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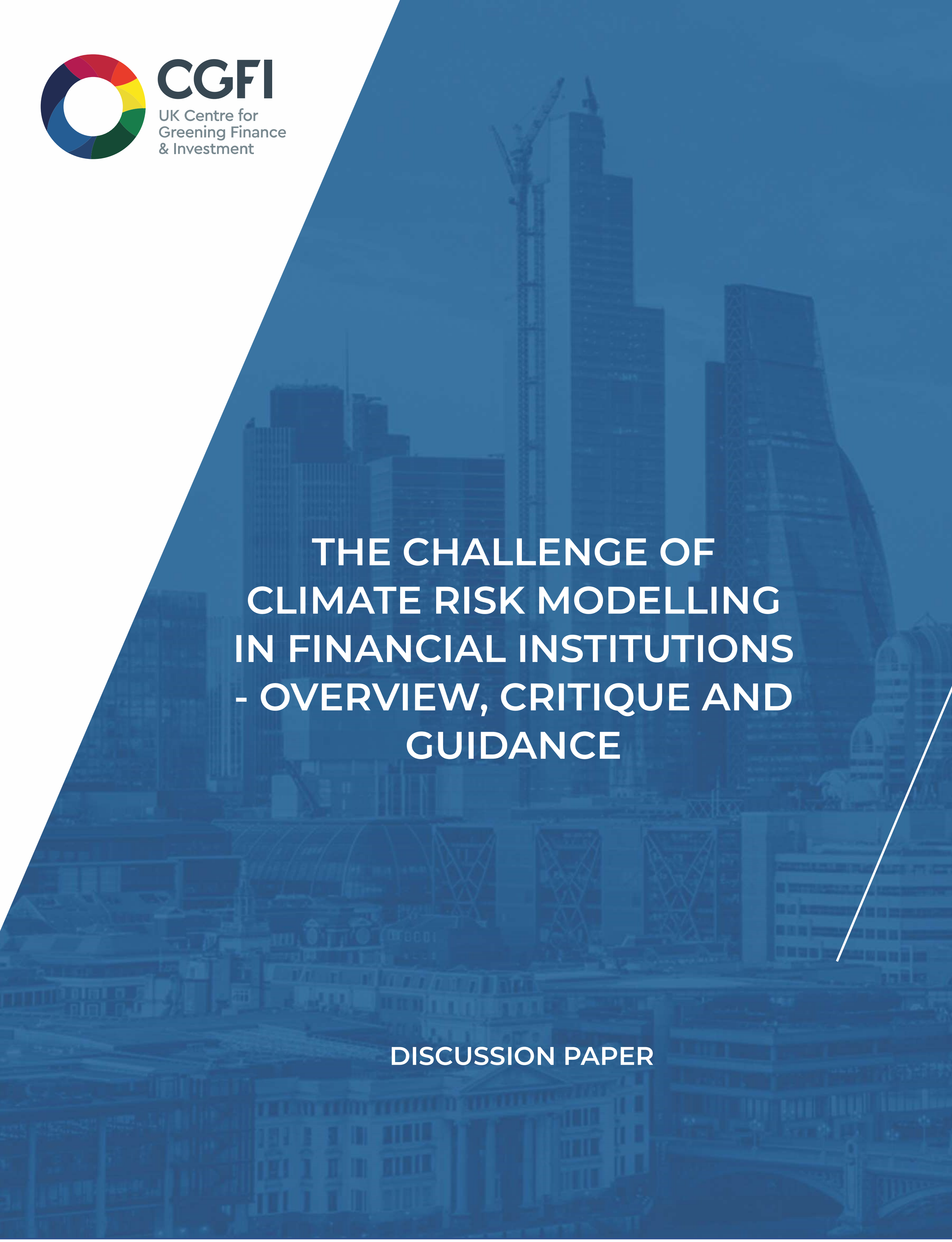

THE CHALLENGE OF CLIMATE RISK MODELLING IN FINANCIAL INSTITUTIONS - OVERVIEW, CRITIQUE AND GUIDANCE

DISCUSSION PAPER

University of Bristol | Imperial College London | University of Leeds | University of Oxford | University of Reading | Catapult Satellite Applications | The Alan Turing Institute | UKRI Science and Technology Facilities Council

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Executive Summary

Climate change poses significant risks to financial institutions and the global economy. However, the quantification and management of these risks is complex and, as a consequence, methodologies that are employed by financial institutions are in many cases incomplete and in some cases misleading. Climate risk modelling in financial institutions is a relatively new field, and it is evident that several challenges in the quantification of these risks need to be addressed.

This paper discusses the various general issues with climate risk modelling in financial institutions, including data availability and quality, model uncertainty, and integrating climate risks into risk management frameworks. Furthermore, as part of this discussion, we highlight the quantitative model risk issues in some commonly used frameworks including the recent ECB modelling framework and publicly available models as well as an overview of useful features of academic models and commercial models. We discuss frameworks for assessing climate risks and propose necessary and desirable model features to meet the needs of financial stakeholders to assess climate risks. The objective is to build a view of how modelling frameworks can better serve the needs of stakeholders in an economy, from members of the populace, banks, investors, central banks, and policymakers.

Specifically, we argue that risk management methodology as typically used in finance needs to evolve to better reflect the real-world economy, such as the impacts from physical risks and policy driven climate risks. Without such a means to causally link these real-world risks to financial outcomes such as markets, all stakeholders run the risk of incoherent inference and compromised decision making as well as missing significant risks. As such this article should be read by academic researchers, financial risk modellers and model validators tasked with building or assessing the emerging field of climate risk modelling.

1 Introduction

Climate change and the threat of extensive loss of natural and human habitats from anticipated acute and chronic weather patterns pose significant risks to the global economy, as has been observed from recent events. These risks include physical risks such as sea level rise and extreme weather events, as well as so-called transition risks associated with shifting to a low-carbon economy. Current financial sector models that have been developed to assess these risks are driven in part by regulatory frameworks set up by the NGFS (NGFS, 2022) and engaged by central banks such as the Bank of England (Bank of England Prudential Regulation Authority, April, 2019) and the European Central Bank and the European Banking Authority (ECB, 2022).

Such models have been challenged for a number of years at a number of methodological levels from the conceptual use of deterministic outcomes to the pragmatic ability to apply and adapt the scenarios to financial portfolios (for a recent overview see Cliffe, 2023). Specifically, the main objections that have been put forward are that the NGFS-style scenarios lack uncertainty and the lack of consideration for significant second-order climate-linked scenarios such as mass migration driven by physical climate events. These methodological gaps have been highlighted across several publications and are explored more in section 4 and in section 4.9.

Whilst it is currently acknowledged that the area of financial risk assessment from climate-related risks is still in its infancy as of 2023 (Baer et al., 2023), with current modelling techniques lacking sufficiently detailed financial risk factor [1] output for a full quantitative analysis of the risks. National policymakers still have to put forward clear plans to decarbonise significant areas of the economy (for example, residential and commercial properties in the UK (H.M. Government, U.K., 2021), or a clear strategy to decarbonise agriculture) and are still subject to policy uncertainty. These discrete policy choices may create challenges for firms, their lenders and investors. Building an understanding of the implications of these policy uncertainties has been one of the critical set of scenarios developed by the Network from Green Financial System (NGFS) NGFS, 2022. In the UK, for example, policymakers are realising the impacts of rising prices and capital costs as interest rates rise, giving rise to a delay in climate policy mechanisms (such as a view on technologies for residential and commercial heating). This transmission of price factors impacting policy choices and timings highlights issues in capturing holistic risks in climate scenarios is an area required for novel research combining the macro more effectively to micro-economic factors.

These challenges highlight the need to build viable and timely scenarios (i.e. useful short-term scenarios[2]). In finance, it is expected to build scenarios that reflect short-term (< 5 year) risk to the organisation. Within climate stress scenarios, financial organisations need to look at not only the large-scale national or global trends but also the risks of short-term impacts on prices, technology disruption, consumer engagement and policy shifts. These issues have, in part, come about because of a lack of sufficiently detailed coherent modelling of the potential impacts. This need for a coherent means of assessing climate economic impacts that can be

[1] Concepts of financial risk factors will be explained in section 2

[2] The NGFS has recently released its guidance on short-term scenarios (Network for Greening the Financial System, 2023

enhanced over time is highlighted in section 5.

This note will focus on some of the gaps and issues, specifically in financial risk estimation, focusing on limitations in current observed methodologies, in particular on lending risks to companies subject to physical and transition risks. We then propose a set of necessary factors that a climate financial risk model should possess for company financial risk assessments. These factors, whilst restricted to companies, can be applied to other risk areas.

The intention is that this paper can be applied by academic researchers, financial modellers and model validators and others within financial institutions. The structure of this paper is as follows: firstly, we define a list of desirable high-level model objectives and features to address the challenges of climate risk assessment. Then in section 3, we provide an observation of climate stress testing methodologies in practice, from academic to commercial. In section 4 we highlight some of the challenges and open problems in capturing climate risks and a critique of specific methodologies that are currently widely used that might give rise to misleading results. In sections 2.2, we go into more detail about the specific risks faced by financial institutions and the need to meaningfully improve the mapping of externality risk into a financial institution risk framework, notably in pricing and the potential impact of climate risks on company defaults. Finally, in section 5, we propose a set of pragmatic and necessary modelling factors to address the set of risks; the intention is that this serves as a means to enhance modelling capabilities for not only climate-related risks but also other externalities.

Observations on the Current Use of Climate Methodologies in the Financial Services Industry

Financial institutions themselves have started to develop a number of products linked to the performance of companies' emissions targets and other ESG criteria. These products are provided for both companies (emission-linked bonds) and sovereign states such as debt for nature swap, such financial instruments with contingent payout clauses present a risk to investors or the institutes that issue them or provide hedging services linked to these products. As such this necessitates sufficient pricing and risk management tools to serve the needs of investors and financial institutions, furthermore the need to provide a regulatory oversight framework for such instruments.

Currently, there is a notable gap in the structure of stress testing and methodologies as put forward by regulators such as the European Banking Authority (EBA) and the Bank of England and conventional stress testing approaches used by banks. The issues that define these gaps are discussed in section 4. However, to highlight one of the main issues: the lack of transparency and consistency in the methods and assumptions used in different models within the financial sector. This makes it difficult to compare results and assess their credibility. This lack of transparency/capability is becoming increasingly important around the world as regulators, legislators, and investors are requesting clear statements of the materiality of exposures linked to climate and other sustainability factors. For example, in, a recent ruling in the state of Florida (The State Board of Administration of Florida, 2022) requires that investments that have been linked to ESG (environmental, social and governance) factors [be] demonstrated to have material risks disclosed. This is an area where improved regulatory understanding of the risks and the set of methodology solutions need to be highlighted by organisations and regulators.

Whether it is through fiduciary duty to investment clients, the need to assess systemic economic risks in banking portfolios, the need to derive a material exposure value for financial climate risks, estimate systemic financial system exposures or the need to plan an economic transition for a nation under a political policy, it is clear there is a need to provide improved quantitative measures of risk, rather than qualitative statements linked to perceived environmental factors.

As it stands, the current set of models does not fully take into account the potential for systemic risks, such as the impacts of physical risks, biodiversity loss, degradation of human-inhabited areas and impacts of economic transitions and their feedback through the broader economy, the financial system and the impacts on political choices.

Whilst the ability to construct comprehensive modelling solutions to address these complexities may be beyond current financial system models, we argue there is a need to improve modelling capabilities across components of the financial system. In the paper, we critique some of the modelling methods that have been commonly applied and highlight those techniques that have a greater ability to provide insight into the risks.

This paper is laid out as follows: in section 2, we provide an overview of the features required to produce a useable and reliable climate financial risk model, highlighting the objectives. Then in section 3 an overview is provided of current climate risk model concepts in the literature and public methods used within industry. In section 4 we highlight the challenges in climate financial modelling from data collection, scenarios, and modelling methods. At the end of that section we provide a critique of public models and known methods in commercial modelling frameworks that could give rise to misleading model results. In sections 2.2 and 2.3 we provide an overview of financial risk and pricing methodologies and highlight the needs of climate models to address the needs to produce pricing and risk information. Finally, in section 5 we highlight a number of pragmatic solutions to address climate risks. We do not mention specific commercial vendors or banks in this paper but highlight issues with modelling approaches that have been observed across this set of models. However, we do discuss openly models that are in the public domain that are used commercially by the finance industry. Therefore, it is essential to consider the limitations and uncertainty of these models when assessing the economic risks of climate change and developing risk management strategies.

2 What Features Does a Usable Financial Risk Model Possess?

Climate risks pose a significant impact on virtually all aspects of human and natural habitats. They can be non-local in impact, where, for example, weather events thousands of miles away can impact the quality of lives of millions of others through, for example, impacts to food prices. Whilst climate-linked impacts may not have an immediately obvious economic impact or the level of expected risk may already be priced into financial securities/derivatives, the objective is to put forward a structure of how a viable model framework could be designed and the features it should possess to enable the user to obtain a view, of climate linked events from both physical and transition factors. Consequently, this section focuses on building a tangible means to quantify these risks to encourage better risk management and planning funding for mitigation. For cases where the risk cannot be currently quantified or may be ambiguous, there is a need to refine views on policy to determine where the cost of climate mitigation is realised or the need for clarity in the definition of the risks.

To build an understanding of what constitutes a useful climate linked economic risk model for the financial system, there is a need to understand the objective of the economies where it will be deployed and the stakeholders that will be impacted. It is clear that for climate transition risk management, the interplay of the major stakeholders will inevitably influence the risks of other parties. To define the set of stakeholders that can manage and mitigate climate transition risks, this set of stakeholders is given in the list below:

- **Populace** - Climate change naturally impacts the Populace to a greater or lesser extent, from increasing risks to individual health from adverse weather and its impacts on the physical world to economic costs and employment opportunities. Modelling transition risks related to individual spending power will have a significant impact on growth, purchasing preference, tax revenues, investment, and the ability to adapt and provide skills to affect a transition economically. This impacts the wider economy of the complexity of climate modelling. Furthermore, exposure to a changing environment and physical risks will impact health costs, insurance and asset values.

Biodiversity: Natural and Agricultural habitats - The degradation of agricultural land, produce yields and desires to reduce associated emissions will have notable local and global impacts on economies and social wellbeing. Understanding the need to improve farming practices, secure food supply chains requires a detailed understanding of regional and produce-linked factors and their impact on global foodstuffs markets and knock-on effects on inflation. The degradation of natural habitats such as water sources can diminish bio-diversity, leading to further habitat failure and direct impacts on human welfare. Further impacts on human economic activity, through the migration of disease vectors (such as the spread of mosquito-borne diseases) to currently temperate climates, tourism and property values. Building a rational economic view on the replacement/remediation cost of natural habitats needs to be engaged by policymakers to ensure that habitat degradation can be clearly defined, managed and ultimately remediated. Frameworks such as the currently emerging TNFD (UNEPFI, 2023a) are providing a clearer means to define the potential business and national liabilities. Furthermore, the mechanism whereby these liabilities (e.g.

fines/remediation funds) are directed to improve the defined degradation to the environment needs to be clearly defined by policy makers so that remediation timelines and duration of liabilities can be clarified.

- **Businesses** - Businesses of all sizes may be significantly exposed to changes in demand, costs, regulatory policy and impacts on their supply chains from the need to change their energy source and policy-driven and customer-driven factors.

- **Commercial Banks** - are exposed to a set of specific climate-linked risks in their portfolio of current and future clients' business clients loan and derivative portfolios, and impacts to other assets such as real estate, project finance and other investments. Banks may be exposed to direct climate regulatory impacts that could be imposed, such as restrictions on lending to specific sectors. Aside from the idiosyncratic climate-linked risks, banks are exposed to potential secondary consequences of regional and global climate impacts, such as macro impacts to inflation, interest rates, FX, equity and commodity prices and their volatility that may be driven by adverse policy or acute physical risks and potential regional / multinational banking defaults linked to climate events.

- **Asset Managers and Investors** - each asset class, whether a corporate bond, loan, equity, real estate of project finance and their derivatives, will be impacted in terms of price and volatility. They are also exposed to macro-economic risks defined above depending on the jurisdiction of their investment. Any business may face investor preference pressure on fund allocation, impacting the economic and strategic risks of the fund.

- **Central Banks** - Central banks have started to play a pivotal role in monitoring and guiding the management of climate risks that can arise in an economy. Whilst climate risks are still being assessed, central banks can provide a means of oversight and data collection on exposures of climate-linked risks across the monitored financial institutions. Some may also push for further regulatory requirements on disclosures, methodologies and risk management practices, creating a regulatory need (and risk of non-compliance). However, given the emergent nature of climate risks [3] it is unlikely that a fully regulatory model of climate risk capital calculation would be implemented in a realistic timeline to affect the transition. For example, the Fundamental Review of the Trading Book (Basel 3) Bloomberg, 2022 is not due to be implemented until 2025 across the EU, with the US still undecided on the implementation date. This is after the initial methodology proposal in 2012 and finalisation in 2016. Hence climate financial regulation in light of methodological and data uncertainties, would more prudently deployed in an incremental way with general require (rather than specific) methodology requirements to assess the materiality of climate / nature-based exposures.

- **Governments** - governments have the challenge of setting policy objectives and managing their associated risks. These risks can extend beyond purely economic considerations to political risks, such as failing to engage the *populace* to enable policy. The manifestation of risks can vary from poorly implemented or risk-assessed policies to policies that fail to achieve broader societal objectives due to narrower political choices. Those narrower political choices can give rise to adverse investment decisions, unwarranted degradation of assets, price inflation and

[3] As will be highlighted in this report.

instabilities leading to adverse economic growth or decline. An understanding of the implications of policy choices to ensure that decarbonisation occurs should rationally require an understanding of the economic factors of policy choices made across all assessments of economic activity. The challenge facing policymakers is a view on the potential outcome, cost and timing of these choices. Governments have the means to assist in reducing and mitigating the above risks across the economic system. The specific application of risk mitigation, as has been observed, can come in the form of subsidies, innovation funding, tax breaks, etc.; governments will likely engage in more targeted methods to ensure means to reduce emissions or reduce the impact of environmental damage. From a policy-setting perspective, it is expected that governments would attempt to minimise the adverse impact of policy implementation with managed timing and short-term means to reduce transition impacts. However, this may not always be the case as political parties / views change.

All the above factors will impact financial choices within the economy and potentially create stress scenarios, requiring an enhancement of current financial risk methods. Within the financial industry, the development of risk methodologies typically follows a set of parsimonious decision factors based on current and future business models based on the portfolio of assets/liabilities.

Risk modelling sophistication and application in the financial industry is highly varied with each institution adopting variations of models to address the main risk to their business, Market Risk, Credit Risk, Operational Risk and Strategic Economic Risks, the models are designed and implemented with a view to parsimony as to the needs of the business and regulatory pressures.

The classification of risk types within a financial organisation are typically classed as follows:

- **Market Risk - the assessment** of impacts to exposures from change in traded instrument and hence their measurable risk factors,
- **Counterparty Credit Risk** - the risk that a counterparty defaults on its obligations,
- **Operations Risks** - the risk that internal actions from employee behaviours, systems failures or external actions such as natural disaster or customer fraud create losses.
- **Liquidity Risk** - the risk that funding may not be available or cash flows are not sufficient to meet obligations
- **Strategic / Economic planning risks** - the risk that current business plans may fail or lead to lower than expected outcomes.

These risk areas are explored in more detail with specific modelling criteria in section 2.2 and section 5.

Across each institution, these models can vary in capability and are usually customised to reflect the business models of the organisation that correspond to the risks managed by that organisation. As a consequence, in specifying a risk model it is important to consider the needs related to the business remit and regional regulatory needs. For example, a commercial bank may engage in corporate lending, hedging services. An asset manager looking to develop new investment funds to drive investment into new energy infrastructure, hedge funds looking to arbitrage differentials in capital structure or growth models of companies undergoing transition, etc. From a regulatory perspective each of the commercial entities is impacted by global and national financial regulators that impose requirements and constraints on the quality of financial and risk reporting. Furthermore, central banks play a role in oversight of their regional financial institutions and their risk capabilities, this has been demonstrated in the climate risk space with recent exploratory stress tests (Bank of England, 2022). Furthermore, central banks play a role in controlling money flows through rate setting or quantitative easing/tightening to influence sovereign borrowing rates. Finally, the other significant financial actors are governments that play a major role in taxation setting, policy setting and, in some cases, price controls (e.g. contracts for difference in the power sector or price caps).

2.1 Objectives for Climate Risk Assessment

In light of the requirements outlined in the previous section, this helps us frame the set of objectives for each of the climate risk stakeholders. Whilst each economic segment will require specific modelling to capture the specific risks, there is a need for a clear set of coherent outputs that can be utilised across stakeholders. Whilst each domain will have its requirements to assess specific impacts within its domain (e.g. financial derivative risk), there is a need to ensure that there is sufficient overlap in the fundamental economic properties to build meaningful ways to aggregate/combine/segment the resulting output. It should be stressed that due to the wide range of climate risk factors across each segment These outputs can be classified into two broad categories for risk assessment purposes: firstly, exposure metrics; such as asset values at risk of physical damage or economic transition; this could include fraction of GDP, cash-flows, cost of remediation, impacts to tax revenue, number of people impacted, secondly quantitative impacts; these outputs will be model specific but aligned along the outputs defined as part of the exposure metrics; ultimately, such output would define several values that could be economic loss, cost of mitigation or economic gain.

Naturally, the objectives of each regional government would be informed by being able to aggregate such information to assist with the further optimisation of policy choice and direction of methods to help de-risk the climate transition.

Risk Assessment Components In assessing climate risks as highlighted in the previous section there is a need to collect data at the relevant stakeholder level, capture through scenario design in conjunction with viable calculation methodologies the potential impacts and ultimately define means to validate and build risk mitigation strategies based on the outputs. In any scenario or stress analysis there are a set of relevant factors:

- Frequency - how often an event may occur
- Severity - the size of the impact
- Scope - the domain of the impact (e.g. asset class, macroeconomic variable, economic agent)
- Duration - the length of time of impact of the shock / occurrence
- Methodology - the need to develop adequate and sufficient methodologies to address the nature of the risks

Risk scenarios in the climate space currently span over long periods of time typically 20 - 30 years and combine a set of discrete evens both in terms of weather patterns but also policy choices. As a consequence of the long timeline impacts and the typical maturity lengths of financial instruments such as corporate bonds and associated hedges such as swaps, swaptions etc, which can go from anywhere from 1 day to 20 years, this requires the ability to build stress testing and pricing frameworks that factor in such long-term impacts. These implications shape the required features for risk methodologies that are highlighted in section 5.

2.2 Overview of Financial Risks for Banks

The banking sector provides an important role for saving, lending, money transfer, trading and corporate financing and risk management services. Banks provide lending facilities across all parts of the economy from retail customers (e.g. personal loans), property loans both residential and commercial.

2.2.1 Banking and Finance Activities

Banking and finance activities encompass a wide range of services and functions that are critical to the functioning of modern economies. In this article, we'll take a closer look at some of the key activities that fall under this broad umbrella, and explore how they contribute to the overall health and stability of the financial system.

2.2.2 Lending and Credit

One of the most fundamental activities of banks and other financial institutions is lending and credit provision. Banks provide loans to businesses and individuals, enabling them to invest in new projects, purchase homes or cars, and cover other expenses. Lending and credit provision help to facilitate economic growth by allowing individuals and businesses to access capital that they might not otherwise have access to. However, it's important for lenders to carefully assess and manage credit risk in order to avoid defaults and protect their own financial health.

2.2.3 Investment and Asset Management

Another key activity in banking and finance is investment and asset management. Banks and other financial institutions help individuals and businesses to invest in stocks, bonds, mutual funds, and other securities, and manage those investments over time. This allows investors to grow their wealth and generate income from their investments. Asset management also involves managing institutional assets such as pension funds, insurance reserves, and endowments.

2.2.4 Payment and Settlement Services

Banks and other financial institutions also provide payment and settlement services that allow individuals and businesses to transfer funds, make purchases, and settle transactions. These services include check clearing, wire transfers, credit card processing, and other electronic payment systems. Payment and settlement services are essential for the smooth functioning of the economy, and they help to ensure that transactions are completed securely and efficiently.

2.2.5 Liquidity Risk

Financial liquidity risk refers to the possibility that an entity may face difficulty in meeting its short-term obligations due to a lack of available funds or the inability to quickly convert assets into cash without significant loss. Liquidity risk can arise from various factors, including unexpected changes in market conditions, funding constraints, counterparty risks, and operational disruptions.

Measuring liquidity risk involves assessing the adequacy and availability of liquid assets to meet short-term obligations. Several key metrics and indicators are commonly used to measure liquidity risk, including liquidity ratios. These ratios assess the ability of an entity to meet its short-term obligations. Examples include the current ratio (current assets divided by current liabilities) and the quick ratio (liquid assets divided by current liabilities). Higher ratios indicate better liquidity.

In conclusion, banking and finance activities encompass a wide range of services and functions that are critical to the functioning of modern economies. These activities include lending and credit provision, investment and asset management, risk management, payment and settlement services, and regulatory compliance and oversight. By performing these functions effectively and responsibly, banks and other financial institutions help to support economic growth, facilitate transactions, and manage financial risks, contributing to the overall health and stability of the financial system.

2.3 Overview of Risk and Pricing Activities

One of the most significant challenges faced by financial organisations in assessing the impact of climate related risks is that of pricing. Arriving at a reliable price using risk-based pricing methods, either real world or more challenging longer-term so-called risk neutral pricing with their appropriate valuation adjustments explored in the sections below. Understanding the associated risks is the first step to being able to build a reliable market in new financial products [7]. Investors will seek clarity on returns from companies or those that repackage (e.g. securitize) these risks[4].

[4] New in this case could mean linked to expected emissions or funding new assets, or just subject to typically non-traded climate or emissions linked risks.

2.3.1 Overview of Risk Management Activities for Financial Pricing

Banks and other financial institutions also play a critical role in managing financial risks. This includes credit, market, liquidity, and operational risks. Prudential risk management is crucial for ensuring the stability and safety of the financial system, and it involves a range of tools and techniques in each organisation, such as stress testing and scenario analysis, distributional risk modelling for traded liquid risks. What is seen within the industry both intra and inter organisation, the level of sophistication across each modelling component can vary, leading to a range of implementations a potential pricing of risk. This can create a number of challenges around consistent

views across the financial system of prices for securities addressed in the next section. For example, as climate transition risks have no real historical precedent on the size and scale of their potential impacts, the reliance on historical data from market values to their correlations will be misleading for forward looking scenarios.

2.3.2 Overview of Pricing in Finance

Within finance, pricing of securities is achieved via a number of different mechanisms, that factor in the set of market and economic factors that may be hedged. Common practice utilises the integration of so-called valuation adjustments, termed XVAs - an overview can be obtained in (Gregory, 2015). These valuation adjustments factor in default and funding impacts into derivative prices and can adjust the price notably where these risks may be high. In the context of climate risk scenarios where an entity may default over the lifetime because of the forecast lack of demand for its produce (e.g.

oil), these valuations adjustments may be significant. The section below provides an overview of the specific valuations adjustments (xVAs) and the challenges posed by long instrument maturities/expiries.

XVA Pricing

XVA (where X is the generic letter assigned for the different valuation impacts such as defaults, CVA, DVA, funding FVA and capital costs KVA) is a framework used in financial instrument pricing to capture the impact of various counterparty and market risks on the valuation of derivatives and other financial instruments.

The term XVA refers to a group of valuation adjustments that are made to the fair value of a financial instrument, in order to reflect the various risks that are associated with the transaction. The main components of XVA include:

- Credit Valuation Adjustment (CVA): This reflects the credit risk of the counterparty. It is the difference between the risk-free value of the trade and its value when taking into account the probability of counterparty default.

- Debit Valuation Adjustment (DVA): This reflects the credit risk of the bank itself. It is the difference between the risk-free value of the bank's funding and the value when taking into account the bank's credit risk.

- Funding Valuation Adjustment (FVA): This reflects the cost of funding the trade. It is the difference between the interest rate used to value the trade and the bank's cost of funding.

- Capital Valuation Adjustment (KVA): This reflects the cost of holding regulatory capital to support the trade. It is the difference between the return on regulatory capital and the bank's cost of capital.

By incorporating these adjustments into financial instrument pricing, the XVA framework provides a more accurate picture of the true value of a trade, taking into account the various risks that affect it. This enables banks and other financial institutions to make more informed decisions about risk management, capital allocation, and pricing of their products.

As part of recent work, a number of practitioners have started to develop frameworks to assess the impact on pricing for long dated derivatives from so called carbon linked Valuation Adjustments see for example (Kenyon, Chris and Berrahoui, Mourad, 2021; Kenyon, Chris and Macrina, Andrea and Berrahoui, Mourad, 2023). In (Kenyon, Chris and Berrahoui, Mourad, 2021) the authors introduce the concept of a trade valuation adjustment to the market observed xVA values (CVA, FVA), they consider a number of exogenous climate driven shocks to default rates (the hazard rates in their model), that simulate the impacts of climate related events.

In (Kenyon, Chris and Berrahoui, Mourad, 2021) the authors used a conventional approach to assess the impact to the trade (or portfolio) valuation adjustments (xVAs) including an estimation of the impact from climate linked factors. To accommodate the long horizons of climate transitions the authors utilise an approximate probability space that combines the risk neutral measure Q for times t up to the maturity of liquid traded instruments T (ie.$t \leq T$) with a physical risk measure Ξ for $t > T$. For times $t > T$ the authors assume that non credit items can be hedged but the credit linked risk factors (defaults) cannot be hedged in the market but instead the form of the credit default swap curve is assumed (e.g. flat extrapolated from the last quoted maturity on the curve T). The then derive the impacts to the credit valuation adjustment (CVA) and the funding valuation adjustment (FVA) as outlined using the formulae below:

$$\mathrm{CVA}^{Y(\Omega,\mathcal{F},\Gamma)} = \mathbb{E}^{\Gamma}\left[\int_{u=0}^{u=T} L_{GD}(u)\lambda(u)e^{\int_{s=t_0}^{s=u}-\lambda(s)ds} D_{r_F}(u)(\Pi(u)-X(u))^{+}du\right]$$

J

$$\mathrm{FVA}^{Y(\Omega,\mathcal{F},\Gamma)} = \mathbb{E}^{\Gamma}\left[\int_{u=0}^{u=T} s_F(t)e^{\int_{s=t_0}^{s=u}-\lambda(u)ds} D_{r_F}(u)(\Pi(u)-X(u))du\right]$$

where Ω is the probability space, *F* the filtration of the processes and Γ the assigned probability space.

To determine the difference in Market Implied CVA and FVA (CVA_{MI} and FVA_{MI}) and the potential valuation adjustments including anticipated climate change (CVA_{CC} and FVA_{CC})

$$\mathrm{CVA}_{\mathrm{MI}} = \mathrm{CVA}_{\text{Market Implied}} = \mathrm{CVA}^{Y_Q \Xi} = \mathrm{CVA}^{Y(\Omega,\mathcal{F},[\mathbb{Q};T;\Xi])}$$
$$\mathrm{FVA}_{\mathrm{MI}} = \mathrm{FVA}_{\text{Market Implied}} = \mathrm{FVA}^{Y}\Xi = \mathrm{FVA}^{Y(\Omega,\mathcal{F},[\mathbb{Q};T;\Xi])}$$

$$\mathrm{CVA}_{\mathrm{CC}} = \mathrm{CVA}_{\text{Climate Change}} = \mathrm{CVA}^{Y_{QP}} = \mathrm{CVA}^{Y(\Omega,\mathcal{F},[\mathbb{Q};T;\mathbb{P}])}$$
$$\mathrm{FVA}_{\mathrm{CC}} = \mathrm{FVA}_{\text{Climate Change}} = \mathrm{FVA}^{Y_{QP}} = \mathrm{FVA}^{Y(\Omega,\mathcal{F},[\mathbb{Q};T;\mathbb{P}])}$$

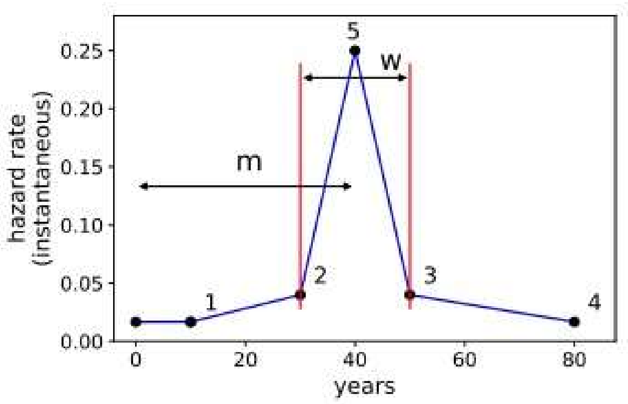


Figure 1 - Illustration of the impact to hazard rates driven by exogenous shocks for XVA estimation (Kenyon, Chris and Berrahoui, Mourad, 2021).

The authors introduce the concept of long dated shocks to the pricing process driven by probabilistic estimates of future events. These shocks are applied at time periods that are very typically beyond the liquid traded markets for most derivatives on corporations. For example, for single name equity options (calls, puts) it is very rate to see market quotes beyond 6 months for most names in a major index such as the S&P500, with only a few companies having derivatives out to 2 years.

As liquidity in single name Credit Default Swaps (CDS). (A credit default swap is a financial derivative that allows an investor to swap or offset their credit risk with that of another investor. To swap the risk of default, the lender buys a CDS from another investor who agrees to reimburse them if the borrower defaults.) will likely not extend beyond 5 years. Hence to price to a long-dated instrument for any corporation will require the use of a viable model that can generate realistic estimates of credit spreads (hazard rates). Furthermore, this will need to be integrated with models for implied volatilities most notably for equity products where liquidity for long dated single name options (e.g. expiries greater than 6 months) is typically non-existent. Furthermore, risk teams need to develop effective scenarios where they believe the market may be mispricing longer dated risks (if such a price is visible). Models that produce forecasts for PD and can apply forward looking shocks provide a viable means of assessing the impacts to a stressed XVA calculation.

2.3.3 Limitations in Long Term Maturity Security Pricing

With the limitations of the liquidity in markets for long dated securities and, in many cases, insufficient products to obtain viable quotes to hedge risks associated with sustainability factors (e.g. GHG emissions or other sustainability-related terms in a financial product.), this alone will prevent the construction of market-driven prices across products, resulting in the need for so called price-to-model to capture impacts to climate events. Aside from current limitations in liquidity, obtaining a meaningful risk-based price for a product issued by a corporation with long maturities beyond the typically quoted 2 to 5 years from the single-name CDS markets will pose challenges for current climate risk assessment frameworks. This limitation in market liquidity in traded instruments has, in part, driven the desire to produce shorter-term stress tests alongside current regulatory risk horizons. However, climate linked impacts for transition risks will likely impact cashflows for the next 20 years and beyond, hence having a more significant adverse valuation impact on long-dated instruments. The most significant stress impacts would likely be observed in applying any climate stress scenario, whether or short-term.

2.3.4 Regulatory Compliance and Oversight

Banks and other financial institutions are subject to a range of regulations and oversight mechanisms designed to ensure their safety and soundness, and to protect consumers and investors. These regulations include capital requirements, liquidity standards, consumer protection laws, and anti-money laundering rules. Compliance with these regulations is critical for maintaining the integrity of the financial system and protecting the public interest. Within the context of Climate change risk and broader ESG (Environmental, Social and Governance) risks there are a number of guidelines issued to assist financial organisations asses the risks (UNPRI, 2023; *Task Force on Climate-related Financial Disclosures* 2022; *Carbon Disclosure Project* n.d.). These guidelines have been geared to assisting with disclosure on exposures requirements. Within the EU there are further disclosure requirements, the Sustainable Finance Disclosure Regulation (SFDR) (PARLIAMENT and UNION, 2019) for sustainable investment products for market traded instruments, to improve transparency around claims made by financial market participants.

3 Status of Current Climate Modelling Approaches

Climate risk models in the literature and those developed for commercial applications cover a wide range of methodological approaches, covering a wide range of applications across both physical and transition risk. Since 2019 - 2020, when The Bank of England (BoE) and the European Banking Authority (EBA) proscribed mandatory stress tests for significant banks and insurers, there have been several developments in techniques and methods and a realisation of the limitations of some of these early frameworks across physical and transition risk modelling.

3.1 Climate Physical Risks

A wide number of vendors currently provide detailed risk assessment for physical risks at a number of geographical scales from country / city level to individual assets and properties. The models capture a number of exposure measures from downscaled weather patterns, distribution of hazards such as excess rainfall, flood risks. Many of these models capture the engineering features of the assets that are risk, such an exact location of components, build quality, materials, structural strength and individual component costs.

3.1.1 Forward looking downscaled models

The solutions provide forward looking models of downscaled weather patterns derived from the IPCC (Intergovernmental Panel on Climate Change, 2021) model set.

3.1.2 Physical Hazards

Many models provide an overview of weather related hazards such as:

- Sea level rise
- Riverine Flooding
- Heavy precipitation (rainfall, ice, snow) - surface flooding
- Increased Wind speed
- High temperatures
- Fire risk
- Freeze thaw impacts

with a view on the geographical distributions of the frequency and severity of these events.

3.1.3 Asset level vulnerabilities

Models posses the ability to determine the vulnerability of assets to the physical assets and provide an economic cost of repair and replacement.

3.1.4 Linked infrastructure impacts

A smaller fraction of models provide an assessment on the impacts to an assets neighbouring infrastructure such as road, rail, shipping ports, electricity, water and gas supplies that could lead to business disruptions.

Supply chain risk estimation Supply chain risk estimation, involves an understanding of the disruption to a business from wider impacts to its supply chain inputs in materials and goods and the downstream impacts to customers. Estimates to wider supply chain disruptions are also uncommon in commercially available physical risk models as such measures are limited by the general availability of data on products in a supply chain.

3.2 Overview of Transition Risk Modelling

Overall, whilst it is recognised that financial models for transition risk are still in development, the published literature and industry knowledge of available models provide sufficient information to highlight those models that may be regarded as insufficient in assessing risks for the financial system. Transition economic risks in the context of climate related risks can be termed as the risk of failure to adapt to the change in from the use of carbon intensive technologies. These risks will materialise in several ways across the stakeholder group as highlighted in section 2. Transition risks manifest typically through a reduction in demand and/or supply of current carbon intensive products (e.g. energy, cement, steel), impacts to costs/prices and challenges to customer preferences. The timing and abruptness of such changes will impact the severity and duration of the risks across the stakeholder group and their ability to adapt. A general list of drivers of transition risks are provided below:

- **Cost** Impacts from changing input (variable) costs and new business operations funding may lead to a reduction in demand and/or profit.
- **Demand and Supply Adjustment** impacts of decarbonisation will adversely impact the business modes across the energy and manufacturing sectors. Reduction in revenue from carbon intensive business lines could give rise to an inability to fund current debt obligations giving rise to default risks. Impacts from shifting customer preference and upstream supply chain disruption could lead to an acute business failure.
- **Changes in Capital Expenditure**, new business models or the need to adapt current buildings, infrastructure, create the need for increased funding.
-

3.3 Categorisation of Climate Corporate Models

There is a wide range of modelling techniques used to assess climate risk exposures; these can be split into two broad classes of model choices: 1 - exposure estimates and 2 - risk models. The first category of exposure models is designed to assess exposure to specific risks and typically does not utilise full quantitative metrics or partial quantitative metrics to high potential risks but without providing a quantitative value, for example a potential loss/gain associated with a given company (or asset) under a climate stress event.

3.3.1 Examples of Climate Risk Metrics

The vast majority (as of 2023) of commercial models provide exposure metrics or scores rather than financial metrics. These scores or metrics exist for both physical and transition risks, the list below has been obtained from methodologies reported by the PRI (Principals for Responsible Investment, 2022).

Transition Risk Metrics Typical transition risks metrics that are commonly utilised include:

- **Emissions** the total emissions from a company. This is normally benchmarked against other companies in region or sector.
- **Emissions** Per Unit Revenue (normally USD based, these emissions cover scopes 1, 2 and 3. Additional data covers both upstream and downstream emissions associated with the company's products.
- **Revenue at Risk**, this metric is used in company models that link demand projections from current to future revenues, this does not use a full model for the company but just index links revenues to the scenario set under consideration.
- **Assets at Risk of Stranding**. This is a metric that indicates if an asset such as an oil field may not be fully exploited.
- **Net Asset Value Exposure to Different Energy Sources** - these metrics would be applied to different energy sources such as coal, oil, gas and other fossil fuelled resources.
- **Percent of portfolio revenue generated from green / brown technology**
- **Percentage of Green vs. Brown investment** a view on the capital expenditure of a firm, or its investment profile.

Physical Risk Metrics Typical physical risk metrics used include:

- **Percentage of portfolio exposed areas with direct asset level physical risks**, this metric assesses companies that have operations located in geographical areas sensitive to physical risks.

- **Percentage of portfolio exposed to issuers sensitive to physical risks.**

- **Percentage of at-risk properties in real estate** that are located in areas at high risk of sea level rise and extreme weather linked events.

- **Outage times linked to climate events**. Outage time values linked to climate hazards.

- **Impact from Supply chain disruption**. Impacts from supply chain disruption for production inputs or downstream demand.

- **Physical Risk Scores**, values eg a 0 - 10 score based on current of future exposures to physical risks based on a provided temperature level.

  Summary of Climate Metrics Climate linked metrics whilst useful for determining potential climate linked losses, are insufficient to be used to measure losses or define a risk appetite for an organisation. This requires improved methodologies that are able to quantify the impacts to assets. From a financial regulatory perspective, such exposure metrics would be regarded as indicative but not necessarily sufficient to assess exposure and should only be used to guide further impacts assessments.

3.3.2 Examples of Transition Risk Models

There are currently a wide range of commercial and academic climate physical and transition risk models. In terms of academic (non-commercial) models well known example include PACTA (and the 2° Investing Initiative 2DII (2° Investing Initiative, 2021), TRISK (based on the 2DII models (Baer, Moritz and Caldecott, Ben and Kastl, Jacob and Kleinnijenhuis, Alissa M. and Ranger, Nicola, 2022) and models from the Paris schools (Battiston, Stefano and Mandel, Antoine and Monasterolo, Irene and Roncoroni, Alan, n.d.). These models and their strengths and weaknesses will be explored in section 4.5.

In terms of commercial models, a selection of well-known models can be found from the UNEPFI review of models (UNEPFI, 2023b), where a summary of each model's risk coverage and capability can be obtained. The methodologies that have been utilised by each of these offerings varies in its sophistication and scope for application across the different asset classes from property, company equity value and bond or loan valuations and associated risks. s such each approach will have better capability is some respect than others. A challenge to some of the modelling techniques used is provided in section 4.

3.3.3 Examples of Physical Risk Models

Physical risk modelling covering the set of risks such as flooding, wildfires etc (highlighted further in section 4.9), requires detailed modelling of not only forward-looking weather, but extreme weather events, knowledge of local geography and the vulnerability of physical assets to these weather events. Furthermore, models may need to capture the impact from the degradation of local infrastructure that may have an adverse effect on an individual assets value. Such infrastructure damage could for example impacts a property's value or a company's productivity. Challenges to some of the approaches used in physical risk modelling and some of the omissions can be found in section 4.9.

4 Issues with Current Financial Climate Risk Modelling

The complexity of climate risk impacts for policy makers, companies, individuals cannot be under estimated. The two broad categories of physical risk and policies to mitigate these risks termed transition risks will create challenges to people's way of life globally. The field of risk modelling in this space is developing rapidly with continuous improvements.

Assessments of climate risk modelling required the ability to estimate the impact of future weather patterns, sea level rises, the response of the planet's biome, the impact to assets, commercial and public infrastructure. Each of these components on the physical risk can lead to not only notable economic damage but also a significant reduction in quality of life for billions of people (**IPCC 2021**, 2021).

The impacts of physical risk range from the acute (flash floods, hurricanes etc.) to the extreme chronic, degradation of agricultural land, coastal land permanently flooded, migration of tropical and other zoonotic diseases. All of these create an impact economically from the direct damage and increased capital expenditure required to mitigate these risks. These economic impacts will happen at all scales of the economy, from the needs of small holder farmers for example who will be displaced from their land, large corporations suffering failure and increased of their commercial assets and impacts on national infrastructure and supply chains. Home owners displaced, increased levels of illness, direct impacts to health. In terms of overall economic activity, this will require notable investments by individuals, companies and national governments (and supra-nationals under the behest of nation states) to mitigate. Given that capital formation is finite this implies that the capital to maintain even status-quo does not generate fundamental productivity and furthermore the costs may be so prohibitive to so many around the world that economic activity has little chance to recover over this period.

The implications of the above are widely discussed, however the integration and the interplay of these risks within economic forecasting models for policy makers, central banks and financial institutions has yet to fully materialise. It is clear from the panoply of risks, their drivers and their consequences require a well-structured, explainable and challengeable economic and risk system to highlight the potential financial impacts and effective investment strategies to mitigate these risks.

It is clear that the breadth and extent of the climate modelling challenge requires a need to review and assess the current state of the art and to provide guidance on strategies for model development. One of the goals of this paper is to highlight effective model strategies that can be applied within the finance industry across the portfolio of assets. With the general philosophy that robust financial modelling can be applied to improve the integration of the financial system in wider scale models.

What is clear is that uncertainty in climate modelling and its impact is significant across all components and the ability to holistically capture these factors is currently missing, the exact set of factors, their importance is highlighted in the sections below.

In recent reviews - see for example the report from University of Exeter (Sandy Trust, Sanjay Joshi, Tim Lenton, Jack Oliver, 2023) - a number of well-known issues have been highlighted relating to the modelling of physical risks within the standard economic modelling frameworks typically used (in this case use of the NGFS scenario set). The authors highlight the potential impacts of warming linked tipping points such as increased methane release from tundra, ice shelf collapse and impacts from sea level rise. Furthermore they highlight some of the non-modelled consequences such as increased migration. For scenarios such as the impact of mass migration capturing this in a general model framework such as the current IAMs will take a notable amount of time. Combining the consequences of such events with drivers such as increased rates of warming from tipping points cannot easily be coherently developed. As the authors (Sandy Trust**,** Sanjay Joshi, Tim Lenton, Jack Oliver, 2023) note, these effects are best achieved with model overlays, which are often used in bank stress testing frameworks. Further techniques such as reverse stress testing [58] business operations that can give rise to financial risk - whether that is for a company or individuals - provides a means to assess how far such an impact is from current observed and/or modelled events.

4.1 Data Collection

From the list of requirements above, it is clear that data collection requirements are considerable, with a need to collect detailed data across a broad segment of the economy. Taking business as an example, there is a need to understand a firm's financial statements, which, even for listed companies, needs to be completed. Information on loans and other liabilities and their maturities. Knowledge of current business segments and cashflows and forward-looking business strategy can be incomplete. On top of this, a view of how a firm engages in its current capital structure planning and risk management. To augment this information as part of a model simulation, knowledge of cost, operational, variable and capital funding needs to be obtained and modelled for each of the active business units, including information on emissions. Alongside the firm-specific data, information on the financial market environment needs to be utilised, such as interest rates, FX, commodity markets, and inflation.

For climate scenario data model inputs on regional policies, current regional aggregate production and demand, currently deployed technologies alongside market prices and macroeconomic data.

Physical climate risk poses even greater asset-level data requirements than the ability to generate downscaled weather patterns. These data requirements at the asset level go from geolocation data to information on construction materials and building layout and replacement costs.

Supply chain risk may require highly detailed knowledge of input materials, their source locations, transport modes and downstream distribution and consumption networks. Further knowledge may be required on manufacturing processes, ease of substitution and their associated economic costs.

From the summary above it is inevitable that organisations would not have access to sufficiently detailed data, resulting in a need to proxy (provide substitutions) or adjust modelling methods. The model design

[5] A reverse stress test is designed to look at causal factors that impact on a system that can give rise to a failure of a system and determine how far these factors are from currently observed or modelled inputs. Its use has been used in regulatory financial stress testing (**Basel Committee on Banking Supervision**, 2017).

naturally needs to accommodate data uncertainty and inference from the model outputs suitably caveated. Risk managers and business planners need to ask this question of any climate risk solution as data uncertainty for meaning risk estimation will be more pervasive for climate risk models. Further details of data collection requirements are highlighted in the sections below and further expanded upon in the pragmatic solutions we propose later.

4.2 Constructing Risk Scenarios

Ultimately when building a risk framework, the practitioner needs to provide a set of shocks to the relevant set of financial factors (e.g. market prices, cash-flows etc). The challenge in climate risk modelling is to derive a set of sensible impacts based on model inputs. This can be achieved through a series of different mechanisms, that fall into two broad modelling categories, the first using historical impact data based on statistical samples and assessing the gross impact to market observables (e.g. for firms credit spreads, stock prices) or to look at a more structured causal model for the entity to be stressed, for example looking at impacts to product demand, costs and prices. A number of these approaches have been applied in climate stress testing to date and each comes with its strengths and weaknesses. We argue that a combination of these techniques needs to be applied if modelling financial entities such as firms, where market traded values are influenced by both fundamentals (e.g. demand, costs etc.) as well as market wide effects. This points to a need to combine both in any model to derive a means of understanding both the causal effects (demands, costs) combine with the more uncertain probabilistic response of the markets. This principal is not only applicable to markets but in general across a number of modelling areas. This is especially important where financial practitioners that are already engaging in building general market linked stress tests wish to disentangle the incremental impact of climate risks on their portfolios.

This ability to understand the causal drivers of a specific risk process, whether that is based on the impacts of physical damage or economic drivers at a firm level provides an important framework for enabling meaningful stress tests with a clear view on how a specific effect (externality) would impact the entity under study. Furthermore, such a causal framework permits a means of challenging and/or validating statistical and heuristic stress impacts.

4.3 Scenario Generation

Climate scenario generation has evolved in the past 5 years (as of 2023), with forecasts provided by national and multinational academic teams (e.g. IPCC), financial consortia such as the Network for Greening the Financial System (NGFS) and commercial bodies such as the International Energy Authority (IEA).

The challenge of stress scenarios for the banking industry has not been unique to climate linked stress tests. Globally significant investment banks (GSIBs) have been required to take part in stress testing that have been mandated by major regulators such the European Banking Authority, the Federal Reserve and the Bank of England through the PRA (the Prudential Regulation Authority) as well as requests from other national regulators where a bank's operations my pose an impact to regional financial systems. Such stress tests are termed conventional shock-based stress testing methods and are described in more detail in section 4.3.1 below.

For climate linked stress tests have been built on richer views of the future economy built on IAMs, for example methods used by the NGFS (NGFS, 2022). At a high level, these frameworks provide views on future outcomes of GDP, populations, changes in the energy system (Coal, Solar, Wind, Gas, Nuclear etc), the transport system, commercial and domestic energy use. This set of scenarios are described in more detail in section 4.3.2.

4.3.1 Conventional Financial Shock Based Stress Testing

As an example of conventional stress testing approaches applied to the regulated banks, the Basel committee approach is outlined in (Basel Committee on Banking Supervision, 2017). These tests mandate sets of specific and general scenarios across a number of factors that could impact banking portfolios, these shocks are typically applied to a subset of traded market factors but also narratives around corporate sector defaults and market liquidity. Within such frameworks, practitioners will then derive related risk factors (e.g. company level shocks from provided sector level impacts) typically using statistically driven conditional distributions of the provided mandated impacts. This normally utilises historical observations combined with standard distributional scenario modelling methods to extended distributions into historically unobserved regions. This methodology is widely accepted and pose little overall challenge to model validation teams in financial organisations. This approach however does not typically look at a deep analysis of the underlying economy (e.g. drivers of company demand, energy systems etc), instead the shocks are typically only applied to market observables or related factors (such as probabilities of default).

Such approaches as given in (Aguais and Associates Ltd, 2023) whilst useful at a bank portfolio level for conventional risk assessment have been justified based on the observation of historical changes. However, in the context of climate driven stress scenarios whether from a physical phenomenon such as damage from weather related events, impacts of causal economic factors such as changing costs/price or demand need to be translated to the market related factors before such traded market factors can be reasonably justified to be linked to climate linked events. The ability to build and define such models that are able to meaningfully quantify the impacts of externalities and the forth coming legislation to protect the natural environment (such as TNFD (UNEPFI, 2023a)).

As a consequence, this would lead to a need for any climate linked stress model that operates on agents of the real economy that such risks can be transparently transmitted to market factors. Hence any viable climate stress testing model needs to capture these causal links from the stressed economic agent with a transparent framework to generate financial market shocks. This framework would inform the basis for market factor shifts and their uncertainty.

4.3.2 The NGFS Scenario Sets

The latest set of NGFS scenarios made available in phase 3 of their work in September 2022 (NGFS, 2022) have integrated a number of climate related macroeconomic and financial risks in combination with three IAMs to model the potential outcome of different greenhouse gas emissions over a period until 2050. The structure of the scenarios is summarised in the figure 2 below.

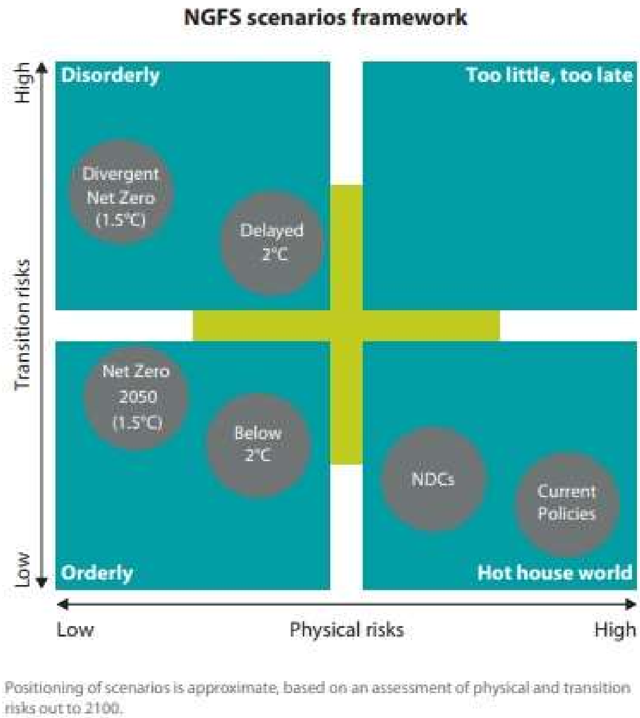


Figure 2 - The matrix of NGFS scenario sets highlighting regions of increased physical and transition risks (NGFS, 2022)

4.3.3 Real World Climate Initiative Scenarios

The "Real World Climate Initiative" scenarios based on a set of scenarios developed by Cliffe et al (Mark Cliffe, 2023) provide a counterpoint to the set of missing factors in the NGFS scenario set (highlighted in section 4.4). Primarily, the initiative identifies the main issues with the IAMs used as part of the NGFS model set, principally the lack of feedback mechanism events, such as physical damage at the microscale, such as companies or the failure of economic agents to deliver an expected transition as forecast by the macro level IAM. This initiative introduces a set of scenarios that could coexist with a climate transition (or otherwise). Whilst the concerns highlighted in (Mark Cliffe, 2023) had been widely aired by the climate modelling community for several years, the broader financial community has struggled to adapt their current quantitative risk models and their associated infrastructure to accommodate the risk scenario analysis required for climate impact analysis. Some of these quantitative limitations are highlighted in this paper alongside solutions that are emerging.

4.4 Critique of Conventional NGFS Style Scenario Generation

Challenges to the NGFS set of scenarios based on IAMs are now well documented in the literature, the set of scenarios as highlighted in figure 2, are developed using the 3 core IAMs (GCAM, REMIND, MESSAGE-GLOBIUM), these models provide smooth transition pathways based on a set of input assumptions linked to energy prices, technology choices and economic parameters. The sets of scenarios such as delayed choices or current policies highlight the impact at a global economic system level of the risk posed to achieve decarbonisation trajectories, however many of the models lack a rich framework for assessments of the full implications of changing energy prices, impacts to commodity price volatility, corporate earnings or the disruption to a populations ability to fund a transition. Furthermore, the models do not directly include models of physical damage to assets. It is these factors that are significant for the assessment of risk impacts for financial institutions. As it stands the utilisation of these models requires considerable engineering adaption to map these smooth trajectories to meaningful risk scenarios for individual sub-regions, companies or assets.

The NGFS set of scenarios is not completely without merit in this space as they have served as a means to highlight at a very high level (that does not mean that they can be regarded as an aggregate view of impacts) the issues to policy makers and corporations of delays to the policy implementation or abrupt policy adjustments.

Whilst the longer run trends predicted from scenarios like the NGFS impact on demand for a company's product (e.g. oil) will have a notable effect on the overall earnings leading to a degradation in the ability to service debt. The user interpreting the NGFS scenario is still required to build a model of its impact to the financial agents in the economy that are linked directly to the banks business lines.

The stress testing paradigm from the NGFS falls into the category of general policy and expected economic impact risk and is generally too high level to be fully utilised for bank level financial exposures. Whilst they provide the potential underlying impacts of wide-scale economic shifts and hence can be used to guide corporate, commercial banking lending strategy, further layers of modelling are required to derive financial impacts to banking portfolios.

4.5 Models in the Academic and Regulatory Literature

There are a number of academic papers on the modelling of the impacts of climate linked risks, each approaches the challenge of financial impact of climate change either directly to those entities in the economy (e.g. business) or attempt to infer the impact to bank exposures through climate linked factors (e.g. emissions, or industry sector).

Academic papers describing potential risk models that transform available macro level scenarios, such as the NGFS suite of models (NGFS, 2022), hypothetical model frameworks such as Monasterolo (Battiston, Stefano and Mandel, Antoine and Monasterolo, Irene and Roncoroni, Alan, n.d.), have built guidelines / frameworks to address both physical and transition risks.

As it stands there is not a complete model academic framework that enables a sufficiently rich combination of micro to macro features to enable a completely coherent model of relevant stress factors suitable for financial stress testing. Such a framework is still some way off.

4.5.1 Agent Based Modelling

Models such as that provided in (Cormack et al., 2020) perform an agent-based simulation of companies capturing several features that are applied alongside macro-economic trajectories driven by macro-policy models (not necessarily IAMs). The purpose of this model framework is to capture corporate investment and risk management behaviours driven by the exogenous global macroeconomic factors from external models. The principle of such a framework is to mimic the approach taken by corporate treasuries in economic planning and risk management with a focus on understanding the impacts of input costs, prices and supply and demand factors. This model framework also utilises a dynamic model of a company's financing costs over time as its assets adapt to the forecast scenarios and market factors. For example, within this model framework, the businesses engage in revenue generation, incur costs (that can be asset-specific), manage dividend payments and actively manage their capital structure. The model evolves the full three statements of the company: Balance sheet, income and cash flow statements, and provides a detailed insight into the company's evolution under climate scenarios, including the physical assets built and decomposition of each business unit's costs and revenues. Alongside the financial fundamentals, the model provides a view on the dynamic credit quality of firms and views, with output on credit rating, credit spreads and funding costs dynamically generated over the life of the simulation.

The model framework also enabled a firm-level assessment of direct physical risk that highlighted the impacts of direct risks to these firms on their worldwide assets.

The principal of the model (Cormack et al., 2020) is to build a framework that resembles the operation of firms subject to a set of potential economic forecasts (in this case, provided by external macro projections). As part of the paper, a study was performed on the impact of energy price setting across European utilities to determine the feasibility of delivery of the projected renewable energy system. Due to the model's ability to capture the idiosyncratic nature of a company's strategy, it has also been used to assess the feasibility of Oil and Gas companies to transition from extraction-based operations to combined renewable development and power marketing. The model framework has also provided impact assessments to general oil companies. This model framework is also commercially available.

4.5.2 PACTA Model Framework

The PACTA model framework (2^{o} Investing Initiative, 2021) has gained popular traction amongst the financial community since 2019 as a means to estimate the associated set of exposures to climate risks. It is worth analysing this model to assess its use in assessing climate linked financial risks.

The PACTA (Paris Agreement Capital Transition Assessment) model is a tool used to assess financial risks associated with climate change. Its primary purpose is to analyse the alignment of investment portfolios with the goals of the Paris Agreement, specifically focusing on the transition to a low carbon economy. In summary the capabilities of the PACTA model are as follows:

- Carbon Footprint Analysis: The PACTA model can estimate the carbon footprint of investment portfolios by analysing the emissions intensity of different sectors and identifying high-carbon assets. It helps investors understand their exposure to carbon-intensive industries.

- Climate Scenario Analysis: The model allows for the assessment of investment portfolios under different climate scenarios, considering potential regulatory changes, technological advancements, and market shifts. This helps investors evaluate their resilience to climate-related risks and opportunities.

- Transition Risk Assessment: PACTA assesses the financial risks associated with the transition to a low-carbon economy. It identifies sectors and assets that may face challenges or opportunities as the world moves towards decarbonization, providing insights for investors to manage their exposure to transition risks.

- Alignment with Paris Agreement Goals: The PACTA model compares investment portfolios to the climate targets outlined in the Paris Agreement, such as limiting global warming to well below 2 degrees Celsius. It helps investors gauge the extent to which their portfolios are aligned with the goals of the agreement.
The PACTA framework, however does not provide financial
risk metrics or valuation information

4.5.3 TRISK

The risk framework as published in TRISK (Baer, Moritz and Caldecott, Ben and Kastl, Jacob and Kleinnijenhuis, Alissa M. and Ranger, Nicola, 2022) highlights the use of the Merton model (R. Merton, November 1973) with loss given default (LGD) of firm *j* estimation given by:

$$\mathbb{E}_t\left[L_{ji}^{s,\text{ loan}}\right]=\left(PD_i^{\text{stress}}-PD_i^{\text{baseline}}\right)*LGD_{ji}^{s}*EaD_{ji} \quad (1$$

within this framework the exposure at default EaD_{ji} is assumed static

$$LGD_{ji}^{s}=\lambda_{\min}+\left(1-\lambda_{\min}\right)S_i \qquad (2)$$

where *s* is the index over the scenario set and S_j denotes the set of stranded assets for company *j*, λ_{min} is a calibrated minimum LGD threshold. The corresponding probability of default given as:

$$PD_i^{s}=1-\mathcal{N}\left(DD_i^{s}\right) \qquad (3)$$

where DD_i^s the distance to default defined below and *N* is the cumulative normal distribution.

$$DD_i^{s}=\frac{\log\left(A_i^{s,t}\right)+\left(\mu_j-\frac{1}{2}\sigma_j^2\right)T_i-\log\left(L_i^t\right)}{\sigma_j\sqrt{T_i}} \qquad (4)$$

where $A^{s,t}_i$ corresponds to the asset value of the firm under scenario *s* at time *t*, μ_j, denotes the expected return of the company (define in equation 5)and in this model is set to the firms specific risk premium. T_j corresponds to the firms average maturity of its liabilities, L^t_j. Within the TRISK model framework the liabilities are taken to be scenario-independent. The assets volatility is defined as σ_j^2 and is held constant from its value set at T_0.

(5)

$$\rho_i=\rho^f+\beta_i\mathbb{E}\left[R^M\right] \qquad (5)$$

where β_i is defined as:

$$\beta_i=\frac{\operatorname{cov}\left(\mathbf{R}_M,\mathbf{R}_i\right)}{\operatorname{var}\left(\mathbf{R}_M\right)} \qquad (6)$$

where $\mathbf{R}_i, \mathbf{R}_M \in N^{1\times|T|}$.$ER^M$ is the expected market return in their model.

Challenges to the PACTA/TRISK Framework
The PACTA /TRISK framework has the desirable feature of adjusting the production assets $A^{s,t}_i$ for each scenario and the ability to adjust demand and price factors, however the integration into the financial metrics such as PD_t^s and EaD_{ji}. This creates a number of challenges to this model framework, firstly the asset and liability modelling is discontented from the relationship with the growth / decline in specific climate linked scenarios in the term, μ_j.Specifically the assets growth are linked to the market factors growth factors that are only calibrated at the start of the simulation T_0 and the liabilities L^t_j are taken to be independent of the scenario. These factors result in an inconsistent evolution of the company that does not reflect its different

investment choices for each scenario. As a consequence, there is a limit on the forward-looking knowledge an investor using this model would have, limiting the meaningfulness of the probability of default and EaD information. Furthermore, the asset volatility is held constant at the initial value. This is unrealistic as risk neutral volatilities for each company is highly variable and would be significantly different as the company approaches default.

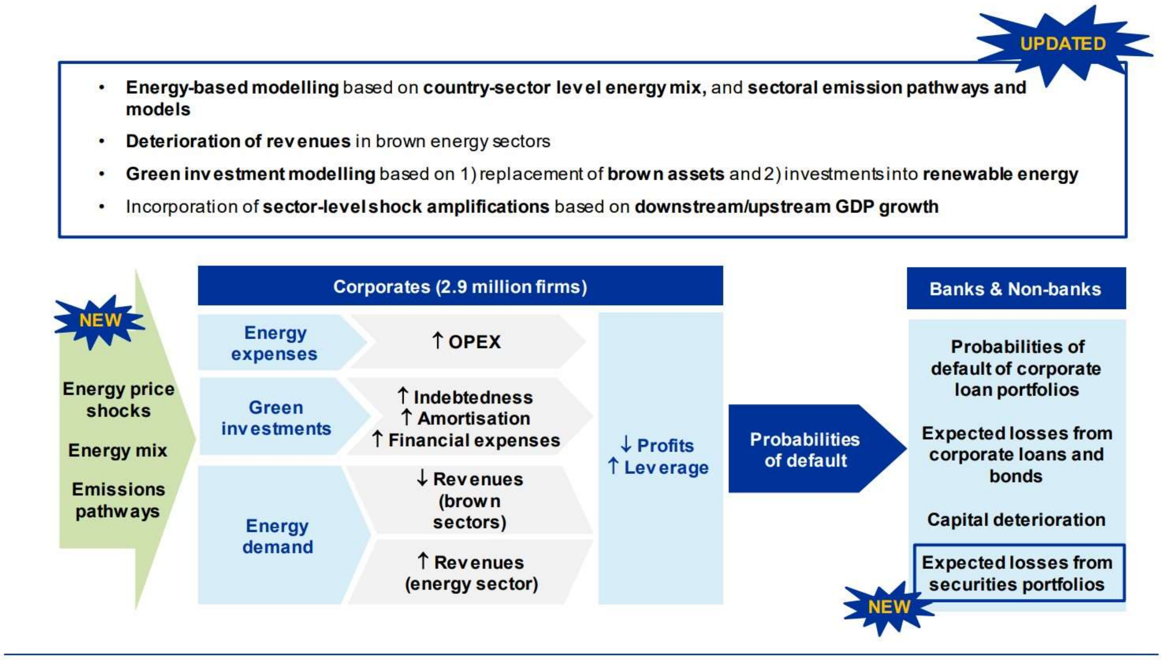
4.5.4 Other Notable Academic Models

Other notable models for firm level climate stress analysis include that from Battiston, Mandel, Monasterolo and Roncoroni (Battiston, Stefano and Mandel, Antoine and Monasterolo, Irene and Roncoroni, Alan, n.d.). Similarly to (Cormack et al., 2020), the authors model the financial dynamics of the firm subject to a set of external macro - climate scenarios denoted in the paper as $P = \{P_1 ..., p_n\}$. Within this framework there is no inter company competition (a company is unable to use its comparative advantage in terms of cost of funding or adaption of strategy). The model uses a random multiplier for the profits $\Pi_t^B := \sum_{s=1}^{S} u_{s,t}^B m_s X_{s,t}^B$ where $u^B_{s,t}$ is a random variable and $m_s X_{s,t}^B$ the expected trajectory of the output of the firm in sector s under the business as usual given the superscript *B*. Corporations in the model raise debt based on the need to raise capital at time *t*, in each technology sector *s*, $K_{s,t}^B$.

Whilst the model can capture some of the features of climate transitions it has a number of factors that do not represent the risks companies would face. For example, funding risks interest rates, credit spreads, inflation, input price volatility. Furthermore, the model does not take into account capital structure controls that all companies seek to impose. Whilst the model has a parameter that permits the variability in profit, this does not permit an analysis of input costs (whether capital, operational or variable costs), or further sensitivities to price / competition factors, hence its ability to be used as a full stress testing environment that is sufficiently rigorous for commercial applications is limited and would require further user engineering to obtain a sufficiently rich risk view.

4.5.5 Models used in the ECB Stress Test

The European Central Bank has recently released a new stress testing model framework at the firm level (Bank, 2023), the model framework as illustrated in figure 3.



Source: ECB.

Figure 3 - Illustration of the ECB firm level stress testing framework, source (Bank, 2023).

The firm level model used in this framework as outlined in (ECB, 2022), this has a dynamic model of the firm's assets, liabilities, costs and revenue lined to current internal assets and leveraged as outlined in equations 10 to 13. Asset growth is driven by macro-economic drivers rather than specific market demand predictions (for example the demand for energy). Unlike (Cormack et al., 2020) the model does not utilise a full balance sheet, cashflow evolution for the firm.

Market Modelling Within the ECB model framework a number of assumptions are made about changes in Gross Value Add (GVA) for firms based on anticipated investment for the different climate scenarios. The challenge to such statements needs to be qualified in the sense that if firms cannot raise capital due to increased cost from inflationary pressures or, the GVA predictions will be incorrect. There is no mechanism within this framework to viably stress such price shocks given the costs are exogenously driven (see the paragraph below on firm level costs 4.5.5).

Energy Consumption Allocation Within the ECB model an assumption has had to be made around the energy consumption at the firm level, specifically an allocation algorithm has been used as defined below for company *i*:

$$EnergyConsumption^{i}_{k,t_0} = \frac{\text{Scope 1 emissions}\ ^{i}_{t_0}}{\text{ConversionFactor}_{\ k} \cdot \text{Share}\ ^{c,d}_{k,t_0}} \tag{7}$$

where the share allocation formula is given by:

$$\widetilde{\text{Share}}^{c,d}_{k,t_0} = \frac{\text{Share}^{i}_{k,t_0}}{\sum_k \left(\text{Share}^{c,d}_{k,t_0}\right)} \tag{8}$$

where k is the energy source index, c the country index and s the sector index and t_0 denotes the initial measurement time.
This approach forces the link to the macro scenarios however this cannot be fully regarded as a direct representation of the firms specific energy use and hence its direct cost of investment to reduce emissions.

Investment Methodology and Firm Level Costs. Within the ECB model there is a component of green investment (see 9); the model uses a formula linked to the reduction in GHG emissions. However, there is no mention of the impact of supply side/demand side factors that would reflect the change in a firm capability or firm-specific cost of funding; the ECB model uses the IPCC "learning-curve cost" metric (further details can be obtained from (ECB, 2022)).

Within the model, green investments in each year are given by the change in emissions scaled by the cost of mitigation, with an allocation of 50% investment forced in the first three years, and the second 50% would be raised in the remaining 15 years.

$$\sum_{t=2023}^{2030} \text{Green investments }_t^{e,s} = \Delta(\text{ Scope } 1,2,3 \text{ tCo } 2)^{e,s} * \text{ mitigation cost}_j \left(\frac{EUR}{tCo2}\right) + \sum_{t=2023}^{2030} G_t^{e,s} * \mathrm{I}_t^s \quad (9)$$

Corporate Credit Risk The ECB model uses a number of dynamics to model the growth in assets of the firm specifically the total assets for firm *i*, TotalAssets^i_t at time *t* are taken to evolve as follows:

$$\text{TotalAssets }_t^i = \alpha + \beta_1 \text{ TotalAssets }_{t-1}^i + \beta_2 \text{ GVAGrowth }_t^{c,d} + \beta_3 \text{ Inflation }_t^c + \beta_4 \text{ SizeDummy }_t^i + \epsilon_t^i$$

where $\beta_1, \beta_2, \beta_3, \beta_4$ are obtained from a regression to historical data, ϵ^i_t, the liabilities of the firm are taken to follow a proportionate model the authors assert preserves capital structure given below:

$$\text{Total liabilities }_t^{i,s} = \text{Total assets }_t^{i,s} * \frac{\text{Total liabilities }_{t_0}}{\text{Total assets }_{t_0}} + \text{ Green investments }_t^{i,s} \quad (10)$$

This model assumes that the green investments are outside the standard capital growth model of the firm and are an addition and would suggest that this model does not preserve the firm's capital structure under decarbonisation path-wise, potentially skewing the firm's results in the simulation framework.

A similar approach to incremental impacts is assumed for operating expenses, where costs are added to a set of costs that scale with growing assets. Such a mechanism is unrealistic for corporate pricing as firms will likely transmit costs to sales prices (revenue). The model does not provide a means to adjust business margins to reflect expected costs, which in the energy-intensive sector would, on average, reflect the ability of the whole commercial energy system to transition. The incremental add-on to costs reflects only a partial impact on firms, modelling the potential demand adjustment rather than just a pure cost impact. The probability of default PD^i_t is modelled as:

$$PD_t^i = \alpha + \beta_1 \text{Leverage}_t^i + \beta_2 \text{Profitability}_t^i + \epsilon_t^i \quad (11)$$

profitability and leverage are defined below:

$$\text{Profitability}_{t,s}^i = \frac{\text{Net earnings before tax } x_{t,s}^i}{\text{TotalAssets }_t^{i,s}} \quad (12)$$

$$\text{Leverage}_{t,s}^i = \frac{\text{TotalLiabilities }_{t,s}^i}{\text{TotalAssets }_t^{i,s}} \quad (13)$$

where ϵ^i_t is the residual, it is not clear that this is part of a random process as it has been assigned a time index *t*.

As it is documented in the paper, there is a mathematical issue with the probability of the default formula in that almost surely it is not bounded [0,1] across all time *t*; there is no mention of how the mathematical support for this formula is constrained, given the regressed coefficients $\beta_{1,2}$ are large $O(1)$ compared to typical probabilities of default that are $O(0.01)$. Ensuring the PD is bounded would require users to assess the model under stress conditions to ensure it produces reliable results.

Summary of ECB Model and Comparison With Other Firm Based Models The ECB model provides a firm-level assessment of the impact of climate, in comparison with other firm-based models such as (Cormack et al., 2020), provides detailed asset level cost and detailed modelling on the depreciation and replacement of specific assets, concepts such as firm-level capital controls are more consistent in these other frameworks where all investments are taken to be inline with current company investment constraints rather than having a green investment add-on as exits in the ECB model. Concepts such as capital and cashflow management are critical to a firm's management; hence, models of the firm undergoing such long-term term (in this case, long term is greater than 1 year) need to factor in these controls in a way that reflects risk management practices within a corporate treasury, else risk misstating risks. Similar principles must be assessed when reviewing the impact of costs and how a firm would transfer or absorb such costs. Models such as (Cormack et al., 2020) permit both modes of price transmission: margin preservation (with a potential impact on demand) or cost absorption (like the ECB model), thus allowing a review of the impact of such choices. Concerning such choices, firms would likely try to stay close to their peers, and such behaviour is linked to whether the industry is facing similar cost pressures or if there is any differentiation.

4.6 Modelling Approaches used in Commercial Model Frameworks

Within commercial applications there are a number of approaches used to assess the impact of climate linked risks. These go from exposure metrics (P. Krüger, 2020) that look at a financial institution's exposures to firms carbon scope 1 emissions as a proportion of the total corporate emissions. To full simulations of corporations subject to changes in prices, costs and demand due to climate transition scenarios.

Common models that are utilised are those that utilise a marginal cost of Carbon (carbon tax) to change the prices of goods within the simulation, this is then combined with a model of demand, typically a straightforward demand elasticity model:

$$\varepsilon = -\frac{P}{Q}\frac{dQ}{dP} \tag{14}$$

where P is the price of goods, Q is the demand and ε is the product elasticity factor. This has been used for TCFD reporting for investment houses such as Schroders (Schroders, 2022). The use of such demand elasticity methods is common and has been used for other investment houses in the past such as LGIM (Legal and General Group Plc, 2020). Such a model is also applied in a commonly used vendor solution.

4.6.1 Challenges to Demand Elasticity Models

There are a number of challenges to demand elasticity models, firstly, these models are driven by a view of a given carbon tax, however as it stands in 2023 very few regions of the world have an active carbon taxation policy linked to emissions. Hence reliable impacts to prices, company demand and revenue cannot realistically be assessed. Secondly the issue of price driven demand impact could create and differential in the total demand for a product (e.g. oil, gas power) compared to the core macro model demand prediction scenario for a region. This last issue is a general challenge for nearly all micro to macro model frameworks and requires a notable amount of individual company data on production assets (e.g. wind turbines). Having a simple demand elasticity model such as expressed in equation 14 may result in unrealistic numbers of products sold by each company, especially if the model does not capture the capacity constraint on that company to supply the indicated number of goods. Users of such models should therefore be wary of firstly unrealistic demand predictions if using a carbon tax metric and secondly of unrealistic demand driven by the company level elasticity prediction based on cost.

4.6.2 Empirical, AI and Data Mined Models

Another common class of model used are those based on the historical or pure empirical performance of companies without factoring the causal impact of climate linked events. Examples can include historical equity betas for impacts to returns or investment choices (e.g. Weighted Average Cost of Capital calculations.) User of such models should be made aware of where empirical data has been used to form model outcomes and if such model inputs / calibrations can be adjusted / stressed.

The use of empirical distributions is naturally a reasonable basis to guide impacts to some parameters in models and in some cases required in economics to define expectations of parameters and ranges of uncertainty. Issues arise where historical data may be used across areas of uncertainty in a model that may going forward in time be impacted differently because of climate linked factors. For example, the use of equity Betas[6] [9] for oil companies going forward or expected dividend yields for utility companies in deriving pricing etc.

The use of artificial intelligence in climate modelling needs to be assessed in the context of the calibration data used and their applicability to estimate forward looking scenarios. For example, AI models that are used to forecast forward looking economic impacts may have been trained on models (e.g. IAMs) that may have well documented model risks or produced inconsistent model outputs for the underlying factors such as prices, interest rates, the predictive powers or statistical distributions of realised events could well be limited by the underlying frameworks they have learned from, giving rise to unrealistic distributional outcomes.

4.7 Modelling Techniques used by Central Banks and Financial Institutions

There are a number of commercial and in-house propriety models that have been developed to address the challenges of climate risks within commercial banks and also by regulators. Whilst some of the methodologies have been shared as they indicate they use frameworks such as PACTA and central banks such as the Bank of England and the ECB have run exploratory stress testing exercises. As climate risk modelling is a new field and financial institutions have only just started working on determining whether they can build effective risk-based pricing, this will inevitably result in risk adjustments for a number of assets. However, a recent review has indicated that

[6] Levered beta (equity beta) is a measurement that compares the volatility of returns of a company's stock against those of the broader market, it is a common measure of risk, and it includes the impact of a company's capital structure and leverage to the market

asset prices underestimated climate risks (Bank for International Settlements, 2022), it is clear that such risks if they cannot be measured cannot be reflected in risk-based pricing. Indeed, from communications with those in banking there is some reluctance where these risks have been identified to pass these fully through to price by some banks. For commercial banks to implementing such frameworks requires enhanced data collection, adaption in business models to engage clients, requiring further training to build new methodology and effective risk controls to address these issues. Whilst regulations to embed these risks have been put forward (for example ECB, BoE), the delivery capital frameworks have yet to be fully defined, consequently commercial banks have typically absorbed these costs across their current balance sheet.

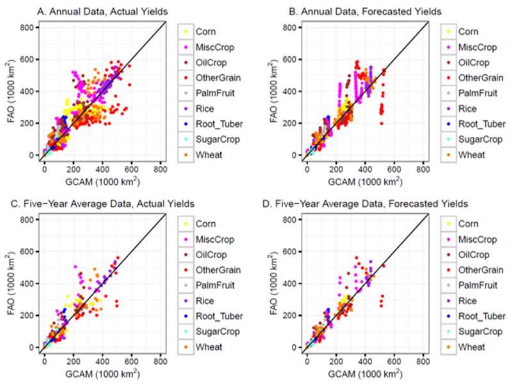
4.8 Back-testing and Hind-Casting: Issues in Quantitative Validation

As climate risk model frameworks are largely designed to be forward looking and data on historical performance of an asset may not be available or meaningfully be used to perform complete back-testing of the financial component in question. To assess the performance of such models, techniques used in back-testing can be applied, however the user must be able to test the components of the framework. Hence the testing criteria need to be adapted for each type of model under study. Model assumptions that cannot be realistically determined by calibrations that cannot be easily reproduced should raise red flags as a model framework for forecasting outcomes. Models that are of a causal nature in terms of economic impact, for example models of corporations that predict changes in demand / revenue / costs can be benchmarked with historical realised numbers used as a forecast to assess how each company performs going forward.

As an example, company level models that utilise a demand model to predict sales can look at revenue and cost impacts can be benchmark based on the use of the historical inputs. Typically models in finance are used to estimate the impact to market observables such as traded equity values or bonds. Further derived metrics such as equity valuations, funding costs, credit spreads should then be tested once the former causal mechanisms have been evaluated.

The equivalent of model back-testing in the financial space so called hind-casting tests of macro level models such as IAMs has typically been performed as can be seen in figure 4 and in figure 5.

In testing or validating climate transition models the analyst will need to decompose the layers of the model and test / challenge the individual components - such as the macro / IAM assumptions / model approach, the scenario meaningfulness (e.g. policy trajectories versus carbon tax). Then an assessment of the asset level methodologies (property, corporation, etc). Finally, an assessment of the market risk factor methodology applied.



Source : A Hindcast Experiment Using the GCAM 3.0 Agriculture and Land-Use Module

Figure 4 - Example of IAM model hind-casting, comparing the agricultural model prediction with realised outcome from the GCAM model (gcam)

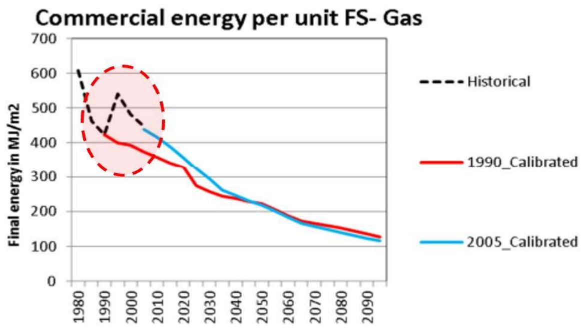


Figure 5 - Example of IAM model hind-casting, comparing the energy model prediction with realised outcome from the GCAM model (gcam). The highlighted area in red shows where there was a short-term jump in realised gas prices that was not part of the GCAM

4.9 Challenges in Physical Risk Modelling

Estimating forward-looking physical risks requires a broad range of modelling capabilities covering knowledge of physics, engineering, geography, and a wide range of micro and macroeconomics across several industries, agriculture and human health. Typically, within the finance industry, such skills are rare (this is undoubtedly the case in 2023), hence applying this knowledge to financial impacts requires the synthesis of internal financial knowledge, external specialist consultants and academic advisory.

Physical risk modelling of economic assets requires the consideration of all the above factors; these factors will not only impact the asset (or entity) *directly* but also impact its. local and *wider* environment. As a broad classification of risks, the direct impacts are termed first-order physical hazards, and the wider impacts are term second-order risks; these are explained in more detail below.

4.9.1 First Order Physical Risks

First order physical risks are defined as the impact of acute forecasted weather-related hazards on a given physical entity, this entity could be a commercial asset such as a building, road etc. or on animal or plant life. Weather events that are modelled in this case cover the following well defined set of *Hazard Set* criteria:

- Sea level rise
- Riverine Flooding
- Heavy precipitation (rainfall, ice, snow) - surface flooding
- Increased Wind speed
- High temperatures
- Fire risk
- Freeze thaw impacts

Physical risk assessment can be decomposed into several
components, geography (or location), frequency of events, severity of events and vulnerability of the entity at risk. The location of the weather event is self-evident; however, the regional geography can enhance the impact of weather-linked physical hazards, such as narrow river valleys, potentially enhancing flood risk. The frequency related to weather events is typically quoted as the number of types of events in a year, for example, the number of times it rains, snows etc. The severity would constitute the amount of rainfall, temperature etc. Vulnerability is

the susceptibility of an asset or geographical region to weather events.

Consequently, assessing weather-related hazards requires detailed knowledge of weather impacts currently and going forward in time to assess the total impact on and assets value. For example, every physical entity will also have several vulnerabilities to these hazards; for example, a building's vulnerability to weather events will depend on its construction from materials used, structural strengths and the positioning and potential localised mitigating factors to the hazards.

Extreme weather events are not limited to buildings and infrastructure; weather events will impact natural habitats, farmland, livestock and wild animals. Naturally, each segment of the human population will have specific vulnerabilities that may depend on the economic circumstances, political factors, age, current state of health and access to healthcare.

Assessing the economic impact of acute and chronic weather events requires considerable modelling expertise to evolve weather patterns and views on changes in the vulnerability of geographic regions, population size, health and economic well-being.
Such a broad range of modelling expertise for full risk
assessment is beyond the expertise of most financial risk management organisations that focus primarily on market or financial risk metrics.

4.9.2 Capturing Second Order Risks

So-called second order climate risks are notably harder to model and cover a wide range of risks. These risks can be classified into impacts from incomplete modelling of current systems (giving rise to increased severity / frequency of events)or completely unmodelled components These factors cover impacts to:

- **Impact from climate tipping points** such as permafrost thawing, changing ocean circulation systems.
- **Landslides** which requires specific geological vulnerability information.
- **Water Scarcity** requiring specific geological vulnerability information, an impact on agriculture, industrial process, migration, remediation costs.
- **Increased frequency and severity of extreme weather events**, such as hurricanes, floods, and wildfires, which can damage infrastructure and disrupt supply chains, giving rise to impacts from geographically distant events.
- **Rising sea levels**, which can lead to coastal erosion, flooding, and saltwater intrusion, impacting low-lying areas and critical infrastructure.
- **Changes in precipitation patterns**, which can affect water availability, agriculture, and energy production, and lead to droughts or floods.
- **Heatwaves and increased temperatures**, which can have impacts on human health, productivity, and energy demand, as well as on crops and ecosystems, agricultural demand.
- **Changes in ocean currents and temperature**, which can affect fisheries and ocean-based industries, as well as lead to more frequent and severe storms.
- **Changes in biodiversity**, including loss of species and habitats, which can have impacts on agriculture, forestry, and tourism, as well

as on ecosystems and the services they provide.

- **Wider infrastructure outage** impacting business productivity where the local damage occurs.

- **Impacts to wider global commercial supply chains** from physical climate damage across global regions.

- **Impacts to individual health from extreme heat and humidity**, direct physical damage from floods, high winds, impacts to individual productivity.

- **Impacts to human and natural habitat health** from the spread of disease, e.g. malaria, dengue fever, other zoonotic viruses and other diseases that may arise, spread and intensify as regional climates change.

- **Impacts from increased political unrest** from driven by reduced economic activity, impacts to agricultural land and systems.

- **Extension of political unrest** to minor and major warfare.

- **Consequential impacts from migration** driven by economic necessity, health and welfare, displacement due to adverse weather and conflicts.

- **Financial Stability Risks** - Impacts across a regional economy can give rise to systemic regional banking and financial risks arising from wide spread defaults. Depending on the specific fragility of a regional economy systemic climate linked bank failure may arise. Such a mechanism will likely result from the emerging second-order risks.

The risks highlighted above can be grouped as second-order consequential risk and network system risks, linking the impacts of geospatial climate and economic impacts from supply chains to banking network failure. The complexity involved in modelling such outcomes is considerable and many of the outcomes would in the short term be addressed through plausible scenario design to capture the specific regional impacts.

Means to address the challenge of integrating such impacts will be highlighted in section 5, where an effective mechanism of transmitting such events to the set of relevant economic agents (for the appropriate stakeholder) will be highlighted.

Stress Testing For Tipping Points
Potential climate tipping points have been identified, as a case in point the (Intergovernmental Panel on Climate Change, 2021) and references within, that highlight the significant dangers of inaction in mitigating these risks. The tipping points lead to run away regime changes in the climate - resulting in new higher average levels of temperature, humidity, extreme weather patterns. Such tipping points will be next to unmanageable by current human scale technologies and hence result in profound changes in the Earth's biome and significant life-threatening impact to virtually all human habitats. An illustration of the impact of sea level rise in recent geological periods is given below:

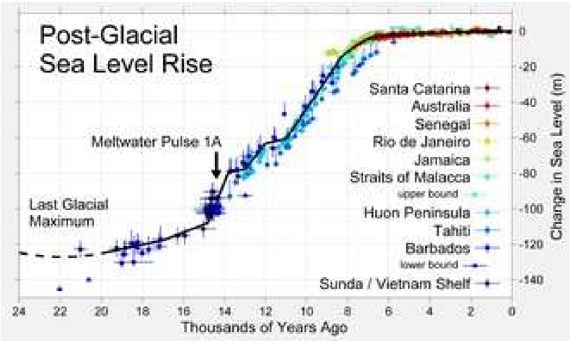


Figure 6 - Meltwater pulse 1A was a period of abrupt sea level rise around 14,000 years ago. It may be an example of a tipping point (Source "Past abrupt changes, tipping points and cascading impacts in the Earth system" Brovkin, 2021.)

The impact of such events will give rise to rapid shocks over the tens to hundreds of years, which is very long by the standards of most financial institutions but will pose enormous burdens on global economies to adapt.

For such events to be integrated into a stress testing framework requires a view of when and how such tipping points could occur with an adjustment to the frequency and severity of the worldwide physical climate events. The occurrence of tipping points over the next 30 to 70 years should be considered as part of long-term regional infrastructure planning as a notable asset class to stress with the outcomes applied to general physical risk stress tests to firms.

Such tipping points would give rise to huge valuation impacts and adaption funding pressures for many of the world's major cities close to sea level - monitoring the specific risks and building national adaption plans as part of a worst-case planning needs to form a part of national climate plans. Whilst such events may transpire over decades the capital flows required to shift residential, commercial regions and infrastructure would likewise require decades of capital investment and place significant fiscal and funding pressures on sovereign states.

5 Pragmatic Solutions to Climate Modelling For the Financial Sector

In this section methods of pragmatic choices for climate risk modelling are explored across the portfolio of assets and liabilities in financial institutions. To set about defining what constitutes a useful risk solution across a complex set of risks and an evolving modelling landscape starts with the objective of the risk assessment exercise. From the discussions on physical and transition risks (section 4), it is clear that integrating all data aspects into a single solution in a meaningful way that captures, not only technological changes, investment decisions and price/demand uncertainty from the set of physical and transition risks, would result in a large sensitivity to the missing data that may obscure some of the detailed analysis required.

In assessing risks and the response of an economic system to those risks, especially when agents in the economy have a need to understand the potential outcomes over a long forward-looking time horizon, requires an understanding of how those agents may respond to those risks. Naturally there is a considerable amount of uncertainty at each time step in the forecasted economic environment, hence economic agents within this environment, would need to make adaptive decisions based on both realised outcomes at time t_i and their view of potential outcomes for times $t_j > t_i$. Hence at the core of the need in climate linked modelling is to capture dynamically how agents in the economy would act and make informed (but not necessarily perfectly informed decisions) within their defined risk appetite. This is the core principal we propose to ensure that a climate model has the necessary general conditions to inform likely outcomes.

5.1 Criteria of Effective Climate Linked Modelling

In addressing the needs for an effective set of climate models a clear set of objectives needs to be outlined by each organisation as to the set of agents that are impacted and the set of stakeholders that will utilise such information. Defining the set of high-level objectives will assist in focussing the amount of information to collect as part of that analysis. This objective implies defining a forward-looking risk appetite for the known risks and embedding views on the currently unquantified risks.

Whilst this is a general statement for any model design, the significant challenge of climate risk impacts is that the transition impacts nearly every aspect of economic activity across the globe almost concurrently. The implications of such a profound impact across stakeholders such as governments (policy makers), their central banks, business, the populace, financial institutions require a reliable interpretation of the quantifiable risks for these segments with a coherence on impacts such that quantified impacts across stakeholders can be managed by all stakeholders consistently. The breadth of the climate risk challenge across the set of economic agents means that there is no single model framework that can accommodate all detailed model requirements in an analytically tractable time frame. However, as a pragmatic point in modelling the sub-components of such as system should aim to achieve coherence and transparency such that risk subcomponents can be seamlessly added to a wider model framework.

This leads to the need for coherence and transparency at every level of modelling to highlight the assumptions, data limitations as well as the ultimate insights from the model. Without such coherence all agents in the economy will likely suffer from poorly executed model frameworks leading to results that cannot be challenged or benchmarked. These concepts are expanded upon taking companies (both large and small) as a case study.

As the risk impact of climate modelling is so wide ranging the ability to build fully coherent models in a useful time frame, is likely to be almost intractable, however there a number of principals that models should provide.

- **Sufficiency : the Model needs to be sufficient for the Risks and/or Rewards** A financial product or an infrastructure investment requires the ability to estimate the risk based on the sophistication of that asset / financial product. Products that are marketed to investors linked to transition funding or risks that are warehoused by financial organisations (e.g. loans) requires a model framework that addresses these issues. This sufficiency extends across the complete set of components for a model, from scenarios design, the application of these scenarios to the generation of financial risks.

- **Dynamic Risk Assessment** Climate change transitions require long term adjustments and requires the ability to adapt to changing economic environment. As many investments are long term typically over ten years. Risk models need to be able to capture this long-term risk and views on adaption/risk mitigation.

- **Clearly Defined and Quantitative Model Assumptions**. The model needs to provide actionable quantitative predictions. Models that utilise scores, whilst useful for indicating potential exposures, typically at the point of assessment only. Model assumptions need to be both testable and can be quantitatively stressed to address the potential uncertainties.

Quantitatively Testable The risk framework needs to have a clear means of testing the outcomes ideally over short time frames as and when the data becomes available as part of an ex-post analysis.

- **Scalable and Coherent** the model outputs need to be such that they can be combined with aggregate economic models, in a scalable way such that those wishing to achieve an overall impact at say a regional / national level have the ability to integrate the results. Such features are critical for central banks / regulators as they seek to identify risks and/associated miss-pricing across the financial system.

In the sections that follow a set of guidelines are provided to shape model design, where relevant we highlight where the issues highlighted in section 4 can be addressed.

5.1.1 Risk Sufficiency

Assessing a model for risk sufficiency requires an understanding of the asset / product or internal risk and return criteria. As a general principal we propose that risk modelling that is consumed by the financial sector needs to reflect the measurement of risk by the real-world economic entity (agent). Financial organisations should then be able to build on this to provide the impacts to financial factors (e.g. traded equity prices, bond spreads etc.)

For example, in assessing the credit spread on a bond for a fossil fuel extraction company with an unknown transition plan or raising project finance for coastal desalination plants. Providing funding for dairy farmers requires bespoke modelling to assess impacts soil and land use, carbon sequestration as well as the cost to reduce animal emissions also a deeper understanding of the impact of nutrition contact, costs compared to dairy replacement food types. Risks can materialise where financiers do not have the depth of knowledge or models to assess the risks or are unable to model the specific technological innovation in these specific sectors(Journal, 2022). For example, the case of scenario design for commercial banks, there is a need for short term stress scenarios that address the potential exposures to liquid traded and non-traded banking book risks. These short-term scenarios look at combined short terms risks from physical impacts and short-term transition shocks. Short term scenarios serve the need for financial institutions to address the needs for market risk (on assets held for trading) and short-term impacts to loan portfolios. For example, in choosing model frameworks to assess credit quality of a firm over the scenario horizon, should as a bare minimum meet the criteria used to asses loan credit quality for example. So would include impacts on cash flow, operational and variable costs, interest costs, debt levels, debt maturity, asset utilisation (stranding), (micro) market environment. This sufficiency criteria will be different from product to product and from firm to firm, however at a systemic level core model outputs should to reflect standard best practice of the firms (and hence minimal regulatory criteria in prudential risk.).

For the use case examples given above for a fossil fuel company (or any firm exposed through policy / strategy to the climate transition) seeking funding a risk assessment and quantification would need to assess the company's current credit quality and an estimate of the viability of the forward-looking business model. The risk assessment would need to determine the forward-looking business strategy, cash flow forecasts, asset lifetime, funding costs, balance sheet strength based on demand forecasts and the uncertainty set around those forecasts. In summary what constitutes risk sufficiency implies a model framework that for a firm captures the corporate treasury related risks over the relevant planning horizon.

A financial organisation assessing such risk should be able to infer the market/instrument level risks that may results. As a consequence, sufficiently addressing the risks of the firm in the way risk are communicated enables a clear causal (in the sense of risk propagation) amongst wider stakeholders.

A desalination plant project finance would need to look at the potential impact from physical climate events, from its position next to a shoreline and the wider impacts to infrastructure, for example its electricity supply.

However, for policy makers, economic policies linked to decarbonisation need to be assessed for longer term viability, for example, impacts to inflation, sovereign debt, funding costs, extent of adaption of funding across the economy. A sufficient understanding of price shocks or climate linked disruption may come from specific firms or other economic agent where the agent-based view will provide a richer impact assessment and an ability to determine the risk vulnerabilities. The use of rich agent models provide a means of linking industry level growth / price shocks, impacts to employment, spending power to the macro-economic environment.

5.1.2 The Need for Dynamic Risk Assessment

Risk management at every level is dynamic; transition risk management by any stakeholder group must naturally reflect that responses to events or anticipated events (with some non-zero probability) will lead to a change in the entity and that entity's forward plans. This anticipation of change leads to the need to model the systems dynamically.

Hence, for the example of corporations, they will respond to planned policies/customer needs over time. As a consequence, stakeholders that depend on the company, investors, lending banks, regional economies, central banks, and employees, if performing a risk (reward) assessment, need to start from a base where their models capture the underlying dynamic response to the forward-looking views (scenarios) those companies may undergo.

From the expectation of forecasted increased physical risks to current fixed assets to the impact of economic transitions on *current* business models, static views of credit risks, for example, those that rely on current knowledge of the company's business operations or based on historical data or the current financial snapshot, will likely be quickly invalidated and miss-state credit risks for most transition and physical impact scenarios.

In assessing risk impacts for a financial loan portfolio, an organisation needs to build a more practical view of their client's transition strategy (including the impacts of global policy and broader economic trends) and develop a clear risk mitigation strategy to limit loan exposures over time.

Consequently, at an individual company level (or other economic agent), any risk assessment framework needs to utilise a dynamic model of that company's likely choices. The ability to anticipate a company's forward-looking strategy naturally requires knowledge of a company's current business model and potential strategy to mitigate climate risks. Assessing the impact of climate risks will fundamentally require the use of dynamic models that can factor in the ability of a client to adapt. Such company-level risk mitigation strategies can cover transition business plans and means to reduce future weather / environmental risks. Models such as (Cormack et al., 2020) use a dynamic view of a company's outcome based on observed business strategy, cost and regional location of assets.

An internal risk mitigation model, as part of the dynamic model framework of the counterparty, would allow the construction of effective exposure mitigation methods, reducing loan facility size and the duration of exposures, hedging or increasing capital reserves.

With these two features in place, a lending organisation can assess risks over longer horizons, permitting them to communicate the likely size of facilities over time and their uncertainties. Such risk mitigation strategy works well with well-defined policy choices for the future needs of an economy. Furthermore, building a coherent view of the risks can highlight poorly judged policy choices in advance that may cause unnecessary adverse economic impact or allow more robust policy choices.

It is the very nature of the climate transition that the world is undergoing, that capital investments are required over long horizons from 5 to 30 years and risk methodology whether looking at short term impacts or longer-term assessments cannot ignore an assessment that requires looking at firms (or agents) financial ability to adapt over these time horizons.

Dynamic Risk Management For a financial organisation's view on the forward-looking risks, most banks have a dynamic view of their risk holdings, for example market risk (aide from high frequency trading) is performed on a daily basis, counterparty risks are assessed daily with a view on holdings over a period of 1 year (Nikola A Tarashev, July 2005), with trading teams adjusting their exposures intraday to manage market related risks. However economic and strategy link risks for new business models are normally reviewed over longer time horizons of a year or more.

As many climate policies have been designed with the goal of considered change to reduce emissions over a period of 25 years or more, the objective has been to ensure that financial organisations can embed transition changes and build an improved view of physical risks to adapt their portfolios accordingly. For these organisations the business rational on providing financial facilities is defined by their current contractual obligations and their risk appetite, their views of the forward-looking risk and the risk management strategy. For example, considerations in managing a loan / financing facility for a portfolio of firms undergoing transitions requires a clear view of the clients business strategy, regional policy as well as the current wider macro-economic environment. As part of that financial institutions dynamic risk strategy they need to have a clear view on sources of uncertainty related not only to policy but the clients ability to drive change in its business model (or deliver its strategy). This requires clearly informed guidelines to these clients driven by a sufficiently rich risk framework that can provide the necessary quantitative insight to their clients. There is an argument that banks that do not have sufficiently rich climate risk assessments and base choices on unclear and unchallengeable information risk treating customers unfairly if arbitrary decisions of divestment or of excessive credit limits are placed on the pool of existing clients. Choices for banks dynamic risk management need to be proportionate to the needs of the economy within the national / international policy implementations. Banks working with their clients need to be able to provide a clear view on the extent of that they would provide future financing and communicate the set of forward-looking limitations to ensure there are no abrupt liquidity shocks across important sectors such as energy. This element of risk guidelines provided by the commercial banks is something that regulators have paid some view to, however this requires an improved coherence on risk modelling and its application for risk management and its dissemination and integration into strategic planning. An incoherent view and lack of clear planning across the system of energy firms, banks, financial regulators and policy makers as fossil fuel revenues diminish under net zero transition policies, risks creating adverse shocks that could largely have been minimised through an improved view of the evolving dynamics of this economic system.

Model users need to assess whether frameworks that provide current exposure metrics are sufficient to address their forward-looking business engagement with clients and if their clients are better served by models that look at their dynamic response, models such as PACTA are not rich enough to address these points.

Pragmatic Climate Linked Oversight As such we propose that regulators request a clear view of funding across supervised banks and private funding institutions of exposures to firms that are part of the critical energy provision / infrastructure and that clear guidelines are provided for those companies that provide a material exposure to such clients. This would be combined with the ability to assess and challenge at a firm level transition risks for such critical firms. With the objectives to have an oversight on potential funding / liquidity gaps within the financing of energy firms that could impact the security of energy supply in the case of insolvency. Clearly this presents the need to mitigate and manage the impact of this insolvency risk. National governments may choose to impose a number of tools from increased capital buffers for energy firms and their supporting lenders to means to ensure smooth running of energy facilities in the case of insolvency to serve the neds of national energy/supply chain security should no viable substitute be found.

5.1.3 Quantifiable Model Assumptions

As the intention is to build a model that can give rise to risk / pricing estimates through stress testing or scenario impact analysis, the model inputs and outputs need to be quantitative, so that models can be tested component by component. Linked to the risk sufficiency criteria the set of quantitative components need to have the required coverage. For example, scorecard-like models do not provide a fully objective measure of risk and can may if not sufficiently granular, miss or conflate specific risk factors.

Testable Predictions With quantifiable outputs, model assumptions and sufficiency can be tested directly. It is recognised that full distributional effects for some market factors may well be untestable at an individual company level due to the very nature of forward-looking scenario analysis. However, models should be testable at the modelled component level. For example, if a model is designed to assess the impact to cashflows (revenues, earnings) based on a change of prices and / or demand, then comparison tests should be provided to demonstrate a model's performance with realised inputs compared to realised outcomes.

5.2 Applying the Criteria : Examples

In the sections below, we apply the principals across the core risk areas within the financial industry.

5.2.1 Credit Risk

Credit risk is typically the most significant financial risk of any bank; it is defined as the potential losses from counterparty defaults on their obligation to make a payment. The very nature of banking means this risk is embedded in nearly every activity and product of the bank; it is typical for large international banks to have hundreds of models to quantify this specific risk alone. Each credit risk model is likely to be specific to a particular financial product and business activity within the bank.

As a consequence, each business domain will measure several features commonly termed risk (and return) factors that indicate default risk (or returns). For loan assessments, these factors have typically been derived from empirical observation of many loans/transactions with counterparties that provide insight into likely returns on the instrument and have evolved and been calibrated to this historical data. Such statistical models based on past observations can pose problems when forecasting the impact of forward-looking events. The reliance on historical data and their distributions dominates the vast majority of risk models used by banks and is not just confined to credit risk. Other modelling involves a deeper understanding of the likely causal factors behind defaults. We will explore a number of these concepts in the assessment and design of risk models.

Assessing climate risk for credit risk poses a significant challenge due to the need to evaluate the long-term impact of economic scenarios spanning beyond the typical credit horizon of less than one year and extending up to 30 years or more within banking, typically a one to three-year risk horizon is considered standard for credit risk assessments and typically reflects the term for loan agreements. The varying analysis horizons are essential for capturing short term risks to current and nascent business models, whilst the long-term scenarios are crucial for the understanding of both the viability of the long-term client relationship as well as highlight any wider economic risk factors that may be posed by a significant firm and its supply chain. This viewpoint was designed to capture the broader implications of short-term, forward-looking economic factors that shape corporate business planning and revenue expectations. However, credit risk assessments under the IFRS9 framework, specifically the so-called expected credit loss 'ECL', require banks to recognise lifetime expected credit losses rather than just 12-month expected losses. For potential lifetime losses where an organisation may have long dated exposures (e.g. swaps), credit reserve or client portfolio holding adjustments may be brought into focus from long-term climate stress analysis.

To achieve this, financial institutions employ a range of standardised risk tests to gauge the sensitivity of their lending operations to changes in market conditions, such as fluctuations in interest rates, commodity prices, and foreign exchange rates, as well as some industry or company-specific factors. These tests aim to determine the necessary capital provisions required to safeguard the continued operations of banks and other financial organisations.

However, extending such concepts beyond the typical 1-year requires a richer set of risk factors and model features as outlined for companies and other financial assets. As we highlight in section 5.1 understanding both the short term and the long terms risks for strategic planning. In the subsections below, we highlight a number of required features in a model framework to ensure coherent and combinable model impacts.

5.2.2 Corporate Loan Book (Banking Book)

For corporate loans in the banking book, several relevant factors need to be assessed, from the short-term viability of the loan subject to a set of plausible shocks to the long-term commercial viability of the client business. As a consequence, the underlying risk framework needs to be able to provide a set of viable expected outcomes of default based on the set of underlying assumptions driving the cash flow of a firm over the risk horizon of the loan. The financial model framework of the underlying firm would need to meaningfully capture the communicated business strategy, capital investment and risk management choices a firm would make as part of its regular business operations. As a stress testing model, it will also require providing company-level stress impacts. Furthermore, where a company may have a systematically substantial impact on a region's energy security or impact on a major supply chain, such a framework would need to account for such impacts across a portfolio as well as any anticipated mitigations. It is likely that such systemically important firms may not be in a credit portfolio level for an individual bank but have a notable impact on the credit quality of its supply chain or the wider economy.

5.2.3 Traded Counterparty Credit Risk

Traded counterparty risk to corporations from hedging commitments to fixed income / foreign exchange business , or equity exposure from support of Merger and Acquisitions, or share options business will typically create a long-term risk for banks. For example, most fixed income hedges can have maturities from 5 to 10 years and hare option schemes may go from 2 to 5 years. Capturing the impact of climate scenarios requires the engagement of modelling methods applied as part of the corporate loan book above as well as a means to build a model for the relevant market factors such as the traded equity price, implied volatilities, credit and liquidity spreads. We argue that a consistent climate model should be able to provide a clear link from the fundamental impacts at a company level to the market observables (prices , derivate prices) such that stress scenarios can produce meaningful causally linked impacts and distributions of these impacts. The combination of the estimation of the default probabilities and the ability to derive coherent views on market exposures can then be realised. The methodology developed to address traded counterparty risk can be applied directly to addressing market risk impacts.

Financial Counterparty Risk Investors or other financial organisations face indirect exposures to climate risks from potential exposure to financial organisations that rely on income from a portfolio of assets exposed to climate physical and/or transition risks. For external non-regulatory parties understanding the impacts on these firms would require a detailed understanding of exposures such as loan exposures to high risk transition sectors or exposed to properties with significant physical risks.

Liquidity Risks The impact of climate risks on funding liquidity risks needs to be monitored; aside from general funding squeezes across a whole economy, a lack of available funding may adversely impact firms subject to transition risks. These risks may arise due to the reluctance of investors to purchase securities in some carbon-intensive firms or a lack of willingness to engage in the support of providing hedging services. Whilst this may impact several firms and their supporting banks, there is a need for financial oversight (through regulatory disclosure from the firm and via commercial banks) to ensure that financial operations for some critical energy firms with the target of decarbonisation policies can receive funding. The emergence of liquidity risk can be sudden and hard to control by financial organisations and hence requires further involvement of external parties and firms to improve disclosure to highlight the systematic issues that may arise due to disruption to the energy system. Modelling such impacts requires a point in time assessment of a company's specific risks and how such risks can be mitigated; liquidity factors could give rise to enhanced jump to default probabilities despite firms having strong fundamentals - impacting a bank's derivative positions as part of its clients hedging services and associated securities they may hold.

5.2.4 Housing Portfolios

In modelling the impact on housing portfolios, an institution needs to build a view of physical risks, impacts on the cost of funding, inflationary pressure, lender disposable incomes and cost of adaption for the set of property-linked finance deals. For example, it is understanding the ability of landlords and owners to adapt insulation, heating and cooking abilities and the impact on the economic value of the property or the ability to carry letting a property and servicing the loans. Such insight would enable firms to build better lending practices and offer informed financing and new products to meet the transition needs.

5.2.5 Personal Finance

Climate transition and physical risks may have an adverse impact on personal finance (e.g. car loans) or suffer increased disruption from weather events. Building an incremental climate-linked stress on top of existing economic factors would be required. For example, understanding if an individual may be at risk of losing their job because of their exposure to firms that are adversely impacted by the climate transition. Firms will need to review the extent of this exposure and adapt lending practices where appropriate.

5.2.6 Project Finance

Adopting the principals for corporate level risk assessments can be scaled to specific project finance. Institutions. Institutions should be able to provide a clear view on the asset value of future cash flows from climate scenarios and the impact to physical risks to the project assets.

5.3 Market Risk

Impacts from short term events from climate physical events and potential abrupt impacts from policy choices can give rise specific events that would impact market risk exposures. In assessing risks financial institutions can follow the risk assessment principals outlined in sections 5.2.3 to build stress impact assessments. In relation to weather linked events it is conceivable that exposures can be reduced or hedged by utilising weather forecasts. In building stress scenarios for such risk views on the extent of the weather event for example a major hurricane and its regional impact need to be embedded into the methodology.

5.4 Operational Risks

Many financial institutions perform stress analysis on the impacts to their infrastructure from adverse weather events, floods etc. Extended these stress event to look at impacts to infrastructure damage is also very common in the industry. Suitable stress tests should look at the severity and the longevity of the impacts going forward in time a determine the need to reduce exposures.

5.5 Sovereign Risk

Climate change driven Sovereign Risks, if they are to be addressed in an incremental way for financial institutions, need to look at the impacts of many of the micro components of an economy and build views on the transmission of these risks to impacts to downgrades or defaults of sovereign debt. Furthermore, there are sovereign level risks that arise from impacts to the populace, e.g. economic emigration reducing a countries productivity, immigration impacting on public expenditure, or reductions in the populations wellbeing, productivity, personal expenditure from climate events. Building a coherent view at this resolution of an economy requires an improved integration of these risks into macro factors. Taking sovereign debt as an example, impacts from fiscal factors such as corporation tax take, value added/ sales taxes, income taxes from the economies business sectors as well as government supply side incentives to fund national decarbonisation will play a role as factors within a stress testing model. As a consequence of the complexity of combining micro to macro level model frameworks, stress testing impacts to sovereigns requires a careful analysis of the causal links (narratives) used to build the climate specific incremental stress impacts and will be driven by national exposures and international events that must be carefully defined as to how they would manifest.

5.6 Capital Calculations and the Path to Risk Based Pricing in the Banking Sector

Whilst it can be argued that for many financial institutions the impact of climate related risks could be material depending on their exposures and the methodologies applied. The ability to quantify risk whilst model frameworks may be regarded as incomplete becomes a notable issue for regulators and financial organisations to address. How the organisations embed these risks as part of their capital process would need to be addressed along pragmatic lines over time to avoid issues where regulators face resistance because of ill formulated climate linked stress frameworks and capital requirements.

Questions on which type of capital (Process, Tier 1 regulatory or Tier 2 and economic capital, Tier 3 disclosures) and the required risk assessment process e.g. stress tests with capital add-ons, capital and liquidity adequacy (e.g. in the UK ICAAP, ILAAP, the capital and liquidity provisions respectively) still exist whilst the modelling and quantification issues are uncertain. Embedding climate linked stress tests and understanding the incremental risks linked to climate events and how to mitigate, adapt risk appetite and subsequently provide a suitable economic capital buffer is the likely minimum requirement for financial firms.

The issue of enabling a regulatory risk capital calculation would generally require multi jurisdiction agreement (e.g. Basel) that would likely proceed in parallel with the input from the major regional regulators and central banks. However, before this could be achieved, the issue relating to risk quantification and model consistency need to be addressed. In discussions with climate leads in a number of banks; whilst risks have been identified, the incompleteness of methodologies and reliable risk quantification has not led to consistent risk-based pricing. indeed, at this stage there is some reluctance to be the first mover by some organisations This presents a number of issues with the danger of systemic risks across some segments of the economy that are currently not directly transferred to prices but absorbed on bank balance sheets. Such issues are where regulatory oversight will provide a view on the classification and magnitude of these risks.

Implementation of tier 1 capital calculations at this stage where the risk quantification process is at a nascent stage where methodologies are regarded as incomplete would likely be counterproductive in terms of the timeliness of delivery. Specifically, the ability for banks to use their own models for these capital calculations would incur significant delays. However, there is cause for driving a standardised assessment framework across the risk classes as well as firms implementing their own risk models for own incremental capital allocation. Such a standardised approach puts the onus on regional regulators to provide prudential guidance in this space.

Implementing such a standardised risk framework to address the build-up of these systemic risks on bank balance sheets in these formative stages of risk model development requires regulators to engage across the financial and modelling community to benchmark and categorise model frameworks and define a high-level view on the risk coverage. As many of the significant second order risks as outlined in section 4.9.2 are currently not fully quantified, capital methodologies would require the input of expert level judgement to quantify in much the same way as forward-looking operational risks are assessed and capitalised in banks.

Alongside a standardised view, regulators are encouraging firms to develop with expert guidance risk frameworks and communicate to the wider financial system, different methodology approaches. Such frameworks will permit specific asset level/micro portfolio instruments level benchmarking and subsequent communication both to banks, the wider modelling community and other stakeholders. Such benchmarking would significantly enhance engagement and improvement of climate risk assessments. This would likely lead to a faster more transparent means to capitalise and build better risk / pricing transfer mechanisms avoiding unnecessary mispricing / or valuation correction (Minsky moments), from the build-up of unpriced systemic risks that exist across banking and risk portfolios.

6 Conclusions

This paper has provided an overview of techniques and methods commonly deployed in climate risk modelling, covering both physical and transition risks. We highlight several issues in current modelling frameworks that can give rise to incoherent and potentially misleading results in the risk domain in which they are applied (such as corporate risk exposure). Where we have highlighted issues in the current, we have provided a set of modelling principles to that we deem necessary to capture the evolving information of the economic agents over time. The objective has been to provide model developers and validators in the industry and those entering the field of climate risk modelling an overview of both the viable and challenging aspects of climate risk modelling.

The issues highlighted arise partly because of the nascent field of financial climate risk modelling, where the challenges of risk modelling, for example, integrating climate scenario impacts across multiple scales within an economy from the microlevel impacts to macro-economic outcomes is still largely incomplete. Whilst this area of modelling is still under development, the ability to capture a stakeholder’s risk by improved modelling of their behaviour can still be achieved and give rise to meaningful risk insights. This should result in a clearer communication not just to the individual stakeholder segment of the economy but also other stakeholders in the economic chain.

As a consequence, we regard that climate risk modelling requires a robust use of agent-based models or, as a minimum, transparent models for segments of the economy that can be integrated to derive macro-economic views for relevant components of an economy. As a consequence of the need for long-term transitions (a model assumption that can be tested), the agent-based models need to be dynamic and capture several important risk management processes that are employed. For example, we highlight the need for models of corporations to factor in impacts on capital structure management, asset and liability matching and other major risk mitigation measures commonplace in a firm's treasury and strategic financial management. These model choices are to better reflect the real-world risks these agents assess and manage and how they currently manage long-term projects, financing and investor engagements.

In regards of financial regulators, to avoid the build-up of unprovisioned systemic climate risks that commercial banks are increasingly identifying, there is a need for regulators, in conjunction with firms, to embed these risks promptly. Furthermore, in the short term, build consistently in capital and risk calculations framework, which can be achieved through standardised scenarios and methodologies. Achieving standardised assessments whilst providing a quicker means to provide a level playing field for banking loan portfolios requires an improved overview of model output by regulators. Benchmarking models across asset classes is critical for regulators and should be addressed across the risk stakeholder group and second-order risks we highlight. Alongside this work, further innovation in modelling methods to develop improved firm and asset-level assessments alongside a standardised approach should be enhanced. We support the argument that modelling needs to reflect the real-world risk factors in the economic agents to ensure coherence and the ability to integrate such risks. Such a coherent framework will enable a more transparent oversight of the transmission of risks from the real-world economy to financial and macroeconomic variables. Such a framework would provide a clearer means for policymakers and all stakeholders to assess the potential impacts of risks and policies across the whole economic system. This would not only improve transparency but enable more rapid action to be taken with forth coming assessments such as nature-based risks.

In putting forward these recommendations, we recognise that many existing model frameworks must be radically improved or enhanced. We encourage financial institutions to assess their current modelling approaches to determine their sufficiency for long-term capital planning and risk oversight and engage in model benchmarking and communication activities not only with regulators but across their stakeholder groups, from those they provide services to investors.

Declaration of Interest

Chris Cormack is engaged in active research topics across areas of climate change, such as agriculture and the financial modelling of climate change. He is also the Managing Director of Quant Foundry and the owner via Climate Foundry Limited of commercial quantitative models that have been published in academic journals, specifically the model published in (Cormack et al., 2020).

In terms of background Chris is a former lecturer at the Queen Mary University of London and researcher at CERN, DESY and Stanford. After academia he built a career in finance where, as a former Head of Traded Market Risk and risk model designer across counterparty credit, operational and market risk has considerable expertise in financial risk assessment and management.

Appendix: Bank Capital Frameworks

The Basel Capital Framework establishes international standards for bank capital requirements, aiming to ensure the stability and resilience of the banking sector. The framework defines different tiers of bank capital, each serving a specific purpose in safeguarding the financial institution. Here is a summary of the tiers of bank capital under the Basel Capital Framework:

- Tier 1 Capital Tier 1 capital is the highest quality capital and serves as the primary measure of a bank's financial strength. It consists of two components:

  - Common Equity Tier 1 (CET1) Capital: This is the core capital of a bank, primarily composed of common shares and retained earnings. CET1 capital provides a cushion to absorb losses and maintain solvency during adverse situations.
  - Additional Tier 1 (AT1) Capital: AT1 capital includes instruments such as perpetual bonds or preferred shares that can absorb losses and support the bank's viability if it faces financial distress.

- Tier 1 capital ensures that banks have a strong capital base to support their operations and absorb losses, enhancing their resilience during financial downturns.

- Tier 2 Capital: Tier 2 capital is secondary to Tier 1 capital and provides additional loss-absorbing capacity. It consists of less permanent instruments, including subordinated debt and certain hybrid instruments. Tier 2 capital acts as a supplementary buffer to protect against losses and supports the stability of a bank's operations. Tier 2 capital instruments have specific requirements and limitations on their inclusion in regulatory capital calculations, ensuring they contribute to the bank's loss absorption capacity without excessively increasing risk.

The Basel Capital Framework sets specific requirements and guidelines for the composition, calculation, and measurement of both Tier 1 and Tier 2 capital. These requirements aim to maintain a balance between promoting stability in the banking sector and allowing banks to allocate capital efficiently.

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