisors can generally turn to the financial variables typically used in conventional risk measurement techniques – data used to project cash flows, valuations, or prices. To perform risk analyses at the bank or banking system level, data on portfolio composition (eg asset holdings or loans) and relevant information on counterparties are needed to estimate potential impacts on these exposures, for example in potential adjustments to probability of default (PD) and loss-given-default (LGD) parameters in the credit valuation process or revenue forecasts in the strategic planning process. Furthermore, for modelling potential bank liquidity impacts due to climate risk, data reflecting the rollover, withdrawal, or pricing behaviours (among others) of funding providers (eg depositors, bondholders, wholesale funds) in response to climate risk drivers would be needed.

2.3. The role and characteristics of a microprudential climate risk classification

As banks and supervisors consider mapping climate risk drivers to financial exposures, they will face decisions on how to classify and differentiate risk across exposures. Building a risk classification that can rank order exposures according to their relative vulnerability to climate-adjusted economic risk factors may be a key step in exposure mapping. However, the categorisation of climate risk exposure has different features to traditional risk classifications. This section presents the purpose of a climate risk classification and outlines key considerations that will factor into its creation.

2.3.1 Definition and purpose

In a microprudential context, a climate risk classification would seek to differentiate between exposures according to their relative vulnerability to climate-related risks. Among other purposes, a climate risk-based classification would allow for the rank ordering, selection, pricing and management of these exposures according to the level of financial risks that they bear as a result of climate-related risks. To provide a basis for risk differentiation, a risk classification should identify specific factors that determine this vulnerability. However, the interaction among these factors – and therefore the level and amount of gross exposure – may be different for every exposure according to its attributes and characteristics (see Section 2.2). Assets with similar traditional risk characteristics, such as loan-to-value ratios (LTVs), debt service coverage ratios (DSCRs), or leverage ratios may be differently exposed to climate-related risks, depending on their geography, counterparty/issuer profile, or maturity and position in the life cycle.

Providing uniform and consistent information about a position's relative exposure to risk, risk classifications already feature prominently in banks' internal risk systems and prudential regulatory standards. Existing risk classifications, such as those used in establishing criteria for banking or trading book exposures, might be a logical starting point for determining the ability to differentiate climate risk among exposures. However, climate-risk-specific heterogeneity adds complexity which is not well reflected in most established risk classifications. For example, current activity- or industry-based classifications do not incorporate the locations of constituent components as a differentiating feature, which can limit their relevance for purposes of physical risk differentiation. Therefore, a climate risk classification would need to account for context-specific features salient for assessing the sensitivity of exposures to climate-related factors. Moreover, compared to most traditional risk classification systems which are less frequently updated, a climate risk classification may need to incorporate dynamic features that respond to future changes in the distribution of climate impacts and evolutions in technological frontiers, or the classification could incorporate provisions for a periodic refresh of selection criteria.[16]

It is important to emphasise that risk classifications are not sufficient on their own to map and monitor risk exposure or to estimate the financial impact stemming from climate risks. Notably, these classification schemes can help rank order exposures according to relative risk vulnerability criteria, but do not determine how to grade those exposures along judgmental criteria for risk (see Section 2.4.2, paragraph on climate risk scores). Rather, risk classification may act as a base component of these processes, providing the foundation upon which these approaches are built.

2.3.2 Features of a climate risk classification

When constructing a climate risk classification scheme, several unique properties of climate risk transmission will be determinative of relative risk exposure and, thus, are likely to be key features within such a scheme. Several of the more prominent features are presented below.

Geographical location

One dimension refers to geographical location (see Section 2.1.5). Broadly, physical risk differentiation is largely predicated on geographical considerations, while transition risk differentiation is largely

[16] For instance, the recently adopted EU Sustainable Finance Taxonomy plans to review and update the technical screening criteria for identifying "environmentally sustainable economic activity" periodically to reflect changes in the environmental impact of a particular economic activity and in technological innovation.

determined by jurisdictional boundaries and, perhaps to a lesser extent, by localisation within these boundaries.[17]

While the precise location of an exposure matters when considering physical risks, in practice, a mapping of individual assets to location-specific hazards may be subject to the trade-off between resource capacity and computational complexity. In this regard, a physical risk-based classification that categorises exposures using thresholds for proximity and vulnerability to physical hazards might simplify the mapping of risk exposure.

A common example might be found in residential mortgage portfolios, where a comprehensive assessment of each exposure to a particular physical hazard would necessitate precise location, the type of surrounding terrain, the characteristics of the construction, and other physical features.[18] However, such an assessment may require a large amount of data to model the complex interactions of these characteristics. Conversely, a classification that categorises exposures according to their approximate degree of vulnerability to that hazard based on a truncated set of collateral characteristics (eg postal code, waterfront exposure) could simplify the identification of at-risk mortgage exposures. Another example of a physical risk classification could include categorising corporate exposures by relative vulnerability to value chain disruptions arising from dependencies on regional transportation infrastructure (land, sea or air) or energy utilities in at-risk regions (NGFS (2020a)).

In the context of transition risk, location matters primarily regarding exposure to national (and international) laws, local government regulation, energy grids, and consumer markets. For instance, the location of a corporate within a national jurisdiction might matter if local government has the authority and the will to impose more stringent emission policies than federal policy. In addition, a corporation connected to a particular energy grid within a region may face differing energy costs (including power disruptions) relative to other domestic competitors on separate grids depending on the particular energy mix of its local power supplier, as disruption to the relative cost of fuel types may differ significantly from a national or regional average.

Granularity in the breakdown of activities

Among exposures towards corporate counterparties, classifications by economic sector can provide a useful differentiator, as they are often predefined, accepted and widely used in the categorisation of economic activities.[19] They can provide initial[20] information on the nature of the activity in terms of its impact on or exposure to climate-related financial risk (such as emission intensity, new technologies, or chronic ecosystem shifts).

In particular, sectoral classification is a commonly observed differentiator for transition risk, as some jurisdictions collect and publish data on GHG emissions by sector. When economic sector classifications are associated with average emissions, the measurement implication is that all corporate entities that share the same classification are associated with the same relative average amount of GHG emissions. Accordingly, all entities within a sector might be categorised according to the transition risk ascribed to the sector, although in reality constituent entities will have different efficiencies or different within-sector activities to others (see also Section 2.1.5). Sectoral classification may also be used, at least

17 Jurisdictional boundaries are the main factor for transition risk because the country's transition policy applies within them. However, localisation within these boundaries also matters, in part because different regions may have different energy mixes.

18 See, for instance, Netherlands Bank (2017). Proximity to a river, construction on an elevation, particular terrain and construction materials all factor into the relative exposure of an individual property to flood risk.

19 See, for instance, the UN's ISIC, or the European Union's implementation of ISIC (NACE), the North American Industry Classification System (NAICS), the Japan Standard Industrial Classification (JSIC), or the China Industry Classification System.

20 Differences will remain between activities and counterparties within the same sector that may require additional classification, such as subsector classifications that do not distinguish between fossil fuel and renewable energy sources (eg NACE D-35.11 Production of electricity).

as a first step, to identify the sectors that are the most exposed to financial risks arising from the impact of a range of physical climate hazards at a regional or local level. For instance, within a given province, federated state or region (and in addition to agriculture, transportation and energy sectors), labour-intensive sectors could see their activities seriously affected by heatwaves, especially if these are conducted outdoors (with the construction sector providing a typical example of such activities) (IPCC (2014b)).

2.4. Candidate methodologies

Estimation of climate-related financial risks is in its early stages and there is as yet no consensus on preferred modelling approaches. This section catalogues the range of conceptual modelling and risk measurement approaches that could be employed to estimate these risks.

2.4.1 Models for assessing economic impacts of climate change

In order to quantify climate-related financial risks, banks and supervisors must first specify the paths of the main economic variables that underpin the performance of assets. Several approaches have been developed by academics as well as practitioners (eg banks and supervisors). All approaches exhibit various strengths and weaknesses relating to complexity, assumption validity, mechanism transparency, data requirements, and computational burden (see Annex for a comparison of these methodologies).

Integrated assessment models (IAMs) combine approaches from energy and climate modelling with economic growth modelling. They have been among the most commonly deployed methods for linking projections of transition risk drivers and GHG emissions to economic growth impacts. These economic impacts in turn inform estimates of the social cost of carbon – the present value cost of the release of one additional ton of carbon – for policy purposes (Nordhaus (2017)). IAMs are highly applicable to policy problems and the mechanisms underlying their output are well understood. While IAMs have been and continue to be the workhorse models for climate-economy projections, it is well described that they do not capture the economic impacts of climate change extreme weather events (acute physical risk), and adaptation possibilities (Burke et al (2016)). By considering only some (mostly chronic) physical risks, IAMs may not provide realistic projections of total GDP losses from changes in climate. In addition, climate models underpinning IAM projections may understate the severity of future outcomes by not capturing certain physical risks that are not yet well understood or measured (including tipping points; see eg Stern et al (2013); DeFries et al (2019)). The absence of precedents for most of these events makes them particularly difficult to include in economic models. They are often assigned a zero probability of occurring in damage assessments, which could imply that the risk is significantly understated (DeFries et al (2019)).

Sensitivity analysis has demonstrated how drastically projections of climate change damages and the resulting welfare losses resulting from increased temperatures vary based on the probabilities assigned to tail events (Weitzman (2012)). Underestimating tail events has been a long-running supervisory concern because of its potentially very large and significant effects on banks' resiliency. In addition, it is difficult to quantify by how much tail risk is underestimated (unknown uncertainty).

Input-output models quantify static economic linkages among sectors and geographic areas to trace out upstream and downstream impacts of shocks to a given industry or region. In the climate economics literature, an input-output accounting framework is leveraged to trace out the impacts of a policy shift like an emissions tax or to estimate supply chain impacts from extreme climate change events. Liu et al (2020) apply an input-output model to a Canadian province to tabulate industry-level GHG emission intensities.

Because policy interventions or shocks in one sector lead to behavioural changes both for agents directly impacted and for those with whom they interact – so-called general equilibrium effects – researchers have developed approaches to macroeconomic modelling that attempt to capture this complex but important phenomenon. Future advances along this dimension may better capture real-world behaviour, but such a gain can come at a cost, like greater opacity.

One approach which is broadly used throughout structural policy studies is a computable general equilibrium (CGE) model. CGE models allow for policy experiments with complex behavioural interactions among sectors and agents in the economy, which are too complex to be solved analytically. Though some mechanisms driving CGE outcomes can be elucidated, the level of complexity is such that the overall importance of each of the many embedded decision rules and parameter values governing economic agents cannot be assessed, resulting in a significant black box aspect. Wing (2004) provides an example of CGE modelling to project the impact of carbon taxes on the US economy. The model produces estimates for different size carbon taxes broken down by sector and at the aggregate level.

Dynamic stochastic general equilibrium (DSGE) models introduce yet further complexity into macroeconomic modelling, especially in the vein of uncertainty in agent decision-making and endogenous technological change. These models do entail a significant computational burden though, and can be difficult to solve. Ongoing investment in improving DSGE macroeconomic modelling, within both academia and central banks, may eventually make these models more useful in the context of assessing climate-related impacts. As one example, Golosov et al (2014) develop a DSGE model with a climate change externality to compute a social cost of carbon and an implied optimal fossil fuel tax.

A more transparent, but also more stylised approach to analysing long-term macroeconomic evolutions are overlapping generation (OLG) models. Their focus on the intergenerational distribution of consumption can highlight one particularly salient shortcoming of other modelling approaches: the large role played by discount rates in estimating the social cost of carbon (Schneider et al (2012)).

Most recently, some authors have advocated the use of agent-based models (ABMs) in measuring climate-related impacts for their ability to better reflect uncertainty and complexity. ABMs are simulations where individual actors in the economy interact with each other and with institutions based on a set of decision-making rules imposed by the modeller. Farmer et al (2015) describe how, in addition to better accounting for uncertainty, ABMs can incorporate technological change and more realistic damage functions. Ciarli and Savona (2019) describe the inability of common approaches like IAMs to capture simultaneous changes in multiple structural features of the economy in response to environmental changes, such as changes in input-output relationships, industrial dynamics, technological transitions, sectoral shocks, and social interactions. ABMs' flexibility can allow all these features to be incorporated in the same climate-economy model. Potential drawbacks of ABMs include their high computational and data demands and some opacity in the underlying mechanisms driving differing outputs across simulation runs.

Outputs of the models described above can be used as inputs into other methodologies. Recent stress testing approaches have started linking the potential future climate paths and resultant economic damages identified in many of the modelling approaches above to the risk in bank portfolios (eg Netherlands Bank (2018); ACPR (2020); ESRB (2020)). These stress testing approaches leverage the projections of economic variables generated by the models described above, and use them as inputs into sectoral or regional decomposition models.[21] The most common output of these models is a carbon tax that can be applied to estimates of the price elasticity of energy demand relevant to certain sectoral exposures. Similarly, the models described above have been used to estimate price differentials between energy substitutes to evaluate the impact of technology shocks in renewable energy or adjacent low-carbon innovation (eg battery storage).

The methodologies generally define the relationships of projected climate variable paths to macroeconomic variables over the designated planning horizon. These outputs are often useful for

[21] This report does not delve into the types of models that may be employed to decompose macroeconomic variables into more finite microeconomic variables. Several, non-exhaustive, decomposition models observed include a country-apportioning stochastic international dynamic general equilibrium model, network production model and vulnerability factor model for sectoral apportionment, as well as nascent methodologies to attribute global or regional physical risk-caused macro impacts to more spatially relevant geographies.

parametrisation at the macro scenario level. However, they often lack the spatial granularity needed to more precisely assess some types of risk exposures, particularly for physical risks. For example, several prominent IAMs slice the world into broad regions for defining damage functions – these regional units may not provide the granularity needed to assess the localised probability of exposure to chronic physical risk drivers. As an alternative, a narrower scenario narrative, such as those produced by geological survey agencies to define minute hazard exposures and scenario probabilities at a more granular territorial unit level, such as postal code or even property parcel levels, can facilitate discussions of specific risks within portfolio segments and exposure concentrations to particular hazards across the bank. Conversely, applying individual hazard scenarios across a bank's broader geographical footprint may prove challenging to aggregate for a firm-wide loss estimation.

2.4.2 Broad risk measurement approaches

In principle, conventional measurements of risk could be adapted to assess climate-related financial risk, as the analysis of climate-related impacts, at both micro and macro level, is not fundamentally different from standard scenario analyses or stress tests. In practice, however, the range of impact uncertainties, time horizon inconsistencies, and limitations in the availability of historical data on the relationship of climate to traditional financial risks, in addition to a limited ability of the past to act as a guide for future developments, render climate risk measurement complex and its outputs less reliable as risk estimators.

Among the risk measurement processes currently being applied by banks and supervisors, some more prominent and conventional practices include risk scores, scenario analysis, stress testing, and sensitivity analysis (see also Section 2.5).

- **Climate risk scores or ratings** (Finance for Tomorrow (2019); Climate Risk Impact Screening (2017)): Climate risk scores (including heatmaps) rate the climate risk exposure of assets, companies, portfolios, or even countries. They combine a risk classification scheme (see Section 2.3.2) with a set of grading criteria to assign a quality score to exposures according to their classification. The grading criteria used within these approaches can be based on qualitative or quantitative factors. Climate risk scores can help banks and supervisors assess the relative climate exposure of existing and prospective credit intermediation. Climate risk rating methodologies and criteria across banks and external parties exhibit a range of approaches, often developed with highly granular data, enabling them to be location-specific, and incorporate supply chain and company-specific information. However, climate risk ratings may exhibit more biases compared to similar approaches used in other contexts, in the absence of data on smaller counterparties and short data histories.
- **Scenario analysis**: Climate scenario analysis is a forward-looking projection of risk outcomes that is typically conducted in four steps: (1) Identify physical and transition risk scenarios; (2) Link the impacts of scenarios to financial risks; (3) Assess counterparty and/or sector sensitivities to those risks; and (4) Extrapolate the impacts of those sensitivities to calculate an aggregate measure of exposure and potential losses. Scenario analysis can be performed at different levels of granularity to identify impacts on individual exposures or on portfolios. By examining the effects of a wide range of plausible scenarios, scenario analysis can also assist in quantifying tail risks and can clarify the uncertainties inherent to climate-related risks. For the purposes of climate-related risks, scenario analyses tend to be longer-term in scope and used to evaluate the potential implications of climate risk drivers on financial exposures.
- **Stress testing**: Stress testing is a specific subset of scenario analysis, typically used to evaluate a financial institution's near-term resiliency to economic shocks, often through a capital adequacy target. Typically, when considering solvency, there are two types of stress tests: macroprudential, which measure how financial shocks affect a financial system and may trigger systemic risk, and microprudential, which evaluate an individual financial institution's solvency given its portfolio risks. Recently, stress testing has been extended by some banks and supervisors to include

climate-related risks and scenarios. Climate stress testing evaluates the effects of severe but plausible climate scenarios on the resiliency of financial institutions or systems. However, the uncertainty inherent in longer-dated assessments (see Section 2.1.6) and the limited predictive power of historical observations to describe future climate-economic relationships (see Section 2.2) render estimates of capital shortfall (or other measures of resiliency) less reliable than those of conventional stress tests employed by supervisors and banks to evaluate resiliency (see also Section 4.2).

- **Sensitivity analysis**: Sensitivity analysis is also a specific subset of scenario analysis that is used to evaluate the effect of a specific variable on economic outcomes. In these analyses, one parameter is altered across multiple scenario runs to observe the range of scenario outputs that result from changes in that parameter. In certain cases, several parameters can be changed simultaneously to observe interactions among parameters. Sensitivity analysis has often been used in transition risk evaluation to assess potential effects of a specific climate-related policy on economic outcomes, particularly in research settings to evaluate the range of economic impacts from the implementation of a carbon tax. Given the uncertainties noted above with scenario analyses, a climate sensitivity analysis may be a useful tool for risk decision-makers to understand the range of potential climate impacts.

In addition to these more conventional practices, several external parties are developing new approaches to assessing risk. Several of these are listed below:

- **Natural capital analysis** (NCFA and PwC (2018)): Natural capital analysis posits nature as a capital stock and accordingly assesses how natural degradation negatively impacts a financial institution. This takes the form of a portfolio-level assessment that helps financial institutions identify their natural capital asset dependencies. It is usually carried out in four steps, identifying: (1) relevant geographies, sectors, borrowers and/or assets; (2) relevant natural capital assets (eg water, clean air, forests); (3) potential natural disruptions; and (4) geographies, sectors, borrowers and/or assets most at risk. While natural capital analysis is usually conducted at a portfolio level, it can be adapted for client- or transaction-level analysis. Most importantly, this analysis emphasises and reinforces the idea that natural capital is limited – because natural resources are now recognised as being finite and their cost increases as they become scarcer, especially if and when climate change accelerates their scarcity.
- **Climate value-at-risk** (Dietz et al (2016)): Climate value-at-risk (VaR) assessments apply the traditional VaR framework to gauge the impacts of climate change on financial institutions' balance sheets. Specifically, these forward-looking, portfolio-level metrics quantify the impacts of climate change on the value of financial assets over a given time horizon at a given probability under particular climate scenarios.

2.5. Characteristics of scenario analysis and stress testing methodologies

Section 2.4 presented a broad description of the main models and approaches for measuring climate-related risks. This section explains the conceptual foundations and most commonly used features in banks' and supervisors' scenario analysis and stress testing.

2.5.1 Scope and uses of stress testing and scenario analysis

Climate risk scenario analyses, including stress testing and sensitivity analysis, are comprehensive assessments of the impact of macroeconomic and financial variables derived from climate-economy models (see Section 2.4.1). Because these scenarios are based on projections of possible future states of the world, they incorporate forward-looking information that can complement historical data. They aim at quantifying the potential financial impacts that banks or the financial system may face by comparing a baseline scenario against scenarios that reflect varying degrees of risk arising from climate change. These methodologies aim at assessing the implications for banks' risk profiles and business strategies, but they may also provide the groundwork for discussions on potential micro- or macroprudential policies. In their current use, climate-related scenario analyses differ from traditional macroeconomic stress testing in terms of their scope, time frame and use of results (see Table 1).

Main differences between macroeconomic stress testing and climate scenario analysis — Table 1

Risk	Macroeconomic	Climate-related risks
Scope	Elements of the profit and loss statement and balance sheet	To date focus more on selected exposures
Time frame	Two to five years	Short, middle, long term (over decades)
Current use of risk assessment exercise	Used in a regulatory context, eg for estimating capital needs and planning capital management	To understand and evaluate the potential impact on a bank's risk profile and strategy due to climate-related risk and raise awareness at financial institutions

Source: adapted from UNEP FI (2018).

Common steps in scenario analysis include the choice of scenario, modelling of economic impacts, and the translation of micro- and macroeconomic impacts into financial risk drivers. In addition, conceptual choices relate to the type of analysis (top-down versus bottom-up; see Section 2.1.3), assumptions on the balance sheet (static versus dynamic) and the time horizon.

2.5.2 Scenario design

Generally, scenarios for assessing climate-related financial risks have two dimensions: the climate outcome and the type of transition. The climate outcome, often expressed as the increase in temperature when compared to a reference period, is translated into emission pathways and related constraints on energy use. The type of transition includes assumptions on whether emissions are reduced gradually ("orderly") or abruptly ("disorderly"), and includes assumptions on the availability of technology such as carbon capture and storage. Models commonly underlying scenarios used by banks and supervisors are usually IAMs (see Section 2.4.1) or the IEA World Energy Model (IEA (2020)).

Though sometimes developed in house, many banks and supervisors rely on externally generated scenarios, notably those designed by the NGFS (NGFS (2020b,c); Bertram et al (2020)) or the International Energy Agency (IEA (2020)).

- The NGFS distinguishes three main scenarios including an "orderly" (early, ambitious transition), "disorderly" (late, disruptive action), both consistent with a temperature increase of 2°C by 2100, and a "hot house world" scenario consistent with a temperature increase of close to 4°C by 2100 and little or no transition policy. These scenarios can be mapped to those used by the IPCC, distinguishing four main "Representative Concentration Pathways" (RCPs).[22]
- The IEA distinguishes three scenarios, including a sustainable development scenario consistent with a warming of below 1.8°C by the end of the century, a "current policies" scenario and a "stated policies" scenario, the latter taking into account both implemented policies and announced policy intentions.

The range of stressed variables in these scenarios mostly apply to the energy sector (fossil fuel prices and demand, etc). However, the scenarios are not systematically translated into a wider set of macroeconomic and financial variables to assess the full range of potential impacts on the bank's balance sheet. In addition, most scenarios do not include detailed economic damages arising from physical risk drivers, ie economic outcomes do not consider the impact of temperature change on the economy

[22] See IPCC (2018), Annex I, glossary entry for "pathways" for a definition of RCPs and SSPs (Shared Socioeconomic Pathways).

(Bertram et al (2020)). Instead, macroeconomic damages can be inferred through the use of damage functions published in the literature. These damage functions currently do not include impacts from extreme events (see Section 2.4.1). However, the landscape is rapidly evolving, with both scenario providers and banks and supervisors developing and improving economic and financial impact modelling and related variables (see also Boxes 1 and 2).

2.5.3 Time horizon and balance sheet assumptions

The time horizons over which climate risks manifest present a considerable challenge for risk quantification. Conventional capital planning horizons have tended towards two- to three-year forecasts (BCBS (2014)), while strategic planning at banks has tended towards three- to five-year periods (EBA (2019)). Conversely, many physical climate risks are expected to increase in materiality over a much longer horizon (IPCC (2013b)). As the measurement horizon becomes further removed from the present, the assumptions about the future operating environment will become increasingly dominant as a driver of measurement outputs, leading to greater modelling uncertainty (see also Section 2.1.6). Given the discontinuity between existing risk measurement processes and the horizon over which climate risks may materialise, existing risk forecasting approaches may be inadequate to capture the risks of a changing climate and may require retrofitting existing or creating new approaches to adequately assess these longer-dated risks (BCBS (2009)).

Nevertheless, the materialisation of increasingly severe physical risks and/or of transition risk is currently advancing into the typical window of bank and supervisory risk measurement and, notably, is already likely to occur within the maturities of longer-dated positions.[23] Indeed, the increased frequency and severity of acute hazard events could be negatively pressuring collateral valuations and regional economic indicators in certain high-risk locations.[24] Similarly, implementation of new building codes, such as mandatory energy labels for commercial or residential real estate, could have a downward impact on the value of buildings that are out of compliance with the new code, which could also negatively impact the collateral value of bank lending.

When considering future scenarios that extend past most asset and portfolio maturities, banks and supervisors need to make assumptions about the evolution of their balance sheets over the chosen time horizon – generally, balance sheets can be held static at their current levels or they can be allowed to adjust over the planning horizon – with each type of approach serving different purposes for assessing climate risks and having its own limitations.

- Static balance sheet assumptions can illuminate climate risk inherent in current exposures. As such, static balance sheet measurement provides insights into potential vulnerabilities in a bank's existing business model and may inform appetite for climate risk as these risks become more probable. Conversely, existing market structures, technologies and interconnections are an unlikely proxy for future outcomes, particularly as climate effects motivate production and consumption adaptation, technological innovation, or policy enactment. The further planning horizons extend beyond current asset durations, the less reliable are static balance sheet assumptions as reasonably realistic representations of future risk pathways, which limits their utility for identifying risk mitigation strategies or testing capital adequacy.
- Dynamic balance sheet assumptions allow banks to assess the effects of possible adjustments to their strategies, such as those that would reduce their exposures to climate risks. These assumptions have the potential to facilitate an evaluation of a bank's options for mitigating

[23] Recent accounting guidance has already shifted the measurement window to incorporate potential lifetime losses in reserve calculations. The IASB's Financial Instruments standard requires recognition of full lifetime expected credit losses if there is a significant increase in credit risk while the FASB's Current Expected Credit Loss standard requires organisations to immediately record the full amount of credit losses that are expected in their loan portfolios.

[24] See companion report on transmission channels.

climate risks and adjusting its strategic operating models. At the same time, projecting management actions involves a high degree of speculation and judgment, which can create additional modelling uncertainty.

3. Measurement methodologies of climate-related financial risks

Building on the concepts laid out in Section 2, this section presents measurement methodologies of climate-related financial risks being used or developed by either banks or supervisors. It first discusses methodologies used to map and measure exposure to climate-related financial risks (Section 3.1). It then elaborates on the methodologies used to quantify climate-related financial risks, scenario analysis, stress testing and sensitivity analysis (Section 3.2). Measurement methodologies are discussed separately for banks, supervisors and third parties, though these respective approaches share many similarities and overlaps. However, they may differ in terms of objectives. The section is complemented by two boxes, giving details on insights from industry outreach workshops (Box 1, BCBS (2020a)) and a TFCR supervisory survey (Box 2).

Banks' approaches for mapping and measuring exposure to climate-related financial risks are generally in early stages of development, albeit evolving (IIF/EBF (2020); GARP (2020); BCBS (2020b); Box 1). Amid a number of ongoing industry initiatives, many banks have developed (or are seeking to develop) methodologies, focusing predominantly on credit risk or market risk. Besides enhancing banks' understanding of risk exposures (see Box 1), currently used metrics also serve disclosure or communication purposes, therefore addressing potential reputational risks. While progress is being made on identifying, mapping and measuring the exposures and portfolios relevant for climate-related financial risk assessments, their quantification and translation into commonly used financial risk parameters is still in its early stages.

At the level of supervisors, methodologies for measuring climate-related financial risks are also evolving (BCBS (2020b); Box 2). This notably includes work on adapting existing prudential data to map and measure exposures to climate-related financial risks, as well as developing scenario analysis and stress testing, from both a micro- and macroprudential perspective. Generally, exposure mapping and monitoring by supervisory authorities has focused mostly on transition risks to date, though some case studies have also focused on physical risk. Several supervisors have piloted and launched scenario analysis or stress testing initiatives for climate-related financial risks, while others are in the process of developing such an analytical framework. Scenario analyses and stress tests being developed often focus on a number of commonly used scenarios, and include both transition and physical risks, though potential economic damages from physical risks are not yet incorporated and need to be estimated with alternative approaches (see eg Bertram et al (2020)).

Finally, third parties such as think tanks, consultancy firms, rating agencies, and academia have also developed approaches for assessing climate-related financial risks in recent years. Given the rapidly evolving need for expertise in this field, financial institutions and supervisors have frequently resorted to third-party methodology providers for the time being – either focusing on individual metrics or scenarios, or adopting third-party methodologies or tools.

3.1. Exposure mapping and measurement

3.1.1 Bank-level methodologies[25]

Portfolio and sectoral exposures

As indicated in Section 2 of this report, an initial component of risk assessment is identifying material risk transmission channels according to the exposure profile of a particular bank or banking group, around

[25] This section is based on banks' publications, insights from supervisors contributing to this report, and insights from an industry outreach conducted in the context of the TFCR (see Box 1). Given the rapidly evolving methodological landscape, its aim is not to draw a comprehensive picture, but rather to highlight emerging practices and commonalities of methodologies in place.

which monitoring processes can be shaped. A variety of indicators have been developed (see also Box 1). Notable examples include measures of carbon/emission intensity, energy efficiency or energy label distribution of real estate, or physical risk vulnerability of collateral positioned in risky regions. Where quantitative information is lacking, some banks have launched an internal process to evaluate climate-related financial risks qualitatively, and map their potential financial impacts. In addition, banks leverage heatmaps[26] to visualise the materiality of their portfolios to such indicators and to monitor concentration risks over time. Indicators or metrics used by banks to map, measure and monitor exposures are usually distinguished by transition and physical risks and are described in more depth below.

Transition risks

An observed practice among banks is to analyse how and to what extent certain sectors could be affected by a transition to a low-carbon economy, through assessing the possible sources of shocks and transmission mechanisms (see eg ACPR (2019)). Sectors often considered for these analyses include oil and gas, utilities, transportation and car manufacturing, metals and mining, and construction (see Box 1). Some banks measure the carbon-related assets they hold,[27] which is used as an approximation to size transition risk. This approach aims at identifying potential "pockets of risk".

Another observed practice is to calculate the carbon footprint of banks' assets as a proxy for transition risk. While going in the same general direction as the identification of carbon-related assets, carbon footprints involve measuring at a more granular level the "financed emissions" associated with lending and investment activities by combining information on sectoral or firm exposures with information on carbon emissions. While a lack of data availability and quality is a frequently reported issue in this context, banks report recent improvements in their counterparties' emissions disclosures, facilitating the analysis of their carbon footprint (see Box 1 and Section 4.1.2). The carbon footprint assessment is sometimes applied to the whole balance sheet, but more frequently covers only those sectors identified as sensitive to transition risk. Based on the carbon footprint calculation, an observed practice among banks is to subsequently assess the sensitivity of certain portfolios to the introduction of different carbon prices (see Section 3.2.1 on shadow carbon prices and scenario analyses).

Observed practices among banks also include the use of indicators related to "greenness" of financial assets and real estate exposures as proxies for transition risk, including measures of alignment with climate targets.[28] Alignment approaches involve measuring the gap between existing portfolios and a portfolio consistent with a specific climate target. They seek to understand whether portfolios, or sub-portfolios (eg sectors), are in line with specific climate targets[29] and to what extent a bank would need to change the composition of its portfolios and activities to align with such targets. This type of approach primarily helps banks understand their (potential) contribution to meeting climate targets, but may also provide insights towards how they might be exposed to transition risk. Applying an alignment approach in the risk measurement context assumes that higher transition and reputational risks tend to be associated with a portfolio misaligned with the climate target. Beyond the risk management context, communication of alignment (plans) with climate targets by banks may also be used in the context of reputational risk or strategic positioning.

In addition, some banks have performed analyses to assess the potential risk differential between "green" and "brown" activities (NGFS (2020d)). One example of a backward-looking analysis is the

[26] A heatmap presents a high-level overview of the materiality to (risk) indicators of a bank's exposure across, for instance, sectors or asset classes.

[27] TCFD (2017): The TCFD recommends that banks disclose significant concentrations of "carbon-related assets", which is "generally considered to refer to assets or organizations with relatively high direct or indirect GHG emissions". The TCFD also acknowledges that the term is not well defined, and suggests further work is needed on this.

[28] The EBA lists the "Portfolio Alignment Method" as a separate methodology in the context of measuring ESG risks (EBA (2020)).

[29] Often referencing the Paris Agreement target to limit global warming to well below 2°C, and preferably to 1.5°C.

comparison of cases of energy firm downgrades with proxies for "green" activities (eg renewable energy power generation) and "brown" activities (eg coal and gas-fired power generation). With a range of methodologies being applied by different financial institutions, strong conclusions on a risk differential have not been established so far. Current commitments to limit "brown" exposures or setting "green" targets are therefore to date mostly considered in the context of reputational, business model or legal risks and strategic positioning. However, more systematic tracking of risk profiles could be enabled by the availability of a clear risk classification system (also see Sections 2.3 and 4.1.1).

Physical risks

Indicators or metrics to map, measure and monitor physical risk at portfolio level aim to identify geographical risk concentrations and the type of hazard as well as its probability and potential severity (NGFS (2020a)). Risk scores or metrics estimate, for example, sensitivity to various acute or chronic physical risks. For instance, some parties have developed location-based physical risk scores, covering a wide range of physical risk drivers such as heat stress, wildfires, floods and sea level rises. For each of these risk drivers, indicators are identified that capture both absolute and relative changes in physical conditions. These indicators can be aggregated and translated to facility level scores, which can in turn be used as part of a bank's client due diligence or annual mortgage review processes.

Banks have also started to use geospatial mapping to assess and monitor the extent to which their exposures may be affected by physical risks. One bank, for instance, stressed its residential mortgage portfolio to assess its exposure to flood risks (see Netherlands Bank (2020)). High-risk regions are identified using publicly available granular flood risk maps (eg postal code level). The bank performed a geospatial mapping of its portfolio on these high-risk regions to identify exposure to elevated flood risk. Another bank assessed its corporate credit exposure at risk of water stress. The bank identified its exposure to clients operating in water-stressed regions, in part using publicly available data (WRI (2021)). Using the geographic coordinates of its clients' assets, the bank was able to identify exposures at risk of water stress.

Client or project ratings and scores

Assessing climate-related financial risks to which individual counterparties (eg large corporates) may be exposed is an approach increasingly undertaken by large banks, for both physical and transition risks (GARP (2020)). While delving further into client and project-related climate risk assessments is starting to be integrated into banks' credit management procedures, such methods do not yet enable banks to thoroughly quantify their financial impact (see also Box 1).

Counterparty-based risk assessments often entail an analysis of the climate-related opportunities and risks for companies that the bank finances or is considering financing (eg considering the company's carbon footprint, climate change adaptation solutions, strategic positioning). The intention of such an analysis is to provide the bank's credit officers with elements that may be useful to inform the credit decision. As described in Section 2.2, this counterparty data can include qualitative or quantitative elements and banks rely on a mix of both qualitative and quantitative analyses to assess their counterparties. The analysis sometimes also includes a forward-looking component such as assessing the transition plans and adaptive capacities of clients.

Rating or scoring approaches for clients or exposures are frequently used by banks (NGFS (2020d)). Such ratings derive from either in-house bank expertise or external ratings from specialised providers or traditional rating agencies. Climate-related risks are commonly assessed separately from standard credit risk assessments. Observed ratings practices include assigning a climate risk rating for each client comprising all physical and transition risks to which the client is exposed, or developing a materiality matrix to apply a climate-related risk rating for existing and new clients (ECB (2020a)).

Metrics used in developing the rating can be based on sector-level characteristics, and then adjusted to account for company-specific aspects. For example, metrics used as proxies for transition risk are carbon intensity metrics such as CO_2 produced per unit of energy (in kg CO_2/kWh) for the power generation sector, or CO_2 produced per distance driven (in g CO_2/km) for the automotive industry – using, for example, industry benchmarks (NGFS (2020d)). In addition to quantifying key metrics for each industry, banks incorporate qualitative information in their rating methodologies, or complement their approach with qualitative overlays to capture the client's climate strategy, management's capability to deal with risks or opportunities, and specific areas of vulnerability.

Although climate risk ratings or scores are generally used to reflect climate-related factors when granting credit, banks have integrated these scores into their overall customer credit rating only on targeted occasions to date (see also Box 1). A number of banks are working towards integrating a climate-related score or rating into their counterparty credit assessment processes and risk management frameworks (NGFS (2020d)). One observed practice includes banks integrating a climate risk assessment as part of their due diligence in client and transaction approval processes. An example of such a climate risk assessment uses a traffic light classification (red/amber/green) to differentiate clients according to their relative exposure to climate-related risks, where clients exposed to elevated climate-related risk are assigned a "red" or "amber" rating. This rating might then trigger heightened credit review, monitoring, or approval protocols (ECB (2020a)). Another observed practice is banks using their climate score or rating to complement the standard assessment of financial risk categories. In principle, credit officers can adjust the credit score based on the climate risk assessment.

3.1.2 Supervisory methodologies

Indicators and metrics used by supervisors to map, measure and monitor exposure to climate-related financial risks are often similar to those employed by banks. Exposures are considered according to the portfolio studied, or their sectoral, or geographical characteristics. Similarly to banks, supervisors consider different sets of indicators for transition and physical risks.

Transition risks

To assess the impact of transition risks on banks' exposures, supervisors' assessments are based on either regulatory information or ad hoc surveys (see eg Bank of England (2018)) that allow indicators associated with transition risk to be matched with banks' exposures.

For corporate portfolios other than real estate exposures, supervisors often use indicators describing the emission intensity, carbon footprint or sensitivity to climate policies of banks' counterparties at the entity or sectoral level, depending on the granularity of the analysis. Sectoral analyses are usually focused on sectors deemed most sensitive to transition risk based on sectoral carbon intensity (eg Bank of France (2020); Central Bank of Malaysia (2019)). A frequently used methodology maps sectors identified according to national classification frameworks into climate-policy-relevant sectors, considered vulnerable to transition risk.[30] Exposures to these sectors based on existing supervisory reporting can then be aggregated. The final output of such an assessment reports, for example, the percentage of total financial sector exposures associated with sectors identified as vulnerable. In addition, some supervisors have leveraged supervisory counterparty-level data, for instance on large exposures reporting, combined with data on counterparties' emissions or emission intensity (eg ECB (2019); ESRB (2020); Faiella and Lavecchia (2020)). These assessments are intended to capture variability of vulnerability within sectors that may not be captured by sectoral assessments. Counterparty exposures mapped to data on carbon emissions or emission intensity can then also be used for sensitivity analyses, for example a sensitivity analysis of banking system exposures to corporate decarbonisation (ECB (2020b)), or build the basis for more comprehensive scenario analysis and stress testing.

[30] The classification of climate-policy-relevant sectors is often performed following the framework laid out by Battiston et al (2017), with sectors including fossil fuel, utilities, energy-intensive, transport and housing. The authors map firms from NACE level 4 to climate-policy-relevant sectors. The approach has been applied and refined; see eg Battiston et al (2020).

For real estate exposures, transition risk analyses are fewer. One example of a transition risk analysis assesses the energy label distribution of a bank's direct or indirect lending portfolio collateralised by real estate, under the assumption that real estate owners may need to make large investments to properties to comply with higher energy efficiency standards (Netherlands Bank (2018)). These can be combined to measure an average weighted energy label associated with each bank's portfolio or determine the proportion of the bank's total portfolio that exceeds a determined threshold, providing an aggregate assessment of how material potential counterparties' energy efficiency improvement costs may be.

Physical risks

Progress in the analysis of exposures to physical risks varies, and assessments are mostly in their initial stages, or presented in the form of research papers. However, some supervisors have made progress in identifying relevant hazards and mapping and measuring exposures, as further explained below (see also Box 2).

To assess the banking system's exposure to physical risk drivers, supervisors identify hazards that are most relevant in their jurisdictions and, within these, the specific regions that are more vulnerable to these hazards. To conduct such an analysis, authorities often rely on information from third parties to identify the main geographic areas at risk and the hazard extent, namely: (i) publicly available information, usually provided by government agencies or other public sector entities, describing past hazards by geographic areas and associated areas at risk and the projection of future hazards under a changing climate; and (ii) climate risk scores offered by commercial vendors. Commonly used indices may describe single hazards and/or the vulnerability of certain locations to these hazards, multi-hazard or aggregate risk scores, and heatmaps.

Supervisory uses of these indicators vary in terms of hazard, geographical granularity and complexity. Examples include the use of flood maps to assess the probability that a certain postcode area may be subject to flooding within a predetermined time frame (Bank of England (2018)), country vulnerability indicators (Netherlands Bank (2017)), the level of water stress on the geographic locations of individual industrial facilities (Netherlands Bank (2019)), the assessment of population in areas below a certain elevation (eg 5 metres above sea level), agriculture as a percentage of GDP, or an assessment of the main areas of vulnerability to climate change (Bank of Mexico (2020)).

Once salient physical risk drivers are identified, authorities may assess the risk exposure of individual supervised entities or of the banking system to geographies with stronger susceptibility to physical risk. Exposures considered for the assessment of physical risks include corporate or real estate exposures of financial institutions (see also Box 2 and Chart 2). In some jurisdictions with global banks, it is relevant to analyse exposures across different countries and therefore consider climate hazards affecting other jurisdictions in which these exposures are located. When granular credit data is available, exposures to physical risk can be measured at the counterparty, activity or sectoral level in addition to the country level. One analysis, for instance, combines country vulnerability with sectoral vulnerability to obtain a physical risk index for each pair of area and sector (ACPR (2020)). Whatever the degree of refinement, a typical output obtained by the supervisor is the proportion of a portfolio located in an area that would display a comparably higher level of physical risk, or the proportion of a portfolio exposed to a particular type of climate event. For the latter, the impact of the specific hazard on the value of the collateral held by the bank can be considered subsequently.

3.2. Risk quantification: scenario analysis, stress testing and sensitivity analysis

3.2.1 Bank-level methodologies

Bank-level scenario analysis and stress testing methods may be used to quantify climate-related financial risks or to inform strategic planning. In general, these tools seem to be still at an early stage, as for example recognised by the TFCR stocktake (BCBS (2020b)). These exploratory exercises are mostly focused on credit risk or market risk analysis. Currently, climate-related financial risk scenario analysis is applied with the goal of understanding the potential impact on selected portfolios, to refine methodologies and assess limitations and benefits. Besides capacity-building, such exercises are also used to identify counterparties which need to be engaged to support their transition. A crucial objective for banks is the translation of transition and physical risk drivers into financial risks, and in particular their incorporation into internal models, which still seems rather challenging and is predominantly being assessed in the context of pilot studies (see also Box 1).

Banks' transition risk scenario analysis tends to focus on impacts to credit parameters for counterparties belonging to specific sectors. This includes in particular corporate exposures in sectors relevant to climate policies (see also Section 3.1.1 and Box 2 for detailed examples). One specific example is the use of a shadow price and its inclusion in a transition risk sensitivity exercise or as part of a scenario analysis: adjustments to basic prices (eg electricity, carbon, fuel price) are used to evaluate how counterparties could be affected. This approach aims at anticipating potential market or policy changes such as the introduction of carbon pricing or a tightening of existing climate regulations, in order to estimate the impact of such changes on the financial profile of a counterparty and assess the bank's adjusted credit risk. It entails defining one or a range of potential future prices, based on external scenarios or in-house expertise. These "shadow prices" can then be used to assess the impact on financial variables (for example cash flows, or EBITDA) and in turn the credit risk profile of a counterparty. Although mostly used by institutions at a more advanced stage of climate risk analysis, a number of other banks already signal that they intend to use such methods in their planning or decision-making (ACPR (2019); IIF/EBF (2020)).

Banks' physical risk analysis tends to focus on corporate and household (particularly mortgage) exposures. They then infer from this a potential impact on the credit quality of counterparties. Corporates in specific sectors (such as electric utilities) can also be subject to assumptions regarding business interruption and hence their financial performance and the level of credit risk that they may exhibit. An observed practice is to focus on sectors more sensitive to long-term change in weather patterns (eg temperature or precipitation). In this case, chronic physical risks are translated into productivity changes, and subsequently into changes in firms' revenues. As for acute physical risks, an observed practice is to assess potential impacts of extreme weather on the value of the bank's real estate collateral and more generally on its real estate exposures (through the impact on housing prices).

A UNEP FI pilot project (UNEP FI (2018), UNEP FI et al (2018)) saw the participation of many banks. The project applied a common methodology aimed at translating climate scenarios into credit risk parameters. The methodology assumes translation of climate scenarios into financial risk drivers through changes in firms' revenues, in the costs of goods, and in property values. These financial risk drivers, as well as the impact of the scenarios on credit parameters, are then assessed at borrower level, focusing on selected sectors or portfolios depending on the type of climate-related risk. Borrower-level impacts are then extrapolated on a sectoral level, and the climate impact is used to adjust credit risk metrics.

Box 1

Insights from industry outreach workshops on banks' practices[31]

Approaches used by banks to measure climate-related financial risks

Participants of outreach workshops held in October and November 2020 indicated that climate-related financial risks link to existing financial risk types, including credit, market, operational, liquidity risk, and are likely to have a meaningful impact on these risks. While both transition and physical risks are considered likely to be material, the exact magnitude is assessed differently by different banks, depending on their business model, for instance. For transition risks, some participants highlighted a dual materiality.[32] All in all, there was agreement among industry panellists that climate-related financial risks are not yet fully understood. Consequently, participants indicated there is initial, but still minimal, evidence that climate-related financial risks are being priced into financial markets across certain sectors or asset classes and significant work remains to improve this pricing ability.

Reflecting varying materiality assessments by participants, the focus of climate-related risk assessment differs across banks. Banks have tended to focus initial assessments of climate-related financial risks on specific economic sectors for transition risks, and specific economic sectors or geographic regions for physical risk. There was broad agreement that the sectors most relevant for transition risks include utilities, metals and mining, energy/oil and gas, transportation and car manufacturing, and construction (especially steel/cement), since they display high average carbon footprints. Physical risk assessments, somewhat in contrast, were assessed to mainly be relevant for the agriculture and utilities sectors, as well as commercial real estate and retail mortgage portfolios.

Data sources and indicators

A number of data sources were identified by participants as relevant for assessing climate-related financial risk, including existing internal client data, recently initiated regular data collections, ad hoc data requests, as well as external data from commercial third parties and rating agencies, NGOs, and public data sources, including companies' annual reports. One example of a regular data collection includes a questionnaire to clients in specific sectors that mirrors TCFD disclosure to collect information concerning clients' governance and strategy, metrics and targets. One participant reported that data quality is assured by using data reported/confirmed by the companies themselves. It is noted that data availability is improving, but is not yet sufficient in all cases in terms of either coverage or quality.

The main indicators mentioned to assess transition risks include firms' carbon intensity or carbon footprint, as well as their alignment with climate targets as a proxy. These metrics are sometimes complemented by insights on firms' transition strategies as well as traditional financial data. An assessment at the asset or company level is mentioned as desired, but not always feasible, and is therefore often complemented or substituted with industry-level data. One specific indicator mentioned for physical risk assessment concerns the probability of flooding.

Integration of climate-related financial risks into current risk management practices

Some participants have started to integrate climate-related financial risk into their risk management practices. Tools that are already in use to inform management decisions include scoring tools such as heatmaps to monitor and manage climate-related financial risks for relevant sectors or portfolios. One example includes a scoring system for individual clients, which starts by identifying sensitive sectors and establishing sector-specific technical risk criteria, before assessing the level of compliance of each client in the portfolio with these criteria and resulting in a compliance score. The process further defines risk acceptance metrics and a minimum threshold for compliance at portfolio level, and the criteria and risk acceptance metrics are reviewed regularly. Some participants report having interactions with clients when they are flagged by a bank's risk officers as being vulnerable to climate-related risks, which are in some cases mandatory according to the bank's regulations.

Currently used methodologies to quantify climate-related risks are often cited as prototypes or pilot methodologies, with the main aim being to increase banks' understanding of their risk exposures. This holds in particular for results from scenario analyses and stress testing. A comprehensive implementation of physical and transition risk assessments is – according to participants – expected to take several years. Analyses currently used aim at helping to create an overview of potentially vulnerable regions or sectors, as a basis for further drilling down into associated specific exposures in these sectors or regions. Similarly, it remains under discussion how exactly climate-related financial risks can be comprehensively integrated into existing risk management processes, including banks' risk appetite, and impacts on financial risk parameters such as PD, LGD and risk-weighted assets.

Stress testing and scenario analysis

Initial scenario analysis, including stress testing, has been undertaken by a number of participants, often with the support of third parties including in the context of industry-wide initiatives (eg UNEP FI (2018), UNEP FI et al (2018)). These analyses have often been limited to selected risk drivers or asset classes (see below). Reported results of these small-scope analyses suggest a limited impact of currently considered transition and physical risk scenarios on financial risk metrics, though some participants indicate potentially high PD impacts for some counterparties. Assessments have mainly been implemented on credit portfolios, but operational risk related to physical damages from climate change has also been assessed in individual cases. The time horizon considered in these scenario analyses ranges up to 30 years, although impacts occurring within shorter time horizons (eg three–five years) are also considered, especially for transition risks. Many participants are currently planning or conducting extensions of these initial analyses. Several mentioned ongoing work on market risk for instance.

For transition risks, initial scenario analyses have focused on the above-mentioned emission-intensive sectors, often combining sectoral and counterparty assessments, with varying coverage of relevant portfolios depending on the bank. One example is the assessment of transition impacts on clients' business performance and the possible consequences for credit costs, with a static scenario (that is, no attempt is made to transform the present business structure) and a dynamic scenario (that is, the business structure is transformed). Transition risk scenarios often build on those provided by the IEA (IEA (2020)) or more recently by the NGFS (NGFS (2020b,c)), including in particular the sensitivity to carbon prices. Based on these analyses, participants calculate an initial impact on credit ratings, the financial impact on the overall credit portfolio, or the alignment of carbon-intensive sectors with climate targets.

Physical risk assessments are reported to focus on the impact of selected physical hazards or selected gradual changes in climate on selected portfolios or clients (eg group of clients). Most frequently mentioned hazards are floods and other water-related risks. A number of different transmission mechanisms on corporate clients is mentioned, including firms' operational risks, supply chain risks (upstream) and risks of market share losses (downstream). Physical risks are usually assessed following the IPCC's RCP8.5 or RCP6.0 scenarios, or pathways with similar temperature projections.[33] Individual panellists report that these scenarios lead to first estimates in changes in default probability, measuring the impact either on the overall credit portfolio, or on selected portfolios. For real estate portfolios, changes in property valuation or LTV based on physical attributes of property are mentioned as an example – which could then be mapped to the main credit risk metrics.

Risk mitigation

Risk mitigation is currently considered by some participants: individual banks have engaged in interactions with clients in the above-mentioned carbon-intensive sectors, to understand their emission reduction strategies, with a high reliance on expert judgment. Some banks also consider insurance coverage as a key risk mitigant, especially for mortgage portfolios, while others note that such coverage may not be guaranteed in the future. In addition, individual participants report strategies to mitigate operational risks.

3.2.2 Supervisory methodologies

Supervisors may use scenario analysis and climate stress tests for microprudential supervision, and to inform macroprudential policies. At the microprudential level, scenario analysis and stress testing may be

31 As part of a workshop organised by the TFCR, three industry outreach sessions took place in October and November 2020, with 10 participants from internationally operating banks. Box 1 includes technical findings on measurement methodologies derived from interactions with the panellists. For a high-level summary of the workshops see BCBS (2020a). The methodologies described in this box may not necessarily be representative of overall methodologies used or being developed by financial institutions.

32 European Commission (2019), pages 6–7: The European Commission's guidelines on reporting climate-related information explain that the EU Non-Financial Reporting Directive implies a double materiality in the context of reporting climate-related information, as the reported information has both a financial materiality (to understand a company's development, performance and position), and an environmental and social materiality (to understand the impact of a company's activities).

33 See IPCC (2013c, Box SPM.1, page 29) for an explanation of RCPs and Bertram et al (2020, page 7), for a discussion of how NGFS scenarios map to IPCC RCPs.

used to: (i) quantify banks' financial exposures vulnerable to specific climate risk drivers; and (ii) understand the vulnerability of banks' business models when confronted with specific climate scenarios, and the implications for their business strategy. At the macroprudential level, scenario analysis and stress testing may be used to assess the size and distribution of climate risks in the financial system, and whether these risks may be systemic in nature. In terms of the financial risk types being assessed, most climate scenario analyses and stress tests focus primarily on credit risks and market risks arising from financial institutions' loan and investment portfolios (eg stranded assets, corporate defaults and sovereign bond revaluation). Future uses of climate scenario analysis and stress tests at macro- and microprudential levels may, however, extend beyond these applications (see also Box 2).

While traditional supervisory stress testing is used by supervisors to determine the resilience of banks' capital positions to financial losses, or inform the calibration of additional capital requirements, climate scenario analysis and stress tests are typically exploratory – and not used for any such specific policy purpose at this juncture. Supervisors also note that the outcomes of scenario analyses and stress tests, and their impact on regulatory metrics, depend crucially on assumptions and methodological choices, and the uncertainty surrounding the assumptions may be larger and harder to estimate than in conventional stress tests, given the nature of the risks and the long time horizon (Netherlands Bank (2018)). As such, climate scenario analysis and stress testing, as currently used by supervisors, serves two main objectives: first, as a tool to supplement supervisors' understanding of the impacts of climate change on their regulated banks' risk management and business strategy, rather than a test of banks' capital adequacy against potential losses; second, as part of their prudential policies, as a means to raise the awareness of the industry with respect to these risks and incentivise banks to develop appropriate risk models and governance and identify data gaps (Bank of England (2019); ACPR (2020)).

A variety of approaches are used to model the impact of climate-related risks, at the macro, sector and firm level. At the macro level, and compared to most existing bank-level scenario analysis, climate scenarios are translated into macroeconomic and financial market variables. Multi-country macro-econometric models such as NiGEM[34] are used to generate such macroeconomic variables. The impact of these variables on point-in-time credit risk parameters, including PD and LGD, are then estimated.

A sector-level calibration may be introduced to differentiate the risk profile across sectors and enhance the granularity of the analysis. An example of this calibration includes assigning a transition vulnerability factor for each industry included in a transition risk stress test, based on the amount of carbon emissions to produce the final goods and services of each industry (Netherlands Bank (2018)). This allows the supervisor to translate macroeconomic conditions into industry-specific losses. Another alternative is the introduction of a multi-country, multi-sector framework, including a production network model calibrated using a global input-output matrix to represent production in each sector and each country as a process involving non-energy and energy intermediate inputs from all countries and domestic labour (Bank of France (2020)). Within this framework, sector-specific carbon taxes are then imposed in proportion to sectoral GHG emitted, with the aim of assessing which sectors are most impacted by carbon taxes.

The macro- and sector-level approach may be complemented with a borrower-level analysis, which requires more granular data, including asset-level data such as location, emission profile or physical hazard. Micro models can then be used to assess the impact on the borrower's production capacity and revenue, and the corresponding impact on their creditworthiness. For example, a supervisor may propose that banks perform a financial analysis of individual companies, including modelling their cash flows and collateral values, and assessing their current mitigation and adaptation plans (Bank of England (2019)). Another example includes the use of a rating model, which provides financial information on firms, to generate probabilities of default at the intra-sectoral level, and assess financial outcomes. This also

[34] NiGEM provides a range of macroeconomic and financial variables across economies worldwide, with individual modelling of all OECD countries, as well as some large emerging countries (NIESR (2020)).

includes identifying the set of firms that exhibit the biggest increase or decrease in credit risk, though this would relate more to financial information than vulnerability data for individual firms (ACPR (2020)).

Box 2

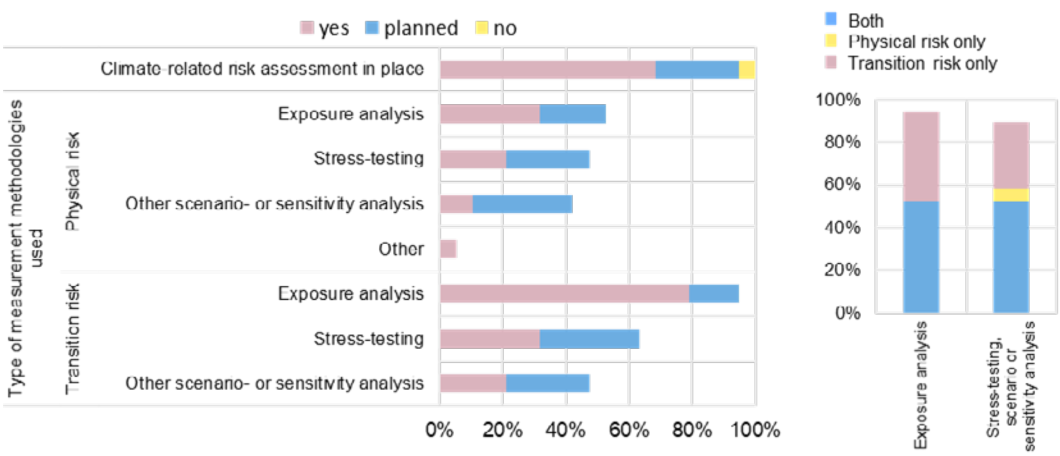
Insights from a TFCR supervisory survey[35]

Supervisory use of measurement methodologies

Responding supervisors report conducting specific climate-related risk assessments mainly for transition risks, with planned further models or methodologies to be implemented for both physical and transition risks (Chart 1). Most supervisors focus on both the macro (banking system) and micro (individual bank) dimensions of climate-related financial risks. Transition risk assessments appear to be of a higher current priority – with only one responding jurisdiction (out of 19 respondents altogether) not planning to address transition risks, while six respondents are not addressing or planning to address physical risks. Few respondents have developed their own risk taxonomy. Exposure analysis (ie mapping and measuring exposures to climate risk drivers) is the most commonly cited method in use for both transition and physical risk assessments, with most jurisdictions planning to conduct stress tests or scenario analyses in the near future.

Although many supervisors are developing their own tools for climate-related risk analysis, for now third-party methodologies and scenarios remain frequently used (see Chart 3 and Section 3.2.3). Specific tools provided by third parties are sometimes used as a foundation, with further tailoring to meet the given supervisor's needs. One example concerned closely collaborating with an external provider, retrofitting the provider's initial tool to answer supervisory-specific questions related to risk-based assessments of financial institutions and their overall exposures to transition risks. Accordingly, the tool's standard outputs could be and were extended, and a new set of analytics and metrics developed, to better answer questions relevant for supervisors (see Finansinspektionen (2021), for the description of the pilot project conducted jointly with PACTA).

Chart 1: Types of measurement methodologies planned or in use, share of total respondents (%)



Based on 19 survey respondents. Multiple answers possible. Left-hand panel does not include number of answers for "no", or cases in which no answer was provided, for the type of measurement methodologies used. Right-hand panel shows aggregate answers for both "yes" and "planned".

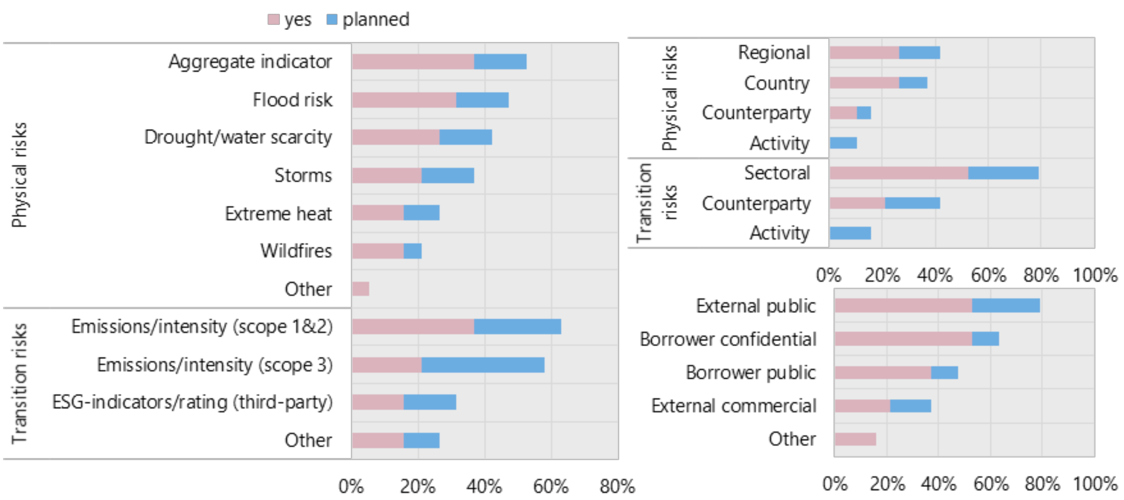
Input and data

The majority of respondents rely on multiple data sources for their assessments, with the primary sources being borrower or public reports (Chart 2). Some respondents indicated that they have issued a request or recommendation to banks in their jurisdiction to initiate targeted data collections.

[35] The survey was designed and conducted with members of the TFCR in October/November 2020. All 19 TFCR member jurisdictions responded to the survey.

For transition risks, most respondents use a single indicator based on either emissions or emission intensity, and perform their analysis using a sectoral approach (Chart 2). Commonly used metrics to identify relevant sectors include either a selection of sectors considered to be relevant based on official statistical sectoral classifications, climate-policy-relevant sectors based on academic studies (as described in Section 3.1.2), or sectors identified as having high GHG emissions. For physical risks, respondents often mention the use of several indicators describing different physical risk drivers, most notably floods, droughts and storms, with the most commonly used metric being an aggregate climate risk indicator. Physical risks are mostly addressed at the regional or country level of aggregation (Chart 2).

Chart 2: Indicators (left-hand panel), granularity of approach (right-hand panel top), and data sources (right-hand panel bottom) used in respondents' measurement methodologies; share of total respondents (%)



Based on 19 survey respondents. Multiple answers possible. Not shown are responses for "no", or cases in which the question was not answered.

Stress testing and scenario analysis assumptions

Almost all respondents (17 out of 19) indicate the use of scenario analysis or stress testing, with bottom-up stress tests involving banks being planned or conducted in a few cases. Many of these initiatives are still in the planning phase (Chart 1).[36]

For transition risks, many respondents refer to policy and technological change scenarios, but only few account for changes in consumer preferences. Respondents particularly highlight the use of the NGFS scenarios (NGFS (2020b,c)). Specific policy scenarios used often differentiate by the timing of the policies (timely/late/none) and their stringency to meet climate targets. The "no policy action" scenario is usually expressed through a high-emission climate scenario (eg similar to RCP6.0 or RCP8.5), for which physical risks are then assessed.

Over two thirds of respondents use two or more models for the different phases of their analysis, with reference scenarios derived from IAMs (often run by external parties), a macroeconomic model to translate IAM output into macroeconomic and financial outcomes, a network model to derive sectoral impacts and financial models to derive asset price shocks and changes in PDs (Chart 3).

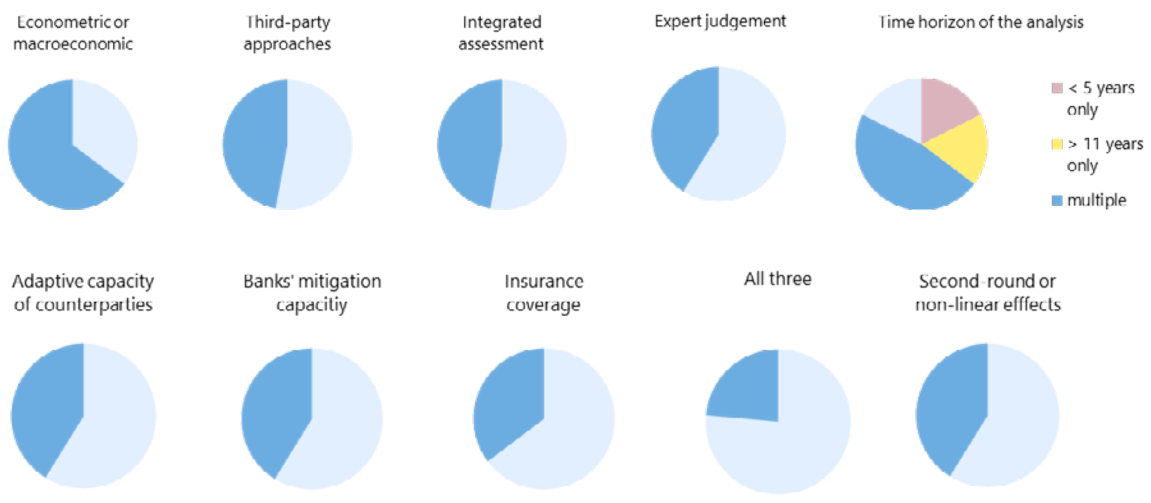
Generally, shorter-term horizons are used to assess transition risks only and longer-term horizons are used to assess both physical and transition risks individually, or a combination of both (see also Chart 3). Commonly used time horizons range from five to 30 years, with stress tests usually providing results for different points in time (eg every five years), and most often being limited to 30 years. A physical risk scenario analysis with a time horizon of 100 years is mentioned in one case. Proposed options for the balance sheet include a static balance sheet for a short (five-year) time horizon and dynamic response thereafter, or separate assessments with both static and dynamic balance sheet assumptions.

Few respondents indicate that they are considering or planning to consider indirect, second-round or non-linear effects (Chart 3). Respondents consider these effects to include microeconomic interactions such as the interaction

[36] Published stress test methodologies or results from TFCR members include the following: Bank of England (2019), ACPR (2020), Netherlands Bank (2018).

or response by financial institutions including insurance, an increase in risk premium, or fire sales of assets due to withdrawal of financing. One respondent also mentions plans to model effects introduced through a potential monetary policy response to price shocks. Finally, a few respondents are considering, or planning to consider, the adaptive capacity of counterparties and banks' own mitigation capacity.

Chart 3: Common features of supervisors' stress tests or scenario analyses, top: model types and time horizon used, bottom: adaptive or mitigation capacity and second-round effects



Based on a total of 17 respondents who indicated scenario analysis or stress testing was planned. Multiple answers possible. Dark shaded areas correspond to the sum of answers "yes" and "planned".

Supervisory methodologies and the existing Basel Framework

Respondents generally view climate-related risks as drivers of the existing financial risk categories (as opposed to a separate risk category). A majority of survey respondents report attempting to map or planning to analyse how climate-related risks affect bank financial risk drivers or the prudential framework within their jurisdiction (see eg Netherlands Bank (2017, 2019); NGFS (2019); IADB (2019); ESRB (2020); National Bank of Belgium (2020); Bank of Mexico (2020)). However, many respondents note that the transmission and quantification of climate-related financial risks still needs to be better understood. In this context, they highlight continued research and analysis needs concerning measurement methodologies in general, and in particular the time horizon of risks, forward-looking analysis of risks, sectoral and geographical concentration of risk, and indirect bank exposures to shocks materialising along the value chain (see also Section 4).

Despite existing knowledge gaps, a number of survey respondents suggest that the current Basel Framework may not be able to capture all cases in which financial risks arise from climate risk drivers in their jurisdiction. Some respondents see the need to review Pillars 1, 2 and 3 in order to fully take into account climate-related financial risks. The importance of the Framework remaining risk-based was emphasised in the responses. Respondents who view risks being sufficiently captured mainly refer to the possibility of capturing these risks under Pillar 2.

Nevertheless, supervisors indicate interactions with banks on this subject have taken place in a number of different ways, with most mentioning surveys, conferences, workshops and supervisory engagement. Respondents are of the view that surveys have contributed to raising awareness among financial institutions and motivated steps to adopt quantification and mitigation of climate-related financial risks. Though most surveys were conducted only recently, respondents already see progress in their supervised institutions, and many supervisors are planning follow-up surveys.

3.2.3 Third-party approaches

In addition to specific data or metrics, supervisors and banks sometimes rely on comprehensive methodologies or tools provided by third parties for reasons that are similar to those identified under Section 2 (see NGFS (2020a, Part 1); I4CE (2018); Cambridge Institute for Sustainability Leadership (2019) for example methodologies used by banks and supervisors). Features of third-party methodologies are generally similar to those discussed for banks and supervisors in Sections 2.4 and 2.5 and in this section, including exposure mapping, scenario selection, introduction of a transition or physical risk shock, and the assessment of impacts on firms' financial performance. Methodologies may then provide a selection of different risk metrics or the tools to calculate these metrics, including climate value-at-risk (climate VaR), firms' PD, the expected shortfall or conditional VaR, or expected losses (see eg NGFS (2020a) for a more detailed description of these metrics), but also firms' growth/income predictions, revenue/cost analysis, LTV ratios or return on equity, and measures of alignment with climate targets (see Section 3.1.1 and Institut Louis Bachelier (2020), for an overview of alignment methods).

Specifically for physical risks, a risk indicator is often proposed in the form of a climate risk score. Some methodologies assign a risk rating to an exposure based on the type of hazard to which it is exposed and vulnerable. Other methodologies leave room for different types of segmentation or aggregation strategies (eg per type of loan/sector/hazard, etc).

Vulnerability or sensitivity to climate events is included in third-party methodologies, for example by identifying resources that are highly dependent on climate change, such as water and energy resources, or by analysing the type of facility that is exposed to a specific risk (eg an energy centre, a crucial warehouse, corporate offices, retail branches, etc). Some methodologies also include adaptive capacities like insurance policies or mitigation tools, and the existence of alternative sources of production (eg alternative supplies and/or suppliers). Some methodologies assessing vulnerability are based on damage functions, which express the (historic) relationship between the magnitude of the natural event (eg flood depth) and the damage caused on certain assets (eg share of building destroyed).

4. Areas for future analytical exploration

Notwithstanding advances made over the last few years, practical considerations reveal significant room for enhancing the robustness of methodologies to measure climate-related financial risks. This section discusses some of the more prominent areas for future analytical exploration and development outlined in this report, for both risk exposure monitoring and forward-looking assessment methodologies. Particular attention is given to three key elements: challenges in the conceptual sphere, data availability, and modelling complexity.

4.1. Exposure mapping: the challenge of risk differentiation

4.1.1 Elaboration of risk classification approaches

Limitations of observed risk classification approaches

The objective of transition or physical risk classification is to group exposures along identification criteria that reflect or approximate these risks. For instance, as described in Section 3, publicly available information such as air emissions accounts[37] or vulnerability indices by geographic area provided by third parties are readily available to identify sectors and countries potentially sensitive to climate change on aggregated levels. Such "aggregate" risk classification may provide operational simplicity and conceptual usefulness to banks and supervisors. On this basis, banks can monitor concentration risk and inform strategic planning and portfolio allocation. Supervisors can use these classifications to identify trends in the broader banking sector or deviations from industry averages at the individual bank level.

While aggregate risk classification approaches exhibit several conceptual and operational advantages, they face a number of limitations in practice. Reflecting the current availability of data, identification criteria may not be granular or specific enough to sufficiently differentiate among counterparties. For instance, several existing risk classification approaches implicitly assume that counterparties belonging to the same geographic areas or the same sector display the same risk characteristics while, in practice, individual counterparties' transition and adaptation capabilities may be different depending on the particular physical or transition risk driver being assessed. In addition, a transition-sensitive sector or a geographic area vulnerable to higher physical risk may not necessarily reflect an individual counterparty's sensitivity to climate-related risks, particularly if the counterparty is transitioning to lower-carbon technologies (eg a transportation company investing in the electrification of its fleet) or adapting to physical risk (eg a real estate owner investing in property "hardening"). At the same time, an inability to clearly identify and measure hedging strategies employed by counterparties might impede the ability to differentiate between gross and net exposure.

To complement the above-mentioned approaches, banks can assign a rating or score (see Section 3.1.1).[38] While these may allow for more granular risk differentiation, their integration into the day-

[37] The air emissions accounts in the System of Environmental-Economic Accounting (SEEA) provide information on emissions released to the atmosphere by establishments and households as a result of production, consumption and accumulation processes using the structures and principles laid out in the SEEA Central Framework. The SEEA air emissions accounts record the generation of air emissions by resident economic units according to type of gaseous or particulate substance. The SEEA has been adopted as an international statistical standard by the United Nations Statistical Commission.

[38] Banks or supervisors may also complement these approaches with methodologies such as financed emissions or alignment measures (see Box 1) for monitoring transition risk exposure. While financed emissions measures do not account also for transition and adaptation capacities, alignment approaches may allow for a forward-looking perspective on the evolution of balance sheets in response to managerial actions. However, the outputs of these approaches do not translate into the notion of a risk exposure and accordingly cannot substitute for a risk-based approach. Banks looking to assess transition risk exposure should understand the political, technical and social environments in which they operate, which may have a nexus with carbon emission targets, but these methodologies may diverge in meaningful ways and thus fail to capture financial risk.

to-day risk management of counterparties is challenged by issues relating to data availability and quality (see Section 4.1.2) and the lack of a yet clearly established empirical link between climate-related information and financial risk parameters (see Section 4.2.1). As such, they are often considered separately from banks' (financial) risk scoring.

Risk differentiation and comparability across banks and jurisdictions

Comparability is generally a desired property of any risk classification system. However, comparability across banks' exposures, whether within or across jurisdictions, implies introducing elements of standardisation and/or simplification that may reduce risk differentiation. Thus, a balance is needed between the desired level of risk differentiation, with the level of granularity and complexity that it may imply, and the need to compare and aggregate banks' exposures. From the supervisory view, comparability could help minimise the dispersion of practices and therefore the mispricing of risk through the application of minimum common standards. However, there are several obstacles to developing such standards:

- **Comparability across jurisdictions.** When comparing banks' risk profiles and exposures across jurisdictions, a simple risk classification may mask important differences among individual banks across jurisdictions. At first glance, some types of climate risk drivers – physical risks in particular – may seem comparable across jurisdictions to the extent that they share a common global definition – for instance, the risk from wildfires. However, determining whether it is riskier to lend in one jurisdiction relative to another with respect to a particular physical hazard involves analysing the events themselves, comparing them, and grading them according to the amount of damage and losses that they may generate based on the frequency, intensity and likelihood of physical risk events in each respective country. To ensure that such a comparison is meaningful, there would be a need for a baseline set of common standards in the methods used to assess the risk drivers and the metrics used to dimension the risk. Transition risks are also subject to the same comparability issues.[39] In this context, while common metrics and assessment methods may exist within a given banking group or possibly within a jurisdiction, the challenge is to develop useful, cross-jurisdictional standards.
- **Aggregation perspectives.** An additional set of issues to consider are group-wide perspectives, particularly for a large international bank's risk profile. Bank lending – and more generally providing financial services – to a corporation active in several regions or jurisdictions will encounter jurisdictional heterogeneity that limits its ability to generate a composite assessment harmonising all material climate risk characteristics to which this corporate (or corporate group) may be exposed. In a related way, an internationally active bank may have exposures in multiple jurisdictions that have idiosyncratic climate risk profiles, which is something that could also make it more difficult to craft a single bank-wide classification. The need to integrate climate risk assessments in ways that reflect local conditions may conflict with the need to ensure these assessments lead to decisions that are consistent across the group and in line with group-wide policy, particularly with respect to risk-taking and risk pricing. [40] Moreover, the IT requirements associated with large climate databases and the potential diffuse manifestation of climate risks across banking groups or jurisdictions may exacerbate existing deficiencies in risk data aggregation and reporting previously noted by supervisors (BCBS (2013)).

[39] Exposures that appear to be similar – for instance two loans to two corporates operating in similar sectors but in different countries or regions – may be exposed to very different transition risks if their regions or business models have different initial energy mixes. The authorities of the respective countries or regions may have decided upon different transition policies, possibly also with different targets and different time horizons.

[40] For additional details on the importance of group-wide risk aggregation, including the lessons learned from deficiencies in risk aggregation during the Great Financial Crisis, please refer to BCBS (2013).

4.1.2 Challenges in the availability of appropriate data

Data and information availability has been highlighted as the major impediment to developing climate risk measurement processes in recent years (see NGFS (2019); FSB (2020)). This observation has been confirmed by the discussions during TFCR industry outreach seminars as well as by a supervisory survey (see Boxes 1 and 2). Depending on data sources and the risk factor(s) studied, several data limitations exist. Recourse to external data providers may help overcome some of these limitations, but a more concerted effort by banks and supervisors is likely to be needed to make sustainable inroads into overcoming these challenges.

Data describing physical and transition risk drivers

For data describing physical and transition risk drivers, a key issue is that information can lie outside the range of traditional financial data collections. The collection and usability of climate data may present methodological challenges. First, the information available may lack sufficient granularity (eg some climate indicators may not be available for some regions), it could be incomplete, or simply not updated in a manner consistent with standard financial risk measurement frequencies. Moreover, these data may present some drawbacks that affect the reliability of the analysis. For instance, climate model information may be presented in the form of discrete and granular grids, which are then aggregated to produce climate statistics. Relying on the resulting data may not be accurate, particularly if the economic and financial impact analysis requires higher granularity (see eg Auffhammer et al (2013); Fiedler et al (2021)). Finally, the quality and availability of climate-related data may differ among jurisdictions (for instance, comparing the situations of more developed and emerging countries) and this heterogeneity may hinder the implementation of comprehensive analyses.

Data describing the vulnerability of exposures

Third-party rating information

External data providers often provide indicators to complete bank counterparty and exposure gaps – notably in relation to transition risk (for instance the CO_2 emissions under different scopes) and/or physical risk, and assign ratings or scores with respect to these risks on an individual borrower basis. Climate ratings, however, may need to be assessed rigorously.

First, end users of ratings provided by data aggregators may have limited insight into the accuracy of underlying information disclosed by the rated entities or the data cleansing process employed by the aggregator. While this opacity is common to any external rating, opacity in climate-related ratings might be further compounded by insufficient standardisation of the underlying information – unlike the financial statement information that informs credit ratings, which benefits from well established accounting standards and a mature assurance industry. Relatedly, as most scores are based on proprietary models, data users may face opacity in obtaining a full overview of the methodological approach taken by the data providers. Significant discretion remains in methodological approaches chosen to derive these indicators (eg Berg et al (2020)),[41] and the integrity and reliability of the methodology will require regular due diligence by the banks and supervisors making use of such indicators.[42] Furthermore, comparability of indicators across vendors is limited. It is accordingly often challenging to reconcile approaches followed

[41] For example, an indicator that is derived from a sample of exposures may bias the model output. This is particularly salient when climate factors, such as emissions, are averaged across entities of differing size, technological capabilities, and regions.

[42] As with all third-party vendors, end users have a responsibility to obtain a sufficient understanding of the modelling approach, limitations and assumptions prior to incorporating them into their own processes. See, for instance, BCBS (2020c,d).

by different providers, thus limiting the integration of multiple, non-compatible indicators within a single risk measurement process (see also IMF (2019); ECB (2019)). A final significant data gap may concern the underlying sample of companies, particularly when the scores or indicators are derived from samples of large (listed) corporates. This issue, notably exacerbated by limited public data availability and reliability for smaller companies, may both reduce banks' portfolio coverage and affect the representativeness of the rated sample.[43]

Counterparty-level information

In establishing a banking relationship and allowing the lender to perform a creditworthiness evaluation, counterparties provide proprietary non-public information, fulfil statutory disclosures, and meet other data requirements established by the bank that inform the latter about the potential client's main features.[44] In evaluating climate-relevant data availability, the ability of the bank to acquire client non-public information via the lending relationship can address some of the data gaps or quality issues on a bilateral basis. However, and especially when the counterparty is small, the availability of proprietary climate-related client data may be qualitative, rather than quantitative and, as suggested during the industry outreach, may face limitations in completeness and precision according to the size and complexity of the client.[45] Furthermore, the ability of the bank to update data after the underwriting and onboarding processes have concluded may be limited, which could create gaps in climate reporting for existing exposures. Banks may have, in practice, less leverage during the life of the contract to obtain updated information that may be costly to produce from counterparties (for instance, the carbon footprint under different scopes).

Where banks are unable to source proprietary non-public information (particularly for existing exposures), they may turn to the public information that borrowers, and in particular corporate clients, may (or, in some cases, must) disclose.[46,47] It should be noted that the quantity and quality of public information is often a function of firm size, limiting comparability of smaller firms vis-à-vis large corporations. Another common comparability limitation arises from differences in accounting principles and/or reporting schemes across jurisdictions; moreover, this challenge is heightened with regard to climate data, as common standards for these data for financial risk assessment are currently non-existent. In the absence of generally accepted standards for climate-related disclosures, data comparability across counterparties may be limited.

Supervisory reporting data

In addition to many of the data sources available to banks mentioned above, supervisors can leverage their supervisory process to augment data needed to perform climate-related analyses on the banking

[43] To this end, caution is warranted when using averaging scores, as scores averaging the adequacy of climate-oriented policies adopted by a sample of companies within a specific sector/country may give a misleading picture. For example, if the sample of firms used to benchmark the scores were biased towards those who actively engage in climate mitigation activities while out-of-sample firms were not engaged in such activities, a sectoral risk score might skew towards lower carbon intensity than is actually reflected by the overall sector.

[44] Although we focus primarily on borrower creditworthiness, climate risks may also arise in non-lending relationships (eg asset management, brokerage, etc); therefore other clients' features (risk appetite and tolerance, financial preferences, budget constraints, etc) may also be relevant.

[45] For instance, in some jurisdictions, companies above a defined threshold (in terms of turnover or number of employees) are required to calculate and disclose their carbon footprint. This information is therefore not necessarily readily available for smaller companies. It may be costly to produce this information as they may need to resort to external expertise.

[46] In some cases, this data can also be available in memorandums of offering for some securities placed on the market, rather than at the firm (issuer) level only.

[47] The TCFD, for instance, has noted that while climate-related financial disclosure has increased in the last few years, more progress in this regard is needed. Indeed, the percentage of companies disclosing climate-related information remains low (TCFD (2019)).

system. Supervisory reports provide recurring and standardised data that could inform or be useful in climate risk measurement. They could offer a broad picture of the overall composition of banks' asset portfolio, from both a macro (eg total exposures towards different economic sectors and geographical areas) and, depending on the availability of the information in a given jurisdiction, a micro perspective (eg on a loan by loan or financial instrument basis). Nevertheless, while existing data provided can be leveraged in combination with third-party providers – as observed in existing practices described in Section 3 – current supervisory reporting may lack sufficient granularity to assess transition and physical risks, as suggested by the supervisory survey (see Box 2). For instance, the geographic and sectoral breakdown of corporate exposures is often only available at a level of aggregation which may not allow for sufficient risk differentiation (see Section 2.3.2), so supervisors may need to develop additional tools to work with existing data or consider amending current regulatory reports as appropriate.

4.2. Forward-looking assessment methodologies: accounting for complexity of climate-related financial risks

When quantifying climate-related financial risks, a challenge that follows from establishing a risk classification and enhancing data collections is designing a modelling framework that facilitates the translation of climate risk drivers into financial risk parameters in a forward-looking manner. Banks and supervisors have initiated efforts in this direction. Nevertheless, as both the TFCR industry outreach and supervisory survey suggest (see Boxes 1 and 2), remaining challenges include in particular: (i) designing a modelling framework that fully captures the economic effects of climate scenarios; (ii) the implications of long-term horizon assessments; and (iii) operational challenges in performing such assessments.

4.2.1 Challenges in designing a modelling framework to capture climate-related financial risks

Scenario design and complexity of climate-related financial risks

Ideally, a scenario representing physical or transition risk drivers would include all the necessary economic and financial variables at a level of granularity consistent with a chosen risk classification to compute financial losses. However, climate-related financial risks are complex and transversal, with considerable variance across regions and sectors with uncertain climate drivers. Such uncertainty may also extend beyond intrinsic future uncertainty inherent to projections of physical and transition risk drivers, to also interact with measurement uncertainty related to data gaps, and model-based uncertainty in the face of uncertain relationships and prospective non-linearities. In this context, banks and supervisors report difficulties in modelling comprehensive scenarios that can be integrated into existing risk assessment processes and structures, in particular related to the following aspects:

- **Uncertainty around the climate risk drivers.** An overarching challenge relates to the multiple levels of uncertainty related to both transition and physical risk drivers, in particular surrounding non-linear aspects of the climate system. For example, many combinations of transition drivers could lead to the same CO_2 concentration outcome with significant variance in the economic and financial impact across and within sectors and geographies. In the light of these uncertainties when developing complex climate and financial scenarios, the degree of discretion underlying the assumption within any single scenario is significant and different methodological choices can give rise to strikingly different outcomes. Therefore, when assessing the effects of future possible climate events, accounting for uncertainty by adopting alternative scenarios as well as the results of different modelling approaches underlying the same scenario may be needed to make the analysis more robust. Nevertheless, exploring multiple scenarios resulting from various climate risk drivers may be particularly resource-intensive.[48]

- **Capturing the specific impacts of climate scenarios.** The overview of currently available methodologies across supervisors and banks to measure climate-related risks in Section 3 suggests the need to continue developing modelling frameworks to capture the impacts of climate scenarios, including stressed variants, within an integrated and tractable modelling framework. Absent such an integrated framework, banks and supervisors are mobilising existing tools depending on their relative strengths with respect to the objective of their use (see Section 2.4 and Annex for an exhaustive discussion). For instance, commonly used IAMs are not currently suitable to comprehensively capture macroeconomic dynamics following a policy shock (eg a carbon tax increase). Accordingly, in assessing transition risk banks and supervisors have resorted to macroeconometric models that adjust for the macroeconomic impact of carbon price shocks – the latter being proxied by a change in relative energy prices. These models, being calibrated on historical data and statistical relationships, may not adequately capture climate scenario dynamics. Regarding physical risk drivers, connecting a climate scenario consistent with these risk drivers to an economic framework remains an area of ongoing research. In particular, existing models estimating economic impacts from climate change usually do not capture the full range of potential climate change impacts. Economic modelling frameworks can often only take into consideration the impacts of chronic physical risk (eg temperature rise). The economic impacts of extreme weather events or of potential future disruptive changes in climate (eg the crossing of tipping points) are usually not captured (see also Section 2.4).

- **Comprehensiveness of modelled impacts.** A related modelling challenge is to capture the impact of climate scenarios at the level of granularity consistent with a chosen risk classification. For instance, for physical risk, the translation of physical risk drivers into firm-level expected losses is challenged by the lack of damage functions available at granular geographic level. A comprehensive assessment would also include modelling second-round effects such as the propagation of policy or physical risk shocks through supply chains or financial contagion while accounting for the adaptive and mitigation abilities of economic agents. For instance, banks and supervisors may need to consider the market power of individual firms in their ability to pass on any carbon price increases to the consumer (see Bolton et al (2020)). At the macro level, evolution in insurance coverage or governments' natural catastrophe schemes would also be key information to assess, as well as the vulnerability of households or companies to the financial consequences of more frequent and costly natural disasters.

To address these complexities, an option has been for supervisors to develop a suite of models. For instance, some supervisors[49] have added specific production network modules to traditional macroeconometric models that aim to capture the sector-level transition impacts of carbon price shocks (eg Hebbink et al (2018); Devulder and Lisack (2020)). Nevertheless, this option entails connecting disparate models with different theoretical foundations, which would require additional research.

[48] Modelling uncertainty may also exist in cases where banks and supervisors rely on third-party providers in their modelling. A direct modelling approach may use internal models to generate economic risk factors from data describing physical and transition risk drivers. Conversely, banks and supervisors might leverage "pre-packaged" models developed by specialised providers and tailor them to their particular needs. These two approaches have trade-offs in heightened computational complexity and resource utilisation versus loss of specificity and utility of results.

[49] Some banks, for their part, rely on a proprietary internal classification (eg rating or score) to infer qualitatively sector-specific shocks.

Translating scenario outputs to financial risks

Another significant challenge mentioned by banks and supervisors has to do with the ability of financial risk models to factor in variables linked to climate scenarios. Financial models used to infer impact on risk parameters such as PDs or LGDs for credit risk have generally relied on the historical statistical relationship between a given risk driver (eg a sharp increase in unemployment following a macroeconomic shock) and these parameters. Sufficient depth and variance in the historical observations of the risk drivers are needed to estimate robust relationships. Historical observations of risk materialisation linked to climate-related risks are missing or are not good predictors for future patterns. Therefore, financial models cannot currently derive empirical risk parameters. To address this obstacle in the case of credit risk, a few banks and supervisors are attempting to attribute the impact of aggregate stressed scenario variables (for instance GDP) on the financial metrics of the counterparties based on relevant characteristics (for instance CO_2 emissions with respect to transition risk) and then infer the impact on risk parameters (eg Bank of France (2020)). This approach faces significant limitations. First, it reverts to the ability of banks and supervisors to gather all the necessary data to classify counterparties along these characteristics. Second, the results are based on a strong underlying simplified assumption about the relationship between scenario-related variables and the financial impact on the counterparty, which limits their usability for certain risk management purposes such as asset pricing or funds transfer pricing.

4.2.2 Time horizon related challenges

The long-term nature of climate change is leading banks and supervisors to consider horizons that can extend significantly beyond the one commonly considered by institutions – up to 2050 in observed practices. This raises a number of challenges for both supervisors and banks with respect to stress testing exercises and forward-looking assessments more generally. Besides uncertainties inherent to climate sensitivity modelling (see Section 2.1.6), such long-term horizons significantly increase the uncertainty around economic and financial projections, which limits their reliability for assessing risk outcomes. The longer the horizons used in forecasts, the more uncertain are the model's projections since the likelihood and the magnitude of a divergence with observed evolutions is likely to be significantly higher compared to usual stress testing analysis with a shorter time horizon. Modelling limitations (eg key parameters of models being estimated on historical statistical relationships) will further impede the robustness of projections.

The current limited ability of banks to factor in or internalise the negative feedback loops stemming from their lending decisions on the nature and the degree of transition and physical risks may also be related to risk frameworks more narrowly geared towards direct and short-term exposures. Moreover, banks' risk frameworks can be further shaped by the time horizons embedded in regulatory standards and expectations. As a consequence, further reflection will be needed on the appropriateness of, and potential modifications to, existing measurement approaches to capture risks over longer time horizons, including the possibility of leveraging best practices in modelling approaches from fields focused on long-dated and complex risks in a bank supervision context, and an evaluation of current, and potentially new, supervisory tools for various time horizons.

Any such efforts should address the greater uncertainty around the future portfolio composition of a given bank, arguably rendering the traditional static balance sheet assumptions more questionable over such a long-term horizon (see Section 2.5.3). While a dynamic balance sheet might seem more plausible at first glance, it implies the need to fully understand how the significant number of assumptions underlying balance sheet projections could impact the results of the risk assessment. In the end, the results of climate-change-related scenario exercises may challenge the traditional supervisory use of scenario analysis in a stress testing capacity, eg informing capital requirements. Such exercises may rather inform the strategic and business model resilience of institutions, thereby underscoring the need to evaluate the appropriateness of individual supervisory tools for various time horizons.

4.2.3 Operational complexity in the measurement of risk

One of the takeaways of the TFCR industry outreach and the supervisory stocktake is that both banks and supervisors should continue building operational capabilities to assess climate-related risks. Climate risk measurement is a highly challenging task that demands significant resources, including adequate systems infrastructure, relevant human resources, and a sophisticated organisation. Notably, a bank's ability to assess its overall exposure to climate risks across all of its significant operations will be heavily dependent upon the quality of its IT systems and its ability to aggregate and manage large amounts of data (eg multiple data on sector and location, related to supply chains for a given counterparty). Most methodologies are contingent on this ability to collect, format and process very large amounts of new climate-specific data (see Section 2.2).

With regard to human resources and expertise, the interdisciplinary nature of climate-related financial risk measurement may require both pooling resources from a wide range of relevant functional and business areas and developing in-house or outsourcing climate-specific expertise. A further consideration influencing a bank's choice of risk measurement methodologies is the size and complexity of the banking group. A higher degree of idiosyncrasy among business lines and banking entities may challenge internal harmonisation towards common risk assessment approaches, risk metrics and methodologies, necessitating more sophisticated modelling techniques, while smaller, less complex banking groups may face trade-offs in resource allocation and sophistication.

5. Conclusion

This report outlines conceptual issues related to climate risk measurement and methodologies, as well as practical implementation of these concepts by banks and supervisors. Building on a companion report on the identification of risk drivers and their transmission channels, this report yields key findings on methodologies for measuring climate-related financial risks, including exposure mapping and measurement and forward-looking risk assessment methodologies.

On mapping and measuring climate-related risk exposures, work by banks and supervisors to date has centred mainly on transition risks – with less emphasis being placed on physical risks. That said, many banks and supervisors are expanding their data collections and taking steps to address several remaining gaps. These include the quantity of climate-relevant risk data provided by counterparties (with many reporting gaps, notably for smaller counterparties), the quality of such disclosures (notably their scope), and the consistency of data across both portfolios and jurisdictions (using a consistent risk classification). Because of such data gaps, multiple external data providers are currently offering their services to numerous banks and supervisors given limitations of in-house collections and expertise. To date, efforts by both banks and supervisors have mainly focused on credit risk and to some extent on market risk, with a much lesser focus on liquidity and operational risk. At the same time, climate-related metrics have helped banks to communicate their strategic position on climate change to their broader stakeholder community as they seek to manage reputational risks.

Frameworks suitable for translating climate change scenarios into the broad array of financial risks to banks remain relatively nascent. Beyond data-related challenges for assessing physical and transition risk exposures, methodologies need to be further developed to adequately address the uncertainty inherent to joining up the modelling of climate and financial variables, as well as analysing unusually long-dated risks. This involves intrinsic future uncertainty inherent to projections of physical and transition risk drivers and ensuring standardised scenarios; measurement uncertainty related to data gaps, which may limit the suitability of backtesting to calibrate loss or damage functions; and model-based uncertainty, with more work needed for a robust quantitative assessment of identified climate risk driver impacts on banks – including risks to counterparties, assets, liquidity and operations. The systemic nature of climate change might imply many interconnections and feedback loops, as well as likely non-linearities and tipping points. In this vein, insurance protection gaps may be an issue, calling into question any assumption about availability of mitigants into perpetuity. This suggests that a combination of multiple methods and models may be needed for a comprehensive understanding and measurement of the potential scope of climate change risks. Ultimately, climate risk measurement and refinement of forward-looking methodologies still remains a work in progress that would benefit from ongoing official and private sector initiatives to fill existing knowledge and measurement gaps. Scenarios used by supervisors should also be consistent across jurisdictions to the extent possible to facilitate risk measurement and management for internationally active banks.

Against this background, several key areas remain for further analytical exploration to enhance the measurement, monitoring and management of climate-related financial risks. They are related to both measurement and methodologies – spanning the potential for risks emanating from both informational and allocative market failures.

On the side of measurement, a first key issue concerns risk classification. Most classification approaches developed so far are generally oriented towards disclosure and stakeholder communication purposes; their features are often different in nature to risk-oriented disclosures. Additionally, classifications embedded within risk metrics are often difficult to compare, as some are static and devoted to point-in-time exposure measurement, while others are rather dynamic and refer to strategies, such as alignment metrics. Further international efforts towards a globally consistent classification of climate risk information, as well as sufficient mapping of this information to usual risk categories, can make an important contribution to proper integration, management and mitigation of climate-related financial risks. A second key issue on the measurement side concerns data gaps. Data needs include more consistent information on climate risk drivers; the vulnerability of counterparties, sectors and regions to these risk drivers and, consequently, their impact on the real economy; and ultimately their translation into financial risks for banks, and financial system impacts. Data acquisition is costly and may explain the different stages of development across institutions. Collective efforts, including evaluating potential enhancements to public data collections, will therefore be helpful to fill these data gaps so as to manage a risk which is global in essence. For supervisors, initiatives to evaluate the appropriate level of data consistency and granularity across firms and jurisdictions would be useful. These initiatives would helpfully evaluate the availability of pertinent data (including the non-financial disclosures from both financial and non-financial corporations), the relevance of particular data to improve market information and enhance effective risk management, and the appropriate standardisation of data to promote comparability and aggregation.

On the side of methodologies, further investments are needed in models to enhance measurement of forward-looking climate-related risk. Here, supervisory requirements, risk measurement and management tools are typically designed for shorter horizons than those inherent to longer-dated climate change risks. As a consequence, a crude adaptation to climate-related risk may contribute to a mismeasurement of risk and – ultimately – impact effective and efficient risk intermediation. In particular, further reflection might be needed both on the potential modifications to existing measurement approaches to capture risks over longer time horizons and on the appropriateness of individual supervisory tools for various time horizons.

In outlining measurement methodologies and the current state of knowledge on their quantification in climate-related risk frameworks, this report has noted areas where mapping to traditional risk drivers for banks is possible, as well as those areas where it remains a challenge. Several key investments needed to address gaps in data and methodologies are emphasised, which – if undertaken by the broader industry and policymakers alike – should foster a stronger quantitative understanding of climate-related financial risks, thereby opening up a clearer path to the prudential management and mitigation of such risks.

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Annex: Methodology comparison

Methodologies can be assessed across several dimensions. Given the scope of the report and its emphasis on microprudential financial risks, the following dimensions are deemed more relevant:

- Complexity versus applicability: Many methods exhibit a high level of complexity and consider the interactions among agents, the economy and the financial system. While these methods are suitable for advanced modelling, it is also useful to consider methodologies that are more applicable for scenario analysis and stress testing, and allow banks and supervisors to concretely quantify climate-change-related risks.
- Granularity: Risk exposures can be measured at different levels of granularity. Starting from the most micro level, exposure can be assessed in relation to an instrument and/or an asset – the two notions are linked since the value of an instrument is based on the value of the underlying asset. Less granular approaches may measure exposures at the portfolio or company level. Some other approaches focus on exposures at the sector level.
- Aggregation: Once exposures are assessed and quantified, it is important to understand whether they can be aggregated. Aggregation could be inherent to firms (aggregating exposures across different portfolios), conglomerates (aggregating exposures across the firms belonging to the same conglomerate), sectors (aggregating exposures across firms in the same sector) and the financial system. Aggregation allows an overall assessment of climate-change-related risks.

Based on these characteristics, the table below provides a summary of different methodologies and their common features. The selected dimensions in the table, which emphasise strengths and weaknesses of the analysed methodologies, are not exclusive of other characteristics, such as analytical approach (top-down/bottom-up), geographical coverage or treatment of uncertainty (deterministic/stochastic). There is as yet no consensus on which method represents the best approach in measuring climate-change-related risks.

Approaches	Strengths	Weaknesses	Time horizon	Applicability Versus complexity	Granularity	Aggregability
Integrated assessment model (IAM)	Captures feedback between socioeconomic and climate systems effectively Projections are internally consistent Models accommodate alternative assumptions and policies	Highly aggregated Typically relies on limited damage function, which may not effectively incorporate risks of extreme weather events Lacks resiliency to imperfect information and unforeseen endogenous events, such as technology or policy change Most IAMs do not model money, finance, or banking	Short to long term	Highly applicable	Less granular	Already (highly) aggregated
Computable general equilibrium (CGE)	Accounts for interlinkages across many economic sectors and agents	Assumes decision-makers have perfect foresight and information	Short to long term	Somewhat applicable	Somewhat granular	Already aggregated

Dynamic stochastic general equilibrium (DSGE)	Incorporates uncertainty in agent decision-making In use by central banks for policy analysis	Computationally intensive Unrealistic agent decision-making process assumptions	Short to long term	Complex	Somewhat granular	Already aggregated
Macro-econometric	Accounts for market distortions through the role of prices	Estimations are based on past observations Macro-focused; inherently excludes micro-level analysis	Short to long term	Somewhat applicable	Less granular	Already aggregated
Overlapping generation	Highlights intergenerational redistribution Incorporates life-cycle investment decisions	Closed economy model Does not consider endogenous systemic risks (climate change or transition) Assumes individuals have perfect foresight about future prices and economic conditions	Long term	Complex	Somewhat granular	Already aggregated
Input-output	Details environmental impacts at an industry level Can capture impacts of demand for goods and services on energy and resources Captures cascading effects of events	Decisive role of prices limits policy alternatives to price mechanisms (such as taxes)	Short to medium term	Highly applicable	Somewhat granular	Can be aggregated across sectors
Agent-based	Micro (agent) level Captures agent/economic interactions well	Computationally intensive Significant data requirements for developing agents' behavioural rules	Short to medium term	Complex	Highly granular	Can be aggregated across all agents
Scenario analysis	Analyses tail risks effectively Scenarios have benefited from industry collaboration Relatively computationally simple Addresses some aspects of climate uncertainty	Scenarios often omit chronic hazards Hampered by data gaps	Short to medium term	Highly applicable	Can be highly granular or aggregated	Can be aggregated at portfolio, sector and system level