Climate risk scenario analysis and the role of central banks and supervisors in safeguarding financial stability in the net-zero transition*

Moritz Baer[1,2,3]

[1]Smith School of Enterprise and the Environment, University of Oxford
[2]Institute for New Economic Thinking, University of Oxford
[3]UK Centre for Greening Finance and Investment (CGFI)

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Supervisors: Dr. Ben Caldecott and Professor Doyne Farmer

Abstract

In response to a growing awareness that climate change and the associated net-zero transition may impact financial stability, academics, financial institutions (FIs), central banks and supervisors (CB&S) have been developing a suite of scenarios and analytical tools to assess climate-related financial risks. This DPhil contributes to the field of climate finance with: (i) a more systematic understanding of the evolving role of CB&S in setting climate-related financial regulation, as well as wider policy challenges involved in navigating the transition (Paper I); (ii) the development of an empirically grounded bottom-up climate stress testing approach – TRISK - to assess transition risks and the distributional consequences for financial institutions' portfolios to scale up capabilities in forward-looking scenario analysis for risk management purposes (Paper II); and (iii) a taxonomy framework for assessing the suitability and credibility of scenarios within financial decisions to advance the understanding of the wider limitations, uncertainties, and trade-offs inherent in climate scenario risk analysis (Paper III).

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1 Overview DPhil

This section aims to provide a high-level overview of the DPhil research, summarising the general context of the topic at hand, as well as highlighting key contributions of the individual research papers and the overall motivation of the DPhil. Please refer to section 2 for wider background context of the DPhil and current state of the literature. For concluding contributions of this DPhil and its substantive research pieces, please refer to section 6.

In response to a growing awareness that climate change and the associated net-zero transition may impact financial stability, academics, financial institutions (FIs), central banks and supervisors (CB&S) have been developing a suite of scenarios and analytical tools to assess climate-related financial risks. Importantly, effective risk management, financial regulation and supervision can play an important role in driving the reallocation of capital, and mobilising finance at scale for the transition in line with the longer-term objectives set out in the Paris Agreement while safeguarding financial stability in the short- and medium-term. Experiences of engagements in the past decade have shown that such initiatives with CB&S can have significant impact and are often more politically acceptable to governments and Ministries of Finance, given the link to financial stability considerations and the wider opportunities associated with building green financial markets.

To this end, this DPhil contributes to the field of climate finance with: (i) a more systematic understanding of the evolving role of CB&S in setting climate-related financial regulation, as well as challenges around the institutional legitimacy and political backlashes of "green" central banking (Paper I, published in Ecological Economics); (ii) the development of an empirically grounded bottom-up climate stress testing approach – TRISK - to assess firms' transition risks and the distributional consequences for financial institutions' portfolios to scale up capabilities in forward-looking scenario analysis for risk management purposes. Further, this paper assesses the variability in financial risk outcomes across different transition scenario narratives to highlight the associated sensitivities and uncertainty inherent in climate stress tests (Paper II); and (iii) a taxonomy framework for climate financial scenario analysis that allows to systematically assess scenario components, key assumptions and the underlying modelling and calibration to derive implications for overall scenario credibility, as well as get an appreciation of the suitability of key features and characteristics of scenarios for financial use cases. (Paper III, published in Frontiers).

Overall, the research presented in this DPhil addresses two relevant dimensions that support the shift to a climate-resilient financial system and informs re-allocations of capital towards nature-positive and resilient patterns of growth:

First, from the policy and regulation perspective, CB&S need to navigate their legal mandates and institutional settings to set the appropriate rules for the financial system. These are the political economy considerations that constraint financial policy and regulation aimed at supporting the transition. Policy motives, the degree of public intervention in private financial markets and the extent to which governments' sustainability objectives are actively supported, need to be carefully balanced in the context of respective mandates and institutional landscapes. Or else CB&S are at risk of losing accountability and legitimacy that could impede the ability of regulators to act upon climate change. Paper I of this DPhil analyses these institutional dynamics against the evolving nature of financial regulation in the aftermath of the global financial crisis, presents stylized scenarios that could avoid an institutional deadlock and discusses geographical differences in the independence and degree of control over financial dynamics by CB&S. The framework developed in this paper aims to provide a more solid institutional and governance foundation to the ongoing debate concerning the role of regulators in addressing climate change and can assist in explaining latest developments such as the increasingly prominent role of the European Central Bank (ECB) or the remit changes for the Bank of England (BoE). However, recent developments also highlight that the institutional setting of the ECB and EU's governance, including the focus area of senior management and the resulting increased confidence about the understanding of climate risk may have been idiosyncratic developments.

Second, the ability of FIs and CB&S to support the net-zero transition is impeded by the technical challenges surrounding the integration of climate and transition-related dimensions into risk management practices. Specifically, as we show in Paper III, scenario analysis for climate financial risk assessment[1] brings new and unprecedented challenges when compared with other types of risks, particularly given the complexities, longer time horizons and uncertainty associated with climate change. Importantly, we identify that currently available scenarios and approaches may not capture the full breadth of scenario narratives and granularity required by the financial sector and miss important characteristics and processes that we argue are critical to fully understand the potential severity and timescales of climate-related risks.

What is more, as we show in this DPhil, the complexity and uncertainty involved in seizing transition risks should not be a barrier to action, if underlying models are understood and adjusted appropriately to fit respective financial sector use cases and are interpreted in full awareness of their characteristics and inherent trade-offs. Specifically, Paper III contributes to a more systematic understanding of these issues with an analytical framework and taxonomy that allows to assess the credibility and suitability of climate risk scenarios for financial decision making. Based on the assessment of currently available scenarios, we draw out key design features that we argue need to be captured in an adequate risk scenario.

[1] For the remainder of this DPhil, climate risk scenario analysis and climate stress testing are used interchangeably.

While it is evident that regulatory pressure is increasing, FIs may not yet have the capabilities to adequately assess the risks and opportunities of the transition to guide and justify decision making. This could lead to avoidance of the active use of scenario results, or the delay of strategic decisions based on the inconclusiveness and uncertainty of such exercises. Consensus from academics and international organisations and fora such as the International Monetary Fund (IMF), the Financial Stability Board (FSB), the World Bank and Network for Greening the Financial System (NGFS) is that due to limitations of currently available climate risk scenario analyses, the risks of financial instability arising from the low carbon transition may be radically underestimated, and similarly benefits of early action and the high costs of delaying the transition may be mispriced by financial institutions.

Complementary to such analytical frameworks and identification of knowledge gaps, we also put forward a transparent climate stress testing model - TRISK - in Paper II that overcomes some of the methodological limitations and research gaps identified by the Bank for International Settlement (BIS) and the NGFS to provide more reliable firm-level transition risk estimates. The set-up of TRISK is also guided by the framework proposed in Paper III. The flexible nature of the TRISK model and the extensive sensitivity testing in its application allows to simulate firm's asset values under a wide range of scenario pathways on how the transition could manifest, including different levels of severity for the policy shock. Here the decision usefulness of the results is centred around informing the variation of firm-level risk impacts that stem from different scenarios. In this context, while the model outputs the quantitative results such as transition-related changes in the net present value of firms or changes in their probability of default, this should not be taken as predictions (even for the given scenario narrative) but always be interpreted as conditional on the manifestation of underlying scenario assumptions. Overall, firm-level financial risk models such as the TRISK model aim to provide CB&S with the required capabilities to quantify transition risk across a rich set of scenarios to inform risk-based regulation.

The methodology and exploratory results of the TRISK model may help financial institutions and central banks and supervisors to identify sectoral outliers and firms that are on average – across a range of scenarios and assumptions – impacted more adversely than its peers. Further, in the TRISK model, transition risk is a function of the misalignment of firm's production plans under a business-as-usual pathway with Paris-aligned sectoral decarbonisation targets. The model does not allow for a strategic response of such firms but assumes they continue to follow their stipulated (and often misaligned) production plans and hence represents outcomes that sit further in the tail of the probability distribution, i.e., are extreme but plausible. This follows the use case requirements of a risk management and stress testing approach as outlined in paper III.

More specifically, Paper II, which forms a substantive part of this DPhil, contributes to the academic literature with the following three key features:

- The bottom-up climate stress testing framework and financial risk measure TRISK is providing unprecedented granularity through a calibration on physical asset-level data and the representation of transition risk at the firm-level. Approaches by academics and CB&S have so far predominantly employed industry level-approaches or top down-macroeconomic approaches that insufficiently capture within-sector variation. While such approaches may provide a systemic perspective on financial market losses, it does not equip FIs with the appropriate level of granularity to distinguish between transitioning firms and climate laggards within the same industry. Also from a regulatory perspective, to increase the resilience of financial institution and to safeguard financial stability in the transition, climate stress tests need to identify exactly where the risk lies and how concentrated it is on the level of individual counterparties. The TRISK measure allows for this.

- Current approaches are insufficiently forward-looking as they rely mostly on current and backward-looking carbon emission intensities as a proxy for transition risk. We argue that disclosing carbon emissions is not a sufficient metric for investors and regulators to determine a firm's transition risk and alignment with the Paris Agreement. Importantly, two firms with exactly the same current emissions today could face widely disparate transition risks. If one firm is an oil major that is planning to keep investing in oil fields, and another firm is planning to transition to a business model based on solar farms, then the latter firm will presumably face much lower transition risk. The reason is that it will not be subject to a carbon tax, demand driven effects or phase-out policies, for instance. Transition risk proxied by current emissions will not capture this relevant heterogeneity of the transition impact between transitioning firms and climate laggards. The TRISK approach overcomes this limitation by allowing for a calibration on the five-year forward-looking production plans of firms, gathered from company and business intelligence reports [2]. As a result, the transition risk - TRISK – expressed as financial losses from transition-related equity valuation changes of firms (market risk) and associated probability of defaults changes (credit risk) - is a function of the misalignment of planned strategies of firms with a Paris-aligned scenario pathway, rather than proxied by historical and current carbon emissions alone.

- Current approaches are limited in accommodating for a wide range of scenarios and underlying modelling choices to better represent prevailing uncertainties and the ability to assess sensitivities to underlying assumptions. There is a need to go beyond current exercises that have just focused on the construction of a few scenario pathways created within

[2]Data is provided through Asset Impact: `https://asset-impact.gresb.com`

the same integrated assessment model (IAM), such as exercises by the BoE and the ECB that both used NGFS scenarios. Effective climate scenario risk analysis needs to reflect the many plausible ways in which the transition may play out, including different beliefs around the speed of technological change, differences in how the energy system is modelled and overall narrative variations. This can give an improved understanding of where in the probability distribution respective scenarios sit given the level of conservativeness of key assumptions. The modular structure of the TRISK approach allows to input many scenario components across different scenario providers and hence allows to compare the financial risk outcomes across a wide range of more or less conservative and restrictive scenario assumptions modelled fundamentally differently, to get an appreciation of the level of uncertainty involved in these exercises.

Overall, the research of this DPhil serves the academic community and financial practitioners with an enhanced understanding of the appropriate design of climate risk scenario analysis and in particular climate stress tests. It provides insights into the institutional drivers and dynamics in the political economy landscape to assess the varying degrees of involvement by CB&S and to effectively communicate the limitations and challenges associated with currently available approaches. The outputs of this DPhil will help policy makers, regulators and financial institutions to better understand the likelihood, the magnitude and heterogeneity of shocks and impacts over time, as well as provides frameworks that allow to incorporate these directly into financial decisions and supervisory practices. As we are in the relevant decade for averting the worst consequences of climate change there is an urgency for developing such capabilities, which this DPhil aims to provide.

In summary, Paper I identifies the role of central banks in incorporating climate risk in decision making (an institutional and political economy contribution). Paper II develops an approach to calculating firm-level climate risk using forward looking data (a technical contribution). Paper III critically examines the use of scenarios in climate stress testing (a contribution focusing on the translation of technical analysis into policy settings).

2 State of the Literature

This section aims to introduce the wider context in which the DPhil is situated and gives the relevant background information. The state of the literature is assessed around current research on climate scenario risk analysis and the role of central banks and supervisors in the transition to net-zero. This section also addresses some of the key limitations and research gaps that the DPhil aims to overcome.

2.1 Climate Change, the Economy and the Financial System

There is an increasing recognition that climate change and the associated transition towards net-zero presents a challenging dual role for the financial system. On the one hand, finance can accelerate the transition, minimise catastrophic climate impacts and contribute to nature-positive and resilient patterns of growth through the provision of funds required for rearranging the economic system, mitigation and adaptation (Bolton, Despres, Pereira da Silva, Samama, & Svartzman, 2020; NGFS, 2019a). This requires financial actors to seize the long-term opportunities in the transition and to reallocate capital towards climate friendly solutions and technologies (see, for example, Batten (2018a); Caldecott (2018); Campiglio et al. (2018); Chenet, Ryan-Collins, and van Lerven (2019); Dietz, Bowen, Dixon, and Gradwell (2016); Giuzio et al. (2019); Mazzucato and Semieniuk (2018)).

On the other hand, if persistent short-term incentives prevail on financial markets and the transition is not managed carefully, climate change and meeting the Paris Agreement's goal of limiting global warming to "well below 2°C" likely involves stranding assets whose net worth is estimated to be in the trillions of USD (Caldecott, Elizabeth, Cojoianu, Kok, & Pfeiffer, 2016; Mercure et al., 2018, 2021; Semieniuk et al., 2022). Without sufficient action, emissions will grow significantly over the coming decades (UNEP FI, 2022), presenting a seismic challenge and significant risk to economic resilience with alarming consequences for the financial system, including financial instability (BoE, 2019b; ESRB, 2020) with global repercussions for long-term prosperity and security (Schoenmaker, 2021). The Ukraine crisis, but also COVID-19 and the global financial crisis (GFC) before it, demonstrate the severe economic and social consequences if financial systems are in distress. Furthermore, such crises may lead to short-term fiscal policies that are reinforcing the status quo of higher emitting activities (Hepburn, Allas, et al., 2020) and hence could slow down the transition.

In response to a growing awareness of these challenges, relevant actors have been developing a suite of scenarios and analytical tools to assess climate-related financial risks accompanied by green financial frameworks and regulation to allow that climate risks are made transparent to investors and priced appropriately (Ameli, Drummond, Bisaro, Grubb, & Chenet, 2020a;

NGFS, 2020). This can act as a guidepost for markets to reallocate capital and mobilise finance at scale for the net-zero transition. Importantly, in light of stagnant progress of international government coordination on mitigating climate change (Carney, 2020; World Bank, 2023), experiences of engagements in the past decade have shown, that initiatives from CB&S can have significant impact and are often more politically acceptable to political leaders, given the link to financial stability considerations and the opportunities to build green financial markets.

Climate change and the aimed transition to a net-zero economy pose at least three major types of financial risks: physical, transition and liability risk (Carney, 2015). Physical risks refer to the direct or indirect effects of extreme weather events and long-term changes in climate patterns, such as rising sea levels or more frequent wildfires, which could negatively affect business and, through them, insurance companies and the banking system (Batten, 2018b; Hubert, Evain, & Nicol, 2018). The scale of physical damage could leave balance sheets impaired (Griffin, Lont, & Lubberink, 2019) and significantly impact vulnerable regions of the world. Transition risks refer to the implications associated with a far reaching and potentially disruptive transformation towards a low-carbon economy, that could induce a sudden reassessment of the value of financial assets as opportunities and costs associated with such climate-related risks become apparent (PRA, 2019).

Such a structural transformation, induced through stringent climate change policies, changes in consumer and market sentiment, as well as innovations in technology (Way, Ives, Mealy, & Farmer, 2021), could result in the stranding of natural, physical and financial assets (see, for example, (Caldecott, Dericks, Bouveret, & Schumacher, 2018; Pfeiffer, Hepburn, Vogt-Schilb, & Caldecott, 2018; van der Ploeg & Rezai, 2020)). The literature has primarily focused on two concepts related to stranded assets: unburnable carbon and the carbon bubble (Caldecott, Clark, Koskelo, Mulholland, & Hickey, 2021). Unburnable carbon is a risk driver of stranded assets and refers to the global fossil fuel reserves and the associated extraction infrastructure that are incompatible with a carbon budget and hence would 'prior to the end of their economic life, no longer be able to earn an economic return' (IEA, 2019). The carbon bubble refers to a potential systematic overvaluation of fossil fuels assets that could trigger a sudden repricing event on financial markets with implications for global financial stability (Caldecott, 2018). Further, as Caldecott et al. (2021) argue, stranded assets can also be caused by biodiversity loss, physical climate impacts and litigation related to environmental factors, as well as further amplified by financial institutions' capital allocation decisions. Therefore, stranded assets and wider risk drivers are of increasing concern for FIs and CB&S (Bolton, Despres, Pereira da Silva, Samama, & Svartzman, 2020). Finally, liability risks refer to the financial losses that could be incurred because of legal actions against firms and regulators for their inaction to tackle climate change. The liability risk is often seen as a part of transition risks (NGFS, 2019a).

Overall, there is a growing body of literature on how preventing global warming in an abrupt and disorderly fashion might have unintended consequences on the stability of the financial system. This has become increasingly influential in shaping policy and investment decisions. The ability of such research, and its underlying models, to produce reliable estimates on the impact of transition risks on FIs' resilience and the wider system is however hampered by the complex nature, challenges, and uncertainty around climate-related risks. These characteristics are now explained in more detail.

First, the complexity around the impact of climate change on the economy and the financial system is unprecedented. Associated climate impacts could include a massive extinction of wildlife, sharp increases in human migration, conflicts, poverty, and inequality (IPCC, 2018; IPCC, 2023; Ripple, Wolf, Newsome, Barnard, & Moomaw, 2020). Consequently, the many complex modelling exercises into the impacts of climate change are characterised by opaque assumptions that may not incorporate a full understanding of such climate-economy dynamics (J. D. Farmer, Kleinnijenhuis, & Wetzer, 2021; Rising, Dietz, Stoerk, & Wagner, 2020). Further, compounding effects between the climate and the economic system could generate fundamentally unpredictable geopolitical, economic and social dynamics that cannot be captured in current modelling approaches (Fiedler et al., 2021; Ranger, Mahul, & Monasterolo, 2021a), but have large macroeconomic impacts, possibly leading to systemic disruptions sometimes referred to as a 'Green Swan' (Bolton, Despres, Pereira da Silva, Samama, & Svartzman, 2020). For instance, current modelling approaches do not capture the interacting effects between physical and transition risk (Semieniuk, Campiglio, Mercure, Volz, & Edwards, 2021), even though there are clear climate-related risk trade-offs that are crucial to inform policymakers; for example, ambitious climate mitigation measures may reduce physical risk in the long term but may exacerbate transition risks in the short term. Further, as Almeida, Colesanti Senni, and Dunz (2023) highlight, existing scenario analysis and model approaches used by CB&S and FIs do not sufficiently incorporate broader environmental risks, such as nature-related risks, in part due to methodological challenges around modelling nature-economy interactions with financial sector dependence. More broadly, IAMs remain limited in their capacity to incorporate complexities in relation to non-linearity, tipping points, and uncertainty (Brock & Hansen, 2017; Stern & Valero, 2021). In such models, rational expectation assumptions lead to individual components of the system being optimised. However, real behavior is different, as participants have limited knowledge to make appropriate choices. For instance, reflecting the behavior of fossil-fuel dependent states in supporting international climate negotiations and carbon tax policies remains irrational, with many geopolitical factors around comparative advantages driving decisions (Mercure et al., 2021). What is more, to date, most IAMs neglect financial market complexities, such as higher-order impacts and second-round losses (Stolbova, Monasterolo, & Battiston, 2018). While some research exists around the potential amplification effect of initial shocks on financial markets (J. D. Farmer, Kleinnijenhuis, Nahai-Williamson, & Wetzer, 2020a;

Roncoroni, Battiston, Escobar Farfàn, & Martinez Jaramillo, 2021), these approaches are not yet integrated into regulatory and supervisory exercises.

Second, the fundamental uncertainty resulting from such complexity is overburdening current economic modelling practices and financial risk management. Many of the factors underlying the potential economic impacts of climate change are deeply uncertain, such as future socioeconomic conditions, the climate system's reaction to increasing greenhouse gas emissions, climate damages and other endogenous and exogenous factors (Lemoine, 2021; Rising et al., 2020). For instance, modelling the relationship between greenhouse gas emissions and changes in weather patterns is subject to high scientific uncertainty. Especially isolating such effects from natural climate variability is increasingly difficult on a granular spatial dimension necessary to estimate physical damages (Fiedler et al., 2021; Hawkins & Sutton, 2011). This deep structural uncertainty has been studied extensively in the environmental economics literature (for instance, see Cai and Lontzek (2019); Hassler, Krusell, and Olovsson (2018); Pindyck (2007); Weitzman (2011)), but has yet to be sufficiently assessed in the branch of research concerned with climate-induced financial instability. In the light of the unprecedented challenges of climate change and the net-zero transition, a more precautionary principle approach by governments and central banks may be required (Chenet et al., 2019; Cullen, 2018).

Third, climate change and its mitigation require a structural transformation of the economic system, which will involve irreversible and chronic changes to our economic and societal structures over a long-time horizon (Bolton, Despres, Pereira da Silva, Samama, & Svartzman, 2020). Such chronic and irreversible changes may represent an incremental worsening and build-up of risk. Current risk modelling practices (e.g., stress-testing, or assessment of cyclical financial and economic shocks) have been focusing on modelling an exogenous shock that is limited in its temporal space, with the economic system recovering from such a shock and bouncing back to an equilibrium (Mercure et al., 2019). In contrast, climate change and the transition can be more seen as an accumulation of shocks over a significant long-time horizon, and hence the manifestation of financial and economic losses resulting from such chronic changes may be misrepresented in either general equilibrium models or similar modelling approaches (Monasterolo, Nieto, & Schets, 2022; Stern & Valero, 2021). Further, when mitigation progress and policy action are not sufficiently considered in climate scenario risk analysis, this may further result in the underestimation of the systemic risk build-up (Behnam & Litterman, 2020), besides the underestimation of idiosyncratic risk for financial institutions. For instance, when firms collectively fail to transition their business strategy due to overly optimistic expectations on policy action, a steeper investment is needed in the future to adjust in a shorter timeframe to remain within a prescribed carbon budget. This will result in a systemic risk-build up, with more economic and financial costs, again increasing the severity and volatility of transition impacts even in central scenarios (Baer, Kastl, Kleinnijenhuis, Thomae, & Caldecott, 2021; Way, Ives,

Mealy, & Farmer, 2022).

Fourth, the fragmented landscape of various fields of expertise, including climate science, geography, financial and economic modelling, and complexity theory, among the issues described above, has so far limited institutions and the academic community from analysing the impact of climate-related risks to individual FIs and the financial system in a consistent and robust manner. A lack of effective communication among these research fields has further complicated the development of harmonized models and scenarios that allow to advance the systematic understanding in this field (Fiedler et al., 2021).

With a focus on transition risks, such wider challenges make it increasingly difficult for CB&S as well as FIs to use the classical analytical tools at their disposal to justify intervention and regulation because such tools are inappropriate to deal with: (i) the unprecedentedness of the transition; and (ii) its endogeneity (see also Battiston and Monasterolo (2021); Monasterolo et al. (2022)). Traditional financial risk management, and in particular stress tests, are usually backward-looking in the form of designing tail-risk scenarios based on historical volatilities of macroeconomic and financial market data. Here, a "stress" situation is created as an exogenous shock to the system with a given likelihood of occurrence to test the resilience of FIs and to determine capital requirements (BIS, 2009). These are backward-looking risk assessments that pose unrealistic assumptions on a highly non-linear problem with a non-stationary distribution (Bolton, Despres, Pereira da Silva, Samama, & Svartzman, 2020). In other words, financial projections of future risk that are inferred from historical volatilities cannot fully capture unprecedented climate risks and the associated transition. Further, risks are not exogenous shocks but endogenous dynamics of the wider economic and financial system shifting to a new state, including a potential build-up of financial fragility (Galí, 2018), especially when investors and policymakers take sub-optimal decisions at the individual and collective level. Further, endogenous market behavior based on misaligned expectations and the endogeneity of money and investment decisions that influence the speed of the transition are hard to capture and may be overlooked by FIs or not yet appropriately priced in (Battiston, Monasterolo, Riahi, & Van Ruijven, 2021; Bolton & Kacperczyk, 2021a; Eren, Merten, & Verhoeven, 2022). Endogeneity also means increased complexity as highlighted above, where current models cannot adequately depict potential disruptions, financial complexity, and feedbacks from the financial system to the real economy.

Overall, such limitations and peculiarities characterize the market failure of the financial system that potentially leads to a systematic underpricing of the risks and opportunities associated with the transition. The novelty of the challenge ahead also means that there is an absence of harmonized data, frameworks, and analytical tools that can produce reliable risk evidence. On the other hand, the climate science is unequally clear of the catastrophic impacts if

unprecedented structural changes and climate mitigation is not happening immediately (IPCC, 2023; Kemp et al., 2022; Rockström et al., 2009).

Translating such risks and opportunities into tangible action, strategies, and risk management has therefore been challenging. For some time, inaction by individual actors was however not associated with material idiosyncratic risk but rather with the risk build-up of the larger economic and financial system. Consequently, FIs had little incentive, beyond reputational risk, to scale up capabilities and act upon such risks through the creation of better frameworks and models. Yet, in recent years, regulatory pressure has scaled up with CB&S prominently entering the sphere of sustainability (Lagarde, 2021; NGFS, 2019a; PRA, 2019).

Moreover, the latest research shows that the economic system may be experiencing a tipping point, where cost-competitiveness and innovation of key sustainable technologies in the energy system, irrespective of supporting policies and individual behavior of market participants, is driving decarbonization. This narrative change is shown in Way et al. (2022) who find that the transition is not only economically feasible but also cost-effective and driven by technological innovation which is likely to save trillions of USD. Similarly, Adrian, Bolton, and Kleinnijenhuis (2022) show that the benefits of a global coal-phase out significantly outweigh the economic costs, even in a conservative scenario. This highlights that the transition is progressing through market-driven approaches confronting FIs with the necessity to adapt to the transition and manage transition risk more effectively, independently of political action. Such developments may start to turn a perceived first mover disadvantage into a first mover advantage.

CB&S and FIs have increasingly recognized this, racing to build out capabilities to act upon such transition dynamics. For this, two dimensions are of increasing importance. First, the challenge to overcome technical difficulties to equip FIs with tools that adequately capture the above-discussed characteristics of climate change and the transition to provide empirical evidence that can effectively guide and justify decision-making. Second, from the policy and regulation perspective, CB&S need to navigate their legal mandates and institutional settings to set up the appropriate rules for the financial system to support the transition while safeguarding financial stability. Broadly these are the political economy considerations that constrain financial policy and regulation that aim to support the transition (Svartzman, Bolton, Despres, Pereira Da Silva, & Samama, 2020). Coordination between governments and regulators is needed, without overstepping institutional responsibilities.

The literature underlying these two dimensions is now discussed in even more detail to give additional background and context for the DPhil research that aims to contribute to a better understanding of both, the political economy and climate finance field, with the development of analytical frameworks, empirical tools, and qualitative insights.

2.2 Climate scenario analysis and the role of central banks and supervisors

In the light of the general complexities and uncertainty, the forward-looking and the endogenous nature of the climate-related transition risks, emerging consensus and also a key recommendation from the Task Force on Climate-Related Financial Disclosures (TCFD), have identified scenario analysis as a critical tool to overcome some of these challenges (BIS, 2020; Semieniuk et al., 2021; TCFD, 2017a). Scenario analysis allows to effectively assess the vulnerability of financial institutions to physical and transition risks over a longer time horizon. Here, plausible hypotheses for the future are set up to examine the effects of a wide range of plausible scenarios (BIS, 2021a).

Scenarios for such exercises have been provided by organisations such as the International Energy Agency (IEA), the NGFS or the IPCC but were initially designed to inform government policy, as these transition scenarios show the cost-optimal mitigation pathways across different degrees and timings of policy action (IPCC, 2023; Monasterolo et al., 2022). As such, they are suitable to reflect the transformation of the economy and can therefore inform more systemic policy decisions (Koberle, Ganguly, & Ostrovnaya, 2021a). For instance, informing the aggregate investment required in low-carbon technologies to transform the energy system in line with temperature goals set out in Paris Agreement. To be effective, scenario users must be able to anticipate future narratives and the range of potential outcomes that could occur given economic-socio-climatic relationships and the likely policy actions that are undertaken.

In the risk context, a particular subset of scenario analysis is of great interest - climate stress testing – which aims to assess the effects of more severe but plausible scenarios (e.g., tail risks) on financial institutions or the system. However, such risk-focused exercises are fundamentally different than those of policy makers (Koberle et al., 2021a). If undertaken appropriately, such approaches can assist in quantifying tail risks (Weitzman, 2009) and can clarify the uncertainties inherent to climate-related risks by representing more of a what-if scenario approach that can derive meaningful upper-bound climate risk estimates under worst case hypothesis, rather than aiming to model and predict anticipated climate risk impacts per se (Hayne, Ralite, Thomae, & Koopman, 2019). It can also be adjusted to capture the longer time-horizon, where standard backward-looking modelling approaches would lead to no meaningful result due to large error margins in the predictive power of models. Generally, climate stress tests can be applied for at least two objectives according to BIS (2021b): (i) help financial institutions integrate climate-related risks into their strategic and operational procedures (e.g., for the purpose of asset allocation); and (ii) allow central banks and financial supervisors to assess the vulnerability of specific institutions or the stability of the financial system. It therefore supports the dual role of the financial system and can be seen as a key tool in the fight against climate change for the financial system. Notably, such exercises are increasingly informing climate-related prudential policies (ESRB, 2020), counterparty-level risk management and business planning decisions.

CB&S, mainly through exploratory exercises, contribution to international fora such as the NGFS and through setting up dedicated climate hubs, have prominently focused on the development of such climate stress tests, with the aim to build out capabilities and ensure the resilience of the financial system (NGFS, 2019a). However, such an elevated role was met with criticism on whether CB&S should concern themselves with climate risks (see for instance Cochrane (2020)). This has raised questions over the purpose of banking and financial regulation and the extent to which such tools should be used without overstepping legal mandates and institutional responsibility. Especially governments and CB&S have had debates over which actors, tools and policy should be employed to fulfill the objectives of the Paris Agreement.

For instance, In 2017, the EU commission expressed support for the idea of introducing a 'green supporting factor' in bank capital requirements - a buffer against shocks that require banks to hold liquid assets to avoid going bankrupt (Fraisse, Lé, & Thesmar, 2017) - to incentivize lending to European sustainable activities (Dombrovskis, 2017). Such prudential measures would allow banks that are lending to green activities to obtain higher profits. The following year, the European Commission included this idea in its sustainable finance action plan (EC, 2018). However, this position was generally greeted with scepticism by most central bankers and financial supervisors themselves, who emphasized that the aim of prudential rules such as bank capital ratios is to mitigate financial risk, not to steer private credit in any particular direction (Dankert, Doorn, Reinders, & Sleijpen, 2018b; Elderson & Breeden, n.d.; Rehn, 2018). The same holds true for other financial policies that CB&S have at their disposal, such as capital charges for global systemically important banks (G-SIBs), lending ratios, countercyclical buffers, targeted refinancing and collateral frameworks. Dikau and Volz (2020) and D'Orazio and Popoyan (2018) give a comprehensive account of the financial policy toolbox that CB&S have at their disposal, and how these could in principle be adjusted to incorporate climate considerations.

Other high-income economies exhibit similar institutional traits that financial policies should not discriminate between low- and high carbon financial assets unless clear evidence of risk differentials is available. In contrast, in several emerging economies, banking and financial regulation is instead actively used to promote specific productive sectors, including renewable energy and other sustainable sectors (Dikau & Ryan-Collins, 2017; D'orazio & Dirks, 2021; Wang, 2015; Zadek & Chenghui, 2014). Financial risk is still monitored, but stronger weight is given to how financial regulation and policies can contribute to the development objectives of governments actively intervening in markets to steer capital (Dikau & Volz, 2021b; Mazzucato, 2016).

Interestingly, the behavior of highly independent CB&S, such as the ECB, to focus solely on the risk dimension of climate change, can be assessed through a political economy lens. CB&S

have a clear mandate and input legitimacy from governments to perform a specific task that is independent of political influence and cycles (Dalla Pellegrina, Masciandaro, & Pansini, 2013; Dietsch, Claveau, & Fontan, 2018; L. M. Goodhart, 2015). As CB&S are not directly democratically legitimized, these institutions need to pay specific attention to a thorough technocratic, evidence-based decision making processes to safeguard their respective legitimacy (Schmidt, 2016). Consequently, CB&S need to carefully balance their legal mandates and consider the wider institutional context to avoid risking their legitimacy. Consequently, CB&S are guided by clear primary objectives, such as price stability and after the GFC also financial stability (Klomp & de Haan, 2009), with clear principles to adhere to. For instance, the standard approach taken by CB&S in Europe and similar jurisdictions is guided by the principle of 'market neutrality', with the intention not to distort the market-driven allocation of capital. This is a unique feature of modern central banking, not observed to the same degree in other jurisdictions globally (Fernández-Albertos, 2015).

However, to understand contemporary actions and institutional conflicts of CB&S in the climate context, the literature on the evolving institutional nature of central banking and financial regulatory architecture in the aftermath of the global financial crisis is of particular importance (Baker, 2013; Blinder, Ehrmann, de Haan, & Jansen, 2017; Calvo, Crisanto, Hohl, & Gutiérrez, 2018; de Ramon, Francis, & Harris, 2016; Fontan, 2016; Mabbett & Schelkle, 2019; Schmidt, 2016). While CB&S generally adhere to legal mandates and associated principles, these are sometimes relaxed in times of crisis, as evidenced in the aftermath of the GFC, when the policy gridlock affecting government actions, forced central banks to become the 'only game in town', subsequently leading to unprecedented monetary interventions (Mabbett & Schelkle, 2019). While these interventions were not directly in violation of CB&S mandates, it was considered to involve certain reinterpretations of the mandate, using so-called 'authorization gaps' (de Boer & van't Klooster, 2020).

There is an important consideration from this branch of literature for the context of this DPhil. CB&S cannot appear to distort markets to accelerate the transition unless clear mandate changes are given from political bodies (e.g., BoE remit change) otherwise CB&S are at risk of losing independence and credibility, which could further hamper their ability to set appropriate financial market frameworks to support the transition.

Therefore CB&S are actively pushing for better analytical tools, to identify a clear risk evidence that can support regulatory actions. It is evident, that actions such as the consideration given to the option of abandoning the market neutrality principle in asset purchase programs (ECB, 2021) or the decision by the ECB to invest a proportion of its own funds portfolio in a green bond fund established by the Bank for International Settlements (Lagarde, 2021), are justified solely on the basis of mitigating risk or by the concern that climate change might affect

price and financial stability, i.e., primary objectives. Consequently, enhancing the rigor, applicability, and usability of analytical risk-based tools, such as climate stress testing is identified as a key priority and serves at the motivation of this DPhil.

To this end, CB&S increasingly set expectations on how financial institutions and banks should scale up capabilities around analytical tools to manage climate-related risks (BoE, 2019a; ECB, 2020a) and proposed guidelines scale up internationally across supervisory institutions. Similarly, various central banks have implemented or are planning to run climate stress tests, including but not limited to the European Central Bank (ECB), the Bank of England (BoE), the Banque de France (BdF), the Federal Reserve System in the US (FED)and the Dutch central bank (DNB). The scope varies between the inclusion of asset side losses for investors, credit risk for banks' loan portfolios and risk faced by insurers. Yet, neither of those exercises have assessed higher-order and second-round financial network effects, bearing the risk of an underestimation of the systemic consequences from climate-related transition risks (J. D. Farmer et al., 2021; Roncoroni et al., 2021). Interestingly, these exercises have almost exclusively relied on climate scenarios provided by the NGFS and therefore are biased towards modelling structures of IAMs.

Generally, risk outcomes and estimates for transition risk are often relatively benign in these supervisory exercises. The BoE concludes that UK banks and insurers are likely to be able to absorb the costs of transition to net zero (BoE, 2019a). Nonetheless, the BoE highlights that further research needs to be undertaken before informing regulatory capital setting. The ECB concludes that the risk is mainly concentrated in high-carbon sectors and has a material impact on the risk profile of the Euro system balance sheet. The disorderly transition and hot house world long-term stress scenarios produce risk estimates that are between 20% and 30% higher than those under the orderly transition scenario (ECB, 2021). The BdF estimates that according to the projections of the IPCC used in their exercise, 50% of the exposures of French financial institutions are relatively less affected than other geographical areas, yet, the vulnerabilities associated with climate risks are far from negligible (APCR, 2020).

Generally, most results are not shown on a granular level and central banks leave significant discretion to the stress tested institutions to come up with an answer on how the climate is represented explicitly in market and credit risk models. Even though this undoubtedly can result in more detailed analysis, it takes away reliable comparability of results across jurisdictions and hampers overall transparency. For instance, it was shown that during the BoE exercise, financial risk outcomes estimated by banks that performed the exercise varied greatly depending on underlying IAM assumptions, scenario expansion choices and their internal modelling (Ranger, Clacher, & Bloomfield, 2023). This bears the risk of little transparency around model approaches to validate the appropriateness of underlying assumptions and leaves the academic community with the task of developing complementary climate stress testing approaches.

However, the literature remains rather scarce up to date, given the methodological challenges, resource intensity and the interdisciplinary nature of the task. A comparison of current climate stress testing efforts with a focus for practitioners has been undertaken by Baudino and Svoronos (2021), as well as reviews on the conceptual issues around scenario analysis, climate-economic models and risk management methodologies are provided by BIS (2021a), Bolton, Despres, Pereira da Silva, Samama, and Svartzman (2020), and Acharya et al. (2023). We add to such literature and outline some of the most relevant approaches, research gaps and findings to provide a basis for the contribution of this DPhil.

Most prominently Battiston, Mandel, Monasterolo, Schütze, and Visentin (2017) have developed a climate stress test to assess the exposure of European banks portfolios to climate-relevant sectors. They find that direct and indirect exposures to such sectors represent a large portion of financial actors' equity holdings portfolios. Moreover, exposures represent a portion of banks' loan portfolios comparable to banks' capital, suggesting concerns around the ability of banks to absorb large losses without inducing a liquidity crisis.

Other approaches, such as the CRISK measure by Jung, Engle, and Berner (2021a), rely on more market-based approaches that identify correlations between a stranded asset portfolio and the largest global banks' stock market valuations. They study the climate risks of large global banks in the US, UK, Canada, Japan, and France. Based on a severe yet plausible scenario in which stranded assets sharply fall in value over a short horizon, they find a substantial rise in climate betas, market and credit risk. Note that such market-based approaches are only a sufficient metric to evaluate a firm's transition risk, to the extent that transition risk is priced into financial markets today. There is ample reason to believe that this is not yet done to a full extent (FSB, 2022).

For the Dutch financial system, Vermeulen et al. (2019) disaggregate EUR 2.3 trillion in assets of more than 80 Dutch financial institutions by industry. Their findings suggest that financial losses are sizeable in severe transition scenarios, with portfolio values declining by up to 11%. The authors conclude that these outcomes suggest that climate-transition risks warrant close and timely attention from a financial stability perspective. Similarly, Reinders, Schoenmaker, and Van Dijk (2020a) develop a valuation approach at the industry-level and use a Merton contingent claims model to assess the impact of a carbon tax shock on the market value of equity and debt instruments for Dutch financial institutions. Relying on firm-level vulnerability data, they find declines in the market value of banks' assets of up to 9-32% of core capital under a severe carbon tax shock.

Roncoroni et al. (2021) is one of the few studies that looked at the second-round losses

from transition risk in a stylized financial network model to highlight the relevance of contagion effects and interbank claims for market volatility. Applying the model to supervisory exposure data for investment funds and banks, they assess the policy scenarios and market conditions under which systemic losses can pose a threat to financial stability.

In a working paper by the IMF, Grippa and Mann (2020) estimate the direct impact of a substantial increase in domestic carbon prices under severe assumptions for Norway. Their results show that such a sharp increase in carbon prices would have a significant but manageable impact on banks.

Nguyen, Diaz-Rainey, Kuruppuarachchi, McCarten, and Tan (2020) analyse transition risk in U.S. loan portfolios, drawing upon the Merton credit risk framework. They find that under stressed conditions, the median loss is 0.5% of US syndicated loans, representing a decrease in CET1 capital of 4.1% but this may grow twice as large in the 1.5°C scenarios compared to the 2°C target with significant tail-end risk (7.7% of loan value, 62% of CET1 capital).

While such developments of climate stress testing approaches from academics are promising, we identify two important technical limitations of the status quo literature. First, most of the available approaches are insufficiently forward-looking as they use as proxy for transition risk the historical and current carbon intensity of firms or sectors. This is insufficient partly because there are systematic gaps and biases in firms' reporting of emissions, as well as differences in the degree to which firms are likely to absorb any increase in their cost of carbon taxes on to their customers. Further, current emission intensities cannot reflect the strategic plans of firms to transition across their operations and to innovate. Second, most approaches are insufficiently granular and cannot differentiate transition risk at the level of the counterparty or at the physical production asset, relevant for financial sector use cases such as risk management (for a more detailed discussion on these technical limitations and how Paper II of the DPhil aims to overcome these see the contribution section 6).

Overall, none of the identified approaches in this review, and to the best of the authors' knowledge, overcomes both limitations in one consistent approach. For instance, climate stress tests that have employed an industry level-approach or top down-macroeconomic approach, insufficiently capture within sector variation (Battiston et al., 2017; Vermeulen et al., 2019). Other climate stress testing approaches, including regulatory exercises, have been employed on a granular level, but these approaches are not reflecting the forward-looking transition strategies of firms (Bank of England, 2021; ECB, 2022; Grippa & Mann, 2020; Jung, Engle, & Berner, 2021b; Reinders, Schoenmaker, & Van Dijk, 2020b). A notable exception is the finance approach by Cormack, Donovan, Koberle, and Ostrovnaya (2020), which incorporates the strategic direction of firms and represents credit and market risk at the level of financial counterparties.

Additionally, most climate stress tests do not explicitly feature transition risk drivers, beyond policy-driven effects, such as demand-driven effects and technological change, known to be an important driver of risk.

Note that beyond the set of highlighted limitations, climate stress tests also inhibit a lack of transparency around key assumptions (mostly in regulatory exercises), insufficient reflection of multiple heterogeneous scenarios and sensitivities and the insufficient reflection of wider complexities and systemic risks, including compounding risks which has been touched upon in this section and is aligned with findings of reviews such as Acharya et al. (2023). The flexible climate stress testing approach - TRISK - put forward in Paper II of this DPhil aims to provide a flexible framework that allows to test the resilience of firms and FIs to a large set of different scenario narratives and assumption variations to better reflect inherent uncertainty.

Summary. The literature review was structured to contextualize the DPhil research. First, it was shown that climate change and the net-zero transition exhibit special characteristics such as the complexity, chronic changes or fundamental uncertainty that require interdisciplinary attention. These characteristics also mean that classical financial risk tools are not fit for purpose for the climate context - especially because these characteristics entail that transition risk is unprecedented and endogenous - both of which current models cannot adequately reflect. This presents the rationale for developing climate scenario analysis, as its design specifically addresses the peculiarities of the climate and transition context. We then discussed how CB&S entered the climate sphere, with increasing capabilities pushing for the development of such tools while carefully managing and balancing institutional responsibilities. We then show that the development of climate stress testing approaches is still in its infancy, which is why currently available approaches still face limitations that may underestimate the risk associated with a disorderly transition. This highlights the relevance to overcome such limitations to make analytical tools more decision relevant to financial institutions and to be able to seize transition-related financial risk more accurately.

3 Paper I: It takes two to dance: Institutional dynamics and climate-related financial regulation

An earlier version of this paper "It takes two to dance: Institutional dynamics and climate-related financial policy"[3] is joint work with Emanuele Campiglio and Jerome Deyris. The paper was published in the Journal Ecological Economics in December 2021.

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Abstract

This article studies how institutional dynamics might affect and be affected by the implementation of climate-related financial regulation. First, we propose a three-dimensional framework to distinguish: i) objectives for policy implementation (prudential or promotional); ii) policy instruments (informational, governance-based, incentive-based or quantity-based); and iii) implementing authorities (political or delegated). Second, we use this framework to show how sustainable financial interventions in certain jurisdictions - most notably, Europe - rely predominantly on a restrictive set of informational policy and recently also governance-based instruments to achieve both promotional and prudential objectives. Policymakers in other jurisdictions also employ incentive- or quantity-based instruments to achieve promotional objectives. Third, we identify two main institutional explanations for this European 'promotional gap': i) a reduced intervention of political authorities on the allocation of financial resources; and ii) a stronger independence of technical delegated authorities supervising financial dynamics. This governance configuration leads to an institutional deadlock in which only measures fitting with both political and delegated authorities' objectives can be implemented. Finally, we identify and discuss the possible institutional scenarios that could originate from the current setting, and stress the need for close cooperation between political and delegated authorities.

3.1 Introduction

In 2017, the EU Commissioner Valdis Dombrovskis expressed his support of the idea of introducing a 'green supporting factor' in bank capital requirements - the amount of capital commercial banks are required to hold as a proportion of their risk-weighted assets - to incentivise lending to European sustainable activities (Dombrovskis, 2017). In principle, such a measure would allow banks lending to green activities to obtain higher profits. The following year, the European Commission included this idea in its Sustainable Finance Action Plan (EC, 2018). However, this position was greeted with scepticism by most central bankers and financial supervisors, who emphasised that the aim of prudential rules such as bank capital ratios is to mitigate financial risk, not to steer private credit in any particular direction (see, among others Dankert, Doorn, Reinders, and Sleijpen (2018a); Elderson (2018); Rehn (2018)). Financial policies should not discriminate between low- and high-carbon financial assets, unless clear evidence of risk differentials is available. In a similar vein, central banks in recent decades have aimed at intervening in financial markets in a 'neutral' manner. For instance, their 'quantitative easing' programmes of financial asset purchases have been designed in a way not to distort the market, without taking into account the carbon intensity or sustainability credentials of the underlying issuers. This notion has been recently called into question by central bankers themselves, as conducive to a perpetuation of an unsustainable economy (Schnabel, 2020). Others have explicitly looked into available options to 'green' monetary policy (Schoenmaker, 2021; **?**).

These debates raise deeper questions. For what purposes should monetary policy and financial regulation be used? Could they be employed to support the low-carbon transition? And who should decide what the admissible purposes are? It appears that in the European Union, at least for now, financial regulation and monetary policy cannot be employed to actively reallocate private financial resources towards sustainable investments in the absence of clear risk differentials - thus for pure political development reasons. However, it is considered appropriate to use them to nudge financial institution into assessing their exposure to climate-related risks and disclosing results to the rest of the market (NGFS, 2019b; TCFD, 2017b). Other high-income western economies (other European countries, US, Australia) exhibit similar institutional traits. In several emerging economies financial regulation and central banking policies are instead actively used to promote specific productive sectors, including renewable energy and other sustainable activities (D'Orazio & Popoyan, 2019). Financial risk is still monitored, but stronger weight is given to development (e.g. green) objectives.

The first objective of this article is thus to explain the observed heterogeneity in institutional behaviours in the field of climate-related financial regulation[4]. To do so, we first develop

[4]In this article, by financial regulation, we mean policies that modify the conditions in which private investment or lending decisions are taken. Climate-related financial regulation refer to a subset of such policies linked to either climate change or the transition to a carbon-free society. We here focus on policies aimed at domestic/regional

a three-dimensional framework to distinguish: i) public objectives for policy implementation; ii) policy instruments; and iii) implementing authorities. Policy objectives include the aim to tackle climate change by directly influencing the allocation of financial capital (promotional) and the desire to ensure the stability of the financial system in the face of climate-related challenges (prudential). Policy instruments can be categorised into tools aimed at expanding the climate-related information available to market actors (informational), policies and supervisory expectations aimed to enhance market discipline through governance changes (governance-based), introducing monetary incentives to make low-carbon strategies more convenient (incentive-based) and direct controls on credit allocation (quantity-based). Implementing authorities can be distinguished between governments and other public institutions charged with defining societal development strategies (political) and public institutions with narrow technical mandates delegated to them by political authorities (delegated).

Our taxonomy builds upon and improves previous categorisations (e.g., Mazzucato (2016), and offers a consistent conceptual framework to study, interpret and compare the mechanisms and rationales behind ongoing policy and regulatory efforts. We then apply this framework to climate-related financial policies in Europe. We show that regulatory initiatives are mostly – if not exclusively – based on informational and governance-based measures, to achieve both prudential and promotional purposes. Such a focus on enhancing transparency meets less resistance given the independence and narrow mandates of delegated authorities in the EU. More market distorting incentive- and quantity-based policies with promotional purposes, which represent a more direct intervention in the financial markets, are absent. We term this restricted usage of climate-related financial regulation for promotional purposes in Europe a 'promotional gap' or gridlock. We explain this with two main institutional dynamics. First, European political authorities have progressively reduced their intervention in capital allocation, leaving more room for market mechanisms. Second, the supervision of these markets has been increasingly entrusted to delegated authorities with narrow technical mandates and strong independence from political pressures. The specific configurations these dimensions take in Europe have so far only allowed for the implementation of consensual regulation and prevented the implementation of far-reaching policies with an inherently more promotional objective. We argue that the more interventionist the policy or regulation, the more the publicly stated objective needs to be of prudential nature and less focus can be on the promotional objective, otherwise, delegated authorities risk loosing legitimacy.

Our second objective is to explore the possible institutional evolution of the current promotional gridlock in Europe. We identify three main stylised scenarios. First, political authorities can step up their efforts to mitigate climate change and support the net-zero transition, allowing

financial systems. We thus abstract from the debate related to international concessional climate finance between high- and low-income regions. In this paper we sometimes use the terms intervention, policy and regulation interchangeably.

delegated authorities to stick to their prudential role and avoid more interventionist regulation in the absence of clear risk justification. While this would respect current institutional boundaries, mandates, and missions, it requires significant action by political authorities in the fiscal and budgetary sphere. Second, as climate pressures intensify, delegated authorities can gradually move towards more interventionist and promotional measures without an underlying adjustment of their mandate. We observe signs of a similar promotional trend in recent documents and speeches by European financial regulators as evidenced by the ECB action plan that considers more interventionist measures such as differentiated eligibility criteria for their purchasing programme to boost climate disclosures[5]. If brought to its extreme, such a drift might eventually lead to a technocratic scenario characterised by an agency defining development objectives with weakened political control. Third, political authorities can decide to regain control of certain policy functions (e.g. banking regulation) and use them to achieve their development objectives (e.g. a low-carbon transition). This might improve the effectiveness of climate financial action, but it also raises concerns regarding the credibility of delegated authorities. Political authorities could instead preserve the independence of delegated authorities by adjusting their mandates (e.g., UK Treasury remit change for Bank of England[6], to give them new input legitimacy and define clear limits to their promotional actions).

Our work contributes to two main strands of literature. First, we provide more solid institutional and governance foundations to the ongoing debate concerning the role of central banks and financial supervisors (CB&S) in addressing climate change and the low-carbon transition (Bolton, Despres, Pereira da Silva, Svartzman, & Samama, 2020; Campiglio et al., 2018; Krogstrup & Oman, 2019; NGFS, 2019a). Second, we contribute to the literature on the evolving institutional nature of central banking and financial regulation in the aftermath of the global financial crisis (Baker, 2013; Fontan, 2016; Mabbett & Schelkle, 2019; Schmidt, 2016), by applying its concepts to the issue of climate change and environmental sustainability.

The research design of this article follows a two-stage approach. First, we develop a conceptual framework to categorise climate-related financial policies, drawing upon primary and secondary data inputs. We critically review the evolving literature around the interactions of climate risks, financial regulation, central banks and supervisors, and improve on it by developing a harmonised and consistent framework. Second, we apply this framework to selected jurisdictions with the aim of comparing the European approach to climate-related financial policy-making to other regions. For this, we analyse official documents, directives, reports, conference interventions and relevant speeches by policymakers, and we engage with relevant experts and stakeholders.

[5] https://www.ecb.europa.eu/press/pr/date/2021/html/ecb.pr210708_1_annex~f84ab35968.en.pdf

[6] https://www.bankofengland.co.uk/-/media/boe/files/letter/2022/november/2022-mpc-remit-letter.pdf

The remainder of the article is structured as follows. Section 3.2 presents our three-dimensional framework to categorise climate-related financial interventions. Section 3.3 examines existing approaches to climate-related financial policy-making and identifies a 'promotional gap' in Europe. Section 3.4 argues that two institutional features, namely a weaker control on financial dynamics and delegated authorities' stronger independence, can contribute to explaining the European setting. Section 3.5 examines the resulting policy gridlock and discusses how this prevents the implementation of more ambitious interventionist and promotional regulatory initiatives. Section 3.6 explores possible institutional scenarios stemming from the present situation. Section 3.7 concludes.

3.2 Setting the scene: objectives, instruments and players

In this section, we present our framework. This allows us to classify climate-related financial regulation along three dimensions: public objectives, instrument and implementing authority. Table 1 proposes a summary of our framework.

3.2.1 Promotional and prudential objectives

We identify two main objectives behind the implementation of climate-related financial regulation, based on which these are publicly justified.

First, interventions could be motivated by the desire of tackling climate change by directly influencing the allocation of financial capital to actively support the transition. This is what we define as the promotional objective. One of the objectives stated in the Paris Agreement is to 'make finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development' (UNFCCC, 2016). Climate-related promotional financial regulation can stimulate physical and financial investments in sustainable activities. They are therefore based on a 'market shaping' approach (Mazzucato, 2016) and usually respond to development strategies defined by political authorities.

Second, regulatory initiatives could be motivated by the desire to ensure the stability of the financial system in the face of climate-related risks. This is what we define as the prudential objective. Several climate-related risks (CRRs) could threaten financial systems and require the implementation of prudentially motivated policies. Since Carney (2015), the literature traditionally distinguishes three categories of risks: i) direct and indirect effects of climate-induced events and trends (physical risks); ii) implications of shifting towards a low-carbon economy (transition risks); and iii) losses incurred as a result of legal actions against companies and regulators for their inaction to tackle climate change (liability risks). CRRs could trigger ripple effects via production and financial networks (Baer et al., 2021; Cahen-Fourot, Campiglio, Godin, Kemp-Benedict, & Trsek, 2021; Roncoroni et al., 2021) and have larger macroeconomic impacts, possibly leading to systemic disruptions sometimes referred to as a 'Green Swan' (Bolton, Despres, Pereira da Silva, Samama, & Svartzman, 2020). Acknowledging this, prudential policies are aimed at identifying, monitoring and mitigating these risks to ensure the soundness of individual supervised financial institutions and wider financial stability.

Table 1: A taxonomy of climate-related financial regulatory initiatives

Policy Objectives	
Promotional	Mitigate climate change by steering credit allocation towards low-carbon activites
Prudential	Mitigate climate financial risks and ensure the stability of the financial system
Policy instruments (ranging from low to high-level of market intervention)	
Informational	Improve climate-related information available to financial actors and provide them with clear definitions, rules and instruments
Governance-based	Issue supervisory expectations and mandate changes with respect to the governance structure of financial institutions to enhance market integrity and strengthen climate awareness
Incentive-based	Introduce (monetary) incentives to make low-carbon strategies more attractive to financial actors
Quantity-based	Impose direct quantitative controls on financial flows
Implementing Authority	
Political	Authorities in charge of defining and pursuing development strategies (e.g. governments)
Delegated	Institutions with specific mandates delegated to them by political authorities (e.g. central banks and financial supervisors)

To sum up, promotional policies are mainly aimed at protecting climate stability from finance-related challenges (e.g., obstacles to low-carbon investing). Prudential policies are instead aimed at protecting financial stability from climate-related risks. The boundary between these two types of objectives is often porous. It is reasonable to expect prudential policies to have some kind of promotional consequence. Likewise, promotional policies will probably have some impact on individual and aggregate levels of financial risks. It is also possible to argue for actively steering credit towards low-carbon activities precisely to mitigate climate physical risks. The taxonomy however aims to reflect on which bases the regulation or policy has been justified publicly and to which extent the regulation may inhibit a secondary or higher-order objectives besides the public primary objective. This is important when we apply the taxonomy to the operational space of central banks and supervisors that have clear mandate boundaries. As we discuss in the next section, the objective becomes increasingly relevant depending on the type of regulation and to which degree it distorts and intervenes in the market.

3.2.2 Informational, governance-, incentive- and quantity-based regulation

Importantly, available instruments have varying levels of how much these intervene in private markets. The more "interventionist" such policies are, the greater the ability to directly influence market participants, but also the greater the public restriction. We classify four sets of policy instruments ranging from low levels of intervention (informational) to medium levels (governance- and incentive-based measures) to high-levels (quantity-based measures).

First, regulators can act to improve the quantity and quality of climate-related information available to financial market players and to provide them with a clear shared set of definitions, rules and instruments. We call these informational policies, as their goal is to bridge the market failures stemming from imperfect and asymmetric information. The informational policy toolkit includes the development of better methodologies to assess the exposure to CRRs, the introduction of disclosure incentives or requirements, the setting of standards and benchmarks, the creation of taxonomies, and others. The latest example of such informational policies is the Green Asset Ratio (GAR) that is mandated for banks to disclose under the EU Taxonomy Disclosures Delegated Act. The GAR refers to the proportion of a credit institution's assets that finance and are invested in EU Taxonomy-aligned economic activities as a proportion of the total covered assets[7]. Similarily, delegated authorities can enhance the information communicated to agents (e.g., awareness campaigns on carbon emissions, EU taxonomy). Such policies can be implemented for both prudential and promotional objectives (dual role) and only indirectly intervene in the market by shaping market expectations. The level of intervention and direct market distortion is therefore low and the focus is on enhancing information available to the market.

Second, policy makers can issue supervisory expectations, standards and initiatives with respect to the governance structure of financial institutions to enhance market integrity. These can range from voluntary proposals to regulations that actively mandate firms to change internal governance or risk management structures. For instance, as part of the SS3/19 supervisory statement of the Prudential Regulation Authority in the UK, banks and insurers are mandated to assign risk responsibilities to senior staff member to increase accountability (PRA, 2019). Such policies inhibit a medium level of direct intervention with minimal unintended consequences. Regulators are increasingly making use of such market disciplining standards with the goal to foster market integrity across actors and to build out and enhance climate-related awareness and capabilities.

Third, policy makers can modify the structure of incentives (e.g., the relative prices) that financial actors face when making investment decisions. We refer to these as incentive-based

[7] https://finance.ec.europa.eu/regulation-and-supervision/financial-services-legislation/implementing-and-delegated-acts/taxonomy-regulation$_en$

policies, as the allocation of capital remains a market prerogative and investors are free to invest in high-carbon or risky assets, although at a cost. Several policies in the financial regulation toolkits (e.g., capital requirements) can be calibrated so to differentiate the treatment of assets depending on the CRR exposure of bank loan portfolios (D'Orazio & Popoyan, 2019). Monetary policy tools can also be adjusted by including CRRs in the evaluation of asset eligibility as part of collateral frameworks or asset purchase programs (Oustry, Bunyamin, Romain, & Pierre-François, 2020). For instance, the ECB has recently announced in its action plan to couple eligibility criteria for the purchasing programme with climate-related disclosure, incentivising financial institutions to disclose relevant information. Such policies can be implemented either to encourage investors to reduce their exposures to CRR risks (prudential objective) or to increase sustainable investments (promotional objective), depending on the primary and secondary motive of the implementing institution. Similarily, political authorities can modify the incentives structure in which they make their decisions (e.g., fiscal policy with carbon taxes). Such policies inhibit a medium level of intervention and implementing institutions need to be aware of potential market distortions and unintended consequences.

Finally, public institutions and regulators can intervene directly on the quantity of financial resources allocated to specific productive activities. We call these quantity-based policies, as these policies impose direct quantitative controls on financial flows rather than adjusting the market environment in which individual decisions are made. These include for example policies targeting directly the composition of bank loan portfolios, such as sectoral credit quotas, minimum credit floors or maximum credit ceilings for certain sectors (Bezemer, Ryan-Collins, van Lerven, & Zhang, 2018). The aim of these policies is usually seen as predominantly promotional. However, they could also be used for a prudential objective (e.g., lowering exposure of banks to industries prone to transition risk by imposing maximum credit ceiling on coal financing).

These policy instruments form a gradient of public interventions ranging from the most diverted to the most direct ways of intervening in markets. These four shades of intervention can be used in conjunction with each other, offering policymakers a set of measures to be implemented in the financial sphere, whether for prudential or promotional reasons.

3.2.3 Political and delegated authorities

Policy objectives (promotional or prudential) as well as the instruments to achieve them (informational, governance-, incentive- and quantity-based measures) can be implemented by different authorities. We distinguish two main types of public institutions that can be involved in the design and implementation of climate-related financial regulatory initiatives. First, we identify political authorities (PAs) as the public organisms in charge of determining the direction of economic development on behalf of their populations, deciding between competing interests. They include parliaments, governments, ministries and other public institutions able to contribute to the definition of development strategies. All of them enjoy some form of legitimacy, at least temporarily (Schmidt, 2016; Schmidt & Wood, 2019). PAs are typically in charge of designing and implementing policies with a promotional aim, as these often have distributional and other socio-economic implications. Depending on the underlying governance framework, they might also be more or less involved in designing prudential policies (D'Orazio & Popoyan, 2020). Second, we identify delegated authorities (DAs) as autonomous or semi-autonomous organisms with specific mandates given to them by the PAs. Their legitimacy thus lies in the nature and limits of the delegation and specified mandate (input legitimacy) and in their ability to fulfil their mission (output legitimacy) (Scharpf, 1999). Two main DA categories interacting with financial systems can be identified: central banks and financial supervisors. Central banks are typically tasked with the mandate of achieving price stability, but their mandate can also include full employment, exchange rate management and others (Dikau & Volz, 2021a). In the aftermath of the global financial crisis (GFC) several central banks have also become responsible of ensuring the financial stability of the system. Financial supervisors are delegated authorities with diverse mandates and shapes across countries, tasked with protecting consumers, ensuring the solidity of individual institutions or the resilience of the financial system. They are sometimes in charge of supervising specific sectors of financial systems (e.g., banks, securities markets, insurance companies, etc.). DAs are usually involved in determining policies with prudential aims. They are often required to have a neutral impact on markets so not to distort financial asset pricing, which, in efficient markets, should already incorporate a correct consideration of risk.

The boundaries between PAs and DAs are not always well defined and vary across jurisdictions. In Europe, for instance, there is a relatively clear distinction of institutional responsibilities. The European Commission (European Parliament) and the governments of member states (national parliaments) are the political authorities with executive (legislative) power and legitimacy to carry out development policies. Monetary policy is delegated to national central banks and, for the 19 countries belonging to the Eurozone, to the European Central Bank (ECB). Financial supervision is ensured by the existence of both European- and national-level supervisory authorities (Calvo et al., 2018). Both central banks and financial supervisors in Europe enjoy a significant degree of freedom in achieving their mandates, and do not have to align to political objectives (Dalla Pellegrina et al., 2013). In other regions the distinction

between PAs and DAs is instead less clear, as the overall governance framework is designed to promote political strategies. In such contexts, central banks and financial supervisors are usually compliant with government's directives (Crowe & Meade, 2007).

3.3 The 'promotional gap' of European climate-related financial regulation

In this section we examine a selection of climate-related financial regulatory approaches through the lens of our framework. In Europe, informational instruments, and increasingly governance- and incentive-based measures are the tools used by political and delegated authorities, for either prudential or promotional reasons. This is not surprising as these measures can be implemented while upholding a less interventionist stance. Interestingly, the more interventionist regulatory initiatives get, the more focus is on the public primary objectives being of prudential nature to avoid conflicts with mandates of European delegated authorities. Similarly, this seems to constraint delegated authorities to implement even more far-reaching interventionist measures where a stronger justification and evidence of risk is needed - evidence which seems to be currently missing. In the absence of clear systemic and idiosyncratic risk evidence, such measures could only be implemented with a partially promotional objective and justification.

By contrast, other jurisdictions, especially in emerging regions, have a more diversified interventionist portfolio that also includes incentive- and quantity-based policies with clear promotional objectives. This reveals what we call a European 'promotional gap', i.e., a restricted usage of the set of conceivable but more interventionist climate-related financial regulation to be used for promotional purposes.

3.3.1 Climate-related financial regulation in Europe

Most policy efforts on climate-related finance in high-income regions rely on informational measures, with increased attention given to governance- and incentive-based measures. We can identify four main categories of instruments: i) clarification of concepts and standards; ii) development of risk assessment methodologies; and iii) disclosure of risk assessment; and (iv) supervisory expectations and governance principles.

First, several initiatives are attempting to create a transparent and common market understanding of what it means to be 'green' by providing new standardised information. For instance, the European Parliament and the EU Council agreed on a taxonomy[8] stating which activities can be labelled as sustainable. Such a taxonomy represents 'an essential step in supporting the flow of capital into sustainable sectors in need of financing' (EC, 2018) and is therefore promotional in nature. The EU Low Carbon Benchmark Regulation[9] enforces disclosure requirement for sustainable benchmarks regarding their integration of environmental, societal and governance (ESG) factors and sets out the conditions to be labelled as 'Climate Transition' or 'Paris-aligned' benchmarks. The aim of this regulation is to improve the reliability of sustainable benchmarks by reducing greenwashing. Finally, the creation of an EU Green Bonds Standard represents the last step of the Commission's Action Plan in order to

[8] Regulation (EU) 2020/852
[9] EU Regulation 2019/2089

'facilitate channelling more investments into green projects' (EC, 2018). The presence of this label would give the information to potential investors that the project is indeed 'sustainable'. Additionally, the Green Asset Ratio (GAR), mandated for banks starting 2024, enhances the information available to market participants[10].

Second, both private financial institutions and regulators are starting to develop and use methodologies aimed at assessing the exposure to climate-related risks. This applies to the operations of non-financial firms, to the portfolios of financial institutions, and to financial systems as a whole. French supervisors, for instance, developed a modelling framework focusing on the potential disruptions associated to 'disorderly' transition scenarios (Allen et al., 2020), and submitted it to a group of banks and insurance companies to perform a pilot bottom-up risk assessment (APCR, 2020). Similar approaches were adopted by De Nederlandsche Bank (Vermeulen et al., 2019), the Bank of England (Bank of England, 2022) with its CBES exercise and the European Central Bank (ECB, 2022).

Third, measures are being taken to facilitate the disclosure of information by financial and non-financial firms concerning their exposure to CRRs and their strategies to address them. For instance, the EU Disclosure Regulation[11] lays down harmonised transparency rules for market participants and financial advisers regarding their integration of ESG risks, including CRRs. The aim of the regulation is to 'reduce information asymmetries in principle-agent relationships with regard to the integration of sustainability risks'. Such efforts to promote transparency and disclosure of climate-related information have proliferated in recent years. In its newest Sustainable Finance Strategy, the EU Commission adopted a Delegated Act on sustainability-related information (EC, 2021). At the national level, France led the way in 2015, requiring listed companies and institutional investors to evaluate, report and address their exposure to CCRs on a comply or explain basis (Mason, Martindale, Heath, & Chatterjee, 2016).

At the global scale, the Taskforce on Climate-related Financial Disclosure (TCFD), created by the Financial Stability Board, supports the development of climate-related disclosure methods in order to improve the information available to financial investors and facilitate the inclusion of climate-related factors into decision making (TCFD, 2017b). It is worth noticing how these policy initiatives have been conducted by both political and delegated authorities, often in collaboration. For example, the European Banking Authority (EBA) was mandated by the European Commission to develop a technical standard for ESG disclosure and to assess how ESG risks (with a particular focus on CRR) could be included in the regulatory and supervisory framework for credit institutions and investment firms (EBA, 2019). The Commission also requested the European Insurance and Occupational Pension Authority (EIOPA) for an

[10] EBA/Rep/2021/03 https://www.eba.europa.eu/eba-advises-commission-kpis-transparency-institutions-environmentally-sustainable-activities

[11] EU Regulation 2019/2088

opinion on sustainability within Solvency II, relating in particular to those aspects that concern climate change mitigation. The three European Supervisory Authorities (ESAs) have also been requested to collect evidence of undue short-term pressure from the financial sector on corporations (EC, 2019).

Fourth, more recent developments also suggest more regulatory initiatives beyond purely informational policies, more towards governance-based and incentive-based measures. First, supervisory expectations are scaling up, with the BoE and the ECB, among other national central banks, issuing clear guidance on how banks and insurers need to enhance capabilities with respect to managing climate risks and enhance awareness around the double materiality of climate change[12]. For instance, as part of the SS3/19 supervisory statement of the Prudential Regulation Authority in the UK, banks and insurers are mandated to assign risk responsibilities to senior staff member to increase accountability (PRA, 2019). The ECB has issued guidance (ECB, 2020b) on how banks are expected to align their governance with supervisory expectations, coupled with regulatory fines and potential exclusion from purchasing programmes if expectations are not met. Further, regulators are increasing standards around greenwashing to pave the way for direct intervention possibilities and tightening of administrative fines in order to discipline markets and ensure market integrity (e.g., stepping in of BaFin in Germany after allegations of greenwashing for Deutsche Bank's DWS[13]). Such measures and regulation inhibit more interventionist behavior, but remain limited in the way these directly distort markets. With respect to incentives-based measures, the ECB in its action plan considers to exclude assets from purchasing programme when disclosure requirements are not met. Such measures are primarily justified to the public as targeted to minimize risk, rather than promoting sustainability per se (although this can be a higher-order effect). For instance the ECB reviews the adequacy of the collateral framework valuation "to ensure that climate change risks are properly reflected"[14].

We argue that in Europe, the more interventionist delegated authorities go, the more focus "publicly" is on prudential objectives. More direct interventionist measures, such as credit ceilings and sectoral quotas for banks, or other forms of direct capital allocation rules, could only be justified by pure promotional objectives and are therefore not present in the European sphere.

[12]For instance, the Corporate Sustainability Reporting Directive includes the concept of double materiality, see https://ec.europa.eu/newsroom/fisma/items/754701/en

[13]https://www.reuters.com/business/finance/deutsche-banks-dws-allegations-greenwashing-2022-06-09/

[14]https://www.ecb.europa.eu/press/pr/date/2021/html/ecb.pr210708_1_annex~f84ab35968.en.pdf

3.3.2 International comparison and the European promotional gap

Based on our framework, all the climate-related financial interventions examined above can be considered as informational, incentive- or governance-based measures. Whether implemented for prudential or promotional reasons, either by political or delegated authorities, the main strategy is always to improve the information available to market players (standards, labels, disclosure requirements, etc.) or induce market discipline in order to nudge capital reallocation or minimise risk without forcing behaviours or providing direct monetary incentives.

Although these measures are widely used around the world, relying solely on information enhancement seems to be more the exception than the rule. Indeed, many authorities supplement informational policies with incentive- and/or quantity-based policies to reach their promotional objectives. The use of such instruments is particularly prominent in emerging markets, but also appear in some high-income countries such as Japan (Campiglio et al., 2018; Dikau & Ryan-Collins, 2017). For example, the Bank of Japan and the Bank of Lebanon have implemented incentive-based policies for banks, with the former offering more favourable refinancing terms to banks that lend to sustainable projects and the latter differentiating reserve requirements based on lending to green projects. Other countries have implemented quantity-based financial policies for promotional motives. For example, the Reserve Bank of India requires banks to allocate 40% of their credits to priority sectors, including renewable energy[15]. Bank of Bangladesh's 'green floor' obliges its commercial banks to allocate 5% of their credits to green sectors[16]. Yet, the most striking example of comprehensive financial policies with promotional purposes can be found in China. In addition to informational measures, China implements a combination of incentive- and quantity-based instruments. These measures are mainly incorporated into the Macro Prudential Assessment (MPA), a scoring system through which the People's Bank of China (PBoC) assesses the performance of banks. It is composed of seven categories, in turn defined by aggregating a large number of sub-dimensions (Zheng, 2018). While several of them are in line with policies being applied in western societies (e.g., capital adequacy ratio), some go well beyond what European regulators would consider as part of the macro-prudential policy toolkit, such as the alignment of banks' loan portfolios with the PBoC 'green' credit policy strategies (PBoC, 2018). The interest rates on banks' deposits at the PBoC are then differentiated across performance categories, hence making it economically attractive for banks to align with top-down policy objectives, such as green lending. Additional promotional measures include the acceptance at favourable conditions (e.g., lower credit rating requirements) of green bonds as banks' collateral within the PBoC's medium-term loan facility; and the introduction of green-related criteria into the assessing of banks managers' performance (Zheng, 2018). Europe

[15] See revised guidelines RBI/2019-20/39 https://rbidocs.rbi.org.in/rdocs/notification/PDFs/NT393B81B166B6EA476BB2D1BF9AF0946AC0.PDF

[16] See Sustainable Finance Policy for Banks and Financial Institutions, https://www.bb.org.bd/mediaroom/circulars/gbcrd/dec312020sfd05.pdf

appears well advanced in the implementation of informational financial policies. However, it uses neither incentive- nor quantity-based policies to actively reorient financial flows towards sustainable activities. This uncovers what we call a 'promotional gap', as promotional objectives of European authorities are only being pursued through a partial use of all the tools at their disposal. This promotional gap raises doubts on the ability of the European financial system to support a rapid low-carbon transition (Ameli, Drummond, Bisaro, Grubb, & Chenet, 2020b).

3.4 Institutional drivers of the promotional gap

In this section, we examine the institutional characteristics that could explain the promotional gap observed in Europe, i.e. the reasons why more interventionist measures for promotional purposes are not implemented. We identify two main explanatory and intertwined dimensions: i) the low level of public control of EU political authorities over financial dynamics; and ii) the high level of independence and power of EU delegated authorities.

3.4.1 Limited public control on financial capital allocation

Political and delegated authorities have different levels of will and power to act on financial markets allocation. We observe in this area a stark divergence between high-income and emerging countries, consistent with the identified promotional gap. European economic frameworks place a strong emphasis on market freedom and efficiency. This reflects the traditional framing of markets as the bottom-up institution that better allocates resources to the most productive uses. The process of economic and monetary European integration has contributed to gradually reducing the role of the 'interventionist' state and simultaneously expanding the 'regulatory' state (Majone, 1997). Public interventions, in this context, should be justified by the necessity to address specific 'market failures', rather than engaging in active 'market shaping' activities steering economic activity in specific directions (Mazzucato, 2016).

In Europe, as in other high income economies, regulators are careful to avoid 'distortions' in financial markets, where interaction between market participants seeking profitable investment opportunities and 'market discipline' are expected to lead to the most efficient outcome. Creation of credit can be restricted as a whole to mitigate excessive risks - as currently done via the Basel III rules (BCBS, 2010) - but the allocation of credit across sectors and technologies should be left to the autonomous decisions of financial actors. This approach is well rooted in the European Union institutional framework. For instance, Article 127 of the Treaty on the Functioning of the European Union (TFEU) states that the European System of Central Banks 'shall act in accordance with the principle of an open market economy with free competition' (EU, 2012). This free market perspective logically leads to European regulators being inclined to finding solutions 'for the market, by the market' (Carney, 2016), entrusting financial markets to direct flows to low-carbon activities, once risks are properly understood. In this context, bridging informational gaps is crucial to restore market efficiency 'without the need for detailed or costly regulatory interventions' (Carney, 2015). An additional reason not to create market distortions in the EU as a transnational entity is given by the risk of inadvertently causing a reallocation of resources among member states without the necessary political processes in support. Monnet (2018) shows that the demise of credit allocation policies in Europe was key for achieving the convergence of central bank practices necessary for the European Monetary Union.

On the contrary, emerging economies' regulators usually maintain a higher systemic control

of macro-financial dynamics, guiding capital allocation towards specific activities deemed as socially useful. This is particularly true for the governance of the banking system, in which central banks and financial regulators in emerging economies appear to be much more hands-on than high-income ones (Dikau & Ryan-Collins, 2017). Promotional interventions in financial dynamics represent the normal day-to-day functioning of 'state capitalism' shaping markets to achieve its development goals, rather than being perceived as distortive shocks to be avoided. For instance, the presence of the Chinese government in the financial network is systemic, as owner of companies and banks and as a top-down creator of new markets. Banks are run by the state, with deep entanglements of communist party hierarchies; financial markets and stock exchanges are politically embedded and ultimately subordinated to the Chinese government (Petry, 2020).

3.4.2 Independence and powers of delegated authorities

EU authorities are reluctant to influence financial dynamics for fear of causing distortions and inefficiencies. But they also have fewer levers to do so, having delegated both monetary policy and financial supervision to independent authorities with restricted mandates and, since the global financial crisis, increasing powers (Blinder et al., 2017; Fernández-Albertos, 2015). Central bank independence is a relatively recent phenomenon. The claim that delegating monetary policy functions to independent technical agencies would improve the ability of societies in keeping low and stable inflation was first put forward by academic economists (see for instance Kydland and Prescott (1977)). These contributions, originating from a period of prolonged high inflation, argued that 'rules', rather than 'discretion', would solve monetary policy time inconsistency issues and protect central banks from the undesired interference by governments and 'political business cycles' (Nordhaus, 1975). Despite the presence of counter-arguments (McNamara, 2002), the theory was successful in triggering the rapid diffusion of interventions aimed at making central banks independent during the '80s and '90s (C. Goodhart, 2010). This independence shift was particularly salient in market friendly high-income countries.

Most developing economies tend instead to preserve a higher level of political control over their central banks (Dikau & Volz, 2021b; Dincer & Eichengreen, 2014). The creation of independent specialised agencies in Europe fitted with the governance shift to a rule-making political authority framework (Majone, 1997). As a counterpart to this greater independence, the mandate of central banks is generally defined narrowly to avoid institutional drift (i.e., to prevent the independent delegated authorities from claiming undue autonomy and powers from the elected political authorities). This is particularly true in high-income regions. Delegated authorities must respond to a precise mandate providing them legal input legitimacy, the fulfilment of which is their sole source of output legitimacy. In high income countries, price stability is central banks' predominant prerogative, although some development objectives may remain (the US Federal Reserve, for example, has a mandate for both price stability and unemployment). This tends to prevent promotional interventions. Financial supervisors are requested to adhere to their prudential mandate without distorting private capital allocation or 'picking winners' among economic activities. In emerging economies, the promotional dimension is often more prominent and central banks are granted less restrictive mandates, which is consistent with their higher level of political control. As a result, mandatory green financial policies and regulations are adopted mainly in jurisdictions characterised by low central bank independence (D'Orazio & Popoyan, 2020).

Finally, it should be stressed that recent developments in EU financial governance have exacerbated this prudential tendency. Indeed, the cascading effects triggered by the global financial crisis have led to a reshaping of the European institutional framework, placing greater emphasis on the prudential missions of delegated authorities, giving them responsibility for new

instruments to govern finance (Baker, 2013; Blinder et al., 2017). In addition to monetary policy and price stability, both the ECB and the BoE (re)gained explicit control of prudential missions after the global financial crisis. The Single Supervisory Mechanism and the Banking Union allowed the ECB and national CBs to expand their functions to include financial stability and macroprudential regulation, and even fostered the creation of new delegated authorities such as the European Systemic Risk Board and the three European Supervisory Authorities (ESAs). With a prudential mandate, delegated authorities have been granted control over new unconventional policies such as quantitative easing or macroprudential discrete interventions, even though their distributional consequences are unclear (Baker, 2013). This expansion led to higher independence and a reinforced prudential side of policy interventions.

3.5 Europe's institutional gridlock: the need for consensus

As discussed in the previous section, European jurisdictions are characterised by a weak public control on private financial dynamics and strongly independent delegated authorities. In this section, we unfold how this institutional framework leads to an impasse, preventing the implementation of far-reaching promotional financial regulation. Table 2 tracks two dimensions of the climate-related financial policy space: i) what fits (or does not fit) with the objectives of political authorities; and ii) what fits (or does not fit) with the objectives of delegated authorities. We identify four quadrants.

The top-left quadrant contains all the 'consensual' policies that simultaneously: i) mitigate (or at least do not worsen) exposure to financial risk; and ii) push the financial system in a direction compatible with the development objectives of political authorities. We find in this quadrant all the policies that we observed being implemented essentially in every jurisdiction: disclosure requirements, taxonomies, sustainability benchmarks, green bond standards, climate stress test exercises, data sharing, supervisory expectations, etc. These informational and governance-based measures do not meet with any resistance from either side, as they fit with both promotional and prudential aims. From the prudential perspective, they are considered means to overcome issues related to imperfect and asymmetric information regarding the exposure to CRRs, which prevents financial market players to price assets appropriately and financial regulators to ensure adequate supervision. From the promotional perspective, these policies are considered a means to encourage financial flows towards sustainable activities, while preventing green washing thanks to comparable and harmonised standards.

The top-right quadrant includes conflictual policies that are likely to have a positive impact on the reallocation of financial resources towards sustainable sectors, but do not fit with the prudential objectives of delegated authorities as they have uncertain or negative implications on the exposure to financial risk. We illustrate this scenario with two salient policy examples: a 'green supporting factor' and 'green' monetary policy.

As mentioned in Section 3.2, a 'green supporting factor' (GSF) on capital requirements has been proposed by the European Parliament and Commission to ease regulatory constraints for banks that are lending to sustainable activities. In principle, this measure would contribute to allocating larger amounts of credit to sustainable activities (although the evidence for the effectiveness of a similar policy implemented in favour of small and medium enterprises has been mixed; see EBA (2016)). However, since solid evidence of lower risks associated to green loans is currently missing, the proposal of introducing a GSF did not meet the favour of delegated authorities, as 'the essence of capital requirements is to safeguard financial solidity and stability' (Dankert et al., 2018b). The European Commission decided to put the legislative proposal on hold and to mandate the EBA to carry out an expertise mission on the relevance of such an

Table 2: climate-related financial regulatory space in Europe

		Delegated authorities	
		Fits with objectives	Does not fit with objectives
Political authorities	Fits with objectives	Disclosure standards; taxonomies; benchmarks; stress-testing; green bond standards; enhanced climate-related supervisory expectations, governance and market integrity standards	Green-supporting factor; other green prudential policies; (green monetary policies)
	Does not fit with objectives	Dirty-penalizing factor; sectoral leverage ceilings; credit controls	

instrument (see the revised Capital Requirements Regulation (CRR 2); EBA (2019)). That is, a delegated authority with a prudential nature has been delegated to decide on the implementation of an instrument designed to serve promotional objectives.

A second relevant example of conflictual policy is the 'greening' of monetary policy tools such as the ongoing 'quantitative easing' programs of financial asset purchases. The standard approach taken by central banks in Europe has been guided by the principle of 'market neutrality'. This consists in buying assets in a way so not to distort the market-driven allocation of capital; for instance, by allocating purchases across sectors in the same proportion to the sectoral outstanding amounts in corporate bond markets. However, the high carbon intensity and heavy impacts on biodiversity of modern financial markets led central bank interventions to reinforce their carbon lock-in (Dafermos, Gabor, Nikolaidi, Pawloff, & van Lerven, 2020; Kedward, Ryan-Collins, Buller, & Wealth, 2021). The de jure principle of not choosing leads to a de facto choice in favour of polluting activities. With these conclusions in mind, several contributions have argued for monetary policy to be 'greened' (Monnin, 2018; Schoenmaker, 2021). This is generally not supported by delegated authorities, who see it as possibly negatively affecting their legitimacy as well as their ability to attain their primary objectives. Weidmann (2020) epitomises such view, arguing that '*it is not the task of the Eurosystem to penalise or subsidise certain industries. Correcting market distortions often has intricate distributional implications. Such decisions need strong democratic legitimacy and are a matter for governments and parliaments.*' So far, delegated authorities have resisted the implementation of such promotional policies that might hinder their mandate or objectives. However, this view may be changing with the ECB adopting some incentive-based measures such as the exclusion criteria for high-emitting assets in their purchasing programme, although this has been publicly justified to serve prudential objectives and safeguard financial stability, rather then pure promotional objectives that may have violated mandate constraints.

The bottom-left quadrant includes conflictual policies that would have a positive impact on the exposure to financial risk but might have contrasting effects on some development objective. For instance, using banking and financial regulation to introduce disincentives to high-carbon investments (e.g., a 'dirty-penalizing factor') might mitigate the exposure to financial risks, but could negatively affect bank credit volumes and economic growth. These measures naturally encounter the opposition of the banking sector, which can lobby policy-makers against them

(Scialom, 2019). For this reason, the policies in this quadrant are generally supported by delegated authorities but not by political authorities.

The institutional setting present in Europe restrains the allowable policy space in green finance to consensual policies (top-left quadrant). Delegated authorities, in charge of preserving price and financial stability, possess the institutional strength and independence to push back conflictual policy initiatives that might put at risk the achievement of their objectives. Other jurisdictions have instead a wider green financial policy space, since the balance of powers between political and delegated authorities is different and development objectives are given more weight. Certain policies are admissible, and often carried out by delegated authorities themselves, even if they could potentially have distributive impacts and/or negative implications in terms of financial risks.

Overall we see a shift that more and more measures and instruments are being used from both sides, however carefully justified to follow the primary objective that fits with the implementing institutions primary mandate (e.g., central banks' financial stability mandate) but arguably have also applied greater weight to higher-order secondary objectives (e.g., promotional side effects of purchasing programme exclusion criteria). In other words, one could argue that more and more measures that were traditionally conceived as being promotional measures are being re-packaged as prudential to the extent the CBs appetite for balancing mandate issues and implementing interventionist measures is satisfied. This has led to criticism around the institutional responsibility of regulators and central banks and whether these institutions are risking their legitimacy by engaging too actively in the climate sphere. We explore a few institutional scenarios that we see as possible pathways for the future. Political Authorities seem to be not opposed to such a development as long as delegated authorities refrain from far-reaching interventionist tools that clearly serve only promotional objectives and may have unintended consequences and conflicts with political authorities objectives - e.g., economic growth - such as credit controls to certain sectors.

3.6 Future institutional scenarios

In this section we leverage on our proposed framework and adopt a forward-looking perspective to identify the possible evolutions stemming from the current promotional gap. Figure 1 provides a schematic view. We assume political authorities to have two main strategies: i) take a strong action to mitigate climate change (e.g., implement a carbon pricing policy in line with climate stabilization objectives); and ii) take no or limited climate action. Delegated authorities also have two main strategies: i) continue adhering to market neutrality and prudential motives; and ii) adopt more interventionist policies with promotional objectives. These strategies represent stylised extremes of a continuum of possible behaviours by both PAs and DAs. We identify four main scenarios (1. to 4.) and three main dynamics (a. to c.)

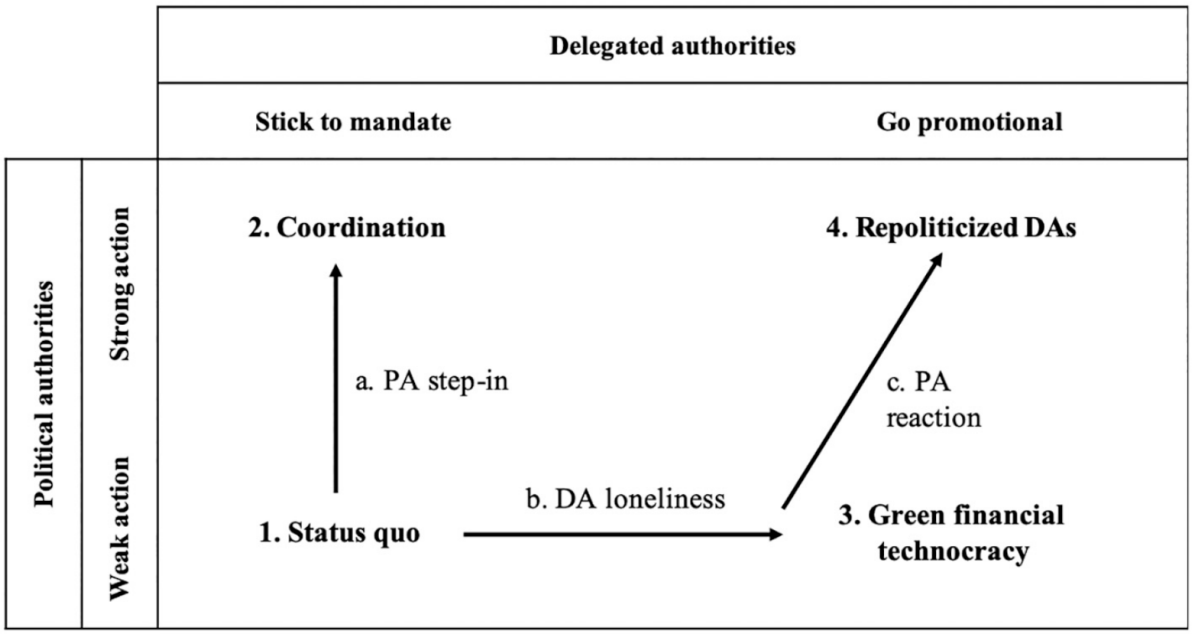


Figure 1: Stylised institutional scenarios

3.6.1 The status quo

We start by analysing the equilibrium we have been experiencing in recent decades (Scenario 1. Status quo). In this setting, limited climate action is taken by PAs, as evidenced by the insufficient adoption of carbon pricing initiatives (World Bank, 2023) and DAs limit themselves to the achievement of the objectives stated in their mandate, without overstepping and risking their legitimacy. When they get involved in climate-related issues, they do so by respecting market neutrality and demanding evidence of financial risks before intervening in a 'market distortive' manner. As argued in Section 3.3, the only policies that can be implemented to shift financial resources towards sustainable investments are mostly informational ones. We argue this equilibrium to be ultimately unstable due to the increasing environmental constraints and the prominent involvement of DAs in the climate debate recently.

However, these policies by themselves may prove insufficient to either fully capture inherently uncertain climate-related risks or to push financial resources towards sustainable activities with the sufficient strength to reach the 1.5°C goal set out in the Paris Agreement(Ameli et al., 2020b; Christophers, 2017; FSB, 2022; Ripple et al., 2023; **?**). A prolonged status quo may lead to a 'too late too sudden' scenario (NGFS, 2020), where the sudden future realisation of the necessity of a low-carbon transition, possibly driven by an unanticipated climate disruption, causes large repercussions to economic and financial stability. To avoid this undesirable scenario, either PAs or DAs may need to adopt more interventionist and promotional measures to steer credit in the direction of low-carbon activities.

3.6.2 PA step-in and coordination

The first path out of the status quo would be for the political authorities to significantly step up their promotional efforts to mitigate climate change, relieving DAs from the necessity to go beyond their prudential objectives (dynamic a. PA step-in). This would lead to a scenario in which each authority separately contributes to a common coordinated objective, while respecting their respective fields of competence: PAs implement fiscal policies shifting the incentive of market players away from carbon-intensive activities, and DAs closely monitor the impacts of climate-related financial risks on price and financial stability (scenario 2. Coordination). However, this scenario poses a number of challenges. First, it is uncertain that sole fiscal action would be enough to tackle climate change. Due to a number of market failures, action in the financial sphere could be needed in conjunction to fiscal policy in order to provide an orderly transition (Campiglio, 2016). Second, if fiscal action were to represent all climate action, it would have to be far-reaching and effective. However, it is unclear how likely strong climate mitigation policies might be implemented in the near future. Ambitious carbon pricing policies have strong immediate economic and political costs making them unpopular, leading to insufficient action from political authorities (Maestre-Andrés, Drews, & van den Bergh, 2019; Ripple et al., 2023). This has not been a phenomenon unique to Europe: despite the decade-long discussion on how essential it would be to price carbon, policy initiatives implemented so far at the international level still do not live up to the stated ambitions (World Bank, 2023). For this reason, some argue for delegating the management of the carbon price path to a new independent authority free from political pressures such as a 'carbon council', or 'carbon central bank', so to improve the credibility and predictability of policy commitments (Delpla & Gollier, 2019; G30, 2020).

In addition, both European national governments and the European Union apparatus appear distracted by a vast range of persistent complex issues (e.g., Brexit, increasing inequality, migration flows, Ukraine war), therefore paying insufficient attention to longer-term objectives as climate mitigation and adaptation. Further, the Covid-19 crisis and imminent fiscal recovery packages could slow down political progress on climate change (Hepburn, O'Callaghan, Stern, & Zenghelis, 2020). Finally, the European institutional framework is further complicated because of the presence of multiple veto players among which it is often cumbersome to find an agreement over ambitious climate policies (Tsebelis, 2002). For these reasons, sufficient action by PAs in the fiscal area to stabilise the climate may be difficult to achieve. Faced with weak or delayed action from PAs, pressure could build up and force DAs to step in. In fact, as we shall see, this move might have started for some delegated authorities.

3.6.3 DA loneliness and green financial technocracy

The second path out of the status-quo would be for DAs to adopt climate-related promotional policies. Whether and to what extent delegated authorities will go promotional without an explicit ex ante institutional agreement will depend on the relative weight they attach to two sets of factors: i) input legitimacy, institutional credibility, and mandate constraints on one side; and ii) output legitimacy and environmental concerns on the other. Some DAs might consider their input institutional legitimacy more important and decide to stick to their prudential-oriented mandates. Other DAs might instead consider climate change likely to jeopardise their primary objectives: besides endangering financial stability with increased physical risks, climate change would disturb monetary policy transmission channels and limit the European central banks' ability to achieve their objective of price stability in the future (Anderson & Robinson, 2021). ECB President Christine Lagarde seems to be of that opinion: '*I contend that price stability can be significantly affected by climate change, and that as a result of that, if we want to deliver on our mandate, we have to be not only mindful but also take action in order to prevent climate change from affecting that price stability that is our mandate*' (Lagarde, 2020).

In a context characterised by political authorities' inaction, this might force DAs to intervene to compensate for the lack of promotional effort in the face of an unfolding climate crisis (dynamics b. DA loneliness). This situation mimics the 'loneliness' of central banks in the aftermath of the financial crisis, when the policy gridlock affecting governments' actions forced delegated authorities to become the 'only game in town' and led to unprecedented monetary interventions (Mabbett & Schelkle, 2019). The longer PAs delay sufficient action, the more likely it is that DAs will step in to compensate for the lack of political will and to avoid irreversible physical risks, using the 'authorization gaps' in their mandate (de Boer & van't Klooster, 2020). Recent developments suggest that we are already experiencing a gradual move of independent DAs towards promotional policies. This move is especially prominent for the ECB. In 2020, ECB set up a dedicated climate-related research group to inform policy decisions and started evoking the option of abandoning the market neutrality principle in asset purchase programs (Schnabel, 2020). In 2021, it revealed its first strategy review since 2003 with a 4-year plan to concretely integrate climate in its actions. This includes modifying the collateral framework and introducing climate considerations in the corporate-sector purchase program (ECB, 2021). Further, observed regulatory initiatives from DAs around market integrity, mandated governance changes to capture climate considerations and enhanced legal standards and scrutiny constitutes a sign that more far-reaching action is continually implemented.

This trend is justified by the concern that climate change might affect price and financial stability, i.e. primary objectives. Promotional interventions to mitigate climate change could therefore be interpreted as an attempt to 'lean against the (climate) wind' (D'Orazio & Popoyan, 2020), in a same preventive way as macroprudential policies proactively counter the

accumulation of risks during the buildup phase.

Delegated authorities could also argue that going promotional is not only a way to achieve their primary objectives, but also part of their secondary objectives. For example, Article 127 of the Treaty on the Function of the European Union (TFEU) states that the European System of Central Banks (ESCB) '*shall support the general economic policies in the Union with a view to contributing to the achievement of the objectives of the Union*' (among which we find protecting and improving the quality of the environment), if this comes '*[w]ithout prejudice to the objective of price stability*' (Consolidated version of the Treaty on the Functioning of the European Union, 2012). Solana (2019) argues that the central banks are also bound by the Article 11 of the TFEU, which states that '*[e]nvironmental protection requirements must be integrated into the definition and implementation of the Union's policies and activities*'. The mandate of the ECB, and more in general those of delegated authorities, could thus leave some room to legitimise a certain greening of financial policy actions. In addition, DAs are sometimes explicitly pushed to be more proactive in the climate policy sphere by PAs themselves (see for instance EU Parliament motion 2018/2007(INI) that '*acknowledges the independence of the ECB and its primary mandate as being to preserve price stability but recalls that the ECB as an EU institution is also bound by the Paris Agreement'*). Besides, reinterpretations of delegated authorities' mandate are possible, as shown by ECB's actions in the aftermath of the global financial crisis (GFC) (de Boer & van't Klooster, 2020). Before the GFC and the sovereign bond crisis, the interdiction of monetary financing[17] of the EU states used to be interpreted in a narrow sense, preventing ECB from buying sovereign bonds to close spreads between national bonds. During the sovereign debts crisis, unconventional policies such as Securities Market Programme (SMP), Outright Monetary Transactions (OMT) and Public Sector Asset Purchase Programme (PSPP) led to largescale buying of sovereign debts on secondary markets, therefore closing the spreads and de facto annihilating the disciplinary role of market pricing. Both OMT and PSPP were brought to court but confirmed ex post as legitimate (see Court of Justice of the European Union's judgments of June 16, 2015 (aff. C-62/14[18]) and October 08, 2018 (aff. C-493/17)). The past successes of the ECB in broadening its actions and reinterpreting its missions could set an important precedent, showing delegated authorities that they can enlarge the spectrum of their actions and engage in the promotional sphere, moving continuously towards a DAs loneliness' outcome, as there is room for safe 'stealth' institutional drift (Schmidt, 2016). However, if brought to its extreme, this trend could lead to the establishment of a climate-friendly technocratic setting (scenario 3. Green financial technocracy), i.e., a situation characterised by independent technical agencies with the power of defining the features of economic and societal development with no or little political control and without an appropriate adjustment of their mandates (Climate Leviathan

[17] See Article 123 of the Consolidated version of the Treaty on the Functioning of the European Union

[18] Articles 72 to 76 of this judgment recognise the legitimacy of the ECB to intervene in an unbalanced way in its asset repurchase when i) the market pricing was unsatisfactory, imposing an 'excessive risk premia'; ii) this undermined the ESCB's monetary policy transmission mechanism.

or Behemoth of sorts, see Fontan (2016) and Wainwright and Mann (2018)). The entrance of delegated authorities in the fight against climate change would certainly help reorienting financial flows and to facilitate the transition. However, letting delegated authorities fully use their authorization gaps without democratic input legitimacy might ultimately put at risk the credibility of these institutions and affect their ability to reach their primary goals (Cochrane, 2020). In addition, promotional DAs may not properly address prudential concerns related to CRRs, possibly allowing or exacerbating a 'disorderly transition'.

3.6.4 PA reaction and re-politicisation of financial policies

We argue that the scenario of a green financial technocracy is also inherently unstable. An increasing disconnection between the de jure institutional arrangement and the de facto distribution of financial governance powers is likely to eventually force a reaction from political authorities. PAs could step in to disavow DA promotional pushes and prevent further agency drift, or to offer its political support by legitimizing them ex post (dynamics c. PA reaction). As delegations were designed and assigned in the past, they can be changed or revoked. In national jurisdictions this can usually be achieved by an act of the Parliament. Governments can thus decide to bring back monetary policy and financial regulations under their control. This would allow them, for instance, to differentiate bank capital requirements according to the carbon intensity of lending for purely promotional objectives, as the European Commission has already proposed. If such a change would represent a break in the historical trend of increased independence of central banks, C. Goodhart (2010) argues this movement towards a new regime of central banking characterised by more intrusive regulations, greater government involvement and less confidence in market mechanisms, has already started since the GFC. This setting would see DAs aligning their actions to PAs development objectives, even if they might have negative prudential implications (scenario 4. Re-politicized DAs). This might seem implausible in the European context, but it is very common in other jurisdictions (see Section 3.3.2), and has been the default institutional setting in Europe for a long period in the past (Monnet, 2018) despite what 'institutional amnesia' often suggests (Braun & Downey, 2020). Several contributions have argued that limiting DA independence could be beneficial to implement effective climate action. However, this could also imply costs, as price and financial stability were delegated to independent authorities to avoid problems of time inconsistency and political capturing. Revoking the delegations could bring these problems back. Of course, PAs' reaction doesn't have to be that radical. Instead of regaining control of the delegated authorities and abandoning central bank independence, political authorities could grant DAs new input legitimacy to implement promotional policies. This would lead to an intermediate situation between scenario 2 (Green financial technocracy) and scenario 3 (Re-politicized DAs) as PAs react to the lonely drift of DAs to give them both clearer grounding and boundaries to democratically clarify the 'authorization gaps' of their mandates. This would allow a new form of cooperation between political and delegated authorities, giving the latter a genuine role in climate change mitigation. We observe such a shift in the UK, where the BoE has received an updated remit to align regulatory monetary policies consistent with the government's economic strategy to reach net-zero[19]. The European case is more complex, as ECB's missions are enshrined in international treaties that require long processes to be modified. Even if a mandate change is preferable, it is not necessary. Indeed, ordinary legislative procedures (e.g., clarifying the ranking of the objectives or the statutes of the ECB) could prove sufficient to grant DAs

[19] see https://www.bankofengland.co.uk/-/media/boe/files/letter/2022/november/2022-mpc-remit-letter.pdf

adequate input legitimacy (van't Klooster, 2021). Another form of reaction could be a legal procedure (similar to the one that followed the programs of the OMT and the PSPP at the European Court) stating ex post the legitimacy of green promotional policies conducted by DAs and providing them with legal ground. Nevertheless, such a procedure acting retrospectively and emanating from a magistrate, rather than from elected authorities, would not have the same force, as judicial review does not by itself provide democratic legitimacy (de Boer & van't Klooster, 2020). Therefore, political authorities will need to intervene at some point, either to rein in delegated authorities or to provide them with renewed legitimacy and boundaries for their promotional actions.

3.7 Conclusions

Using a novel framework distinguishing policy objectives, instruments and implementing authorities, we have argued that the ability of European countries and similar jurisdictions to introduce far-reaching interventionist climate-related financial regulation is limited by: i) a weak public control on private financial markets; and ii) the presence of strong independent technical authorities with delegations concerning financial markets. These traits limit the European green finance regulatory space to consensual informational, and more recently governance- and incentive-based initiatives that do not conflict with key objectives and mandates of respective delegated and political authorities. However, proposals of more far-reaching interventionist financial incentive- and quantity-based regulations with uncertain prudential implications that would need to be justified solely on promotional objectives - such as differentiated capital requirements - are not adopted by delegated authorities. CB&S cannot appear to distort markets to accelerate the transition unless clear mandate changes are given from political bodies (e.g., BoE remit change), otherwise CB&S are at risk of losing independence and credibility, which could further hamper their ability to set appropriate financial market frameworks to support the transition. This is less the case in emerging economies, where central banks and supervisors often align financial policies with governments' development and sustainability objectives through direct financial intervention.

With the climate emergency demanding more action from all actors, it will need to be seen if this promotional gap will be filled by delegated authorities and in which constellation. Several scenarios of future institutional evolutions have been explored. First, governments could introduce ambitious mitigation policies (e.g., carbon pricing), allowing delegated authorities to focus uniquely on price and financial stability. This promotional-prudential coordination would be welcome. Recent elevated engagement from political authorities to discipline markets mainly for promotional purposes around market integrity and increased scrutiny around greenwashing and the management of risks could be observed as an attempt to foster such coordination. However, several hurdles still exist that prevent strong government action on climate beyond market disciplining regulatory initiatives. Second, in the face of timid political action, delegated authorities concerned about their output legitimacy might decide to go promotional and more and more interventionist 'by stealth' and without an appropriate underlying change in mandate. Recent changes by some European delegated authorities hint that this change may have begun. While scope for extending their actions within their current interpretation of mandates exist, this trend, if brought to its extreme, might result in a green technocratic setting or trigger a coercive repossession of policy functions by political authorities. Finally, political and delegated authorities could cooperate in making the necessary adjustments to achieve a new institutional setting, such as a revision of the mandate, or an ex-post validation of promotional drifts. The stylized scenarios can partially explain the remit changes for the Bank of England (BoE) - a case where the UK government and HM Treasury have issued clearer guidance around the

mandate with respect to the wider net-zero strategy. But some of the scenarios were strongly informed by developments in the EU and around the ECBs prominent role in the climate sphere. The unique institutional setting and idiosyncrasies around EU's governance, the focus area of ECB senior management and the resulting increased confidence about the understanding of climate risk, may suggest only limited external validity if the framework is applied beyond the EU. Further, a stronger coordination was observed between the EU commission, the European Banking Authority, and other supervisory institutions with respect to governance around risk management and climate change more generally. The stylised scenarios should therefore be seen as thought-provoking extreme forms of different possible evolutions. While debates and contentions around legitimacy and division of roles between CBS and supervisors still remain relevant, recent developments have shown that coordination has already improved significantly, positioning today's situation it in an intermediate stage between coordination, status quo and green financial technocracy.

In a 2018 speech meaningfully titled 'Let's dance', the chair of the NGFS Frank Elderson, outlined the contributions that central banks and supervisors could make in the societal effort to address climate change (Elderson, 2018). This article shows that central banks cannot and should not dance alone. Either through strong action in the fiscal sphere and/or through new clear delegations of climate missions to delegated authorities, political authorities will have to step-in at some point, as central banks and other delegated authorities cannot do it all. It will take two to dance: only through strong cooperation from early stages will it be possible to simultaneously achieve effective climate action and continued strong institutional legitimacy.

4 Paper II: TRISK - A Climate Stress Test for Transition Risk

The paper II "TRISK – A Climate Stress Test for Transition Risk[20]" is joint work with Ben Caldecott, Jacob Kastl, Alissa M. Kleinnijenhuis and Nicola Ranger. The paper is available at SSRN. An earlier application of this paper was published as report at the Smith School of Enterprise and the Environment at the University of Oxford.

[20]I would like to thank Gireesh Shrimali, Chris Cormack, Jakob Thomae and two anonymous reviewers for valuable feedback to earlier versions of this paper. The TRISK model can be found open source on github: `https://github.com/2DegreesInvesting/r2dii.climate.stress.test`. The code infrastructure is hosted and maintained by 2°Investing Initiative. The authors acknowledge funding from the European Union's Life NGO program under Grant No LIFE20 NGO/SGA/DE/200040. The paper reflects only the authors' views and the Agency and the Commission are not responsible. The authors declare no conflict of interest. Corresponding author: moritz.baer@smithschool.ox.ac.uk

Abstract

Climate change has the potential to impact the stability of the financial system. We develop an empirically grounded firm-level climate stress test for assessing transition risk. As part of this, we present a forward-looking risk measure - TRISK - which is the expected loss of a financial institution given the uncertain materialisation of a transition stress scenario. The approach is rooted in asset-level data and represents transition impacts on the level of the firm in a microeconomic and financial model. Key distinct features of the climate stress test are its forward-looking nature leveraging data on the transition strategy of firms, the explicit representation of technological costs and firms' comparative advantage, and the transparency and flexibility to accommodate for a wide range of scenarios and underlying modelling choices. We perform an exploratory analysis to 135 international power firms. We find that transition impacts entail significant heterogeneity across firms and the financial sector with clear distributional consequences. This highlights the need for granular risk assessments able to reflect the complexity of the transition and identify climate laggards from front runner firms to inform governments, financial markets as well as financial policy design.

4.1 Introduction

The impact of climate risks on financial stability are increasingly recognised by governments, investors, central banks and financial regulators. The Network for Greening the Financial System aims to support best practices and contribute to building a climate-resilient financial system (NGFS, 2019). Believes around the materiality of climate risks have begun to shape financial decision making and risk management practices (Bolton & Kacperczyk, 2021a; Krueger, Sautner, & Starks, 2020). Depending on institutional responsibilities, actors have engaged in either steering financial capital, adjusting fiscal measures to support the net-zero transition or in analysing climate-related financial risk. Central banks and supervisors (CB&S) have prominently focused on the risk dimension of climate change. To this end, they are analysing prudential and financial policy measures that are targeted to safeguard financial stability. In particular, climate stress testing and scenario analysis has emerged as a key analytical tool, used by a vast array of stakeholders (BIS, 2021a). Yet, current climate stress tests are in their infancy from a methodological standpoint and are therefore only exploratory in nature (see e.g. Bank of England (2021); ECB (2021)). In particular, we identify two important technical limitations of climate stress tests:

First, most of the available approaches are insufficiently forward-looking as they use as proxy for transition risk the historical and current carbon intensity of firms or sectors. This is insufficient, partly because there are systematic gaps and biases in firms' reporting of emissions and current emission intensities cannot reflect the strategic behavior of firms to transition across their operations and to innovate - arguably a key factor in determining transition risk[21]. We argue that disclosing carbon emissions is not a sufficient metric for investors and regulators to determine a firm's transition risk and alignment with the Paris goals. Importantly, two firms with exactly the same current emissions today could face widely disparate transition risk. If firm A is an oil major that is planning to keep investing in oil fields, and firm B is another one planning to transition to a business model based on solar farms, then firm B will presumably face much lower transition risk. The reason is that it will not be subject to a carbon tax, demand driven effects or phase-out policies, for instance. Transition risk proxied by current emissions will not capture this.

Second, most approaches are insufficiently granular and cannot differentiate transition risk at the level of the counterparty or at the firm-level. This is however relevant for financial sector use cases such as risk management (Baer, Gasparini, Lancaster, & Ranger, 2023). There is a fundamental problem with failure to distinguish transitioning firms from climate laggards within the same industry due to disclosure of similar current carbon emissions. Firms belonging to high-carbon-emission sectors today, such as the energy sector, will need to receive plenty of funding at a low cost of capital in order to finance the transition to a green energy economy

[21] see also discussion paper by WTW: `https://www.wtwco.com/-/media/wtw/insights/campaigns/learn-more-about-quantifying-climate-transition-risk-gb.pdf?modified=20221115104226`

while expand world energy capacity. If investors, including central banks, divest from firms in high-carbon industries, based on their disclosure of currently high carbon emissions, as is the custom now among many investors (Bolton & Kacperczyk, 2021a) and under consideration in central bank circles (NGFS, 2021), then these sectors are drained of the financing needed to transition. From a market perspective, accurately capturing the heterogeneity of the transition impact between climate laggards and transitioning firms is highly relevant. This informs effective capital allocation and accelerates the transition, rather than hindering it. Investors should divest only from those firms that do not plan to transition to a greener business model, thereby driving up the cost of capital for climate laggards but keeping the cost of capital low for greening firms. From a regulatory perspective, to increase the resilience of financial institution and safeguard financial stability in the transition, climate stress tests need to identify exactly where the risk lies and how concentrated it is.

To the best of the authors knowledge, no climate stress test overcomes both limitations in one consistent approach. Current climate stress tests that have employed an industry level-approach or top down-macroeconomic approach, insufficiently capture within sector variation (Battiston & Monasterolo, 2021; Vermeulen et al., 2019). Other climate stress testing approaches, including regulatory exercises, have been employed on a granular level, but these approaches are limited in capturing the forward-looking transition strategies of firms (Bank of England, 2021; Cormack et al., 2020; ECB, 2022; Grippa & Mann, 2020; Jung et al., 2021a; Reinders et al., 2020b). Approaches such as the CRISK measure by (Jung et al., 2021a) rely on more market-based methods that identify correlations between a stranded asset portfolio and the largest global banks' stock market valuations. This is only a sufficient metric to evaluate a firm's transition risk, to the extent that transition risk is priced into financial markets today. There is ample reason to believe that this is not yet done to a full extent (Bolton, Despres, Pereira da Silva, Samama, & Svartzman, 2020; FSB, 2022).

In addition, current approaches are limited in accommodating for a wide range of scenarios and underlying modelling choices to better represent prevailing uncertainties. Specifically, regulatory exercises most often leave significant discretion to supervised institutions in adjusting their own risk models and hence lack the transparency and consistency to compare and validate risk outcomes (BoE, 2020). This bears the risk of biased scenario selection and design choices that lead financial institutions to support existing strategies and solely to fulfill supervisory expectations without an appropriate risk assessment.

We are therefore in need of a forward-looking, transparent, flexible and granular climate risk assessment approach. We contribute with such a model framework and present the risk measure - TRISK. The approach represents transition impacts on the level of the firm in a microeconomic and financial model that reflect firms' asset values under different scenarios. We present TRISK

on two levels. On the firm level, TRISK is expressed as the difference in the discounted net present value (NPV), as well as the probability of default (PD) for a firm under a baseline and transition stress scenario. On the financial level, TRISK is expressed as the difference in the expected loss (EL) of a portfolio under a baseline and stress scenario. Key distinctive analytical features of our approach include the calibration on physical production asset-level data and representation of the transition risk on the firm-level. Further, it is sufficiently forward-looking as the model represents the strategic behavior of firms by allowing for a calibration on the five-year forward-looking production plans of firms. As a result, the transition risk - TRISK - is a function of the misalignment of planned strategies of firms with a Paris-aligned scenario pathway, rather than proxied by historical and current carbon emissions alone. It is our view, that classic risk management practices and risk metrics are inadequate to assess transition risk and it will only be priced in so far as investors have developed forward-looking measures of transition risk of firms. TRISK also allows to input many scenario pathways across different scenario providers and hence allows to compare the financial risk outcomes across a wide range of more or less conservative scenario assumptions, to get an appreciation of the level of uncertainty and range involved in these exercises.

Beyond the methodological contribution, we showcase an initial application of the TRISK model to analyse the transition risk for a set of 135 public power firms that in 2021 capture around 30% of global power production and are responsible for 4.543 Gt of CO2 or around 34% of power-related global emissions.

We highlight **two key findings** that strengthen our argument for the need of innovative approaches that are forward-looking and capture the heterogeneity involved in the transition:

First, we find that transition impacts entail significant heterogeneity across individual firms, with the 5^th and 95^th percentile of the transition-related NPV changes between -49% and 11.56% respectively. Further, we find a significant variation in the transition-related probability of default (PD) changes, between -0.15 and 2.17 percentage points, reflecting that some firms see positive changes to their creditworthiness while other firms may see large PD increases in the net-zero transition. Across two synthetic portfolios, the overall transition-related financial losses relative to the overall portfolio size varies between a highly negative impact of around 18% as opposed to an overall positive impact of around 8%. The heterogeneous impact on firms and portfolios, highlights that the transition inhibits clear distributional consequences across the financial sector that cannot be captured in other sector-focused climate stress testing approaches that do not represent risk on the firm-level.

Second, we identify a significant variance of transition impacts - TRISK - across different scenario narratives and model parameters, highlighting the elevated levels of variability and

uncertainty of such approaches. For instance, we find that the transition impacts on firms' valuations across three net zero scenarios with the same climate target (well below 2°C) from different providers are substantially different in the overall impact and shape of the risk distribution. We also vary the timing and severity of the stress scenario - reflecting a gradually more delayed and more disruptive scenarios. We demonstrate that every year the transition is delayed, the cost of the financial sector is increasing. This suggests a systemic risk build up that could cause further disruptions and setbacks in the transition, if not carefully managed.

The paper is structured as follows. Section 4.2 outlines the climate stress testing framework, discusses calibration strategies and the model limitations. Section 4.3 presents the results of the empirical application. Section 4.4 discusses the sources of uncertainty arising across the layers of the climate stress tests and presents the sensitivity analysis and mitigation strategy. Section 4.5 concludes and discusses avenues for future research.

4.2 Climate Stress Testing Model Framework

The asset-level climate stress test (ACST) or TRISK model[22] consists of three interlinked layers. The first layer 'Scenarios' describes the source of transition risk, represented by a set of climate-adjusted economic parameters, designed and curated in a set of severe but plausible transition scenarios. The second layer 'The Economy' describes the real economy, as well as individual firms' asset values under different scenarios. It represents a firm by its physical economic assets and the associated ownership structure. The third layer 'The Financial System' describes the financial system, represented by heterogeneous financial institutions and their balance sheets. Each of these layers is connected through a set of transmission channels, which propagates the climate-adjusted economic impact to the asset value of firms and subsequently translates the impact into financial risk. Figure 2 shows a stylistic overview of the model transmission channels.

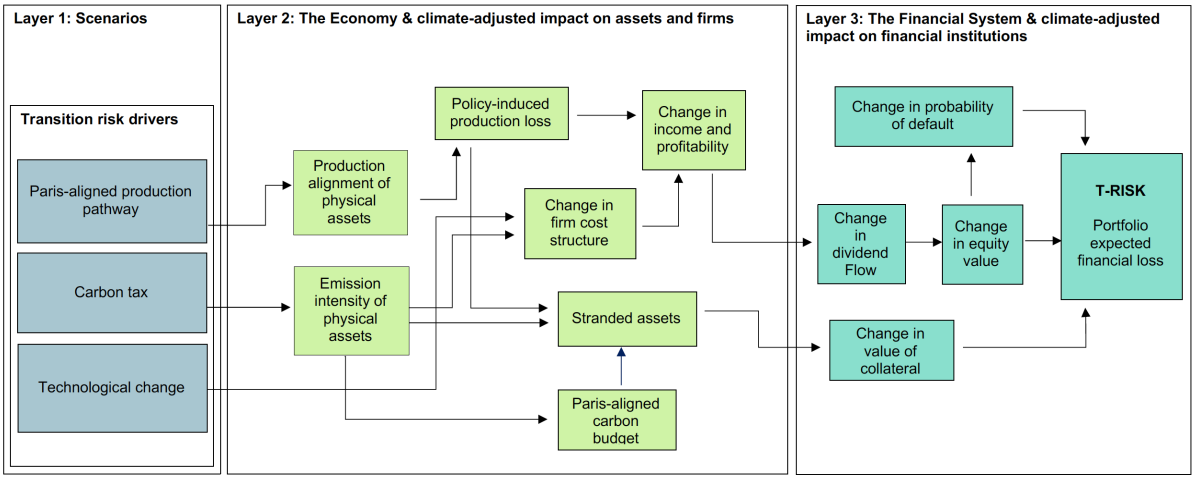


Figure 2: Representation of the key model layers, stylised overview of the climate stress testing framework and its transmission channels.

At its core, the approach models the individual firms' net present values under different stressed transition scenarios. Hereby, the firms' valuation depend on its unique composition of physical assets across its ownership structure, production capacities across key technologies and along business units (e.g., electricity generation across renewables or coal-fired power plants) to determine the drivers of firms' revenues and potential vulnerabilities. In our framework, transition scenarios are constructed in a way to simulate a tail "stress" event in which exogenous policy-induced changes rapidly alter the demand across climate-critical sectors and key technologies (e.g., phase out and demand reduction for coal-fired electricity generation). Moreover, firms are confronted with changes in technological unit costs (e.g., to reflect increasing cost competitiveness of solar) and additional carbon taxes that alter firms' cost structure and their market shares across technologies according to decarbonisation pathways. For instance, a

[22]For simplification, the terms ACST and TRISK model will be used interchangeably

firm with high-carbon intensive power production assets, such as coal-fired power plants, will see its demand decline according to stipulated sector decarbonisation plans on a pro rata basis and will see its cost rise due to a high emission intensity of its assets that are subject to the potential phase in of a carbon tax. Importantly, the model takes into consideration the firm' specific five-year forward-looking production plan. If a firm is planning to increase high-carbon intensive production in this time period, it gradually increases its misalignment with stipulated targets, and hence will be faced with an even more disruptive realisation of the transition to overcompensate for previous misalignment. Similarly, if the same firm also operates in another business unit, e.g., owns and operates solar farms and wind parks to produce electricity, it will see its demand from such business units increase according to the growing share of renewable power in the energy system transition scenario. It will further benefit from decreasing unit costs for such sustainable technologies.

Overall, the firms' transition impact is therefore a function of the misalignment of its business units and technologies with mitigation scenarios. High-carbon intensive firms that are planning to reduce carbon-intensive production units and shift their strategy to sustainable technologies (e.g., from coal to solar) can even be positively affected in the model, if the firms' plans are more ambitious than the target scenarios and lost profits from declining business units are overcompensated with increasing profits from more sustainable aligned business units.

Asset and firm-level impacts are then translated into equity valuation changes, through a discounted cash flow model. Using a time-horizon adjusted Merton credit risk framework, equity impacts are subsequently translated into changes in the probability of default. In addition, a firm will also be faced with stranded assets, i.e. a share of firms' production that is incompatible with a carbon budget set out in the mitigation scenario. This impacts the balance sheet of the firm through reduced collateral values that increases the loss given default for creditors to such firms and hence contribute to a deteriorating creditworthiness. More formally, the transition impact - TRISK - is expressed as the difference in the discounted net present value (NPV), as well as the probability of default (PD) for a firm under a baseline and transition stress scenario. On the financial level, TRISK is expressed as the difference in the expected loss (EL) of a portfolio under a baseline and stress scenario.

In this section, we present in detail the modelling choices and underlying assumptions. We further discuss current model limitations in Section 4.2.4. Note that the methodology is described in a data-agnostic fashion, highlighting its flexibility to be adjusted to different needs. Further, we restrict our empirical application of the TRISK model in this paper to the power sector only, while in principle the ASCT can be calibrated across other climate critical sectors for which asset-level data is available (e.g., oil and gas upstream, automotive, cement, steel)

4.2.1 Layer One: Scenarios

We represent the set of transition scenarios by a set of climate-adjusted economic parameters with geographical differentiation to account for institutional and regulatory heterogeneity across economic systems. This allows to capture the different capabilities and responsibilities of individual countries in climate change mitigation.

4.2.1.1 Scenario Parameters and Calibration Strategy

The set of scenario parameters includes: (i) decarbonisation pathways; (ii) unit cost projection; and (iii) carbon tax pathways. This reflects different climate policy scenarios, demand shifts and technological change in energy and industrial systems. The scenario parameters are exogenous and depict various socio-economic and climatological assumptions that are generated across a variety of climate-economic models (e.g., IAMs) with underlying differences in modelling choices and granularity. The approach used in this paper is scenario-agnostic and can be applied with a variety of scenarios ranging from the Network for Greening the Financial System (NGFS, 2020) to the International Energy Agency (IEA, 2020). The level of granularity that can be adopted in a our model will largely depend on the granularity of the scenario data on which the stress scenario can be calibrated.

More specifically, the set of transition scenarios $\mathcal{S}$ is defined as $\mathcal{S} = \{s_1, ..., s_N\}$, where s_i denotes the applied scenario and N are the total number of scenarios. Each scenario s consists of the specification of three matrices of climate-adjusted variables over time: (1) production $\mathbf{P}^s \in \mathbb{R}^{|\mathcal{Y}|\times|\mathcal{H}|\times|\mathcal{T}|}$; (2) technology unit costs $\mathbf{c}^s \in \mathbb{R}^{|\mathcal{Y}|\times|\mathcal{H}|\times|\mathcal{G}|\times|\mathcal{T}|}$; and (3) carbon taxes $\boldsymbol{\psi}^s \in \mathbb{R}^{|\mathcal{G}|\times|\mathcal{T}|}$. The elements in these respective matrices are $P^{s,t}_{yhg}$, $c^{s,t}_{yhg}$, and $\psi^{s,t}_{g}$. Here $\mathcal{Y}$ is the set of sectors, $\mathcal{H}$ is the set of technologies, $\mathcal{G}$ is the set of regions and $\mathcal{T}$ is the set of time. In what follows, we explain these scenario parameters in greater detail. We also briefly describe the calibration strategy and data inputs.

Production Decarbonisation Pathways. $P^{s,t}_{yhg}$ denotes the production levels in sector $y \in \mathcal{Y}$ of production technology $h \in \mathcal{H}$, in region $g \in \mathcal{G}$, across scenario $s \in \mathcal{S}$. The production composition across scenario s in time t reflects the required transformation of a sector y to meet the net-zero targets. For instance, to transform the global energy sector, the IEA projects the phase out of electricity production from fossil-fuel-related technologies, while scaling up renewable energy to meet increasing demand. Most of the scenarios are designed on the global, regional and, more importantly, sectoral and technological level. Hence, these inputs do not provide for the required level of granularity to perform an asset- and firm-level approach. To capture the heterogeneity of risks associated with the transition for individual firms, we need to adjust the regional production pathways $P^{s,t}_{yhg}$ into firm transition pathways, using asset-level data. This data provides a comprehensive picture of the geolocation, characteristics and capacity of physical assets, as well as the ownership structure to firms in climate-critical sectors. We rely

on data from the provider Asset Impact (AR)[23]. This is one of the distinctive key features of our approach that gives an unprecedented level of granularity.

More formally, we calibrate our model and represent the balance sheet of firm $i \in C$ through its unique composition of individual physical production assets $a \in A$ across business units[24] and technologies h, where C and A is the set of climate-critical firms and assets. More specifically, we obtain a firm i's production $P_i^{s,t}$ by summing over the asset production $P_{yhga}^{s,t}$ across each sector y and technologies h across its ownership of assets a, i.e. $P_i^{s,t} = \sum_{g\in\mathcal{G}} \sum_{y\in\mathcal{Y}} \sum_{h\in\mathcal{H}} \sum_{a\in\mathcal{A}} P_{igyha}^{s,t}$.

Additionally, we then obtain the market share η_{iyha}^t of asset a of firm i in sector y and technology h in region g at time t, which is given by its asset production P_{iyhga}^t relative to the total production P_{yh}^t in sector y and and technology h in region g at time t; i.e.,

$$\eta_{iyha}^t = \frac{P_{iyha}^t}{P_{yh}^t}. \tag{1}$$

The market share η_{iyha}^t of asset a of firm i is typically defined based on current data, but could in principle be defined based on the market share at a future time t projected under a given scenario s. Therefore, the market share $\eta_{iyha}^{s,t}$ could be given a superscript s.

Obtaining firm i's asset market share η_{iyha}^t allows us to derive the firms pro rata basis in implementing the requisite change in the absolute production levels in scenario s to achieve a decarbonisation climate target. For instance, according to a Paris-aligned scenario, electricity generated from coal will slowly be phased out according to government commitments and the cost-disadvantages due to the replacement of renewable power generation. In this case, we assume that the firm that operates a coal-fired power plant will contribute to such a decarbonisation by decreasing its production according to its relative market share. A firm that has both, production assets in high-carbon technologies and power plants that produce electricity from solar, will need to adjust its respective production levels in high-carbon production (downwards) and solar power (upwards) depending on the location of the plants and applicability of regional targets that are consistent with climate objectives. More formally, the requisite production level change $\Delta P_{iyha}^{s,t}$ by asset a of firm i is given by its asset-specific market share η_{iyha}^t times the change in production levels $P_{yh}^{s,t}$ specified in scenario s, i.e.

$$\Delta P_{iyha}^{s,t} = \eta_{iyha}^t \Delta P_{yh}^{s,t}, \tag{2}$$

where the change in production in region g in technology h under scenario s is defined as $\Delta P_{yh}^{s,t} = P_{yh}^{s,t} - P_{yh}^{s,t-1}$.[25] Firm i's overall market share across technologies and sectors at a given

[23] `https://asset-impact.com`

[24] For simplicity, in this paper, we use the terms technology and business unit interchangeably. In the power and automotive sector, a firm has its production composition across technologies such as electricity generation from solar or electric vehicles. However, for fossil fuel companies that extract oil and gas, strictly, these are not technologies, henceforth these are better described as business units

[25] Henceforth, the Δ of a variable is always defined as the difference between a variable at time t and $t-1$.

time t is ultimately a composition of its market shares η^t_{iyha} of asset a at time t. Importantly, it can be seen from equation 2 that a firm with a smaller market share across its assets in sustainable technologies today will be at greater transition risk tomorrow if its high-carbon technologies are subject to a phase-out according to the requisite scenarios production levels $P^{s,t}_{yh}$. Further, from equation 1, it is clear that η^t_{iyha} is time-varying and could be made dependent on the firms' own production plans as observed in the data.

A unique feature of the Asset Impact data is that it contains information on the 5-year production plans of firms. This allows us to represent a forward-looking dimension that depends on the transition plan of firm i, stipulating how it may or may no shift its production composition towards sustainable technologies. Firms that do so will then see their production levels and associated carbon emissions fall, and will be less vulnerable to a carbon tax, a demand change, policy-induced phase-out, or other climate policies that could harm their profits. Note that these data points are asset-specific, where there is information on planned production expansion or reduction (e.g., retirement of asset due to end of lifetime) and do not represent simple emission reduction pledges. For example, the data captures when a power company is expanding production capacity through a new power plant that adds a certain amount of capacity in the next years that changes the firm's respective electricity production mix.

Graph 3 below show the production plans for an illustrative selection of energy firms across its business units and technologies, as well as the associated emission levels. It follows, that the TRISK model projects the net present value of a firm based on its misalignment with a decarbonisation scenario. The results highlight the transition related changes that the firm may face if it continues to follow a business-as-usual strategy, calibrated on the 5-year asset-specific production plans of firms with the average market share held constant over the time horizon of the stress test.

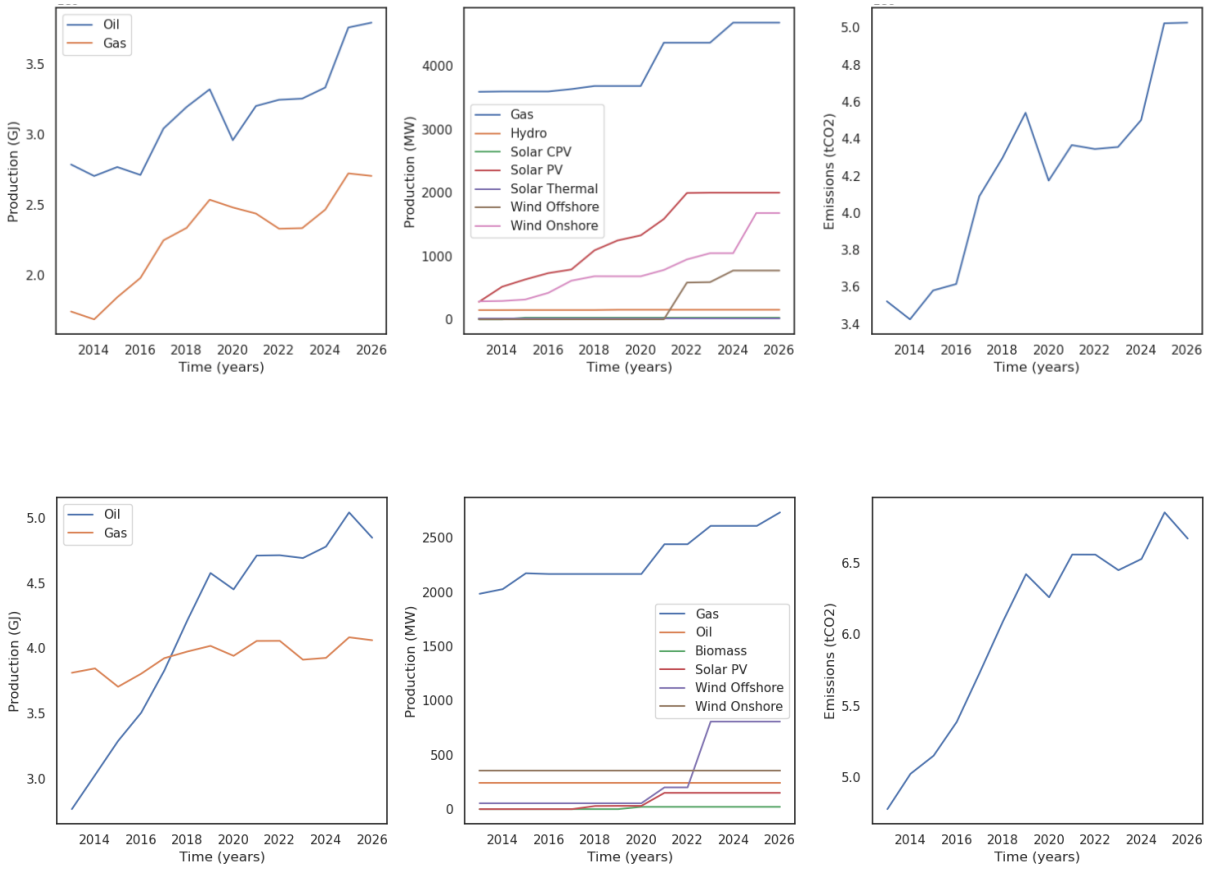


Figure 3: Historical and forward-looking production plans across business units for a representative energy firm, as well as associated total carbon emissions from 2013-2026. Data based on Asset Impact. Fossil fuel extraction in Giga Joule (GJ), emissions in $1e^8$ tonnes of CO_2

The TRISK framework was designed in a way to leverage off such forward looking production plan information.[26] This allows to model the strategic direction that firms are moving towards and integrate such information in the construction of the baseline scenario (see section 4.2.1.2). Relying on production plans of firms highlights a crucial advantage compared to other stress testing frameworks. Most models are calibrated using the historical carbon emission of a firm or sector as a proxy for transition risk. Contrary to the emerging consensus, we argue that historical carbon emissions are not a sufficient metric to determine a firm's transition risk. Importantly, two firms with exactly the same current emissions today could face widely disparate transition risk depending on their strategic operational decisions across technologies.

Carbon tax. Another scenario parameter is the carbon tax $\psi_g^{s,t}$, given in dollars per ton of $C0_2$ emitted resulting from a unit of production in region g under scenario s at time t.[27] Depending on policy and regulatory changes across regions and jurisdictions, governments are

[26] Alternatively, information on CAPEX plans and or investments across technologies h of firm i could be gathered to project strategic plans

[27] If a global carbon tax is applied, the carbon tax will be the same across all regions.

well positioned to tackle the market failure around climate change and carbon externalises through direct pricing mechanisms in the economy (Stern, 2007). Depending on the envisioned speed of the structural transformation towards net-zero, carbon price regimes may be enacted very differently, also depending on geopolitical, economic and trade-related strategies across jurisdictions (Mercure et al., 2021). Such a carbon tax will directly alter the cost structure of firms in climate-critical sectors and create incentives to change the production composition. We allow in the model to integrate a regional- or country-specific carbon tax pathway that is given exogenous by scenario providers. Figure 4 illustrates various global carbon tax trajectories from the NGFS under different transition scenarios s.

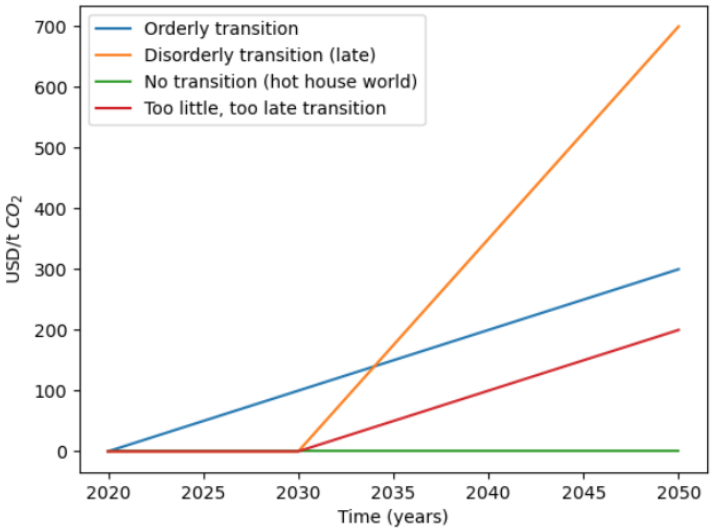


Figure 4: Climate policy scenarios s corresponding to different carbon tax paths $\psi_g^{s,t}$ over the period $t = 2020, ..., 2050$. The scenarios are consistent with those formulated by the (NGFS, 2020).

Unit cost projections. The projected speed of achieving net-zero is significantly driven by technological advancements. This is reflected through $c_{yhg}^{s,t}$, which is the unit cost of production in sector y, across technologies h, in region g, in scenario s at time t. Most often, cost pathways are in IAMs or by academics such as as Way et al. (2022) who use historical trends in production costs and statistical methods to forecast future trends. For instance, the costs of many sustainable technologies, such as producing solar power, have fallen exponentially over the last decades in line with Wright's law. In contrast, the costs of high-carbon power technologies have not experienced exponential decay, but rather stayed relatively constant (Way et al., 2021). Future trends of production costs are an integral part of the transition scenario, as it reflects the likely diffusion and comparative advantage across a range of high-carbon and sustainable technologies. Unit cost developments may be significantly different under various climate mitigation and policy scenarios. Information on time-variant, regional different and scenario-specific unit costs is a critical information in the set of scenario parameters that underlie our climate stress testing approach. Figure 5 shows an illustrative selection of cost projections across scenarios

that are suitable to calibrate the TRISK model.



Figure 5: Projection of the Levelized Cost of Electricity (LCOE) by technology and scenario for the IEA Sustainable Development Scenario (IEA, 2020) and Oxford scenarios (Way et al., 2022). Oxford no transition refers to a counterfactual scenario where the technological improvement is frozen to current levels.

We acknowledge that a wide range of scenarios exist in the academic and non-academic sphere, with varying degrees of granularity, specificity and transparency around underlying assumptions. Note that different scenarios can be integrated in a complementary fashion as long as the scenario narrative and assumptions are consistent. Moreover, as shown in section 4.4, the TRISK model can also serve the purpose of comparing and constructing several benchmark scenarios to assess the fundamental differences in assumptions and compare different stress test outcomes based on the scenario narrative. This can be valuable to better understand the uncertainties and sensitivities around scenarios. The methological framework proposed here is also consistent with emerging consensus around the need for clear scenario principles to assess the robustness of individual climate scenarios (Fankhauser et al., 2022). Note that further advancements around the granularity of scenarios are urgently needed. For instance, global and regional scenarios from the NGFS and other providers, are underpinned by high-level assumptions on the global or regional level, rendering those narratives of limited use for country-specific analyses that are influenced by government commitments, as well as specific legal and economic contexts.

4.2.1.2 Design of Baseline and Stress Scenarios

In order to construct a set of suitable scenarios, we need to calibrate scenario parameters and curate a baseline scenario and a set of stress scenarios. This process is flexible and can be adjusted to various forms of different scenario narratives, depending on the scope of the stress testing exercise. We propose the following way forward to reflect the transition risk in the model.

Baseline Scenario. We construct the baseline scenario $s_1 = \{baseline\}$ in a way that reflects the production plans for each firm i. Firms are expected to follow their planned 5-year production across technologies and sectors $P_{iyh}^{s,t}$ over the period $t = \{2020, ..., 2025\}$. After that, the firm i follows the respective production change $\Delta P_{iyh}^{s,t}$ prescribed in a business as usual scenario for the remainder of the stress testing horizon ($t = \{2025, ..., 2040\}$), where $\Delta P_{yha}^{s,t}$ is obtained from the current policy scenario 'CPS' by the IEA (2020). The CPS reflects a baseline picture of how the global economy would evolve if governments and firms made no changes to their existing policies. Further, the firm i will be faced with scenario-consistent unit cost developments $c_{yhg}^{s,t}$ by the IEA (2020) and carbon tax trajectories $\psi_g^{s,t}$ from the 'no transition' scenario by the NGFS (2020). The resulting scenario $s_1 = \{baseline\}$ reflects a narrative of firms producing according to their strategic plans, irrespective and with no foresight to the materialisation of transition risks other than already reflected in their firms production plans.

Target and Stress Scenario. In order to construct a stress scenario, we need to first define a scenario $s_2 = \{target\}$ that is aligned with future climate targets. We choose the 'Sustainable Development Scenario" (SDS) by the IEA (2020). This scenario prescribes the requisite production changes across sectors and technologies $\Delta P_{yh}^{s,t}$ that are needed to transform the economy, comply with carbon budgets and achieve a Paris-aligned climate target of below 2°. The scenario $s_3 = \{stress\}$, or late and sudden scenario, is then constructed in the following way: firm i continues to produce according to the scenario $s_1 = \{baseline\}$ until the introduction of "climate action" shock in year Z in the set of $\mathcal{Z} = \{Z_{2025}, ..., Z_{2035}\}$.[28] This shifts the production of firm i across sector y and technology h onto a Paris-aligned path, to comply with the climate targets and carbon budgets set out in scenario $s_2 = \{target\}$, while overcompensating for previous misalignment. Note that in the stress scenario the required production change $\Delta P_{iyh}^{stress,t}$ for firm i is greater than the production change prescribed in the scenario $s_2 = \{target\}$, i.e. $\Delta P_{iyh}^{stress,t} > \Delta P_{iyh}^{target,t}$ for the period $t = \{Z, ..., 2040\}$. This is intuitive, as firms need to decarbonise their production more steeply, following a potential misalignment prior to the shock year $\mathcal{Z}$. It follows that Z defines the degree to which a transition is considered 'disorderly', i.e., the later transition policies are implemented, the longer firms in climate-critical sectors remain misaligned with the target scenario, and the steeper a potential adjustment in production levels. See Figure 6 for a visual representation of the SDS target and stress scenario across technologies

[28] Note that the shock year can be varied for sensitivity purposes to reflect varying degrees of a disorderly transition.

and the overcompensation mechanism.

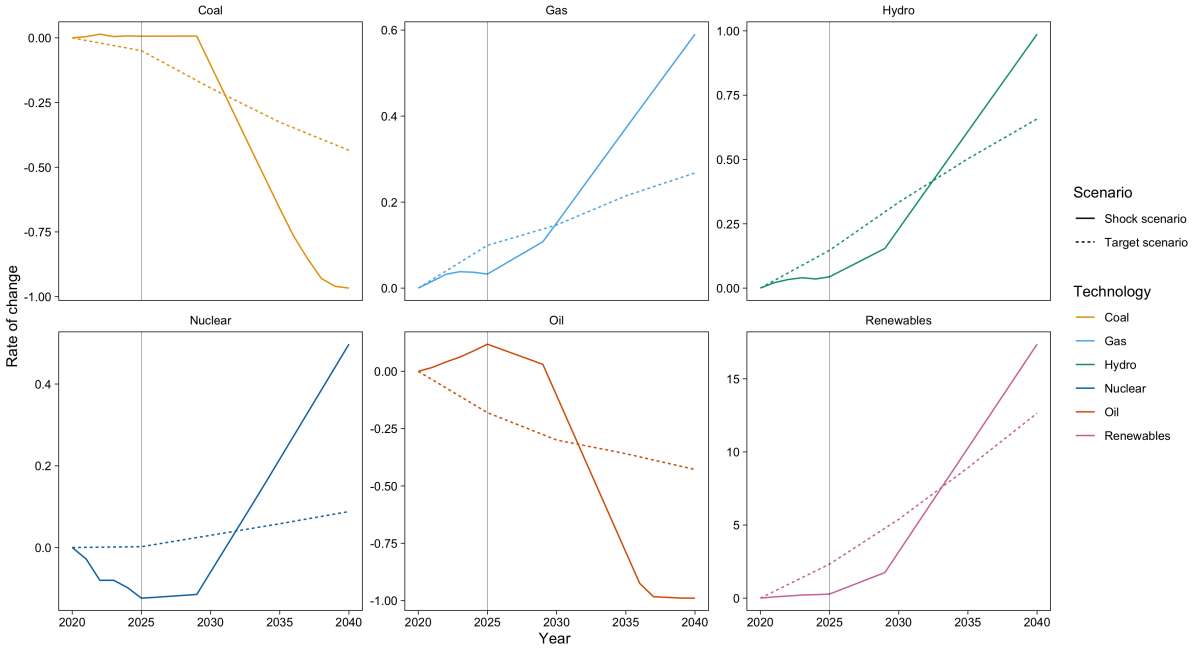


Figure 6: Stress Scenario. The graphs depict the constructed firm-specific target and stress scenario for a set of power firms. The scenario $s_2 = \{target\}$ reflects the IEA SDS that shows the required global change across high- and low-carbon technologies to meet the final energy demand by the global economy, while achieving the temperature goal set out in the Paris Agreement (below 2°Degrees). The scenario $s_3 = \{stress\}$ assumes that firms remain on their business as usual production trajectories as outlined in the Asset Resolution production plan data until a shock in 2030, that requires firm to shift production to meet the SDS while overcompensating for previous misalignment.

Further, the firms in $\mathcal{F}$ will be faced with scenario-consistent unit cost developments $c_{yhg}^{s,t}$ by the IEA (2020) and carbon tax trajectories $\psi_g^{s,t}$ from the 'disorderly transition' scenario by the NGFS (2020). The resulting scenario $s_3 = \{stress\}$ reflects a narrative of a disruptive production phase-out across technologies, unit cost changes due to technological progress and the sudden implementation of an increasing carbon tax. For a more detailed discussion on the construction of the scenarios and baseline settings of our exploratory analysis, please refer to section 4.3. In the next section, we outline how we model the different asset values of firm i under the baseline and stress scenario.

4.2.2 Layer Two: The Economy

In order to understand the propagation from the transition risk scenario s to the real economy, we need to introduce the heart of the TRISK model. That is a microeconomic framework to model the asset value and profitability of climate critical firms in the real economy based on their physical assets.

4.2.2.1 Firm Value under Different Scenarios

We represent the real economy as a set of heterogeneous firms i across sectors $y \in \mathcal{Y}$. Each firm i has a unique asset value $A_i^{s,t}$ that is given by the value of its stock of physical assets. We represent a firm i across its corresponding ownership tree and subsidiaries. We assume that a parent companies production levels $P_i^{s,t}$ are aggregated relative to the parent company's equity stake in its subsidiary (see Figure 24 for an illustration).

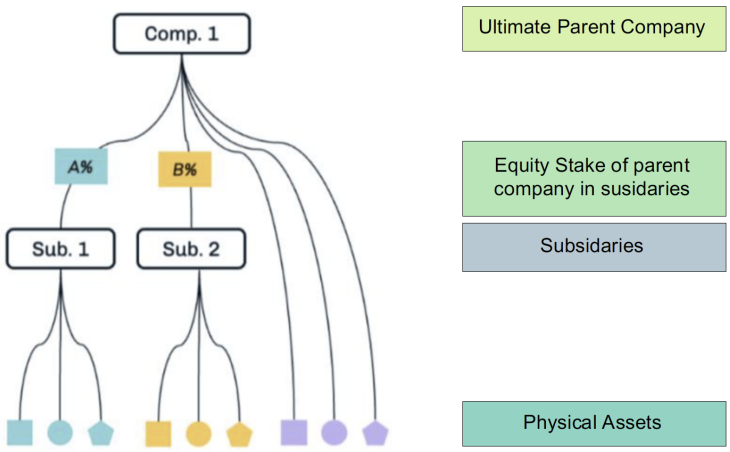


Figure 7: Illustrative example of asset-based activity aggregation in ownership tree of firms in climate stress testing framework. Note, that this has important risk implications, as the transition impact is modelled on the level of individual physical assets.

Importantly, each parent firms' asset value $A_i^{s,t}$ at time t in scenario s is given by the sum of the values of its physical assets $A_{i,a}^{s,t}$ across its ownership structure and subsidiaries, i.e.,

$$A_i^{s,t} = \sum_{a \in \mathcal{A}} A_{ia}^{s,t} \tag{3}$$

where the value of physical production assets $A_{ia}^{s,t}$ at time t in scenario s is given by the discounted sum of the profit generated by the asset a, i.e.,

$$A_{ia}^{s,t} = \sum_{t \in \mathcal{T}} \exp^{-\rho_j (t-T)} \mathbb{E}_t[\pi_{i,a}^{s,t}] + \Omega_{iar}^{s,T}, \tag{4}$$

where $\mathbb{E}_t[\pi_{i,a}^{s,t}]$ gives the assets' expected profits in scenario s at time t. Future profits are discounted at the firm-specific risk premium ρ_i that is given by

$$\rho_i = \rho^f + \beta_i \mathbb{E}[R^M], \tag{5}$$

where ρ^f is the risk-free rate. β_i represents the covariance between the firm return R_i^t and the market return R_M^t over the variance of the firm return, i.e.,

$$\beta_i = \frac{cov(\mathbf{R}_M, \mathbf{R}_i)}{var(\mathbf{R}_M)}, \tag{6}$$

where $\mathbf{R}_i, \mathbf{R}_M \in \mathbb{N}^{1\times|\mathcal{T}|}$. $\mathbb{E}[R^M]$ is the expected market return, which is also referred to as risk premium. We assume that after the time horizon of the stress test, future profits remain in a normalized state forever, given by the terminal value (perceptual growth) $\Omega_{iar}^{s,T}$, i.e.,

$$\Omega_{iar}^{s,T} = \frac{\pi_{ia}^{s,T}(1+r)}{\rho_i - r}, \tag{7}$$

where r is the long-term growth rate. The resulting expected profit of firm i can be estimated as the average profits over M Monte Carlo (MC) runs, i.e.,

$$\mathbb{E}_t[\pi_{ia}^{s,t}] \approx \frac{1}{M}\sum_{m=1}^{M} \pi_{ia}^{s,m,t}, \tag{8}$$

where $\pi_{ia}^{s,m,t}$ represent the realized profits of asset a of firm i in MC run m in scenario s at time t. For simplicity, we assume that the profit in each MC run m is the same[29]. Hence, as shown in equation 3 the asset value $A_i^{s,t}$ of firm i represents the sum of the net present values $A_{ia}^{s,t}$ of its assets a derived from a discounted cash flow model.

The profits $\pi_{ia}^{s,t}$ of firm i's asset a at time t are given by its revenues $R_{ia}^{s,t}$ minus its costs $C_{ia}^{s,t}$, i.e.,

$$\pi_{ia}^{s,t} = R_{ia}^{s,t} - C_{ia}^{s,t}, \tag{9}$$

where the revenue $R_{ia}^{s,t}$ of firm i's asset a is given by its production $P_{iyha}^{s,t}$ times the price $p_{yh}^{s,t}$, i.e.,

$$R_i^{s,t} = \sum_{y\in\mathcal{Y}}\sum_{h\in\mathcal{H}} P_{iyh}^{s,t} p_{yh}^{s,t}, \tag{10}$$

and the cost structure of firm i's asset a is represented, i.e.,

$$C_{ia}^{s,t} = \sum_{y\in\mathcal{Y}}\sum_{h\in\mathcal{H}} P_{iyha}^{s,t}(c_{iyha}^{s,t} + (1-\omega_y)\theta_{jyha}^{s,t}) \tag{11}$$

[29] hence we omit the m superscript going forward

and $\omega_y \in [0,1]$ represents the elasticity of sector y to pass through the carbon tax and avoid additional costs. $\theta^{s,t}_{jyha}$ represents the carbon tax in dollars, if any, per unit of production in industry y and technology h at time t applicable in scenario s to firm i' asset a. It is given by

$$\theta^{s,t}_{iyha} = \epsilon^{s}_{jyha}\psi^{s,t}_{iyha}. \tag{12}$$

Here ϵ^{s}_{jyha} denotes the tons of $C0_2$ firm i's asset a emits per unit of production in $\{y,h\}$ at time t. In other words, it is the emission intensity on the asset-level. $\psi^{s,t}_{jyha}$ denotes the carbon tax in dollars per ton of $C0_2$ emitted applicable in year t under scenario s.

From equation 10 and equation 11 it becomes clear that the profit margin ν^{t}_{i} of firm i across technology/business unit h is time-varying and dependent on the unit cost and price differentials across scenarios, i.e.,

$$\nu^{s,t}_{ih} = 1 - \frac{c^{s,t}_{ih} + (1-\omega_y)\theta^{s,t}_{ih}}{p^{s,t}_{h}} \tag{13}$$

This way the model captures changes in profit margins due to comparative advantages of individual firms and incorporates the cost-savings present in transitioning to a green business model resulting from advancements in technological innovation. This reflects increased profits for firms due to declining costs in, e.g. levelised cost of electricity in low-carbon technologies for the energy sector[30]. Note that while the model assumes firm-specific discount rates when modelling net present values of firms, these remain scenario independent and do not capture changes in finance cost, including dividend payments. Further, we recognise that also macro-financial pathways around changes in interest rates will impact financing costs and hence determine the ability of real economic firms to realise their transition plans in a cost-effective manner. Such dynamics are currently not captured and. Such a model advancement is left for further research to increase the sophistication of the corporate financial projections.

4.2.2.2 Stranded Assets

Our model allows to estimate the share of stranded assets for firm i that has an impact on the collateral value of a firm and their creditworthiness. More specifically, we assess carbon budget implications of a scenario s on the asset composition of firm i. We hereby rely on the respective carbon budgets set out in the transition scenarios defined in section 2. Put simply, we define stranded assets S_i of firm i as the ratio of the sum of firms' physical asset production $P^{s,t}_{ia}$ that is incompatible with a given scenario budget over the period $t = \{2020, ..., 2040\}$. Incompatibility is expressed as the overshoot of cumulative committed emissions across assets beyond a regional

[30]Note that the same principle applies to a wide range of climate-critical sectors and can be implemented with slight adjustments. For instance, in the automotive industry, different technology assumptions for batteries, internal combustion engines and electric cars can be applied.

carbon budget. We proceed in two steps.

First, we estimate the committed emissions $\chi_{iga}^{s,t}$ under scenario s for each emitting asset a of firm i in region g over the remaining period starting from time t under the transition baseline scenario.

$$\chi_{iga}^{s} = \sum_{t \in \mathcal{T}} P_{iga}^{s,t} \epsilon_{iga}^{t} \tag{14}$$

where ϵ_{iga}^{t} is the emission intensity of asset a of firm i.

Second, we identify the contribution of the asset to the carbon budget consumption of region g to identify an incompatibility threshold, beyond which the assets' production and emissions exceed the allowed consumption of the carbon budget. More specifically, we assume that the regional carbon budget B_{iga}^{s} is distributed according to the relative share of the assets production in the given region. Hence, the carbon budget B_{iga}^{s} as of time t of asset a of firm i in region g under a Paris-aligned scenario is given by:

$$B_{iga}^{s,t} = \frac{P_{ga}^{s,t}}{P_{g}^{s,t}} B_{g}^{s,t}, \tag{15}$$

where $B_{g}^{s,t}$ is the total remaining carbon budget in region g under scenario s as of time t. Hence, we have that at time t the share $S_{ig}^{s,t} \in [0, 1]$ of firm i's production across its assets a in region g, given the materialization of scenario s, is given by

$$S_{ig}^{s,t} = \sum_{a \in \mathcal{A}} \frac{\chi_{iga}^{s,t} - B_{iga}^{s,t}}{\chi_{iga}^{s,t}} \tag{16}$$

From equation 16 it becomes clear, that the stranded assets of firm i are given by the share of the firms production that is incompatible with a Paris-aligned carbon budget. Note that firms with a more sustainable asset composition and lower emission intensities face lower stranded assets than firms that have a large share of their production in high-carbon technologies and business units. We assume that this stranded asset measure is a key driver of financial risk as it indirectly depreciates the value of the firm's assets, when such assets serve as underlying collateral for outstanding debt or refinancing on capital markets (UNEP FI, 2018). Stranded assets directly feed into our credit risk model described in section 4.2.3.2 by linearly increasing the loss given default of firm i.

4.2.3 Layer Three: The Financial System

In order to understand the propagation of transition risk from the real economy to the financial system, we need to introduce the third layer of the TRISK model.

4.2.3.1 Financial Institutions

We represent financial sectors $s \in S$ (e.g., banks, investment funds, insurance and pension funds), by a set of individual financial institutions j. We represent each financial institutions j with a unique balance sheet composition. The exposure of each financial actor j to firm i can be decomposed along the main types of financial instruments. Following Battiston et al. (2017), A_j^t gives the total assets of financial actor j, $\mathcal{C}$ the set of climate-critical firms, and $\mathcal{V}$ = [equity, bond, loan] the set of financial instruments. The assets of financial institution j are then given by the asset value across its asset types with each counterparty, i.e.,

$$A_j^{s,t} = \sum_{i \in \mathcal{C}} \sum_{v \in \mathcal{V}} A_{jiv}^{s,t} \tag{17}$$

In what follows, we focus on the formulation and transmission channels of risk propagation through financial instruments that directly affect financial institutions balance sheets.

4.2.3.2 Expected Financial Loss

We then estimate the expected total financial loss $\mathbb{E}_t[L_{ji}^s]$ that financial institution j is facing in the scenario s as of time t. This is expressed as the sum of the expected losses from its individual asset exposure A_{ji}^v across all relevant asset classes $v \in \mathcal{V}$, i.e.,

$$\mathbb{E}_t[L_{ji}^s] = \sum_{v \in \mathcal{V}} \mathbb{E}_t[L_{jiv}^s] = \mathbb{E}_t[L_{ji,\text{equity}}^s] + \mathbb{E}_t[L_{ji,\text{bond}}^s] + \mathbb{E}_t[L_{jj,\text{loan}}^s]. \tag{18}$$

Equity. The expected financial losses for financial institutions j's equity exposure can be described as follows:

$$\mathbb{E}_t[L_{ji}^{s,\text{equity}}] = E_{ji}^{\text{stress},t} - E_{ji}^{\text{baseline},t}, \tag{19}$$

where $E_{ji}^{s,t}$ denotes the equity value of j's investment in firm i under the baseline and stress scenario and is given by

$$E_{ji}^{s,t} = \frac{u_{ji}^t}{u_j^t} E_i^{s,t}. \tag{20}$$

Hence, institution j's equity value in firm i is given by the current equity value of firm i in scenario s, $E_i^{s,t}$, times the number of equity shares j holds of firm i, u_{ji}^t, relative to the total number of outstanding shares of firm i, u_i^t. Equation 20 makes clear that institution j's equity investment in i changes proportionally to changes in the equity value of i. For simplicity, we assume that firm i's equity value at time t under scenario s is equal to its asset value $A_i^{s,t}$ in this scenario, i.e., the sum of all of its future dividend payments when discounted back to their present value. Refer back to section 4.2.2.1 which discusses how the asset value of firm i is obtained.

Bond and Loan. The expected financial losses for financial institutions j's bond and loan exposure can be described as follows:

$$\mathbb{E}_t[L_{ji}^{s,\text{loan}}] = (PD_i^{\text{stress}} - PD_i^{\text{baseline}}) * LGD_{ji}^s * EaD_{ji}, \tag{21}$$

For now, we assume that EaD_{ji} is not dependent on the scenario s, hence we assume a static balance sheet.

The LGD_{ji}^s of institutions j's investment in firm i is inversely linear dependent on the stranded assets S_i in the stress scenario, i.e.

$$LGD_{ji}^s = \lambda_{min} + (1 - \lambda_{min})S_i, \tag{22}$$

where λ_{min} represents the loss given default threshold that can be calibrated accordingly. Assuming log-normal asset returns of each firm $i \in \mathcal{C}$, the PD[31] of firm i in scenario s is, according to the Merton model (Merton, 1974), given by

$$PD_i^s = 1 - \mathcal{N}(DD_i^s), \tag{23}$$

where $\mathcal{N}$ is the cumulative standard normal distribution, and where the distance to default (DD) of firm i in scenario s is given by

$$DD_i^s = \frac{\log(A_i^{s,t}) + (\mu_i - \frac{1}{2}\sigma_j^2)T_i - log(L_i^t)}{\sigma_j\sqrt{T_i}}, \tag{24}$$

where μ_i denotes the expected return of the assets of firm i (and can be set to the firm-specific risk premium as defined in section 4.2.2) and σ_i the asset volatility of firm i. For now, we assume that this is scenario independent. Further, T_i represents the average maturity of firm i's liability. In the Merton model T_i is the maturity of the single liability of the firm. The asset value $A_i^{s,t}$ of firm i is scenario dependent and will be impacted in the stress scenario, depending on the firms strategic alignment and individual cost structure (see 4.2.2.1). The firms' liabilities L_i^t are assumed to be scenario-independent. The liabilities L_i of firm i can be calibrated based on observable debt levels.

4.2.3.3 TRISK

We now define the transition risk measure – put differently TRISK – of a firm i or financial institution j associated with the stress scenario $s_3 = \{stress\}$ relative to the baseline scenario $s_3 = \{baseline\}$. More formally, the TRISK of any firm or institution is the current value at time t of the expected dollar loss that it is estimated to suffer given the materialisation of the transition scenario. TRISK can be obtained across a wide range of different transition narratives and parameters in the set of scenarios $\mathcal{S}$ to represent a plausible range of risk estimates, depending on different beliefs around future transition pathways, technological change and carbon tax policies. More formally, TRISK for financial institution j is defined as:

[31] Note, that the creditworthiness of some state-owned firms are highly dependent on the home countries' credit profile (Hoepner, Oikonomou, Scholtens, & Schröder, 2016), which cannot be sufficiently captured yet.

$$TRISK_j^{s,t} = \sum_{v\in\mathcal{V}}\sum_{i\in\mathcal{C}} TRISK_{ji}^{s,v,t} = \mathbb{E}_t[L_{ji}^{s,\text{equity},t}] + \mathbb{E}_t[L_{ji}^{s,\text{bond},t}] + \mathbb{E}_t[L_{ji}^{s,\text{loan},t}], \tag{25}$$

where $TRISK_{ji}^{s,t}$ represents the dollar loss that financial institution j could suffer on its portfolio of assets of type $v \in \mathcal{V}$, where $\mathcal{V}$ is the set of financial assets. Further, $TRISK_{ji}^{s,v,t}$ denotes the TRISK institution j faces in scenario s on its asset investments of type v in firm i, where $\mathcal{C}$ represents the set of analysed firms in climate-critical sectors. This can also be expressed as expected loss in relative terms to the overall exposure of financial institution j, i.e.,

$$\mathbb{E}_j[L] = \frac{TRISK_i^{s,v,t}}{A_j} * 100. \tag{26}$$

We can also define the TRISK for each real economic firm i across two dimensions, irrespective of the financial risk implications. First, $TRISK_i^{NPV}$ is expressed as the relative percentage change in the net present value of firm i between the stress and the baseline scenario , i.e.,

$$TRISK_i^{NPV} = \frac{A_i^{stress} - A_i^{baseline}}{A_i^{baseline}} * 100. \tag{27}$$

Further, $TRISK_i^{PD}$ is expressed as the difference in the probability of default of firm i between the stress and the baseline scenario , i.e.

$$TRISK_i^{PD} = PD_i^{stress} - PD_i^{baseline} \tag{28}$$

This way risk implications can also be reflected on the country level. Here, $\mathcal{O}$ represents the set of firms i headquartered in country c. The $TRISK_c$ of country c is then the sum of TRISK across domestic firms, i.e. $\sum_{i\in\mathcal{O}} TRISK_i^{NPV}$ and $\sum_{i\in\mathcal{O}} TRISK_i^{PD}$.

Indirect impact. A large portion of total assets held by financial institutions are issued by other financial institutions (Battiston et al., 2017). As a result, there is a potential systemic risk that can materialize through the so-called second-round effects (Stolbova et al., 2018). In the breakdown of total assets $A_j^{s,t}$ by financial institution j , we can distinguish the securities issued by firms in the financial sectors $s \in \mathcal{S}$ (whose values additionally depend on their own assets' values as A_j) from those issued directly by firms in the climate-critical sectors $i \in \mathcal{C}$ to obtain:

$$A_j^{s,t} = \left[\sum_{i\in\mathcal{C}}\sum_{v\in\mathcal{V}} A_{jiv}^{s,t}\right] + \left[\sum_{j\in\mathcal{S}}\sum_{v\in\mathcal{V}} A_{jjv}^{s,t}\right]. \tag{29}$$

Put simply, financial institution j is not only directly exposed to firm i (which asset value $A_i^{s,t}$ is impacted by the transition shock), but also holds exposure to other financial institutions j across financial sectors $s \in \mathcal{S}$, which itself has exposure to transition-affected firms and hence see their own asset values diminishing. Note that such a representation of indirect holdings

represents the potential second-round losses in its simplest form and neglects amplification mechanisms due to the reactive behavior of financial institutions, fire-sale assumptions and broader contagion effects. However, the shocks on the individual firm-financial level could inform more complex heterogeneous network models, such as (J. D. Farmer, Kleinnijenhuis, Nahai-Williamson, & Wetzer, 2020b). Such an integration allows for a more comprehensive analysis of systemic resilience across a set of financial sectors and goes beyond the scope of this paper.

4.2.4 Model Limitations and Main Assumptions

The model faces some limitations, some of which require assumptions that are discussed more in detail here.

The Economy. While the framework accounts for the three drivers of a transition shock, i.e., demand changes, technological change and policy-induced carbon pricing, these are modelled in isolation. There is no interaction mechanism between scenarios in the model that represents the potential compounding and amplifying nature of the risk drivers. Further, the TRISK framework has a simplified representation of the asset value of firms. For instance, we assume that the revenue of a firm is solely dependent on the future cash flows generated through its physical production infrastructure. For now, the model does not account for other revenue or income generated from other than the firms core business activities. It neglects the potential income due to investments in other business segments or other financial income.

Table 3: Main assumptions and justification

Main model assumptions	Jusitification
(1) Market share of firm i remains constant following 5-year production plan and demand changes are downscaled on a pro rata basis	• Lack of predictability of changing market conditions and firms behaviour. While relative market shares for technologies remain constant, firms profits from this market share will be differentiated based on scenario-dependent unit cost developments, firm-specific profit margins and overall business unit and technology composition
(2) Constant emission intensity based on asset-level characteristics	• The emission intensity remains constant for each specific asset technology. So the overall emission intensity of the firm is a unique composition of its assets. When a firm reduces high-carbon technologies production it will also significantly lower overall carbon emissions. Also, emission intensities for high-carbon technologies will likely remain relatively constant in the future (Way et al., 2021) (except in the face of uncertain deployment of CCS technologies)
(3) Firms debt structure remains constant	• Firm liabilities are calibrated on current observable market values. The lack of model complexity does not allow for scenario-dependent changes in firms' debt level. Changes to the firms leverage are solely driven by transition impacts to the asset value. A more adequate representation of firms balance sheet is left for further research
(4) Equity volatility and asset drift in the credit risk model remains scenario-independent	• Increasing the complexity of the credit risk framework may not yield more precise estimates in the face of increasing uncertainty around these parameters.
(5) Firms profits depend only on physical production base	• Given the calibration on asset-level data, and the availability of such data only for core technologies in climate-critical sectors, we assume that the firms profits are solely dependent on its physical production. When firms generate significant cash flows outside of their core activity, the model is likely to result in an over or underestimation of TRISK.
(6) Limited adaptive capacity modelled	• Data-driven production plans of firms stipulate the ability to adapt to changing markets. Model mechanisms are currently set in a way that firms that have not yet build out, and are indeed not planning to build out sustainable technologies in the near future, miss out on the opportunity to capture market shares in an expanding market. This assumption is justified on the basis of a lack of predictability and explicit representation of adaptive capacity and is closely linked to assumption (1).

More importantly, we assume that a firms' market share remains constant based on the pro rata changes across technology demand, stipulated by the sector decarbonisation pathway. This is not a realistic representation of firms competitive behavior, where first-movers that invest early in such markets are likely to dominate over climate laggards, hence increasing their

relative market share through competitive advantages. The constant market share assumption does not permit a comparison of a firms' competitive strategic response against its peers. While this assumption may hold true in mature sectors with high barriers to new entrants, it needs to be sensitised for a better understanding of the risks, where sectors are facing a higher penetration of new market entrants and highly competitive dynamics among peers. However, note that the objective of the stress test is to provide a risk estimate based on the assumption that firms have only limited foresight and make no adjustments to their current plans to represent the baseline scenario. It is not intended to model the strategic response and interaction of those firms. This is left to further research and agent-based models may provide a promising further avenue for this as discussed in the conclusion of this paper. Consequently, the model is faced with limitations in fully capturing the adaptive capacity, dynamic shifts in companies strategies and reactive behavior in competitive markets. For instance, the model mechanisms are currently set in a way that firms which have not yet build out, and are indeed not planning to build out sustainable technologies in the near future, miss out on the opportunity to capture market shares in an expanding market throughout the stress testing horizon. This indirectly penalises firms that are climate laggards in some technologies, preventing them from catching up throughout the time horizon. What is more, for the calculation of the stranded assets and the applicability of the carbon tax on the firm-level, we assume constant emission intensities on the asset-level due to data limitations. This may underestimate the potential of firms to utilise carbon capture and storage technologies. Further, it should be noted that the impact of the carbon tax scenario is sensitive to the calibration of the pass-through rate ω_y. Future research could include a sensitivity analysis around varying levels of the pass-trough rate by sector to reflect a competitive advantage of low-cost producers.

The Financial System. The model does not fully capture a probabilistic approach around the expected shortfall and unexpected loss of exposed financial institutions. Note, that also the choice of financial models, the discounted cash flow model and the Merton approach are not without limitations. For instance, the Merton credit risk framework assumes perfect competition and efficient financial markets without frictions, as well as a normal distribution of the shock and market value of assets - assumptions that, in the context of tail-risk distributed risks under a extreme but plausible transition scenario could be violated[32].

Further we assume a scenario-independent asset volatility, where the shock transmission will enter the credit risk only through a relative change of the equity value of firm i and the impact of stranded assets on the loss given default. This is clearly a limitation and may lead to an underestimation of the TRISK, as it is reasonable to expect that also the volatility increases in relation to a declining absolute equity value. Such a stochastic representation of the transition

[32]For a detailed discussion on the limitations and assumptions underlying the Merton framework please refer to e.g. Sundaresan (2013)

risk channel is however currently not incorporated in the model and is left for future research. This also highlights the need for a better representation of firms reactive behavior to initial shocks. This could be modelled through the representation of both, dynamic balance sheets of financial intuitions exposed to transition risk, and the dynamic response of financial institutions itself to restructure their balance sheet in response to a TRISK shock. For instance, if a bank suffers a financial loss due to the direct impact of climate-related risk (e.g., decreasing loan quality and increased probability of default to TRISK exposed firms) it is likely to deteriorate their capitalisation and profitability. This may trigger certain amplification effects within the banking sector, as it could be perceived from an investor perspective that this particular bank has a lower creditworthiness. This in turn may result in an increase of funding cost on the inter-bank market, further deteriorating the bank's profitability and ultimately threatening banks' solvency.

Last, it should be highlighted that the transition-related changes in PDs should be interpreted carefully, due to the context of longer time horizons. The TRISK probability of default does not represent a one-year PD as interpreted in the classical financial context. The PD changes incorporate the discounted shock effect that spans across the horizon of the stress test and hence do not represent the true probability of a firm defaulting, but rather reflect the potential range and spectrum of a default if the future transition dynamics were priced in today. This incompatibility of classical finance risk models with longer time horizons highlights the need for new innovative climate-related financial models that are designed for the purpose of higher uncertainties and longer time frames. This is a more fundamental critique, where the finance and research community needs to accelerate efforts to develop more appropriate tools and techniques.

4.3 Results of Exploratory Application

This section presents the results of an exploratory application of the TRISK model to an illustrative set of 135 public power firms that in 2021 capture around 30% of global power production and are responsible for 4.543 Gt of CO_2 or around 34% of power-related global emissions (see Appendix A for descriptive statistics). These firms are headquartered in 29 countries, and through their ownership structure own 8025 physical power assets across 92 countries. We further decompose these firms into relevant business units to capture the unique composition of electricity generating technologies.We distinguish between electricity generation from oil, coal, gas, renewables, hydro and nuclear. Together, these firms represent a total market capitalisation of US$ 1.87 trillion and outstanding debt of US$ 1.86 trillion US$.

We present our results on two stages, reflecting the flexibility of the model to produce TRISK estimates on economic firms ($TRISK_i^{NPV}$ and $TRISK_i^{PD}$ respectively; see subsection 4.3.2) and on financial institutions ($\mathbb{E}_j[L]$; see subsection 4.3.3). In the next section we explain in detail the calibration of the baseline results.

4.3.1 Calibration Strategy

We calibrate the TRISK model for a set of public power firms across multiple scenario inputs. Table 4 presents the detailed calibration strategy of main parameters in the model. Information on firms production composition P across technologies, five-year plans and emission intensities θ_a on the physical asset level are taken from Asset Impact, but the availability of asset-level data across many climate critical sectors is steadily increasing across different providers, e.g. Spatial Finance Initiative (SFI)[33], Global Energy Monitor[34], the World Resource Institute[35] among others.

Table 4: Baseline settings of results.

Time horizon [t,T] of climate stress test	• $t = 2020$, $T = 2040$
Shock Year	• 2030
Stress Scenario	• $s_1 = \{baseline\}$ until the introduction of "climate action" in shock year Z_{2030} • from $t = \{2030, ..., 2040\}$ $\Delta P_{iyh}^{stress,t}$ derived from $s_2 = \{target\}$ • unit cost developments $c_{yhg}^{s,t}$ by the (IEA, 2020) • carbon tax trajectories $\psi_g^{s,t} = 0$
Baseline Scenario	• $P_{iyh}^{s,t}$ over the period $t = \{2020, ..., 2025\}$ calibrated on production plans of firm i from AR and $\Delta P_{iyh}^{s,t}$ obtained from the current policy scenario 'CPS' by the (IEA, 2020) for the remainder of the stress testing horizon ($t = \{2025, ..., 2040\}$) • unit cost developments $c_{yhg}^{s,t}$ by the (IEA, 2020) • Carbon tax $\psi^{s,t} = 0$
Discount rate, ρ	• $\rho = 4{,}83\%$ (Cost of equity with $\rho^f = 0.02$, $\beta_j = 0.0073$ and $\mathbb{E}[R^M] = 0.0387$)
Profit margin ν_i	• Firm-specific for $t = 0$, EIKON data, adjusted by firm-specific cost evolution for $t > 1$,
Prices, $p_h^{s,t}$	• We assume that the unit end-price for each technology $p_h^{s,t}$ at time t in scenario s depends on the average unit costs for the technology $\bar{c}_h^{s,t}$ as well as the average net profit margin $\overline{\nu_i}$ of firms, i.e. $p_h^{s,t} = \bar{c}_h^{s,t}(1 + \overline{\nu}_i)$
Carbon budget, B_{iga}^s	• $B_{iga}^s = 466$ Gt/CO_2 (1.5° Degree Target)
Volatility of asset, σ	• firm-specifc; Refinitiv Eikon data (48 month average as of 2022)
asset drift, μ	• firm-specifc; Refinitiv Eikon data (48 month average as of 2022)
growth rate r	• $g = 0.02$ (World Bank average 2012-2022)
Maturity of financial instrument, T	• Global corporate average for sample portfolio (Chen, Ganum, Liu, Martinez, & Martinez Peria, 2019)
Loss given default threshold λ	$\lambda = 0.45$
Set of Firms	• 135 public firms, $\mathcal{Y}$ = power sector, $a = 8025$ assets • $\sum E_i = 1.87$ trillion US$ • $\sum L_i = 1.86$ trillion US$
Production levels $P_{iyh}^{s,t}$	• Asset Impact data
Asset emission intensity ϵ_{jyha}^s	• Asset Impact data

Scenario pathways are taken from the International Energy Agency for the baseline results. Profit margins are firm-specific and gathered from EIKON Refinitiv, as of December 2022 (see Appendix A). Using those profit margins we construct unit end-price for each technology $p_h^{s,t}$ at time t in scenario s by taking the the average unit costs for the technology $\bar{c}_h^{s,t}$ as well as the average net profit margin $\overline{\nu_i}$ of firms, i.e. $p_h^{s,t} = \bar{c}_h^{s,t}(1 + \overline{\nu}_i)$. We calibrate the discount rate with the weighted-average cost of capital (WACC) for the respective sector y that is 4,83% as of December 2022, assuming a constant beta, constant risk premium and a constant risk-free rate. The risk-free rate ρ^f can be set equal to the 30Y US treasury yield, the firm- or sector

[33] `https://www.cgfi.ac.uk/spatial-finance-initiative/`

[34] `https://globalenergymonitor.org`

[35] `https://datasets.wri.org/dataset/globalpowerplantdatabase`

specific beta β_i and the global risk premium $\mathbb{E}[R^M]$ to be the excess CAPE yield of Shiller[36] (see again table 4). Further, to estimate the terminal value in equation 7 we need to calibrate the standard economic growth rate r, based on historical observations, which is assumed to be 2%. This enables us to compute the cash flow for each firm and asset under different scenarios.

To calibrate the financial layer of the TRISK model, additional information for firms is needed. This includes the total number of outstanding equity shares of firm i, annualised volatility σ_i and rate of change of the market value of the firm's assets μ_i, market capitalization E_i and outstanding debt levels L_i, debt-to-equity leverage ratios, and standard PDs[37]. We take those values, where possible as 48 months averages, from EIKON Refinitiv as of December 2022.[38] Note, to estimate the expected financial loss in this exploratory analysis we construct two synthetic portfolios, the asset composition of which is described in detail in subsection 4.3.3.

[36] See: `http://www.econ.yale.edu/~shiller/data.htm`

[37] A common challenge with the Merton framework is the alignment of model predicted PDs with empirically observed PDs (Cormack et al., 2020). Note that our TRISK model produces estimates on the transition-related changes in probabilities of default, which can then be used to adjust the empirically observed probabilities of defaults (Cormack et al., 2020).

[38] Note that further assumptions have to be made for firms and FIs on which we do not have such granular information. Here, we propose to construct meaningful benchmark averages to populate missing values. Especially for private firms we can, for example, assume that the leverage of each energy company is given by a target leverage of debt over enterprise value of similar sized public firms in the same region.

4.3.2 Impact on Firms

The transition risk across our analysed set of firms shows significant heterogeneity. Table 5 summarises the transition related impact on firms' net present values (NPVs) - $TRISK_i^{NPV}$ - and probability of defaults (PDs) - $TRISK_i^{PD}$ - expressed as relative changes from the baseline scenario. We observe that depending on the firms' alignment of business strategy, cost-advantages across its business units and technologies, as well as individual balance sheet compositions and leverage, the $TRISK_i^{NPV}$ varies significantly, with an average impact of -14%. Such an average impact is largely aligned with findings of previous studies, such as Vermeulen et al. (2019) and Reinders et al. (2020b) that find market risk estimates for firms between 9-34% depending on severity of shock, although for a wider range of high-carbon sectors and not explicitly restricted to the power sector[39]. Importantly, TRISK estimates highlight the significant within-sector variation that these studies do not explicitly capture. We observe a large standard deviation, with the 5^{th} and 95^th percentile of $TRISK_i^{NPV}$ around -49% and 11.56%. Individual firms that are highly misaligned even see their net present values decline by around 80% in the stress scenario relative to the baseline scenario. Unsurprisingly, firms with a Paris-aligned strategy even receive net positive impacts of up to 21% from the transition shock.

Table 5: Descriptive statistics of key results for TRISK of 135 international power firms, expressed as average net present value changes and probability of default changes.

	5th Percentile	Mean	Median	95th Percentile
Net present value changes (in %)	-48.96	-14.22	-10.31	11.56
Probability of default changes (in percentage points)	-0.15	0.34	0.00	2.17

On average, we observe an additional 0.34 percentage points in probabilities of defaults for the analysed firms in the stress scenario relative to baseline scenario. Yet, there is significant variation in $TRISK_i^{PD}$ between -0.15 and 2.17 percentage points, reflecting that some firms see positive changes to their creditworthiness (negative PD change) while other firms may see large PD increases in the net-zero transition. For highly impacted firms this represents an up to five-fold relative decrease in their creditworthiness. While PD changes tend to be smaller in absolute scale, in part due to difficulties in reflecting longer time horizons in credit risk models (see limitation section 4.2.4 for discussion), we see a strong heterogeneity in the impact and a negative correlation with the impacts on the firms' asset values, as shown in Figure 8.

Differences in PD changes across the worst affected firms can be attributed to initial differences in debt-to-equity ratios and profitability. This is intuitive, as firms with a strategic

[39]Note that our subset of firms is not externally valid for the global power sector, hence comparison to other studies should just be taken as initial indication.

transition misalignment see their NPVs worsened, which moves those firms closer to their default thresholds in credit risk models. Further, we can decompose the impact on firms' creditworthiness, by representing the annual changes in the PDs across the time horizon of our stress test exercise. We find for the sample of analysed firms that the additional annual PD change due to the transition-related shock remain largely unaffected in the years following the shock. Following this, we observe a non-linear increase towards the end of the time horizon, reaching an additional 3.5 percentage point increase in the average PDs between 2030-2040. This highlights the significant impact on the credit quality of analysed firms towards the end of the time horizon, with potential severe effects on the expected losses for financial institutions exposed to these firms.

Overall, we observe that a large share of the analysed firms are highly misaligned with the climate targets of transition scenarios.[40] Most firms are therefore not only at high risk of significant transition disruptions and decreasing profitability, but also hinder the structural transformation of the global power sector. Further, we identify significant variation in the transition impact across firms, with the risk distribution negatively skewed due to highly affected climate laggard firms. Figure 8 highlights the complexity and variation in transition impacts across firms, that would be missed in purely sectoral exercises.

[40]Note that for this exploratory analysis, we assumed a global shock scenario, that does not adequately reflect the regional differences and policy landscape of economic decarbonisation trends. We expect that more geographically differentiated stress scenarios will deflate the negative impact on firms operating in developing and emerging economies. This is due to the fact that climate commitments remain behind advanced economies and high-carbon dependencies are higher for several economic, political and development reasons. Transition decarbonisation scenarios are therefore less strict and the phase out of high-carbon technologies is delayed.

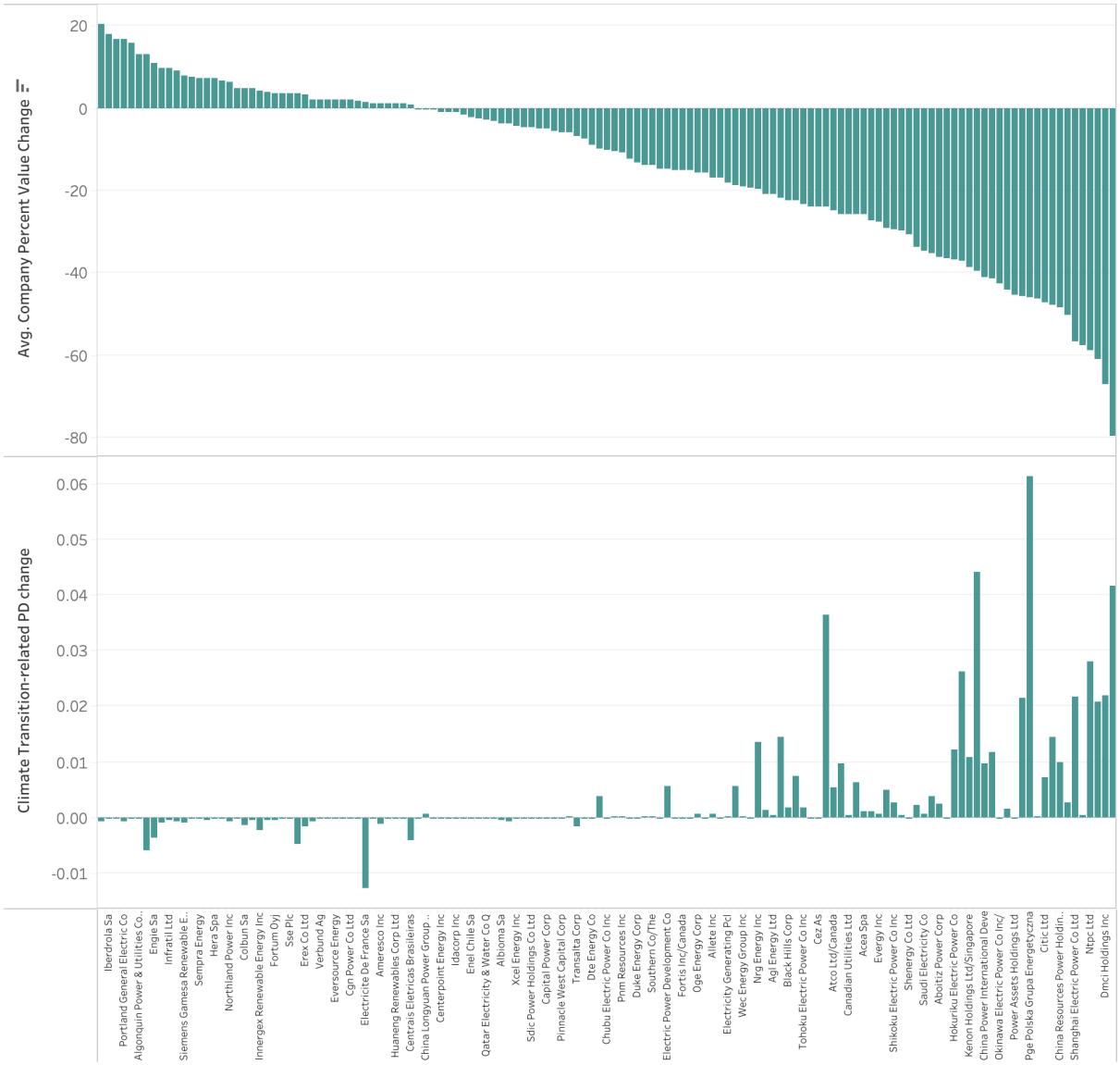


Figure 8: Heterogeneity in transition risk for the set of international public power firms. TRISK is expressed as the relative change in net present value of a firm in percent and the absolute percentage change in the probability of default of a firm in the stress scenario relative to the baseline scenario

This highlights the added-value of granular stress testing frameworks that allow to differentiate between transitioning firms and climate-laggards, to effectively inform policy makers and financial institutions across jurisdictions on the distributional transition impact. However, it should be noted that the strengths of such a granular firm-level risk approach is to simulate firm's asset values under a variety of different scenarios rather than to focus on the quantitative result per se. The decision usefulness of the analysis lies in the flexibility of the approach to test a large set of firms within a sector to different assumptions on how the transition could manifest. What is more, as the model does not allow for an explicit response by firms to the

policy-induced shock, it cannot be seen as a predictive model. Rather, the model can highlight which firms are at higher risk, for example, which firms are more misaligned with the applied decarbonisation pathways under the assumption that firms continue on a business-as-usual trajectory until the end of the stress test horizon. It follows that the results of the TRISK application represent risk estimates that sit further in the tail of the probability distribution, i.e., are extreme but plausible. This follows the use case requirements of a risk management and stress testing approach as outlined in paper III.

The analysis also allows us to draw some initial conclusions on the geographical risk distribution. The analysis suggests that European power firms are on average less negatively impacted by the transition, than US and Asian counterparts[41]. However, we still observe individual firms across all jurisdictions that significantly deviate from peers in their region - both, negatively and positively. Our empirical analysis further allows to assess firms' subsidiaries and individual physical assets across the ownership structure of firms globally. Such interconnected economic networks, where production facilities in Asia are owned by European counter-parties and vice versa, stresses the need for a global analysis on the firm-level. Even the relatively small selection of international power firms, while headquartered across 22 countries, own more than 8.000 individual power assets across 92 countries. This reflects interconnected modern production networks. As transition risks not only depend on the institutional framework and governments' net-zero commitments where firms are headquartered, but also on the policy landscape and efforts in countries where supply chains and production facilities lie, it seems crucial to structure climate stress tests based on bottom-up microeconomic and spatial models, able to capture such differences.

To showcase what is driving the results on the firm-level, figure 9 shows for a selection of firms the infra-firm variation of transition impacts across business units (technologies) and the overall weighted $TRISK_i^{NPV}$. We observe that firms with active business units and high dependencies to production in high-carbon technologies (i.e., electricity generated from coal, oil and gas) are negatively impacted due to demand changes and increased relative unit costs, lowering their future cash-flows. For instance, some firms see their net present value of coal power business units decline between 55-60% depending on firms' cost advantage vis-a-vis its peers. Note that the technology demand shock is the same across all firms, allocated on a pro rata market share basis. This variation in impact across firms is even more prominent in operations focusing on renewable power generation. Here, depending on the respective market share of a firm in such technologies, cash flows from such business units are increasing, driven by first mover advantages. This is especially prominent for E.On Se. While the firm' cash flows are significantly negatively impacted across its high-carbon technology business units, its overall

[41]This finding may be more robust for the US, as Asian counterparts may be more severely affected by the global scenario as they would be in a more adequate regional one.

TRISK is positive at around 20% due to its growing renewable electricity generation that more than overcompensates for the declining profitability in other segments.

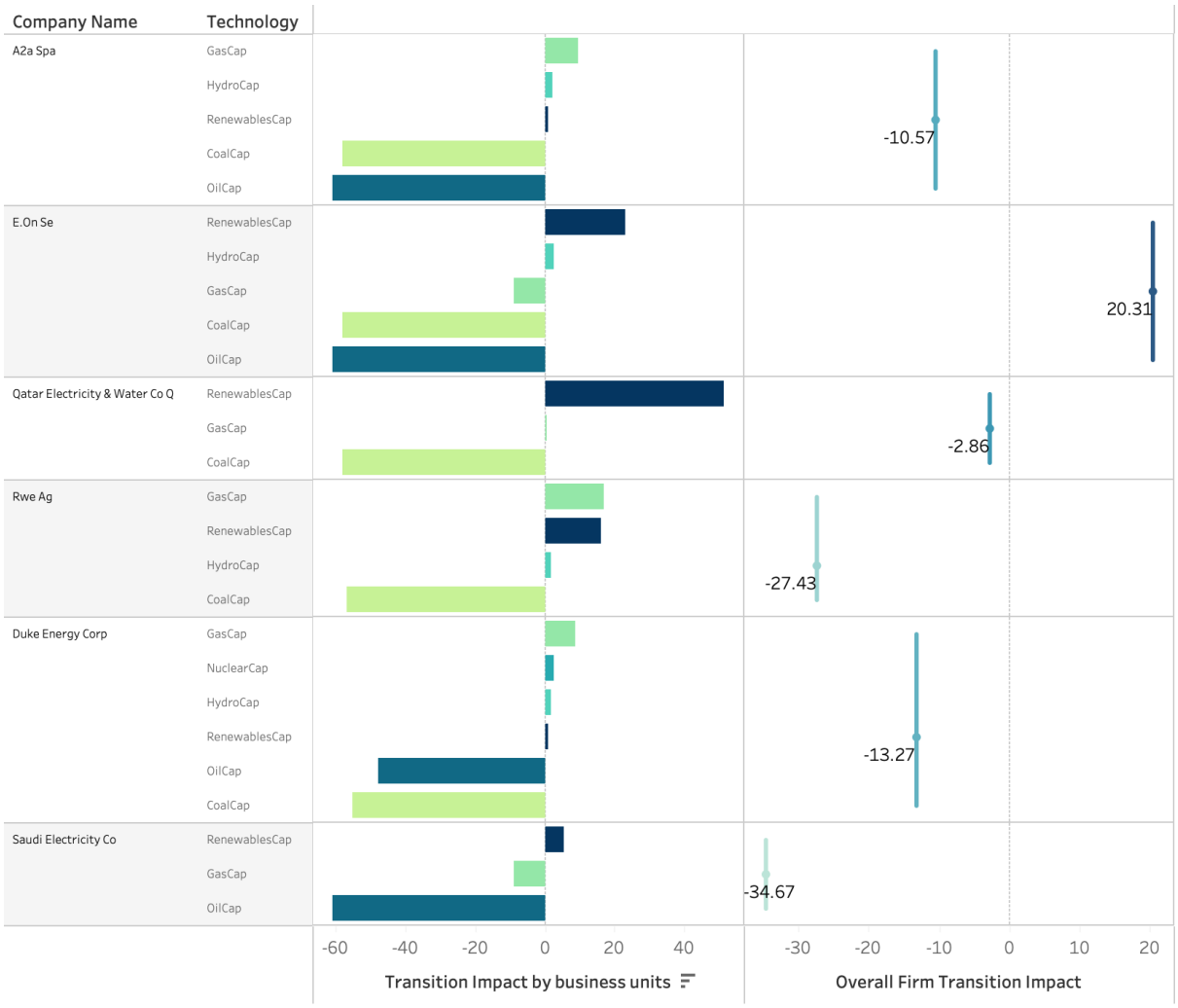


Figure 9: Within Firm heterogeneity across business units and overall transition-related impact

This shows, that the transition impact is in addition to technology-driven cost differentials, driven by the firms production composition and demand effects across its relevant business units[42]. Such demand effects are represented in the model as the required production change derived from the target scenario. Note that such changes can be driven endogenously by strategic shifts of firms operations, consumer behavior or policy induced-phase outs of high-carbon technologies[43]. The model aims to leave the reason of the introduced "stress" to the system open for interpretation. However, as the model mechanisms allows for a parametrisation of the

[42]Note that not all firms in our sample are pure power firms and may generate income from other business units outside of climate-critical sectors, in which case we would overestimate the transition impact on the firm.

[43]Or mixture of the above drivers, e.g. governments introduce a steep carbon tax on fossil fuels, which increases the prices to the end consumer and demand flattens

shock year, the degree of disruption resulting from such a shock can be adjusted and tested. Further, the TRISK model is set up in a way to allow for sufficient flexibility around the severity of the stress scenario. The approach can represent different levels of conservativeness of key scenario assumptions. For instance, it can be assessed what the risk implications are for energy companies if a faster uptake of renewables in the energy system is assumed as opposed to more pessimistic assumptions around technological deployment of low-carbon technologies. This is discussed more in detail in section 4.4. of this DPhil. The aim of this exercise is to enhance the credibility of the TRISK model by showing the large variations that result from different key underlying assumptions that are highly uncertain due to the long-time horizons involved and the inherent difficulty to plausibly describe how the energy system is evolving over time.

In this context, while the model outputs the quantitative results such as transition-related changes in the net present value of firms or changes in their probability of default, this should not be taken as predictions (even for the given scenario narrative) but always be interpreted as conditional on the manifestation of underlying scenario assumptions and in the context of the imitations and set-up of the model (this is discussed more in detail in subsection 4.2.4). This can provide important decision-useful insights such as how are energy firms impacted differently conditional on variations in the rates of change of a fossil fuel phase out stipulated in the energy decarbonisation scenario.

Stranded Assets. The TRISK model also allows to estimate stranded assets, i.e., the share of production that is incompatible with the carbon budget in the target scenario. This allows us to proxy the impact on collateral values and the resulting loss given default in the financial layer. As a baseline setting, we assume a global carbon budget of 460bn tonnes of CO2 as outlined in the SR15 by the IPCC[44]. We further allocate the carbon budget for the set of firms in our sample, by estimating the share of firms' individual production levels in 2020 relative to the global power production and the attributed carbon emissions[45].

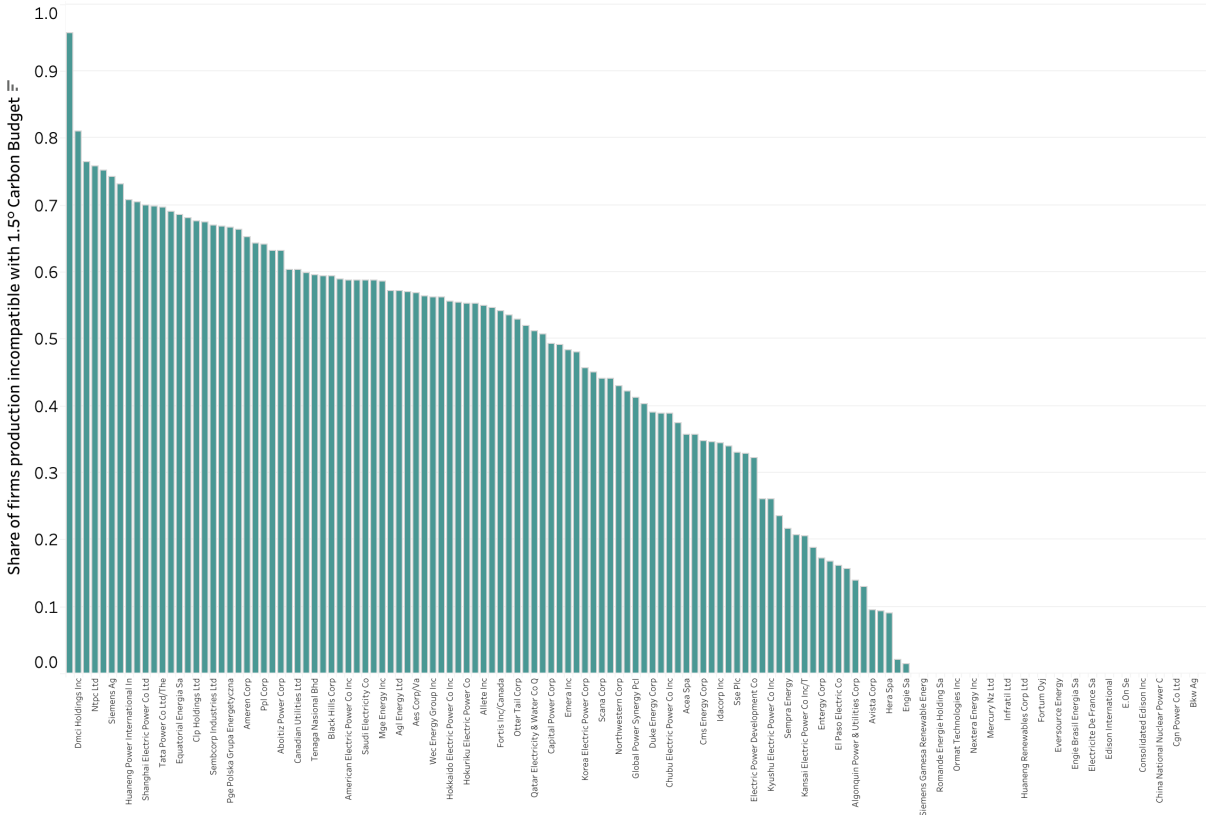


Figure 10: Share of Stranded Assets by firms

Figure 10 shows the distribution of stranded assets ($S_i^{s,t}$) across the set of analysed firms. While the power production of around 26% of the firms are compatible with a 1.5° carbon budget, the majority of firms face the risk of stranded assets. Individual firms risk up to 95% of their production to be stranded, hence rendering production facilities uneconomically in the face of strong climate action and demand changes.

[44] `https://www.ipcc.ch/sr15/`

[45] The share of the power sector carbon emissions is based on World Electricity Power Production: BP Statistical Review of World Energy, Ember Global Electricity Review (2022) Ember European Electricity Review (2022)

4.3.3 Impact on Financial Institutions

In this section, we present the TRISK that individual financial institutions face in a stress scenario, expressed as the expected loss $\mathbb{E}_j[L]$ relative to the overall portfolio size. The focus of the analysis is to highlight the distributional consequences of the transition depending on the unique portfolio composition and balance sheet of an FI. For this, we construct two portfolios that represent extreme cases[46]. Portfolio A includes equity and debt to the 18 least impacted power firms in the stress scenario, with an overall portfolio exposure of 512 billion US$. Portfolio B includes equity and debt to the 24 most impacted power firms in the stress scenario, with an overall portfolio exposure of 524 billion US$. These portfolios hence represent the full spectrum of transition impacts. We further assume a constant balance sheet throughout the time-horizon of the stress test, hence do not represent strategic behavior of FIs or feedback mechanisms between the economy and the financial system.

We estimate the TRISK - i.e., the expected loss from transition-related market and credit risk - across the two constructed portfolios. The results are intuitive. FIs that are invested or provide credit to firms that are aligned with climate objectives are the winners of the net-zero transformation, even seeing an overall reduction in expected losses. FIs that are exposed to misaligned firms are the losers and might be facing significant financial losses. Across the two portfolios the overall TRISK relative to the overall portfolio size varies between a highly negative impact of around 18% as opposed to an overall positive impact of around 8%. Table 6 provides a summary. The impact is stronger on market risk losses, reflecting that equity prices are more volatile and sensible to investors and market behavior than expected losses or provisions from outstanding debt. It is evident that the transition inhibits clear distributional consequences across the financial sector, with potential amplification and second round effects if the TRISK creates solvency issues. It is borne by financial institutions that have portfolio exposure to firms most at risk from the transition.

Table 6: Descriptive statistics of key results for TRISK in the two sample portfolios, expressed as transition-related market risk and expected loss from credit risk relative to overall portfolio size in %.

	TRISK $\mathbb{E}_j$[L]	Portfolio Size (in $US billion)	No. of firms exposed
Portfolio A (least impacted firm)	7.80	512	18
Portfolio B (most impacted firm)	-18.03	524	24

Capturing such a heterogeneity in scenario and stress testing models is crucial to inform

[46] We assume all outstanding debt is held with a maturity of 5.61 years, representing the global corporate average (Chen et al., 2019). We further assume impacts on the firms profits are passed on directly to shareholders by reducing dividends accordingly.

financial markets and regulators. The failure to distinguish transitioning firms from climate laggards within the same industry in current financial risk management practices is problematic. Firms belonging to carbon-intensive sectors today, such as the power sector, will need to receive plenty of funding at a low cost of capital in order finance the net-zero transition and expand world energy capacity to meet the increase in world demand. Large energy firms may have the most know-how and skills to produce energy at scale to meet future demand. Therefore, investors should divest only from those firms that do not plan to transition to a greener business model. The TRISK results show how the portfolio composition determines the exposure to transition risk and shows how a well aligned portfolio can not only serve to hedge risk but also contribute to providing finance to those firms that are planning to transition.

4.4 Treatment of Uncertainty and Variability of Risk across different scenarios

Given the uncertainties around the transition scenario, we recognise the need for the TRISK model to incorporate a wide range of plausible scenarios (BIS, 2021b). This goes beyond current exercises that have just focused on the construction of a few scenario pathways created within the same integrated assessment models, such as exercises by the BoE and the ECB, that both used NGFS scenarios. In contrast, we identify the need to include scenario pathways across multiple providers that are generated across a wide range of models.

We differentiate the sensitivity analysis across (a) scenario-dependent parameters (marked with an asterisk *) and (b) scenario-independent parameters, as shown in table 7 and table 8. Scenario dependent parameters are highly dependent on the scenario narrative itself and therefore create variation in the results that can be beneficial for the interpretation of the plausible outcome ranges of the risk exercise. These include the introduction of the shock year, as well as the demand mechanisms and technological change assumptions made in the scenario.

In contrast, the scenario-independent parameters represent choices made in the model set-up and therefore create noise in the outcome ranges that are due to different calibration. Scenario-independent variables primarily include the choices made around the discount rate and other financial parameters in the model.

This differentiation is relevant when the aim of the analysis is to isolate methodological variation and to allow only different scenario narratives to drive the impact on firms valuations. To achieve this, we perform a sensitivity analysis for the key parameter in the model. The findings are now discussed more in detail across they key scenario assumptions:

Varying degree of disorderliness. Unsurprisingly, we see a significant variation as a result of changing the shock year parameter in the model. This reflects the changes in the stress scenario narrative, as a later shock year reflects an even more disruptive transition and hence represents an even more tail-risk scenario. Our results suggest that delaying the transition from 2025 to 2035 will almost double the $TRISK_i^{NPV}$ in our sample (from around -10% to almost - 19%) and more than double the transition-related changes to the firms PDs (from 0.24 to 0.51 percentage points). Interestingly, the standard distribution of these impacts increases substantially, with the 5^th percentile of impacts to firms valuation increasing from around -37% to almost -70%. This entails clear implications for a delayed transition. Firms that are continuously misaligned with the target scenario will be more severely impacted, the later the transition is introduced, suggesting a continuous risk-build up in the system. In other words, the increases in TRISK reflect the cost for the financial sector if climate action by firms are further delayed.

Table 7: Sensitivity analysis of TRISK for firms based on different parameter settings. Net present value changes in % and PD changes in percentage points.

		$TRISK_i^{NPV}$			$TRISK_i^{PD}$		
		5^{th}	Mean	95^{th}	5^{th}	Mean	95^{th}
Shock Year, Y (*)	• $T = 2025$	-36.79	-10.33	9.89	-0.2	0.24	1.45
	• $T = 2030$	-48.96	-14.22	11.56	-0.15	0.34	2.17
	• $T = 2035$	-69.64	-18.75	20.49	-0.36	0.51	3.41
Target Scenario, s (*)	• Sustainable Development Scenario IEA (IEA, 2020)	-48.96	-14.22	11.56	-0.15	0.33	2.17
	• NGFS net-zero scenario (NGFS, 2020)	-63.54	-19.73	29.85	-0.22	0.70	4.67
	• Oxford Fast Transition Scenario (Way et al., 2021)	-64.28	2.41	121.57	-1.41	0.51	4.05
Unit cost projections, $c_{gyh}^{s,t}$ (*)	• Cost projections (Way et al., 2021): Fast Transition	-46.08	-6.17	28.53	-0.86	0.21	2.20
	• cost projections SDS (IEA, 2020)	-48.96	-14.22	11.56	-0.15	0.34	2.17
Discount rate, ρ	• $\rho = 7.5\%$ (Average WACC public power firms)	-48.53	-14.11	11.51	-0.15	0.33	2.14
	• $\rho = 4{,}83\%$ (Cost of equity with $\rho^f = 0.02$, $\beta_j = 0.0073$ and $\mathbb{E}[R^M] = 0.0387$)	-50.62	-14.74	11.78	-0.16	0.35	2.31
	• $\rho = 3{,}83\%$ (Cost of equity with $\rho^f = 0.01$, $\beta_j = 0.0073$ and $\mathbb{E}[R^M] = 0.0387$)	-51.40	-14.98	11.88	-0.16	0.36	2.37

Unit Cost Variation. Further, our result show a significant variability due to different cost projections (between the IEA and the Oxford Fast Transition Scenario). The mean transition-related impact on the firms valuation $TRISK_i^{NPV}$ varies between -6% and nearly -14%, while we see less variability in the transition-related PD changes[47]. However in the 95^{th} percentile, we observe that the Oxford Fast Transition Scenario leads to a more significant positive impact on firms' valuation (around 29%) that benefit from the accelerated renewable energy market share in the energy system, while under the SDS firms are less positively affected (around 11%). This is due to very different assumptions around technological change in the respective scenario narratives. The Oxford Fast Transition Scenario assumes a much quicker decline in the unit cost for renewable energy technologies, based on learning effects that can be empirically validated. Hence, firms benefit from reduced costs that feed into increased profits. In contrast, the IEA takes a less optimistic stance, but was shown to continuously underestimate the speed of cost reduction (Way et al., 2022). For instance, The IEA scenario reaches a Levelised Cost of Electricity (LCOE) of approximately 30 dollars per MWh in 2040, while the Oxford Fast Transition Scenario projects a LCOE of 15 dollars per MWh.

Energy System Demand Variation. The most striking results are the differences in the TRISK outcome based on different target scenarios $s = target$, which stipulate how the energy system demand and supply changes. The three scenarios used in our analysis exhibit differences in key assumptions and narratives. For instance, in 2040, the share of energy produced from renewables is 42% and 55% in the IEA and NGFS scenarios respectively, while it reaches over 85% in the Oxford Fast Transition scenario. The electricity generated from gas ranges from

[47] This is intuitive, as the cost directly feed into reduced cash flows and only indirectly feature in the credit risk model

18-7% by 2040 in the IEA and NGFS pathways, while it falls to around 5% in the Oxford scenario. In contrast, the IEA and NGFS scenarios still include a substantial portion of energy generated from coal and oil (around 14% and 5% respectively), whereas both energy sources are expected to account for a minimal share of energy in the Oxford scenario. There are also other differences around assumptions of negative emissions, cost of capital, technological development, innovation breakthroughs and carbon pricing that substantially influence the outcome of the scenarios and, in turn as we show, the transition impact on individual firms. This demonstrates the need to assess a wider range of scenario narratives, to understand the impact that such key methodological and narrative differences could have on the financial risk estimates associated with the net zero transition. Not surprisingly, we identify a large variation in the results when using different target scenarios (see Figure 11).

In the Oxford scenarios, some firms are significantly positively affected (in the 95^{th} percentile up to 121%) while the worst performing firms receive a significant negative shock that is higher in magnitude compared to scenarios by the NGFS And the IEA.

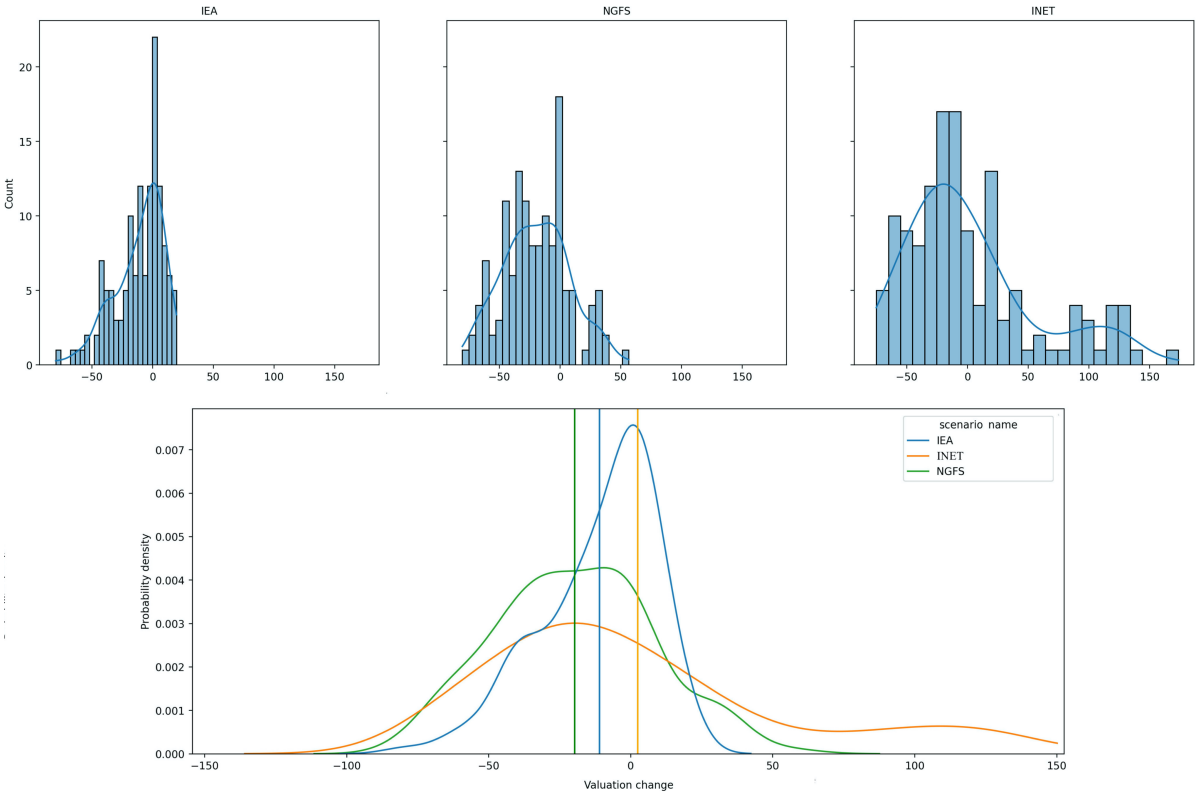


Figure 11: The top three bar charts represent the distribution of firms' $TRISK_i^{NPV}$ for the three different climate scenarios - SDS, NGFS Net Zero 2050 scenario, and Oxford Fast Transition scenario (INET). The bottom chart displays the density plots from the three scenarios. Vertical lines represents the mean of each scenario distribution. The change in valuation represents the change in net present value of future profits in percentage terms compared to the baseline scenarios.

The standard deviation for the Oxford scenario (54%) is roughly twice as much as the IEA (20%) and the NGFS scenarios (27%) and hence suggests a broader difference between the companies that are positively and negatively affected by the low-carbon transition. Overall, the average impact on the valuation of power firms in our sample is the most severe for the NGFS (around -20%) and the IEA (-14%) scenarios. It is slightly positive (2%) for the Oxford scenario. In a context where a rapid transition unfolds (Oxford INET scenario), companies strategically well-positioned would benefit more from the transformation of the energy system. This leads to a longer right tail in the distribution of impacts for the Oxford scenario compared to the other two. In contrast, energy producers exposed to fossil fuels would remain significantly negatively impacted in all scenarios, either because cheaper renewable energy replaces carbon-intensive sources, or because carbon taxation makes these technologies more expensive. Nevertheless, the differences in impacts vary substantially across the three scenarios.

The same interpretation holds true for the sensitivity of the TRISK outcomes on financial

portfolios (see Table 8), although to a lesser degree, as the construction of the portfolios focused on two extreme cases and is not representative of the full sample. We observe the valuation decline of sample FI portfolio B from transition-related market risk $\mathbb{E}_t[L_{\text{market}}]$ increase from -14% to -26%, when the shock year is delayed from 2025 to 2035, reflecting a more disruptive transition. Similarly, sample FI portfolio A, that holds exposure to the most aligned firms in the transition scenario, is slightly positively affected in the SDS scenario (with a 7.7% increase) and significantly positively affected in the Oxford Fast Transition Scenario (with a 62% increase).

For the scenario-independent parameters, such as the discount rate, we see some variations in the results, however the order of magnitude remains robust to changes in these parameters ($TRISK_i^{NPV}$ mean change from -14.11% to - 14.89% and $TRISK_i^{PD}$ mean change from 0.33 to 0.36 percentage points). Nevertheless, more transparency around the choice of such parameters is highly desirable, especially in the context of climate stress testing and scenario analysis, where longer time horizons and the involved complexities of the model place inevitably greater emphasis on these parameters. Reflecting the robustness of our results, we identify that the model is less sensitive to other scenario-independent parameters, such as the loss given default threshold on the financial layer of the TRISK model. However, we see a non-negligible variation in the results of the relative impact to the credit risk of our constructed portfolios, due to the maturity parameter for outstanding debt. This is initiative, as expected loss for short-term debt will be less impacted, given the longer time-horizon and shock year introduction in the TRISK model.

Table 8: Sensitivity analysis of TRISK for sample Portfolio A and B, expressed as expected loss from transition-related equity as share of overall portfolio exposure and PD changes.

		Sample FI Portfolio B		Sample FI Portfolio A	
		$\mathbb{E}_t[L_{\text{market}}]$	$\mathbb{E}_t[L_{\text{credit}}]$	$\mathbb{E}_t[L_{\text{market}}]$	$\mathbb{E}_t[L_{\text{credit}}]$
Shock Year, Y (*)	• $Y = 2025$	-13.67	-0.44	6.70	0.03
	• $Y = 2030$	-17.97	-0.61	7.77	0.03
	• $Y = 2030$	-25.71	-0.93	11.86	0.04
Target Scenario, s (*)	• Sustainable Development Scenario IEA (IEA, 2020)	-17.97	-0.61	7.77	0.03
	• NGFS net-zero scenario (NGFS, 2020)	-24.72	-1.43	19.05	0.01
	• Oxford Fast Transition Scenario (Way et al., 2021)	-23.51	-1.64	62.97	0.03
Unit cost projections, $c_{gyh}^{s,t}$ (*)	• Cost projections (Way et al., 2021): Fast Transition	-17.84	-0.61	15.28	0.04
	• cost projections SDS (IEA, 2020)	-17.97	-0.60	7.77	0.03
Discount rate, ρ	• $\rho = 7.5\%$ (Average WACC public power firms)	-17.84	-0.60	7.74	0.03
	• $\rho = 4{,}83\%$ (Cost of equity with $\rho^f = 0.02$, $\beta_j = 0.0073$ and $\mathbb{E}[R^M] = 0.0387$)	-18.54	-0.64	7.94	0.03
	• $\rho = 3{,}83\%$ (Cost of equity with $\rho^f = 0.01$, $\beta_j = 0.0073$ and $\mathbb{E}[R^M] = 0.0387$)	-18.81	-0.65	8.01	0.03
Maturity of debt instrument, T	• $T = 1$	-17.97	0.00	7.77	0.00
	• $T = 3$	-17.97	-0.13	7.77	0.00
	• $T = 5$	-17.97	-0.61	7.77	0.03
Loss given default threshold λ	• $\lambda = 0.45$	-17.97	-0.61	7.77	0.02
	• $\lambda = 0.25$	-17.97	-0.56	7.77	0.03
	• $\lambda = 0.65$	-17.97	-0.65	7.77	0.04

Table 9 further shows the sensitivity of the loss given default (LGD) based on different carbon budgets that influence the share of stranded assets. While under a 1.5° carbon budget of 466 Gt/CO_2 the average share of stranded assets for our firm sample amounts to 36% of production incompatible with the target, this share decreases to around 15% and 0.7% in a 2° and 3° degrees target respectively. This points to the fact that most of the firms' production in electricity generation is not compatible with targets set out in the Paris agreement, and may significantly influence the collateral value of underlying physical production infrastructure. This is in line with recent findings of the magnitude of stranded assets by Rekker et al. (2023).

Table 9: Sensitivity analysis of Stranded Assets and resulting loss given default (for $\lambda = 0.45$) for different carbon budgets (in %)

		Stranded Assets SA_j			Loss given default LGD_j		
		5^{th} percentile	Mean	95^{th} percentile	5^{th} precentile	Mean	95^{th} percentile
Global Carbon Budget	• 1.5° Degree Target (466 Gt/CO_2)	0	36.04	71.43	45	64.82	84.29
	• 2° Degree Target (762 Gt/CO_2)	0	15.40	50.31	45	53.46	62.67
	• 3° Degree Target (2082 Gt/CO_2)	0	0.7	0	45	45	45

Overall, our sensitivity analysis highlights two important features of climate risk scenario analysis. First, different scenario narratives around technological change, the future energy mix to meet net-zero targets and the degree of disruption of the transition, lead to a significant

variability in the TRISK results. Such a variability can effectively inform decision-making and the respective implications on financial risk management. The flexibility of the TRISK model therefore allows to test various pathways and manifestations of a delayed transition, reflecting different underlying assumptions on how the transition could manifest. Second, the results of the TRISK model are robust to scenario-independent parameters and therefore less sensitive to calibration problems.

4.5 Conclusion

This paper presented a novel firm-level climate risk assessment methodology that advances the field of transition risk analysis with the following contributions.

First, the TRISK model provides unprecedented granularity through a calibration on physical asset-level data and the representation of transition risk at the firm-level. Most current top-down and sectoral approaches fall short in identfiying how the transition risk is concentrated or dispersed within a sector, making it increasingly unsuitable for policy makers and market participants to inform capital allocation and risk management. The results of the exploratory analysis of the TRISK model for 135 international power firms demonstrates this point. While the sectoral transition risk estimates are broadly in line with other studies (-14.22 % mean change in firms' net present values), our granular results identify also the firm-level variation around this mean, which ranges from +20% to -80% for the most aligned firms and climate laggards respectively. Other sectoral estimates and studies miss this important heterogeneity and may lead central banks, regulators and market participants to restrict financing with unintended consequence that may hinder the transition.

Second, the TRISK estimates are a function of the misalignment of firms forward-looking production plans with sectoral decarbonisation targets, rather than proxied by current and backward-looking carbon emission intensities. We argue that this is a necessary pre-requisite for risk assessment methodologies to distinguish between climate laggard firms and frontrunners. From a market perspective, we argue that investors should divest only from those firms that do not plan to transition to a greener business model, thereby driving up the cost of capital for climate laggards but keeping the cost of capital low for greening firms. From a regulatory perspective, to increase the resilience of financial institution and safeguard financial stability in the transition, climate stress tests need to identify exactly where the risk lies and how concentrated it is.

Third, this paper contributes with a comprehensive analysis that identifies a significant variance of transition impacts across different scenario narratives and model parameters. We find that the transition impacts on firms' valuations across three commonly used net zero scenarios with the same climate target (well below 2°C) from different providers lead to substantial differences in the shape of the risk distribution. These results indicate that the degree of uncertainty in financial stability research might be substantial and that the existing literature might be susceptible to the assumptions and narratives of the climate scenario considered. Further, we also test sensitivities of our results to timing and severity of the stress scenario, reflecting gradually more delayed and more disruptive scenarios. We demonstrate that every year the transition is delayed, the cost for the financial sector is increasing, highlighting the need for early and decisive action to avoid a risk-build up in the system.

However, it should be noted that the strengths of such granular firm-level risk approaches are to simulate firm's asset values under a variety of different scenarios rather than to focus on the quantitative result per se. Further, the results of the TRISK application represent risk estimates that sit further in the tail of the probability distribution, i.e., are extreme but plausible. It follows that the results should not inform strategic planning purposes that seek to identify the most likely scenario outcome. The model is more 'suitable' and decision relevant in a risk management context. This can be a useful indication for central banks and financial institutions to identify sectoral outliers, such as firms that are on average – across a range of scenario pathways – impacted more adversely than its peers. Such results show relevant insights into the risk that those companies carry through the transition and can inform subsequent engagement with those firms or an additional in-depth analysis.

While we showed an exploratory application of the TRISK framework to a selection of international power firms, the external validity of the results can be improved by running the model on a larger set of firms across more sectors, where sufficient asset-level data is available (e.g., Asset Impact, Oxford Spatial Finance Initiative or World Resource Institute capture firms and assets in oil and gas, coal extraction, steel, cement, aviation, automotive and shipping that together account for around 80 % of global carbon emissions). Focusing the analysis on more country- and regional specific assessments that better accommodate jurisdictional differences with respect to carbon budget allowances, net-zero policies and political commitment could even further improve the practical relevance of such an exercise for policy makers. Lastly, we did not represent individual balance sheets of financial institutions. This would allow to assess the TRISK in investors, banks or insurance portfolios and further unravel the distributional effects within the financial system.

The TRISK model, due to its flexible and transparent set up, presents an early stage approach that can be subsequently improved. The framework can serve as a foundational module that can be extended to model physical risk impacts in order to comprehensively assess the interdependencies and trade-offs between physical and transition risk, as well as compounding shocks. There is increasing concern that physical risks such as changes in the frequency and distribution of extreme weather events pose a systemic threat to the financial system (Giuzio et al., 2019; Mandel et al., 2021). What is more, the TRISK model could be extended to account for systemic impacts and second-round losses in a financial network approach. to more adequately reflect potential amplification mechanisms within the financial sector that have the potential to aggravate direct climate-financial impacts.

5 Paper III: All scenarios are wrong, but some are useful' - a taxonomy framework for assessing the usability and credibility of scenarios within financial decisions

A Previous version of this paper titled 'All scenarios are wrong, but some are useful' - a framework for assessing climate risk scenarios within financial decisions[48] was joint work between Matteo Gasparini, Ryan Lancaster and Nicola Ranger. Earlier versions of this work are published in the Frontiers journal as part of the Research Topic 'Decision Making for the Net Zero Transformation: A Compendium of Best Practice' and was published as a discussion paper through the UK Centre for Greening Finance and Investment (CGFI).

[48]The authors would like to thank David Wilkinson and Gireesh Shrimali for their useful comments on previous drafts of this paper. We also thank two anonymous reviewers for their valuable feedback.

Abstract

In response to a growing awareness of the potential impact of climate change on financial stability, academics, financial institutions (FIs) and central banks and supervisors (CB&S) have developed a suite of scenarios and analytical tools to assess forward-looking climate-related financial risks, inform macro-prudential policies, counterparty risk management and business planning decisions. Climate scenario analysis brings new challenges versus traditional scenario analysis by FIs, particularly given the limitations, uncertainties, and trade-offs inherent in the data, models, and methods for such financial risk assessments. As a response we propose a taxonomy framework for climate financial scenario analysis that allows the user to systematically scrutinize scenario components, key assumptions and the underlying modelling and calibration (partial analysis) to then decide on the overall scenario credibility, as well as get an appreciation of the suitability of key features and characteristics of scenarios for financial use cases, including its adequacy to reflect risk (system analysis). We show that scenarios in their current form may often not be fit for purpose for the financial use cases of stress testing and risk management. We demonstrate that individual scenario components may be incoherent with the overall scenario narrative, making it increasingly difficult for users to judge where in the probability distribution those scenarios sit. Most scenario deficiencies point towards a systemic underestimation of the risk, potentially giving rise to a false sense of security on how the transition may unfold. The taxonomy contributes towards mitigating the implications of wrong scenario design and misuse of scenarios. We also put forward four key design features that an adequate climate-related financial risk scenario should reflect.

5.1 Introduction

Climate scenario analysis and stress testing are widely recognised as valuable tools for private and public financial institutions (FIs), central banks and supervisors (CB&S) to assess the opportunities and risks presented by physical climate change and the transition to a low carbon economy (among others see, APCR (2020); Baer, Caldecott, Kastl, Kleinnijenhuis, and Ranger (2022); BoE (2019a); NGFS (2021). Consequently, in recent years, these actors have developed a suite of scenarios to inform the assessment of forward-looking climate-related financial risks to inform sector-level macro-prudential policies, counterparty-level risk management and business planning decisions.

Climate scenario analysis is different to traditional approaches in several ways, and this introduces new challenges. Firstly, the past is not a guide to the future and the transition and extreme climate physical events manifest through unprecedented changes. As a result, FIs and CB&S cannot simply derive a probability distribution from past events through the design of tail-risk scenarios based on historical volatilities of macroeconomic and financial market data (BIS, 2009; ESRB, 2020). Such a design is less suitable, as the transition is driven endogenously and represents a fundamental shift between different states and compositions of the economic system. The risks that the transition entail are also more complex than classical financial risk, as beyond just financial system complexity, it involves socioeconomic and ecological feedbacks and unprecedented structural changes across economies which are hard to capture and may be overlooked by FIs or not yet appropriately priced in (Bolton & Kacperczyk, 2021b; Eren et al., 2022). Capturing such complexity is inherently difficult and exacerbated due to the increased difficulty to communicate between areas of scientific research, such as modelers, climate scientists and financial economists (Fiedler et al., 2021). Finally, regulatory exercises are pushing FIs to consider longer timescales and so are pushed in the realm of even deeper uncertainties. But also for CB&S that are starting to explore shorter time horizons for regulatory setting, elevated uncertainty represents a risk appetite challenge for micro and macroprudential regulators, as acknowledged by the Bank of England's report on climate-related risks and the regulatory capital frameworks.[49] Assessing forward-looking climate-related risks and opportunities hence represents a unique challenge vis-a-vis classic financial risk management. Nevertheless, the scale of the climate challenge that lies ahead, political developments and increased scrutiny from regulators have now confronted FIs and CB&S to move away from standard risk management practices and enhance capabilities around climate-related financial risk.

To date, organisations like the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) have played a central role in developing the scenarios that many FIs are beginning to use. Other commonly used scenarios for climate risk assessment include those of

[49] https://www.bankofengland.co.uk/prudential-regulation/publication/2023/report-on-climate-related-risks-and-the-regulatory-capital-frameworks

the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA).[50] As a result, so-called integrated assessment models (IAMs) have become the core tool used to produce climate-adjusted economic pathways.[51] Scenarios are created by augmenting such IAMs coupled with macromodels that have been proven effectively in modelling economic relationships and trends based on a variety of socio-economic assumptions. Yet, this may have resulted in a bias to generate climate scenarios in an integrated way that is not necessarily adequate to capture the shock-based logic used for certain financial risk use cases. Critically, IAMs have not yet allowed to represent frictions, tipping-points and amplification dynamics beyond the smooth changes in trends that are reflected based on socio-economic and climatic optimisation paths. This was also highlighted by Trust, Joshi, Lenton, and Oliver (2023) that argue the financial sector service may severely under-estimate the economic impact of climate change, especially for physical risk due to simplifying and unrealistic assumptions that miss important risk drivers. It is important to recognise that current IPCC and IAM-based scenarios were fundamentally not built for financial scenario analysis; they were built to inform climate policy.

Assessing and managing climate risk is a new and ongoing process, with substantial learning and refinement happening continually. The NGFS is to-date on its fourth iteration of scenarios and with each release comes substantial refinement and improvement (NGFS, 2023). Similarly, the Bank of England's CBES results stressed the learning nature of the exercise (Ranger et al., 2023). As reflected by recent supervisory statements, it is critical that firms get started in strengthening their capabilities in climate scenario analysis and begin to build climate dimensions into risk management and business planning. Yet, firms that responded to the PRA's consultation paper indicated that scenario analysis is one of the most challenging aspects of meeting supervisory expectations (CFRF, 2020). Further, regulatory divergence on supervisory expectations make it difficult for firms to understand the status of emerging best practices[52].

Overall, we identify the gap that FIs and CB&S lack a systematic framework to select and analyse currently available scenarios, as well as identify potential gaps in the available range of scenarios and to contextualize their interpretation. For climate scenario analysis to be a decision-relevant tool that drives risk management and capital allocation processes, the financial sector needs an improved understanding of where in the probability distribution respective scenarios sit, given choices around the conservativeness of key assumptions and model design.

[50] See latest climate financial risk forum guide 2022 - scenario analysis in financial firms by CRFR here: `https://www.fca.org.uk/publication/corporate/cfrf-guide-2022-scenario-analysis-in-financial-firms.pdf`

[51] Arguably this trend can be traced back to the prominent use of IAMs to produce mitigation pathways, supported by the scientific community and the Intergovernmental Panel on Climate Change (IPCC).

[52] Firms face difficulties in assessing how they are developing against peers (Ranger et al., 2023). Further, regulatory divergences are challenging cross-border financial firms (see `https://www.ey.com/en_br/brexit-and-financial-services/how-regulatory-divergence-is-challenging-cross-border-financial-firms`)

Similarly, CB&S need to understand which scenarios are adequate to support their own risk appetite decisions on capital setting within micro prudential frameworks, and to balance potential short-term disruptions and longer-term financial stability objectives. For this, a more detailed understanding of the critical components that underpin scenarios is important. It is true that financial practitioners are largely dependent on existing third-party climate scenarios and IAMs. Expertise in these models, and the scenarios they produce, sit predominantly in the academic community. To date there are no frameworks that allow for a systematic assessment of climate scenarios for the financial sector. This is a gap that needs to be bridged.

As a response, also to calls by the Climate Financial Risk Forum (CFRF)[53], we propose a taxonomy framework for climate financial scenario analysis that allows the user to systematically assess relevant scenario components, key assumptions and the underlying modelling and calibration (partial analysis) to then decide on the overall scenario credibility, as well as get an appreciation of the suitability of key features and characteristics of scenarios for financial use cases, including its adequacy to reflect risk (system analysis). We further use the taxonomy to categorise current climate scenario risk exercises by CB&S and assess a shift towards more narrative driven scenarios that are less dependent on process-based modelling.

We apply the taxonomy with a focus on representative key elements of commonly used scenarios by the NGFS, IEA and Oxford INET[54], to demonstrate the stages and basic functioning of the taxonomy with a particular focus on financial use cases of stress testing and risk management. First, we demonstrate how to assess individual scenario components based on the assessment criteria set out in the taxonomy. For this we scrutinize the coherence and likelihood of key assumptions, underlying modelling, and calibration with a focus on key components - the negative emissions, market behavior, and the energy system - of the above-mentioned scenarios.

We find incoherence of those components with the overall narrative, and discrepancies between assumptions, recent developments and empirical observations that question overall scenario credibility and make it increasingly difficult to judge where in the probability distribution a scenario sits. In other words, to position how optimistic or pessimistic scenario components and resulting impact pathways are, and how likely those materialise given our current understanding. This is important to assess the suitability of a given scenario for a variety of use cases. Further, our assessment of such key components allows us to assess the wider risk implications stemming from scenario design and narrative choices. We show that our application of the taxonomy can provide meaningful insights into critical processes and characteristics of underlying

[53]CFRF calls upon FIs, CB&S and research institutions to work closely together to develop a more comprehensive understanding on scenario characteristics and underlying model construction to enhance capabilities around climate scenario analysis in the financial sector. (Ranger et al., 2023)

[54]Energy and technological scenarios by Way et al. (2022) at the Institute for New Economic Thinking (INET) at Oxford University

models that determine how risks and volatilities could be represented and that may be missed in currently available scenarios.

Based on our assessment of commonly used scenarios, we draw out key design features that we argue a credible risk scenario should possess to adequately capture transition risk dynamics. These features build upon and complement more fundamental principles around stress testing of previous work such as the Basel Committee on Banking Supervision. More specifically, the features specific to the transition context can be seen as complementary considerations to the Basel principle 4 that discusses the requirement for stress testing frameworks to "capture material and relevant risks" and to "apply stresses that are sufficiently severe"[55]. While this paper has a limited scope in drawing out these features conceptually rather than discussing in detail how to operationalise those, it discusses to what extent the features have been implemented in recent supervisory stress test exercises to guide decision makers whether risk scenarios are appropriate by design. Operationalising those scenarios is then a highly idiosyncratic exercise that depends on the models used, scope and objective of the exercise, institutional capabilities and data availability.

We highlight that transition risk is the result of potential misaligned market expectations that lead to sudden and abrupt reactions when physical, climatic, economic, or financial constraints are hit (Feature I: changes in market expectations or Minsky moment). Most importantly, an adequate risk narrative then needs to capture the feedbacks and unintended consequences of misaligned expectations and how they repercuss through the system (Feature II: Feedback). Risk and volatility are higher when the speed of change is fast (Feature III: Speed). This combination of frictions and feedbacks need to be reflected in a shock logic surrounding the structural transformation trend, rather than smoothed out over a longer time horizon. What is more, a risk scenario should capture when such sudden behavioral reactions and deviations from expected pathways happen in a compounding fashion (Feature IV: compounding severity). We argue that those critical design features are often not represented in currently used scenarios, which is why there is a risk of systematic and collective underestimation of the consequences of the transition. Nonetheless, while we argue all scenarios are wrong, it is not a barrier to action if they are understood and interpreted in full awareness of their characteristics and their inherent trade-offs. The taxonomy provides a systematic framework that is designed to aid with such an assessment.

The paper is structured as follows. Section 5.2 presents the scenario taxonomy for the financial sector. Section 5.3 is applying the taxonomy with a focus on representative key elements of commonly used scenarios to assess scenario credibility and suitability. Section 5.4 discusses implications on the design of risk scenarios. Section 5.5 concludes.

[55] https://www.bis.org/bcbs/publ/d450.pdf

5.2 A Scenario Taxonomy Framework for the Financial Sector

The multidimensional taxonomy of climate scenario analysis provides a systematic framework to describe and analyse key features and characteristics of scenarios. Across its assessment criteria, it allows for a partial or system-level analysis to assess the credibility and suitability of a scenario given a financial use case, as well as identify potential gaps in the available range of scenarios. For this, the high-level narrative of the scenario, the underlying key assumptions, and dependencies as well as the underlying modelling and calibration needs to be identified and assessed. Figure 12 outlines the main dimensions of the taxonomy and assessment framework, which is now discussed in more detail throughout this section. Financial use cases are guided by the analyses of UK supervisory statements on climate change (Appendix A). The framework and analysis presented in this paper build upon and complement classifications and taxonomies provided, among others, by Monasterolo et al. (2022) to describe the different characteristics of IAMs, or for physical risk scenarios, by Ranger, Mahul, and Monasterolo (2021b).

Scenario	
High-level narrative and components	Narrative across key scenario components (e.g., policy, energy, technology, climate system, narrative breadth, market and consumer behaviour, feedbacks)
Key assumptions and dependencies	Key assumptions and relations that govern specific scenario narrative component and express the state of the system
Underlying modelling and calibration	Governs key assumptions. Varies across level of granularity, complexity, and integration

Assessment Criteria (component- and system-analysis)		
Suitability		Suitability of scenario requirements to needs of financial use cases and implementing authority
Credibility	Coherence	Coherence of narrative, assumptions, and scenario components
	Likelihood	Level of conservativeness of assumption based on discrepancies of assumptions with empirical observations and policy developments

Financial Use Case	
Strategic and business planning (alignment)	Medium to longer-term physical climate and socio-economic trend analysis
Risk Management and Stress Testing	Plausible but extreme scenarios and shocks
Implementing Institution	
Central Banks and Supervisors	Regulating institution concerned with financial stability and systemic risk
Financial Institutions	focused on idiosyncratic risk and specific impacts, opportunities and vulnerabilities to business activity or own portfolio exposure

Figure 12: Multi-dimensional taxonomy framework of climate scenario analysis for financial sector

5.2.1 Scenario

We differentiate a scenario by examining its components and understanding all the relevant features and characteristics. We decompose a scenario into: (i) its high-level narrative that specifies the narrative across its critical components; (ii) the key assumptions that underlie and further specify those individual key components; and (iii) the underlying modelling and

calibration that governs these key assumptions at the most detailed level. Graph 13 outlines an illustrative decomposition of a scenario, which then allows to apply the assessments criteria.

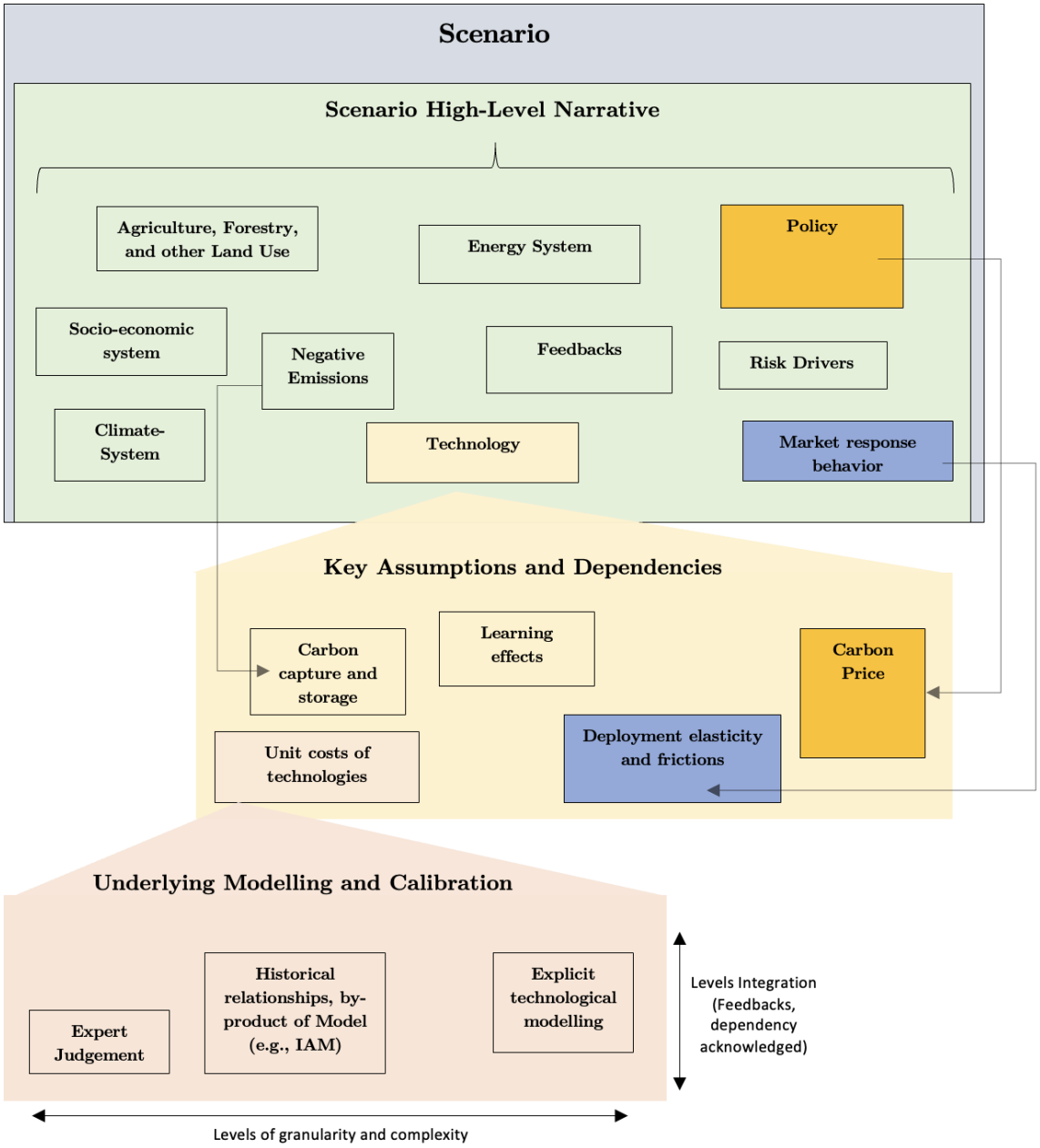


Figure 13: Illustrative scenario decomposition based on taxonomy framework

5.2.1.1 High-level narrative and components

In principle, the scenario narrative should reflect all elements of the scenario that specify the physical, socio-economic and financial implications. We break down a high-level scenario into the varies scenario components it encompasses, such as the policy representation, negative emissions, the socio-economic and climate system, market and consumer behavior, feedbacks, as well as the narrative breadth or coverage of other risk drivers[56]. Importantly, these individual components and how they relate to each other specify the overall scenario narrative. For instance, most scenarios place great emphasis on the policy component that determines different ways and level of disruptions to ensure that the climate-economic system is remaining withing a carbon budget and temperature target with a given likelihood. The different ways this component is reflected – for instance through a disorderly or an orderly narrative - is perhaps the most significant difference within most scenarios.

5.2.1.2 Key assumptions and dependencies

This stage considers the key assumptions and relations that govern the translation of the scenario narrative component into a detailed pathway projection that express the state of the system. For instance, the narrative component of market and consumer behavior is governed by the key assumption that policy such as a carbon price drives an instantaneous system response, such as demand for fossil fuel; or unit costs developments drive the energy system supply. Importantly, key assumptions are dependent on other components and assumptions. For instance, the relationship between the energy system supply and unit cost developments is also dependent on behavioral assumptions that determine how quickly the market reacts and implements technological changes. Such key assumptions and how they relate to each other govern the key characteristics of a scenario and need to be better understood to allow for an adequate interpretation of scenario analysis.

5.2.1.3 Underlying modelling and calibration

This dimension captures the underlying modelling and calibration that in turn governs the key assumption. The way in which assumptions and resulting pathway projections are calibrated vary greatly across scenarios and providers. In our taxonomy framework, we differentiate between the model and calibration strategy among a continuum level of complexity, ranging from least complex qualitative narrative-based expert judgement (qualitative narrative scenarios), to abstracting from backward-looking data and empirical relations (hybrid) to explicit process-based modelling (model narrative scenarios). Those approaches also differ across secondary dimensions such as levels of integration and granularity that are implicitly captured in the

[56]Note that this is not an exhaustive list of scenario components but rather an indication of key components across commonly used scenarios.

complexity dimension. This allows to identify and describe core differences across scenarios, giving the user an appreciation of the strengths and weaknesses of respective approaches (see also Graph 13). We describe both ends of the spectrum in more detail, driven by the degree of qualitative expert judgement versus quantitative modelling used to translate the scenario narrative into impact pathways.

The former approach is often associated with low levels of integration, varying levels of granularity and low levels of complexity. It is highly sensitive to the expert judgement involved. We term the scenarios that were designed with such an approach **'Qualitative Narrative Scenarios'**. Here, a simple shock or trend parameter is defined exogenously that alters macro-financial pathways in a way that reflects the envisioned socio-economic transition narrative. Values can be amplified or adjusted based on beliefs of future trends and knowledge around potential impact severity by expert judgment. For instance, one could assume that historical financial impacts could be amplified to reflect the size of the assets at risk based on aggregate estimates of stranded assets in the net-zero transition vis-à-vis the great financial crisis (GFC). This is without explicit representation of the relevant transmission channels that may be unique to the transition context. Here, the scenario outcome would be highly sensitive to the assumption that governs the relation between the size of the stranded assets and the historical housing bubble. This approach requires relatively low levels of capabilities but depends on the sophistication and plausibility of the qualitatively expressed narrative. For instance, there needs to be a good understanding of how the shock of the GFC differs from impacts in the transition, even when the overall magnitude or severity is believed to be similar. The composition of the shock here is the critical assumption that needs to be calibrated based on judgement. For instance, it needs to be considered that during the GFC initially financial institutions with housing market exposure in the US were hit the most by direct financial losses, whereas in the transition FIs with most vulnerable exposure to high-carbon energy firms may be affected relatively stronger. The credibility of the scenario output then rests upon this exogenous assumption and may be sensitive to judgmental bias when deciding on the shock magnitude and calibration of the shock composition. This approach is shaped by the argument that one should focus on getting the shock design right, rather than building more complex process-based models that are capable of endogenously reflecting transition shocks (and climatic constraints). The recent climate stress testing by the US Fed (Jung et al., 2021a), as well as the recent exercise by the Banque du France (ACPR, 2023) partially apply this approach. This is closer to classical scenario analysis and risk exercises performed by regulators to assess exogenous shocks and impacts to financial stability.

At the other end of the spectrum is the more process-based approach that aims to quantitatively generate scenario pathways using integrated assessment models (IAMs) or other types of model approaches. These represent endogenously transition dynamics in an integrated way.

We term the scenarios that were generated with this approach **'Model Narrative Scenarios'**. The calibration process therefore entails not only to qualitatively inform an exogenous shock or trend but to explicitly integrate financial, economic, and climatic constraints into the model underlying the scenario. Here the qualitative narrative still specifies model relationships and the setup (e.g., how the financial model is linked with a macromodel and the climatic sub-module), but the outputs are dynamically generated by solving the varies sub-systems of the model. This approach requires more capabilities and expertise in quantitative analysis, but allows to represent more system-level complexities. Nevertheless, this approach is only as good as the model and may severely underestimate the severity of transition dynamics when crucial transmission channels, risk drivers and processes are not captured in the model. Yet, in principle, this allows for a more objective assessment with endogenous relationships explicitly represented, which can be grounded in empirical data with less dependency on expert judgement. Such approaches to scenario generation are typically associated with a higher-level of complexity and integration, with varying levels of granularity.

The NGFS scenarios (NGFS, 2020), the IEA scenarios (IEA, 2022) and Oxford INET scenarios (Way et al., 2022), and subsequently the regulatory exercises that employed these scenarios (e.g., see the climate stress test by ECB (2022)) fall into this category. Although, as we show in the assessment of critical components of those scenarios throughout the next section, the current state of such models may be insufficient to fully capitalize on the potential of this approach.

Note that within a scenario, various components can also be modelled in different ways. For instance, while the narrative around financial market behavior might be calibrated based on the narrative of a simple financial value re-adjustment, the narrative that governs the energy system dynamics could be represented through more granular models that reflect economic demand interactions conditional on policy and explicitly represent technological change.

5.2.2 Assessment Criteria

At the core, our framework guides an assessment of the scenario credibility and suitability to help with the interpretation and aid with the use of scenarios. A comprehensive application of the framework includes assessing each individual scenario component (component analysis) across all scenario components and across all assessment criteria conditional on use cases to derive conclusions on the overall scenario level (system analysis).

The scenario decomposition guided by previous dimensions, gives a comprehensive mapping of all relevant components of the scenario of interest. Each component should then be assessed based on the likelihood and coherence, which in the taxonomy framework determine the overall scenario credibility, and its suitability for different financial use cases. We explain those dimensions more in detail.

Likelihood. To make practical use of scenario analysis, one requires a view of the likelihood of the different potential future outcomes over the relevant time horizon. For this, one needs to position relevant key assumptions across the spectrum of how optimistic or conservative they are. For this, we draw on additional research and recent developments – including policy - to draw out discrepancies of assumptions with empirical observations. Conceptualizing such components with current developments allows to better understand where those assumptions sit in the probability distribution. This can then feedback into the overall scenario generation process to keep scenarios "honest".

Coherence. Further, we scrutinize the individual components' coherence across two dimensions. First, we check if components and assumptions are coherent among each other and assess if the level of conservativeness of the individual components is coherent with the overall scenario narrative. For instance, we identify incoherence when assumptions governing the energy system are on the optimistic end, while other parts of the scenario, such as policy or technological assumptions are highly pessimistic. Note, this assessment is closely informed by the 'likelihood' determination of individual key assumptions. Further, scenarios become incoherent if there is a mismatch between the high-level narrative and the underlying assumptions. This is any bias introduced on the level of modelling or calibration (e.g., by approximations or simplifications) that diverges or is incompatible with the overall narrative. For example, if the policy narrative specifies early and decisive policy action to reach net-zero, but the technological assumptions around decarbonisation of the energy system are following projections based on a business as usual path. Here, incoherence stem from different levels of conservativeness (or likelihood) of assumptions across components that contradict each other and therefore make it hard to judge the overall likelihood of the scenario but can very well materialise.

In contrast, incoherence can also arise from modelling approaches and calibrations that are entirely incompatible with each other. For instance, when macro-pathways of the scenario project an increase in global electricity supply – and across the sectoral modelling component, the electricity sectors' economic activity size is represented as declining. This shows that there are different levels of incoherence with different implications. While the former make interpretation more difficult, the latter proves parts of the scenario wrong, implications of which should then be carefully considered separately.

Credibility. Assessing the likelihood and coherence of scenario components then allows to judge on the internal credibility of the scenario. For example, a scenario designed to be a central projection for strategy setting might look to represent the expected or most likely pathways for a given high probability narrative across all components (e.g., a current policy scenario that reflects business as usual or stated emission reduction targets across all components). Scenarios

where different components have very different probabilities associated with them will lack coherence and credibility. How credible a scenario is, is also closely linked to whether the scenario characteristics are suitable for a specific use case.

Suitability. Use cases and requirements of the financial sector should be better understood to identify how suitable a scenario is in the selection process. Assessing for likelihood allows us to judge on the system-level where in the probability distribution the overall scenario sits. This is crucial to prevent a systematic misuse of a scenario in its application of use cases that require different scenario probabilities (e.g., plausible but extreme tail-risk scenarios for stress testing vs. more central case scenarios for strategic planning). Further, the assessment of the suitability of a scenario in section 5.3.2 can serve as a basis for assessing whether a scenario may be adequately reflecting risk. In this context, the suitability of a scenario could also influence and be understood as the external credibility of a scenario application. A scenario can be internally credible (e.g., coherent) but it could be wrongfully applied and would therefore lack external credibility.

While the above-mentioned dimensions should be the main determinants for credibility, overall scenario transparency should not be neglected and should be considered throughout the assessment. If scenario providers do not publish sufficient information to scrutinize assumption relations, underlying modelling and detailed calibration, such components will only be of limited credibility. This could be avoided if scenario builders apply the taxonomy framework as part of their publicly available documentation.

5.2.3 Financial Use Case and Implementing Authority

To aid the suitability assessment, requirements by financial use cases and objectives of the implementing authority should be better understood and matched with specific scenario characteristics that are most suitable. Our taxonomy draws out the relative importance of various scenario features, model characteristics and wider scenario considerations. Table 10 can serve as a starting point to assess the suitability of currently available scenarios against specific user requirements. We explain this more in detail.

The taxonomy framework differentiates by the financial use case and the implementing authority. We broadly differentiate between two major types of use cases (strategic/business planning and stress testing) across two types of institutions (FIs and central banks/regulators)[57]. For strategic business planning, a central scenario that captures reasonable expectations is re-

[57]These dimensions provide a starting point and could be expanded upon based on user requirements, for instance to differentiate FIs among banks and insurers, that may place different emphasize on key scenario characteristics.

Table 10: Relevance of key scenario features, model characteristics and wider scenario considerations for financial use cases

Institution type	Use case	Key Scenario Features			Model characteristics					Wider scenario considerations	
		Time horizon of scenarios	Where the scenario sits within the probability distribution	Scenario Pathway	Systemic Risk	Economic and financial frictions	Risk coverage of IAMs	Information pass-through in climate modelling chain	Scenario and Model granularity	Scenario likelihood conditional on mitigation progress and policy action	intertemporal trade-off dimensions
Financial Institution	Medium Term business planning	5 years	Central Scenario and reasonable expectation scenario	Cost optimisation and relatively smooth	Very High Relevance	Medium Relevance	Very High Relevance	High Relevance	Medium Relevance	Medium Relevance	Low Relevance
	Strategic planning	5-50 years	full spectrum/broad range of long-term scenarios	Cost optimisation and smooth	Very High Relevance	Medium Relevance	Very High Relevance	Medium Relevance	Low Relevance	Very High Relevance	Very High Relevance
	Internal Stress Testing – Balance sheet	Balance sheet Velocity (1-3 years)	reasonable worst-case scenario (tail-risk)	Significant short-term disruptions and volatility around scenario pathway	Very High Relevance	Very High Relevance	Very High Relevance	Very High Relevance	Very High Relevance	Medium Relevance	High Medium Relevance
	Internal Stress Testing – Business Model	10 years	reasonable worst-case scenario (tail-risk)	Cost optimisation and relatively smooth	Very High Relevance	Very High Relevance	Very High Relevance	Very High Relevance	Very High Relevance	High Relevance	Medium Relevance
Central Banks and Supervisors	Regulatory Stress testing and capital setting	0-5 years	Reasonable worst-case scenario (tail-risk)	Significant short-term disruptions and volatility around scenario pathway	Very High Relevance	Very High Relevance	Very High Relevance	Very High Relevance	Very High Relevance	Very High Relevance	High Relevance
	Learning Exercise stress testing (long-time horizon)	0-30 years	Reasonable worst-case scenario (tail-risk)	Cost optimisation and relatively smooth	Very High Relevance	Very High Relevance	Very High Relevance	High Relevance	Medium Relevance	Very High Relevance	Very High Relevance

quired. This is usually associated with a medium- to longer-term assessment of physical climate impacts and socio-economic trends using less granular analysis of the business mode.

In contrast, stress testing and risk management exercises generally require scenarios that allow FIs to test their resiliency to more extreme (or worst-case) plausible outcomes in the short- or medium term (further in the pessimistic tail of the probability distribution). Here, reasonable risk scenarios in the short- to medium term are required with sufficient granularity and explicit representation of volatilities and frictions throughout the climate modelling chain. The transition is likely to crystallise through several discrete shock events along a longer-term net-zero pathway. Such scenario characteristics should be represented as they are key to the objective of risk management exercises.

Risk applications are particularly relevant for CB&S to assess the adequacy of capital requirements and the identification of systemic risk, as well as FIs, for exploring the resiliency to the potential systemic implications of climate change. Arguably, scenarios should also capture second-round financial losses and amplification within a financial network to adequately reflect the systemic risk-build up (Battiston & Monasterolo, 2021; Roncoroni et al., 2021).

The differentiation by implementing institution is further important as it reflects differences in underlying objectives. CB&S are concerned about balancing the mitigation of short term disruptions while ensuring longer-term financial stability, meaning scenarios need to exhibit specific characteristics that support such an objective. For instance, scenarios should represent the intertemporal trade-offs between short term implications of the transition and longer-term physical impacts. This is relevant for risk appetite challenges for micro and macroprudential

regulators.

FIs on the other hand will place greater emphasis on idiosyncratic risks and are interested in those scenario features and components that match their operational activities and portfolio exposure (e.g., more sophisticated representation of transition impacts in the agriculture sector, when banks hold large exposures). Scenarios need to capture enough detail to provide FIs with the relevant information to perform a risk assessment at the counterparty-level, otherwise microeconomic overlays and expansions need to be performed. In contrast, granularity may have less priority for informing the long-term strategic direction of financial institutions, where the consideration of more systemic and sectoral effects may be more important.

5.2.4 Application Fields and Contribution of the Taxonomy Framework

More generally, the application of our proposed taxonomy to currently available scenarios by academics and practitioners can be interpreted as checks and balances to help continuously keep scenarios more realistic and avoid misuse. Academics, FIs and CB&S can use the taxonomy to engage in information exchange and keep abreast of any developments to reveal limitations across scenario components and the status of policy and developments versus assumptions. Hence, the academic contribution of this paper is foremost the presentation of the first taxonomy framework that can be applied to systematically scrutinise and categorise scenarios conditional on financial use cases.

Beyond this, we propose three different application fields for the taxonomy. First, the completion by the scenario builder as part of the model documentation to aid end-users in scenario selection and interpretation of results. Second, for use by academics or expert reviewers as part of the peer review process to scrutinise available scenarios and avoid potential systematic underestimations of the risk associated with the transition. Third, for use by FIs and CB&S to conduct their own review of a third-party scenario as part of the scenario selection process. Here, the taxonomy provides a framework to support effective use of scenario analysis in the financial services sector.

In our application of the taxonomy throughout section 5.3, we touch upon some of these elements – namely the peer-review aspect to assess the credibility of commonly used scenarios and by assessing their suitability for financial risk use cases - to demonstrate the functioning of the taxonomy framework. Our assessment therefore contributes to the academic literature with an improved understanding and analysis of key scenario components across scenarios, that reveal systematic weaknesses regarding the ability of such scenarios to adequately reflect risk. Similarly, the analysis presented in this paper provides a mechanism to transfer expertise from the academic community to the end users in the financial services sector.

In our assessment, we focus on a simple representation of the high-level scenario narrative and components. Instead, the framework allows for enough flexibility to increase the level of detail across the components. A more thorough peer-review of a comprehensive set of scenario components would need to involve the expertise of academics from many different disciplines (i.e., economics, climate science, finance, geography, engineering, etc.). Here, a detailed assessment might be supported by additional layers that describe each relevant component more in detail, as well as the expansion models that translate scenario pathways into financial metrics (such expansion of the taxonomy is beyond the scope of this paper). For instance, coherence, credibility and suitability should be assessed across all stages in the climate scenario modelling chain, including additional assumptions in, for example, the credit risk models and regulatory overlays. For instance, if there is a lack of granularity and sophistication around key assumptions of scenario components that are of particular interest to the user, then expansion models may be needed. However, such expansion introduces a risk of incoherence. For instance, when the assumptions in the third-party expansion modelling choices and associated calibration is inconsistent with the scenario narrative. This is especially relevant for a CB&S comparing scenario analysis outcomes across financial institutions in a regulatory exercise, where inconsistent expansion choices could be a larger driver of financial risk differences than individual portfolio exposure.

5.3 Analyzing Currently Used Scenarios through the Lens of the Taxonomy Framework

We apply the taxonomy to currently used scenarios by the NGFS (NGFS, 2020), IEA (IEA, 2022) and Oxford INET (Way et al., 2022), as well as drawing upon latest insights from CB&S climate scenario exercises, such as the ACPR exercise for insurers (ACPR, 2023) and the recent biannual climate exercise (CBES) by the BoE (Bank of England, 2022). While it is beyond the scope of this paper to assess all components of above-mentioned scenarios, we focus on representative key elements to demonstrate the dimensions of the taxonomy framework. In section 5.3.1 we decompose the scenarios across the key components - energy system, negative emissions and market behavior - and then perform an analysis across the assessment criteria of key assumptions, underlying modelling, and calibration. We then derive implications on the overall scenario level (section 5.3.2) to determine scenario credibility, and judge currently available scenarios against the financial use case requirements.

We find that the under-representation of frictions and omission of some key risk drivers, a lack of coherence across key assumptions and overall scenario narratives, as well as the dependency of scenario components to less and less feasible policy, supports a conclusion that scenarios may lack credibility and further systematically underestimate the scale of transition risk. Yet, we also highlight that the deficiencies in scenarios are not a barrier to action if they are applied and interpreted in full awareness of their characteristics and inherent trade-offs. The application of the taxonomy framework is designed to aid with this.

5.3.1 Component Analysis: Scrutinizing Likelihood and Coherence

We focus on the NGFS transition pathway scenarios generated by three process-based IAMs, which are models screened by the IPCC: GCAM (Calvin et al., 2019), REMIND-MAgPIE (Kriegler et al., 2012), and MESSAGE-GLOBIUM (Rogelj, Geden, Cowie, & Reisinger, 2021). These scenarios focus on the orderly and disorderly narrative which projects global action to get us to below 2°C, but with varying levels of policy timing and severity. Aside from the key component of the narrative around policy, we identify that the scenario is described by key components such as: (i) the energy system; (ii) negative emissions; and (iii) market behavior.[58] We explore those more in detail throughout this section. These components are also critical across other scenario providers such as the IEA scenarios (IEA, 2022) and the fast transition scenario by Oxford INET (Way et al., 2022), which we draw into our assessment. We focus here only on the transition dynamics and neglect the physical risk dimension. However, the taxonomy can be used to assess other components, including the climate system and economic damage relationships in the same spirit.

To decompose those scenarios, we follow the taxonomy framework and draw out the key assumptions that govern the respective scenario narrative component. In the NGFS scenarios, the component market behavior is governed through the key assumption that policy – represented as an implicit carbon price – drives an instantaneous system response by the market, such as demand for fossil fuels, without a time-lag. Further, the realization of a carbon budget and the alignment with a temperature target in the IEA and NGFS scenarios is highly reliant on negative emissions to decarbonize the global economy. This negative emission component of the narrative is governed by various underlying assumptions around the deployment at scale of carbon capture and storage (CCS) technologies, as well as the emission reduction potential of the Agriculture, Forestry and Other Land Use (AFOLU) sector. Additionally, across the NGFS, IEA and INET scenarios, the energy system component is governed through a key assumption that unit cost developments of different technologies (e.g., solar, wind, coal, fossil fuels) drives the composition of energy supplied in the transition.

Subsequently, we draw out the specific calibration and underling modelling that governs these assumptions. Unit cost developments are extrapolated linearly based on historical data and adjusted based on expert judgement for the IEA and NGFS (IEA, 2022; NGFS, 2020). In contrast, Oxford INET uses underlying models that project these developments based on empirically observed learning rates and stochastic processes. While AFOLU negative emissions

[58] Note that this is not a comprehensive analysis that reflects an exhaustive list of all assumptions that govern a scenario component. For instance, in the IEA, the energy system component is also driven by exogenous assumptions such as population growth or energy efficiency. To perform a comprehensive analysis of all scenario components these should be considered. In our partial analysis we just aim to demonstrate the key functioning of the taxonomy and hence refrain from an exhaustive analysis.

are not explicitly modelled and represented in the Oxford INET scenario, it has significant weight in shaping the decarbonisation pathways in the narrative of the IEA and NGFS. It is calibrated based on a regional mitigation potential that is assumed to be realized in a cost-effective way through the introduction of carbon taxes in relevant regions. CCS is also a key determent across NGFS and IEA. In the orderly NGFS net zero scenario, to reach 1.5°C, CCS deployment and Carbon Dioxide Removal (CDR) technologies are calibrated based on expert judgement to compensate for around 10% of the global yearly allowed emissions from 2050 on[59].

While this is not a comprehensive representation of all relevant scenario components, they are among the key determinants that describe a scenario narrative. Table 14 provides a summary of the components of interest and findings of our analysis. Importantly, some key assumptions are embedded across a wider range of components (assumption dependency). We identify that the market behavior assumption is implicitly embedded also in the labour market component, where the process based IAMs underlying the NGFS scenarios assume perfect labour substitution, the financial market component (if represented), or in the energy system where there is a perfect market response from deployment of technologies following changes in cost drivers. Scenario components can also equally be dependent on overall policy assumptions, such as negative emissions that are not only a function of the emission reduction potential of a region, but also dependent on policy to realise such a potential. Key to the analysis is to draw out the sensitivity and dependency among identified key assumptions and scenario components. We can identify that some assumptions have more relevance and importance (e.g., market response or policy assumption across multiple scenario components) for the overall scenario narrative. Hence a greater weight should be applied to those, as these can be considered system critical.

To assess where those key assumptions sit in the probability distribution of materialisation (likelihood assessment), we draw on additional research and empirical observations – including recent policy developments - to position those sub-components in the spectrum of how optimistic or conservative they are. This allows us to make judgements on the credibility of the components these assumptions govern and their suitability across use cases.

Energy System. As identified, for the energy system component across all three assessed scenario providers, the speed of technological innovation and cost developments are an important driver. It determines the deployment of renewable energy and the scale of disruption across the energy system. Interestingly, Way et al. (2022) and J. Farmer et al. (2019) highlight that energy models underlying NGFS and IEA scenarios still do not properly account for positive feedback and learning effects on a global scale and have failed to realistically forecast the speed of renewable technology cost decline. Moreover, these studies highlight how a faster drop in

[59] 5 gigatons emission removal per year on average from 2050 (NGFS, 2023). Based on a lower bound carbon budget estimate of 400GtCO2 to limit global warming to the 1.5°C goal with 50% probability (Fankhauser et al., 2022).

	Scenario narrative component			
	Energy System	Market Behaviour	Negative Emissions	
			CCS	AFOLU
Key Assumptions	• Technology unit cost drives energy mix (through deployment of technologies)	• instantaneous market response to changes without time-lag (e.g., carbon tax drives changes in demand)	• Exogenous deployment rate of CCS	• Policy drives regional mitigation potential
Dependency of key Assumption	• Market Behaviour (changes in cost translate into instantaneous deployment) • For NGFS and IEA also on policy that changes relative cost (for Oxford INET based on empirical learning rates, irrespective of policy)	• Policy	• Policy	• Policy
Likelihood Assessment of Assumption	Overly pessimistic for IEA and NGFS, slightly optimistic for Oxford INET	Overly Optimistic	Overly Optimistic	
Justification of Assessment	Empirical data on cost decline proves most expert judgement wrong	Empirical evidence of price hikes during current energy crisis proves less elastic market response	The status of policy action versus scenario assumptions around mitigation progress may become increasingly decoupled	

Figure 14: Overview of scenario components use cases and assessed likelihoods

the cost of renewable energy might lead to a faster uptake of renewables in the near future. Through the identification of the calibration of these dynamics in the NGFS and IEA scenarios we have uncovered that the energy system narrative is represented by extrapolation of historic trends, adjusted and complemented by qualitative expert judgement that define constraints on how quickly renewable costs can decline. However, as figure 15 A and B shows, the empirically observed drop in costs has far exceeded the expert imposed price floors for renewable technologies year after year. This highlights that the rate of change was significantly underestimated since 2000 by most IAMs, including the ones underlying the IEA and NGFS scenarios. Further, figure 15 shows the resulting variation in the implied rate of change of cost developments (LCOEs) in a below 2°C transition scenario for solar technologies in the power sector globally across different scenario providers. Consequently, scenarios may be overly pessimistic when they are are based on expert-adjusted calibrations that do not capture sufficiently the non-linear positive feedbacks surrounding technological change. For the NGFS and IEA[60] scenarios we can therefore conclude, that key assumptions in the energy component and the resulting scenario pathways are overly restrictive based on significant deviations between expert projections and empirical observations (see also table 14). This places such assumptions further in the tail of

[60]The IEA has recently recognised these systematic underestimations and has employed new methods to overcome this. Most often this is however not yet reflected in currently used scenarios.

the probability distribution, with a lower likelihood of materialisation.

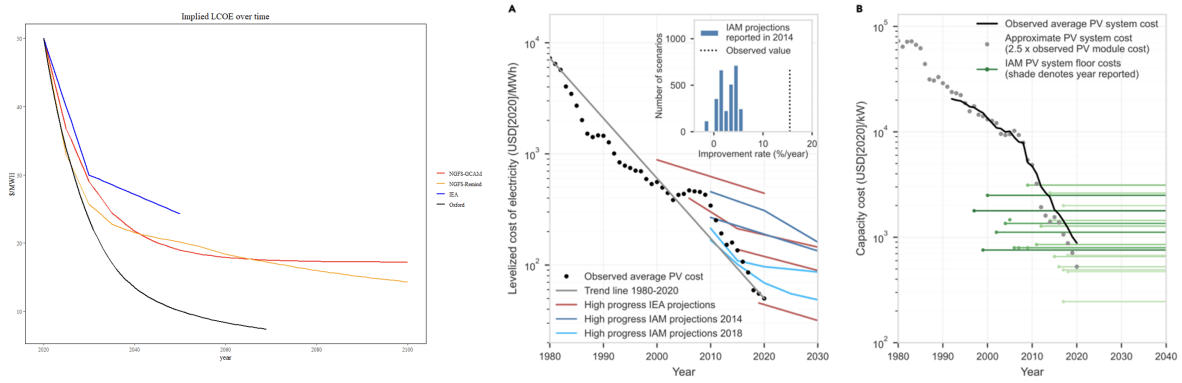


Figure 15: Projected implied rate of change of cost developments (LCOEs) in a below 2° transition scenario for solar technologies in the power sector globally across different scenario providers and models (left). On the right: LCOE rate of change and capacity cost across different IEA projections and empirical observations (Way et al., 2022)

As shown in Way et al. (2022), the Oxford INET scenarios reflect more accurately those exponential learning trends through more empirically grounded modelling of the projected technological pathways with positive feedbacks. Nonetheless, the Oxford INET scenarios represent a stylised scenario that may be slightly optimistic in how the energy system evolves. This is because of additional assumptions around the cost competitiveness of technologies, that lead to an instantaneous deployment and uptake of these technologies, ignoring potential political barriers or differences in the cost of capital across regions. The resulting pathways on how the energy mix evolves through time in the Oxford INET scenarios may thus not be a central expectations scenario, but rather shows how the energy system could evolve if other constraints on deployment of renewable energy were removed. This also results in a lower likelihood of materialisation.

This points to a more systemic limitation across transition scenarios and underlying modelling approaches. Most of scenarios do assume a smooth substitution with no explicit friction or representation of non-linearities for the transition between high and low-carbon technologies in the energy sector. For instance, as the energy system becomes greener, its lobbying power increases and the likelihood of a carbon tax may increase, triggering a sudden reaction from markets that abruptly price in those effects. Such frictions and amplification mechanisms could further induce tipping points where the system shifts very rapidly, causing assets to be stranded suddenly without a smooth divestment. Beyond financial markets this could have severe impacts on labour markets, unemployment and governments. Such impacts are most often not reflected in those scenarios due to stylized and simplified assumptions. Firms should

also remain cognisant of how a short-term energy mismatch could be more impactful across geographies that lack policy regimes and the appropriate fiscal infrastructure spending capacity to react to different mismatches within the transition. This has implications on the suitability of such scenario components for risk use cases, as discussed in section 5.3.2.

Additionally, the analysis reveals the different levels of complexity of the scenario approaches, as defined in the taxonomy. While all scenario providers are relying on quantitative modelling to generate energy system pathways, the Oxford INET scenario inhibits higher levels of complexity than IEA and NGFS, and is hence less sensitive to expert judgement.

Negative Emissions. We can draw on Roe et al. (2021) and recent policy developments to judge the conservativeness of the key assumptions around the regional emission potential that determines the overall negative emission pathways in the NGFS scenarios. We identify that most of the global mitigation potential lies in emerging and least developed economies. Therefore, the actual realized negative emissions depend critically on policy developments in those regions to ensure cost-competitiveness and to reap this mitigation potential (see figure 16). Yet, carbon price initiatives in emerging economies fall behind that of developed countries, and even the latter fall short of commitments close to the required levels (World Bank, 2023). This places the negative emission component in both, the orderly and disorderly NGFS scenarios in the optimistic tail of the probability distribution.

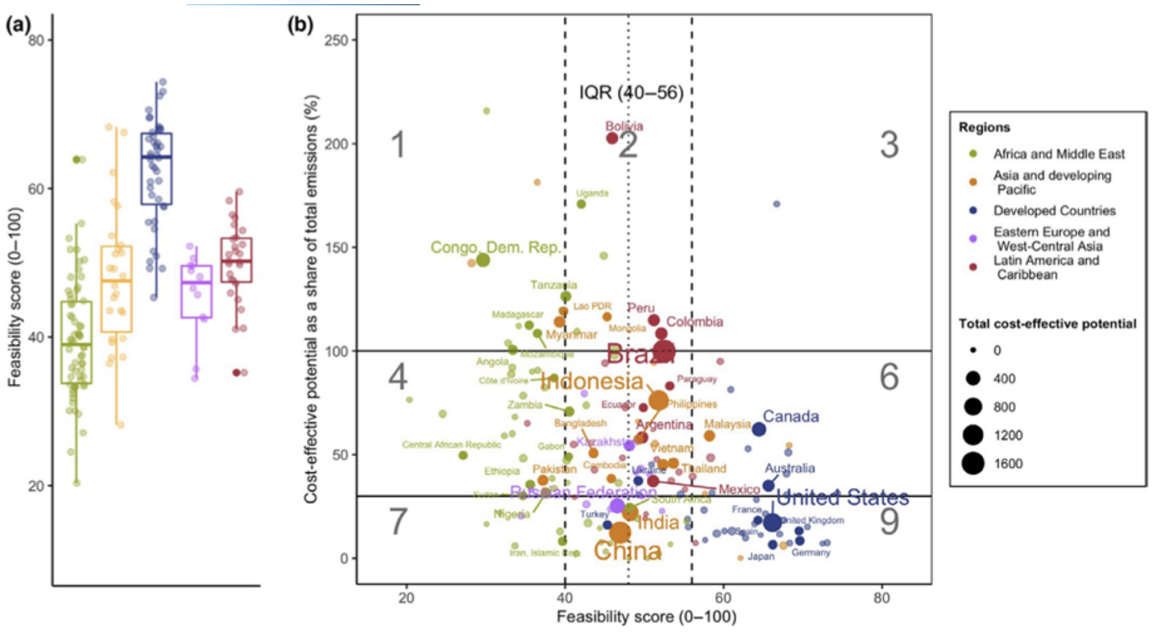


Figure 16: Mitigation feasibility score for selected regions and geographies by Roe et al., (2021)

What is more, the credibility of the negative emission component is sensitive to whether

the narrative takes into consideration other exogenous shocks beyond climate that may impact policy developments (e.g., geopolitical crisis such as the Ukraine war). For instance, the transition itself will likely see periods of acceleration and deceleration of policy commitments and experience "shocks" from non-climate-related exogenous factors, especially in emerging markets. As observed in recent times, governments may increase fossil fuel subsidies and private finance may flow back to fossil-fuel firms, all of which is likely to set back the transition and undermine the critical carbon pricing to realise AFOLU negative emissions in those regions. In other words, assumptions around mitigation potential, that significantly influence the overall narrative of NGFS scenarios, are highly sensitive to political developments and business cycles and should be considered optimistic.

We observe similar effects in relation to model assumptions around the potential for removal of carbon when judged against the status of policy action and technological progress. Smith et al. (2023) find a significant gap between proposed carbon dioxide removal (CDR) deployment and what will be needed to meet the Paris Agreement and achieve 1.5°C target, placing such scenario assumptions further in the optimistic tail of the probability distribution. Importantly, those components of the NGFS scenarios therefore should not be used as baseline or central expectation scenarios. Carbon removal assumptions have a similar relevance in IEA scenarios.

Overall, we find that the negative emission component plays a critical role in the decarbonisation narrative across most types of scenarios. Note that the NGFS offers a view on scenario pathways with varying levels of CCS technologies, however strong reliance on the mitigation potential of the AFOLU sector persists. This places even greater weight on assumptions around the mitigation potential of critical regions.

Market Behavior. We now assess the key assumption in the market behavior component, namely that policy drives instantaneous market responses without a time-lag, such as changes in demand across sectors. It further implicitly assumes that there is no market inertia and that responses to transition changes - market-based or policy - are highly elastic. These assumptions can be found in most IAMs and other models in various components, such as the energy system or labour markets. We show that both assumptions, which implies the absence of frictions in scenarios, are stylized simplifications that are not observed empirically. While such a modelling choice may be justifiable in a classical economic framework that assumes the economy is affected by a shock that temporarily leads to a disequilibrium, it is flawed in the context of a transition that requires a fundamental structural shift of real economic activity and supporting infrastructure that exhibits inertia (Mercure et al., 2019). In other words, a structural transformation of the economy is likely to hit physical constraints that delay or even mitigate the effect of policy and delay emission reduction efforts. We draw on parallels of recent geopolitical developments and persistent supply shortages that led to the recently observed energy price volatility. This

demonstrates the friction of inertia of market and consumer reactions. Short-term economic pressures (e.g., the Ukrainian war) and associated macroeconomic developments provide an ideal setting to test market behavior assumptions and their likelihood.

For instance, figure 17 below shows the divergence of current fossil fuel price developments away from scenario pathways. According to this, the current price of fossil fuels should be discouraging demand by more than the anticipated carbon tax in the NGFS orderly 1.5°C scenario. This was not the case due to inelastic demand and market responses blocked by inertia of real economic activity and unavailability of alternatives to the scale needed. This can be considered a mismatch of energy supply and demand that could occur when the ramp down of high-carbon intensive assets with the ramp up of low-carbon and supporting infrastructure is not managed carefully.

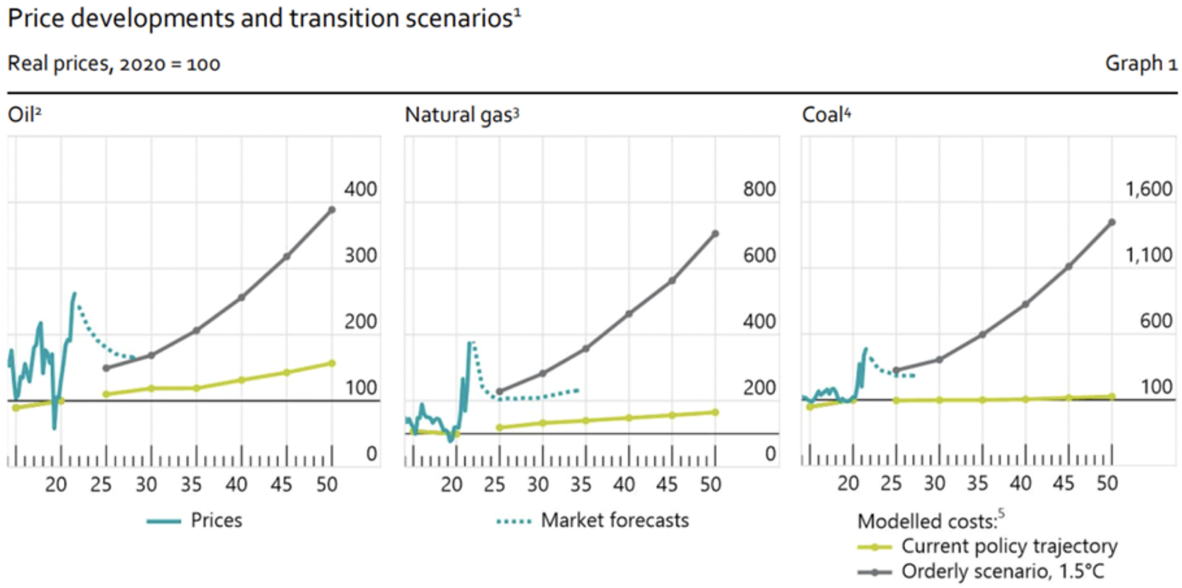


Figure 17: Current volatile price developments across key technologies and projected prices based on transition scenario by (NGFS, 2022)

This evidence suggests that increased prices in high-emitting technologies (e.g., due to a carbon tax) may not lead to the warranted demand shift or market response as stipulated in current transition scenarios. This places the assumptions around market behavior, as well as the related demand elasticity assumptions in NGFS scenarios in the optimistic tail of the probability distribution. This would suggest that the emission reduction response to policy may be delayed or impaired (Asefi-Najafabady, Villegas-Ortiz, & Morgan, 2021). In particular, when standard transition investment projects that are incentivized trough climate policy become effective only from months to years, rather than instantaneous (Kolev, Riess, Zachmann, & Calthrop, 2012). For example, the time required for institutions to adapt their pricing strategies or approve new investments, and any related consumer response associated with changing behaviors, should not

be neglected.

While our analysis is restricted to the energy context, additional empirical evidence on market inertia for other critical scenario components should be assessed to validate and extrapolate these findings. For instance, the lack of such behavioral frictions in financial market components of scenarios, or adjacent financial models, may significantly downplay the amplifying role of misaligned expectations among financial actors in turbulent times. For instance, Gasparini (2023), analysing the impact of climate policy uncertainty on the valuation of fossil-fuel stocks, has found that on average brown companies are valued as if their investors believe the green transition will never happen, while green companies are valued as if their investors believe it will happen in less than 20 years. The two groups of investors cannot both be right, indicating that a major realignment of stock prices is likely to happen. Such frictions could again move a system very rapidly. This could cause major and sudden stress across the financial system, further slowing down the required investment to support the transition. Since a quarter of the value of global stock markets, and a significant share of corporate bonds and syndicated U.S. loans are from fossil fuel-related companies, the consequences of this for markets are significant[61].

Current scenarios do not account for such behavioral frictions on financial markets. Note that academics such as Battiston and Monasterolo (2021) and Monasterolo et al. (2022), among others, have stressed the importance of such effects, and the NGFS is further raising awareness on such deficiencies. Operationalising such complexities in IAMs is however an ongoing process.

Overall, the component analysis so far has revealed discrepancies of key scenario assumptions with recent developments and empirical observations. Further, we identify that there is an underrepresention of frictions in those scenarios. We now turn to the assessment of the coherence of scenarios, as well as their overall credibility and suitability.

[61] see `https://www.ft.com/content/c1e31c6f-6319-4bfc-bde3-3ace80b46a2b`

5.3.2 System-Level Analysis: Assessing Overall Credibility and Suitability

Having assessed individual scenario components, we can derive implications on the system-level. First, we scrutinize the individual components and key assumptions' coherence with each other and with the scenario narrative to decide where in the probability distribution the overall scenario sits. This is important for FIs and CB&S that want to assess how suitable a scenario is giving a certain level of risk appetite. Scenarios where different components have very different probabilities associated with them, will lack coherence and credibility. This also influences how suitable a scenario is for a specific use case.

Overall Scenario Credibility. For the NGFS and IEA we showed that the energy system component is governed by overly pessimistic assumptions around technological change when compared with empirical evidence on the speed of technological learning effects and deployment rates up to date. In contrast, the negative emission component that determines the degree to which the narrative allows to overshoot the carbon budget, is overly optimistically represented – both through overly optimistic assumptions around CCS deployment and over-reliance of AFOLU mitigation potential reduction in emerging economies that is increasingly detached from policy feasibility. Further, the assumptions underlying the market response component within the NGFS was also shown to be overly optimistic.

As an example, for a NGFS disorderly scenario that reflects a pessimistic narrative centered around delayed policy action in 2030 (NGFS, 2022), these components would be largely incoherent given their different probabilities. A scenario designed to reflect a pessimistic view on the transition, should coherently represent key narrative components that sit in the pessimistic tail of the probability distribution. While for the energy component this would be the case, the negative emissions and market behavior components contradict this. Similarly, a central projection, such as the NGFS and IEA stated policy scenarios should represent the expected or most likely pathways across all narrative components. In the NGFS scenarios the stated policy scenario however still relies heavily on negative emission reduction potential. Further, overly pessimistic assumptions around technological progress seem also incoherent with recent declines in renewable energy cost and positive trends in deployment.

Consequently, we argue it is increasingly difficult to derive the right use case for a scenario and interpret it. Overly pessimistic assumptions around the speed in which the energy system evolves is difficult to combine with a view on rapid deployment of CCS technologies and negative emission reduction. While such an overall narrative is not impossible, it is difficult to attach an overall probability to the scenario outcome, that FIs and CB&S can map to their respective risk appetite. Especially if users are interested to test vulnerabilities of their portfolio or business model to the pessimistic tail of the probability distribution, as usual in risk exercises, then those scenarios would be incoherent, and hence lack credibility.

Further, it is important to acknowledge that likelihoods of components are not static but move in time. Some scenario assumptions become less and less credible (move even further into the tail of the probability distribution), the more policy action gets delayed. Overall, the status of policy action versus scenario assumptions around mitigation progress may become increasingly decoupled as time passes by and if not regularly updated. An orderly transition that limits global warming to 1.5°C may not be feasible anymore and a disorderly transition may be the central expectation benchmark. For instance, evidence continues to show that previous central estimates on emission reductions may no longer be realistic. The international community is falling far short of the Paris goals, with no credible pathway to 1.5°C in place (UNEP FI, 2022). The probability of a more disorderly transition pathway is therefore significantly increasing over time with central expectation assumptions moving more and more in the tail of the distribution. We argue this needs to be considered more strongly when assessing the overall credibility of the scenario narrative, as increasingly scenario components that are critical to achieve net-zero rest upon assumptions that are increasingly decoupled from political developments and empirical observations.

We also draw out examples of incoherence that fundamentally contradict each other and impact the credibility of a scenario and its application. For instance, in the ACPR (2023) insurance stress test, based partially on NGFS scenarios, we identify an incoherence in the financial impact component. The scenario is represented by a short-term 5-year stress narrative running from 2023 to 2027 based around acute weather events in France and central Europe that trigger the global markets to price in an abrupt transition (ACPR, 2023). Given the relatively short-term nature of the scenario much of the impact is driven by market expectation rather than actual transition dynamics. The underlying modelling of the financial impact component was undertaken with the Banque du France sectoral general equilibrium macroeconomic model (ACPR, 2023). This produces modest shocks to GDP and unemployment in comparison to the baseline. Throughout the scenario, the absolute GDP growth remains largely positive across all regions other than a slight dip in late 2025. In contrast, sovereign yields are significantly impacted in the stress scenario with differentials to the baseline of up to ca 7% for some regions. This seems incoherent given the deflationary nature of the scenario and the limited impact on GDP, although a rigorous assessment is difficult due to limited transparency on the exact calibration of the models. If scenario providers do not publish sufficient information to scrutinize assumption relations and detailed calibration, such components will only be of limited credibility.

The credibility of a scenario and its application is also driven by its suitability for a given use case. So far we have established that scenario components may lack coherence across key assumptions and that model simplifications may underestimate the level of disruption, as well as that there is an over-reliance of scenario components to less and less feasible policy. Foremost,

this may increasingly reduce the suitability of such scenarios to risk management and stress testing use cases, where overly optimistic assumptions may severely underestimate the risk of the transition. We assess this in more detail in the next sections.

Scenario Suitability. We draw upon the parts of the taxonomy that map the requirements of financial use cases with scenario characteristics to assess if NGFS, IEA or Oxford INET scenarios are suitable for risk management purposes.

We find that those scenarios are likely to be the most appropriate for policy planning applications, given the nature of the underlying models. This is because these transition scenarios show the cost-optimal mitigation pathways across different degrees and timings of policy action (IPCC, 2018). In other words, components of the narrative are suitable to reflect the "smooth" transformation of the economy and can therefore inform more systemic policy decisions. For instance, informing the aggregate investment required in low-carbon technologies to transform the energy system in line with temperature goals set out in Paris Agreement. This is supported by the analysis of key components of those scenarios. For example, the Oxford INET scenario may not be a scenario suitable for risk management purposes as it may be overly optimistic with respect to the transformation of the energy system, but can guide policy makers on the potential speed of the decarbonisation if other barriers and frictions are removed. These scenarios provide insights into the temporal effects of change and the different options we have as a society and how they may play out under reasonable expected conditions. Such scenarios can therefore act as a guide for policy makers and financial markets in setting business strategies, helping to shape market expectations and to realise the benefits from a variety of aspects of the transition.

As identified in the taxonomy framework, risk scenarios need to be inherently different to a central case or best-case scenario used for longer term planning (Koberle, Ganguly, & Ostrovnaya, 2021b). However, most of the scenarios that are being explored for risk management purposes by FIs are longer-term scenarios that do not reflect relevant transition dynamics and volatilities. For instance, the models underlying the IEA, NGFS and Oxford INET scenarios allow for a smooth transformation of the energy system, with no time-lags, infrastructure inertia and instantaneous market response to policy. The absence of such frictions across various scenario components makes them less suitable for risk management exercises. As a way of illustration, figure 18 shows the relevant energy transition pathways from NGFS net-zero scenarios over the time horizon 2020-2100 (left) and when zoomed in to 2020-2030 (middle) and 2020-2040 (right).

It is evident that the smooth trends depicted for a 10- and 20-year time horizon respectively represent trends that are unlikely to produce meaningful volatilities that could drive risk. For

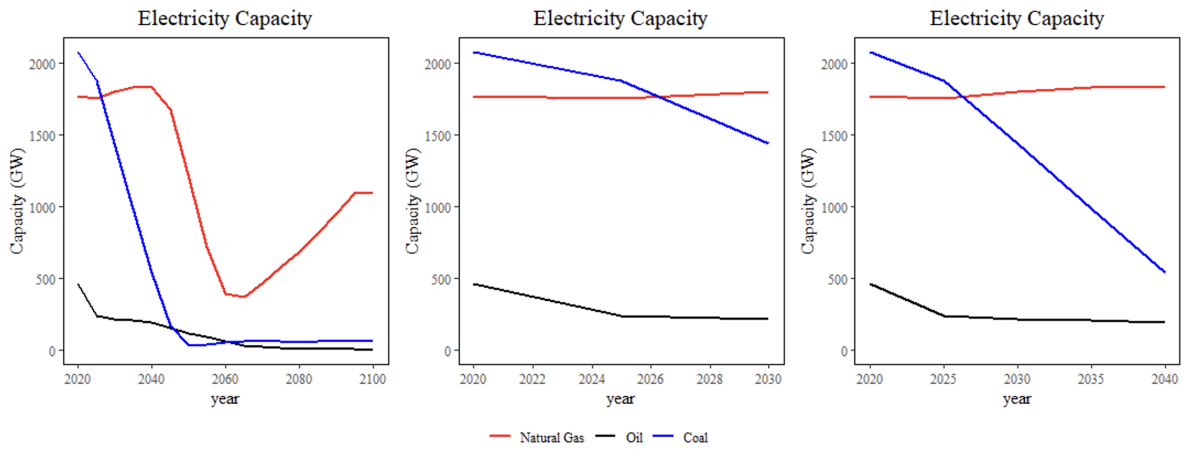


Figure 18: Energy-sector pathways (electricity capacity across natural gas, oil and coal) from the NGFS GCAM Beyond 2° scenario, zoomed in across different time horizons. Authors' own calculation based on IIASA scenario explorer database

instance, as Aguais and Forest (2022) show in an empirical multi-factor credit portfolio model, credit risks are generally not driven by smooth macro-economic trends but by unexpected economic shocks that represent higher volatility and systematic deviations from average trends. Their analysis shows significantly higher climate-related credit risk in contrast to NGFS scenario approaches. Underlying modelling or calibrations of scenarios need to reflect this, such as financial consequences of energy price spikes, sudden asset-repricing, and increased volatility around macro-financial variables.

In the previous section, we showed that key assumptions across the analysed scenarios do not allow for such frictions (e.g., market behavior component) and therefore miss important risk drivers such as volatilities in markets as observed in recent geopolitical developments. Assessing and judging currently available scenarios against the financial use case requirements therefore supports the conclusion that these scenarios are not fit for the purpose of stress testing and risk management. The representation of economic and financial frictions is key to fulfilling the objectives of such exercises and may be insufficiently reflected in currently available scenarios. We observe that most of these deficiencies arise in the context of what we define in the taxonomy as 'Model Narrative Scenarios'. This highlights limited suitability and further questions the external credibility of the scenario exercises that used those scenarios without sufficient attention to identified deficiencies. These findings further support the conclusion that is such scenarios are misused, the outcomes may systematically underestimate the scale of the transition risk.

In the next section, we draw important conclusions from our analysis about the general design of risk scenarios and discuss recent applications by individual CB&S that starting to acknowledge those limitations. Given limited capabilities and influence over the innovation and

development of process-based models, CB&S as well as FIs turned to less complex, qualitative narrative approaches.

5.4 Implications on Design of Risk Scenarios for the Financial Sector

Our assessment of critical scenario components through the taxonomy dimensions so far provides meaningful insights on which design features (critical processes and characteristics) should be reflected in scenarios moving forward to adequately capture risks. Table 19 summarizes those key design features.

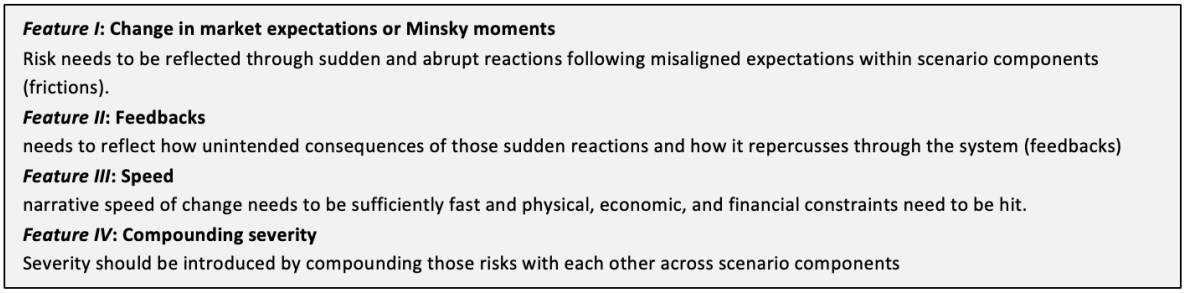


Figure 19: Overview of design features for adequate risk scenarios

We argue that transition risk is fundamentally characterized by misaligned expectations around key scenario narrative components that lead to sudden and change in expectations when physical, climatic, economic, or financial constraints are hit (Feature I: change in market expectation or Minsky moments). For instance, economic and financial actors allocate capital based on overly optimistic expectations on negative emission technologies, but then such technologies are proven to be limited in their ability to be scaled cost-effectively, or technical constraints around innovation are hit, the consequence of which is sudden market reaction. An adequate risk narrative then needs to capture the feedbacks and unintended consequences of those misaligned expectations or market reactions and, importantly, how it repercusses through the system (Feature II: Feedback). These feedbacks can ripple through the economy and financial system through (a) shortages or (b) asset stranding, depending on the political choices and policy reactions throughout the transition. The former may lead to abrupt price hikes, inflation, unemployment or interest rate hikes. The latter may be materialising through sudden equity changes, defaults and write downs. Political actors and governments are therefore always faced with the trade-off between those two impact 'buckets', each with its respective set of severe but unique consequences. Such feedbacks need to be represented in scenarios and conceptualised in the political context of different economies with varying strategic preferences. Further, risk and volatility are higher when the speed of change is fast and constraints are hit due to physical, economic, or financial realities (Feature III: Speed). For instance, risk in the system emerges when markets realise that decarbonisation potential across components were systematically overambitious, and therefore, more-than-expected changes are required to offset this elsewhere. Hence, frictions and feedbacks need to be represented through expectation changes in sufficiently short-time horizons in a shock logic with sufficient speed of materialisation.

For instance, in the case of overly optimistic AFOLU emission reduction potential as identified in the NGFS scenarios, a key focus of risk analysis should assess what happens if even stronger policy action cannot overcompensate for the speed of change that is required in negative emissions to stay within the carbon budget (technical or natural constraint). Other scenario components would need to make up for the lost emission reduction through faster decarbonisation pathways (e.g., energy system changes such as an accelerated coal-phase out). Importantly a scenario would then need to capture the unintended consequences of such a sudden expectation change, such as reduced supply of electricity due to the 'disorderly' coal-phase out and resulting energy price spikes, coupled with spikes in unemployment and rising inflation rates in those regions. Alternatively, an implausible representation of the transition in the energy sector without accounting for a policy time-lag or technological innovation constraints may have knock-on effects on other scenario components such as the scale and speed of the transition required by the industrial and mobility sector to offset this, resulting in a combination of shortages and stranded assets.

This combination of both, frictions and feedbacks, needs to be reflected across key relevant scenario components. What is more, a severe risk scenario should capture when such sudden behavioral reactions and deviations from expected pathways happen in a compounding fashion across scenario components (Feature IV: compounding severity). They could have common feedback effects that reinforce and amplify each other. For instance, the failure of firms to anticipate transition policies could lead to sudden unemployment spikes in labour markets that compound with a re-pricing event in the same industry on financial markets due to a sudden realization of potential stranded assets on balance sheets. Further, a sudden realization of severity of climate damages following a physical risk event could induce stronger policy action while simultaneously the markets have underestimated the speed of technological progress, leading to supply and demand mismatches and price spikes, further worsening unemployment. Coupled with general economic cycles and period of de- and acceleration due to geopolitical headwinds and other socio-economic crisis, such transition dynamics could introduce severe stress in the system. Further, knock-on effects are increasingly a source of systemic risk (European Systemic Risk Board (ESRB), 2020) and need to be closely monitored through climate risk scenario analysis not only by CB&S but also by governments and individual financial institutions.

Importantly, we argue, that those design features are not reflected in current scenarios because the process-based model approaches underlying the 'Model Narrative Scenarios' (we classify NGFS, IEA and Oxford INET into this category) miss important characteristics and risk drivers. This further contributes to the systematic and collective underestimation of the risks associated with the transition. An exception is the reflection of sudden policy shocks in most scenarios, including the NGFS. Here, in principle, the friction is captured, but most nar-

ratives and underlying models lack how this impact repercusses through the system. But most importantly, we argue that the policy component is the least suitable to introduce such frictions and associated feedbacks. Policy as a process is a coordinated mechanism that balances unintended consequences with policy objectives. Hence it is unlikely for policy to have disruptive effects that trigger systemic stress. In contrast, we argue markets and consumer behavior can be much less coordinated and may result in sudden behavioral shifts or tipping points that induce systemic stress. Risk therefore needs to be represented in those scenario components that look at how financial markets react, how economic actors behave, or consumers decide based on expectations that may turn out to be misaligned with transition realities.

Generally, we argue for two ways in which the design features for risk can be captured in scenarios. First, through a qualitative risk narrative that is then represented through the adjustment of impact pathways that the scenario designer judge as adequately severe and comprehensive (corresponds to the 'Qualitative Narrative Scenarios'). Second, through integration of pre-defined frictions into the underlying modelling that endogenously generate pathways that are the result of the modelling process (corresponds to the 'Model Narrative Scenarios'). Critically, as the IAMs underlying the NGFS scenarios have not been designed for risk purposes, those scenarios capture it neither in the narrative nor in the underlying modelling. This is in line with criticism by (UoE & USS, 2023) that argue that, besides model deficiencies, even commonly used scenario narratives are insufficiently severe.

Importantly, design features need to be implemented in a way that matches the granularity required by financial sector firms. Otherwise, across the scenario modelling chain it may underestimate the pass-through of tail risk (irrespective of the scenario design) when such volatilities are "smoothed" away in classical financial risk models or microeconomic expansion models, where additional incoherence could be introduced.[62]

While we acknowledge that process-based scenario calibration and underlying models are limited in their capacity to incorporate complexities such as feedbacks and frictions with sufficient granularity required by the financial sector today (Kemp et al., 2022; Monasterolo et al., 2022; Stern, Stiglitz, & Taylor, 2021), there needs to be a paradigm shift around what constitutes a relevant and credible risk scenario narrative to avoid systematic misuse and wrong interpretation of the implications of scenario outcomes. Interestingly, some design features (such as feature 1 and 4, changes in market expectations and compounding severity) can be found prominently in the recent NGFS short-term scenario conceptual design[63] where acute physical

[62]For instance, critical variations in expansion assumption (e.g., discount rates) or choices of corporate financial impact modelling (e.g., different credit risk models) may produce significantly different pathways for the same asset, making it impossible to disentangle the impact effect of the transition shock (Bank of England, 2021).

[63]https://www.ngfs.net/sites/default/files/medias/documents/conceptual-note-on-short-term-climate-scenarios.pdf

risk shocks trigger policy and market reactions across subsequent time steps. However, we argue that the shock-logic and the potential far-reaching ripple effects through the system (feature 2 and 3, feedbacks and speed) are still not captured sufficiently.

Recent Trends in Regulatory Exercises. Awareness that scenarios may not be suitable and are missing important characteristics is increasingly acknowledged by individual CB&S and parts of the financial community. Interestingly, we observe a shift of CB&S exercises in moving towards what we in the taxonomy defined as 'Qualitative Narrative Scenarios'. This can be explained by two interlinked dynamics. First, most CB&S, including those in advanced economies, have limited capabilities and influence over the innovation and design over process-based models, which sit predominantly in the academic community. Second, capabilities to build, adjust and interpret such models is limited. Consequently, CB&S and FIs turned to less complex, qualitative narrative approaches that are compatible with their classical financial risk models and less dependent on academic models. This can be seen as a shift back towards the traditional way of stress testing and scenario analysis in finance. For CB&S this seems to be more immediately feasible. Note that some CB&S have employed hybrid scenario analysis that partially relies on process-based NGFS scenarios for more longer-term trends and additional qualitatively defined shocks to reflect short-term disruptions. For instance, in the recent insurance stress test performed by the French regulator (ACPR, 2023), various scenario narratives were combined from multiple sources, including the NGFS, to enhance granularity and spatial impacts of acute physical risk to FIs portfolios and to better reflect financial market frictions. The scenario narrative combines a sequence of components around (i) extreme drought shocks in 2023 and 2024, calibrated on previous historical experiences and health impacts, as well as damages to agriculture and subsidence risk; (ii) fluvial flooding in 2025, calibrated on historical extreme floods but amplified through the narrative of previous droughts (e.g., expert judgement about the volatility of the average monthly flow of the Durance river increasing up to 50% during flash food episodes); and (iii) a qualitative narrative-driven shock on stranded assets[64] that impacts credit spreads, asset prices and government bonds (ACPR, 2023). All of these components are less dependent on process-based IAMs and integrated scenario generation but focus more on isolated shock narratives that are thought to be appropriate in magnitude and impact based on judgement and historical observations. Another example for this is the US FED climate stress testing methodology that looks at how a pre-defined write-off of equity values impacts banks depending on their exposure to brown and green firms (Jung et al., 2021a)).

While such an approach is more sensitive to errors in expert judgement and less grounded in modelling empirical relationships, it places greater weight on reflecting frictions that are missing in current models. Therefore, we argue it incorporates some of the design features put forward

[64] https://www.banque-france.fr/sites/default/files/medias/documents/bdf245-3_greenflation_web.pdf

in this paper at least in the narrative and may therefore be more suitable to reflect risk. This may be more impactful for risk management purposes than having underlying models that are missing critical features all together.

While 'Qualitative Narrative Scenarios' may be an intermediate solution that is more immediately feasible, it is important to highlight limitations. Such approaches are more sensible to a "bias" introduction through expert judgement and are less empirically driven. As shown with the consistent underestimation of technological change by experts (uncovered by empirical models and analysis), this may also result in a consistent underestimation of the severity of physical and transition risk. Therefore, greater emphasis should be placed on sensitivity testing a variety of different levels of narrative severity. In this context, Baer et al. (2022) show how different narratives with varying assumptions can drive significant differences in financial risk that should be carefully assessed.

5.5 Conclusion

This paper contributed with a multi-dimensional scenario taxonomy framework that guides the user to systematically scrutinize relevant scenario components, coherence of key assumptions and the underlying modelling and calibration (partial analysis). This allows to make judgements around the credibility and suitability at the overall scenario level (system analysis). More specifically, it allows the user to assess currently used scenarios to: (i) judge the suitability of key scenario characteristics to a variety of financial use case; (ii) assess where in the probability distribution the scenario and its components sit, given the level of conservativness of key assumptions; (iii) assess whether scenario components are coherent among each other and with the overall narrative; and (iv) assess whether the narrative, modelling and calibration design allow to adequately reflect the risks associated with the transition. Such an assessment contributes to the effective selection, usage and interpretation of scenarios, within climate financial scenario analysis. This is aimed at increasing the suitability of scenarios for decision making. We applied the taxonomy with a focus on representative key elements of commonly used scenarios by the NGFS, IEA and Oxford INET with a particular focus on financial stress testing and risk. Further the taxonomy aids in positioning and understanding the implications from recent shifts in the scenario design of regulatory risk exercises by CB&S.

We highlight the following key findings. We identify that key NGFS scenario components, namely the market behavior, the energy system, and negative emissions exhibit incoherence across its key assumptions, making it increasingly difficult to situate scenarios in the probability distribution of materialisation. We demonstrated that scenarios where different components have very different probabilities associated with them will lack coherence and credibility. Further, we show that some scenario assumptions become less and less credible when compared to empirical observations and recent policy developments, making it increasingly difficult to judge whether the scenario is suitable for a given level of risk appetite. Overall, we identify that current scenarios miss important characteristics and processes, most prominently frictions, that we argue are critical to fully understand the potential severity and timescales of climate-related risks. Climate transition scenarios in their current form may therefore not be suitable for financial risk use cases.

In response, based on our component and system-level assessment of currently available scenarios, we drew out four design features - changes in market expectations, feedbacks, speed and compounding severity - that we argued need to be captured in an adequate risk scenario. Further, we showed that those features are only partially reflected in currently available scenarios, further reinforcing the argument that current scenarios may underestimate the risk associated with the transition.

We identified that recent developments among regulatory exercises suggest that CB&S and

FIs start to recognise such deficiencies and hence return to developing what we termed 'Qualitative Narrative Scenarios'. Such design approaches to scenarios may be more immediately feasible and better reflect our design features, but also face limitations. It may also introduce more fragmentation of unharmonized and increasingly bespoke scenario narrative variations across CB&S. This places further relevance on the use of our taxonomy by scenario designers and modellers to transparently describe key components of scenarios, their characteristics and suitability for use cases.

We argue that in the long term the development of more sophisticated IAMs and alternative modelling approaches that better capture frictions, feedbacks, and non-linear system dynamics is necessary (e.g., agent-based models). In principle, these can generate more decision-relevant and reliable scenarios with enhanced integration and complexity. Further those approaches need be more tailored to financial use cases.

In the meantime, as climate scenario risk assessments for the financial sector are at an early stage, it is important that FIs and CB&S are fully cognisant about missing characteristics in their processes to avoid the risk of misinterpreting the outcomes of climate scenario analysis. The application of the taxonomy to scenarios can aid with this. Detecting issues around coherence, understanding the likelihood of assumptions and assessing the overall suitability for specific use cases is highly important. An insufficient understanding may lead to a misuse of scenarios and consequently inadequate management of climate financial risks. The recent report by the Financial Stability Board (FSB) and the NGFS acknowledged the challenges, stating for example, that while continuous progress is made, current exercises may understate climate exposures and vulnerabilities, especially in capturing tail risks for risk management and stress testing purposes (FSB, 2022).

6 DPhil Conclusion and Contribution

Latest developments in the field of sustainable finance and around climate-related financial risk analysis show that financial institutions may be facing a dilemma. Given that past historic data is not good predictor for the net-zero transition and to capture uncertainty and elevated levels of complexity, classical financial approaches are not fit for purpose. But as we have shown throughout this DPhil, new climate risk scenario approaches also have deficiencies for financial risk management purposes, as these often lack the granularity required and are not sufficiently forward-looking. Simultaneously, regulatory pressure from CB&S to build out capabilities is increasing. Hence, a challenge for relevant actors that employ climate scenario analysis remains to balance the applicability of currently available approaches with their deficiencies in the face of the unprecedented risk, urgency of the transition, increased supervisory pressure and planetary boundaries (BIS, 2020; Chenet et al., 2019; Rockström et al., 2009).

This dilemma of increased pressure from regulators coupled with the inadequate progress on the technical development of analytical tools – if not handled appropriately - could contribute to a systematic underappreciation of transition risk build-up (FSB, 2022). Indeed, consensus from academics and international organisations and fora such as the International Monetary Fund (IMF)[65], the Financial Stability Board (FSB)[66], the World Bank[67] and Network for Greening the Financial System (NGFS)[68] is that due to limitations of currently available climate risk scenario analyses, the risks of financial instability arising from the low carbon transition may be radically underestimated, and similarly benefits of early action and the high costs of delaying the transition may be underpriced by financial institutions.

It is important to note however that assessing and managing climate risk is a new and ongoing process, with substantial learning and refinement happening continually. Nonetheless, as reflected in recent supervisory statements, it is critical that firms get started in strengthening their capability in climate scenario analysis and beginning to build climate dimensions into risk management and business planning.

A lack thereof may potentially give rise to a false sense of security on how the transition may unfold or could result in financial actors using relatively benign and inconclusive results

[65] https://www.imf.org/en/Blogs/Articles/2023/01/04/how-economies-and-financial-systems-can-better-gauge-climate-risks

[66] https://www.fsb.org/2022/11/current-climate-scenario-analysis-exercises-may-understate-climate-exposures-and-vulnerabilities-warn-fsb-and-ngfs/

[67] https://documents.worldbank.org/en/publication/documents-reports/documentdetail/760481644944260441/assessing-financial-risks-from-physical-climate-shocks-a-framework-for-scenario-generation

[68] https://www.ngfs.net/sites/default/files/media/2022/09/07/not_too_late_-_confronting_the_growing_odds_of_a_late_and_disorderly_transition.pdf

as justification for inaction, hindering the much needed reallocation of capital to support and accelerate the transition. It is therefore a contribution of Paper III to provide a taxonomy framework that allows for the first systematic assessment of current scenarios and whether they are fit for purpose. The multi-dimensional scenario taxonomy guides the user to systematically scrutinize relevant scenario components, key assumptions and the underlying modelling and calibration (partial analysis) to derive implications for the credibility and suitability of such scenarios conditional on the financial use case (system analysis). We draw upon existing empirical evidence and recent policy developments to identify the key limitations, and to analyse recent trends of latest scenario exercises by regulators, including their strengths and weaknesses. More generally, we identify that financial institutions may lack the expertise to fully understand the modelling choices and assumptions within a scenario. Scenario selection and interpretation is therefore inherently challenging. Importantly, we identify that currently available scenarios may not capture the full breadth of frictions and risk drivers required by the financial sector and hence could potentially be misused within risk management and climate stress testing. Put differently, our analysis suggests that current scenarios miss important characteristics and processes that we argue are critical to fully understand the potential severity and timescales of climate-related risks. What is more, FIs and CB&S are at risk of misinterpreting the outcomes of climate scenario analysis when inherent challenges, trade-offs and model limitations are not adequately understood. We identify that commonly used scenarios by the NGFS, IEA and Oxford INET and their assumptions around market responses, the energy system, and negative emissions – are often incoherent with the overall scenario narrative and hence provide only limited credibility. Further this makes it increasingly difficult to judge whether in the probability distribution such scenarios sit and whether this is appropriate for a given level of risk appetite. Based on our suitability assessment of currently available scenarios, we drew out key design features that we argue need to be captured in an adequate risk scenario, either through designing appropriate narratives to derive what we term 'Qualitative Narrative Scenarios' or through embedding those features in the underlying modelling to get more empirically and quantitatively driven 'Model Narrative Scenarios'. Further, we show that those features are only partially reflected in currently available scenarios and discuss latest regulatory exercises that have recognized such deficiencies.

Beyond this contribution, Paper II aims to advance the emerging field of climate finance with a quantitative climate stress testing approach – the TRISK framework – that inhibits the following advancements vis-a-vis current approaches: (i) it has an enhanced granularity, through an empirically grounded calibration on the asset and firm-level; and (ii) the transition risk is derived from the misalignment of firms' strategic plans rather than current and historical carbon emission intensities, to allow for a more forward-looking assessment. This can robustly disentangle the heterogeneity of transition risk across climate laggards and aligned firms. The TRISK framework put forward in paper II therefore contributes to overcoming the two main

limitations identified in current approaches and aims to provide more reliable transition risk estimates for financial institutions. The technical contributions are discussed more in detail.

Granularity. The bottom-up climate stress testing framework and financial risk measure TRISK is providing unprecedented granularity through a calibration on physical asset-level data and the representation of transition risk at the firm-level. While other top-down or sectoral approaches may provide a systemic perspective on financial market losses, it does not equip FIs with the required level of granularity to distinguish between transitioning firms and climate laggards within the same industry. Also from a regulatory perspective, to increase the resilience of financial institution and to safeguard financial stability in the transition, climate stress tests need to identify exactly where the risk lies and how concentrated it is. Asset-level data allows to identify the geographical location of firms' physical infrastructure across its ownership structure up to the ultimate parent firm, production capacities across key technologies and along business units (e.g., a granular decomposition of production infrastructure of an integrated oil firm, across its oil exploration sites, fossil-fuel and renewable electricity generation to determine components of revenue and potential vulnerabilities). For instance, to determine the transition risk, decarbonisation pathways and unit cost developments for individual technologies across business lines in climate-critical sectors, can be applied at the level of the asset to reflect different mitigation responsibilities across regions. The TRISK of a firm is therefore not dependent on the mitigation pathways of the country its headquartered in, nor its overall carbon intensity at the firm-level. Rather TRISK is based on the vulnerability of individual asset characteristics and spatial heterogeneity and mitigation misalignment of the physical production infrastructure. What is more, such granular stress test approaches are even more critical to determine financial risk stemming from physical risk and extreme hazard events (see for instance (Bressan, Duranovic, Monasterolo, & Battiston, n.d.)). Hence, granularity is key to unravel the impacts of transition and physical risk in a meaningful way. This DPhil was among the first research to utilize such granular asset-level data and put forward a transparent methodology for scenario risk analysis, supporting the potential of an ever-increasing field of research.

Forward-looking Nature. What is more, current approaches are insufficiently forward-looking as they rely mostly on current and backward-looking carbon emission intensities as a proxy for transition risk. We argue that disclosing carbon emissions is not a sufficient metric for investors and regulators to determine a firm's transition risk and alignment with the Paris Agreement. Importantly, two firms with exactly the same current emissions today could face widely disparate transition risk. If one firm is an oil major that is planning to keep investing in oil fields, and another firm is planning to transition to a business model based on solar farms, then the latter firm will presumably face much lower transition risk. The reason is that it will not be subject to a carbon tax, demand driven effects or phase-out policies, for instance. Transition risk proxied by current emissions will not capture this relevant heterogeneity of the transition impact between transitioning firms and climate laggards. Overall, the failure to dis-

tinguish the heterogenous impact of the transition – either through a lack of granularity or a lack of representing the forward-looking strategies of firms - presents a fundamental problem. For instance, firms belonging to high-carbon-emission sectors today, such as the energy sector, will need to receive plenty of funding at a low cost of capital to finance the transition to a green energy economy while expanding world energy capacity. If investors, including central banks, divest from firms in high-carbon industries, based on their disclosure of currently high carbon emissions, as is the custom now among many investors (Bolton & Kacperczyk, 2021b) and under consideration in central bank circles (NGFS, 2021) then these sectors are drained of the financing needed to transition. From a market perspective, accurately capturing the heterogeneity of the transition impact between climate laggards and transitioning firms is highly relevant. This can inform effective capital allocation and accelerate the transition, rather than hindering it. Investors should divest only from those firms that do not plan to transition to a greener business model, thereby driving up the cost of capital for climate laggards but keeping the cost of capital low for greening firms. From a regulatory perspective, to increase the resilience of financial institution and safeguard financial stability in the transition, climate stress tests need to identify exactly where the risk lies across firms in the real economy – a task most regulatory exercises up to date have shied away from. Overall, identified approaches fall short of capturing forward-looking strategies of firms and lack the granularity to capture the relevant heterogeneity involved in transition risk. The TRISK approach overcomes this limitation by allowing for a calibration on the five-year forward-looking production plans of firms across its physical assets, business lines and technologies, gathered from company and business intelligence reports provided by Asset Impact data. As a result, the transition risk - TRISK – expressed as financial losses from transition-related equity valuation changes of firms (market risk) and associated probability of default changes (credit risk) - is a function of the misalignment of planned strategies of firms with a Paris-aligned scenario pathway, rather than proxied by historical and current carbon emissions alone.

Results from an exploratory application of the climate stress testing framework – TRISK – in Paper II suggests that firms in climate-critical sectors are significantly misaligned based on forward-looking data on strategic plans, indicating a high financial risk for exposed financial institutions. We demonstrate that every year the transition is delayed, the cost of the financial sector and the likelihood of financial instability is increasing. This suggests a systemic risk build up that could cause further disruptions and setbacks in the transition, if not carefully managed and mitigated by CB&S as well as FIs themselves. Further, our results suggest that the transition impact entails significant heterogeneity across our sample of energy firms, with the 5th and 95th percentile of the transition-related equity valuation changes ranging from -49% and 11.56% respectively. Further, we find a significant variation in transition-related probability of default changes, between -0.15 and 2.17 percentage points, reflecting that some firms see positive changes to their creditworthiness (negative PD change) while other firms may see large

PD increases in the net-zero transition.

Further, European power firms are on average less negatively impacted by the transition, than US and Asian counterparts. Yet, we still observe individual firms across all jurisdictions that significantly deviate from peers in their region. The TRISK framework also allows to estimate stranded assets. We find that individual firms risk up to 95% of their production to be stranded, hence rendering production facilities uneconomically in the face of strong climate action and demand changes. Across two synthetic portfolios, the overall transition-related financial losses relative to the overall portfolio size varies between a high negative impact of around -18% as opposed to an overall positive impact of around 8%. The impact is stronger on market risk losses, reflecting that equity prices are more volatile and sensible to investors and market behavior than debt. The heterogeneous impact on portfolios, highlights that the transition inhibits clear distributional consequences across the financial sector that cannot be captured in other climate stress testing approaches with insufficient granularity.

Moreover, as identified in the state of the literature, most regulatory exercises and academic approaches predominantly rely only on one set of scenario provider to determine how the transition may unfold – e.g., the NGFS scenarios. However, as we have discussed, the elevated levels of uncertainty, but also the complexity involved in modelling the socio-economic response to climate change and policy, means that different model approaches have different fundamental assumptions on how the transition is modelled. This represents different transition narratives. Implicit key assumptions on the structure of the energy system, the speed of technological progress, the extent to which socio-economic and climate constraints are reflected, as well as assumptions on institutional inertia are important in shaping the scenario narrative. For instance, within most IAMs, shocks are reflected as diverting away from a general equilibrium, with the economic system recovering from such a deviation and bouncing back to an equilibrium. This shift is associated with high economic cost in the short to medium turn (Mercure et al., 2019) but may not reflect the transition to another equilibrium state. The macroeconomic model choice therefore represents a significant difference in the scenario narrative that needs to be better understood when deciding on scenarios according to the users' beliefs and market expectations. As a result, across scenario providers, e.g., the IEA vis-à-vis the NGFS, there is a high degree of variability across key assumption. This is most often not transparently conveyed to the financial sector and difficult to grasp for practitioners. Such a variability, without sufficient information on what's driving it, makes it increasingly difficult for financial practitioners to judge the credibility and level of conservativeness of different parameter values and pathways.

Importantly, current approaches are limited in accommodating for exactly such a wide range of scenarios and underlying modelling choices to assess sensitivities to underlying assumptions. In contrast, the modular structure of the TRISK framework allows to input many scenario

components across different scenario providers and hence allows to compare the financial risk outcomes across a wide range of more or less restrictive scenario assumptions that are modelled differently, to get an appreciation of the level of uncertainty involved in these exercises. Paper II showcases this feature by providing a more in-depth analysis of the variability in market risk estimates for a set of energy firms across different scenarios with varying narratives. We find that the transition impacts on firms' valuations across three net zero scenarios with the same climate target (well below 2°C) from different providers is substantially different, as observed in the shape of the risk distribution. This highlights that financial risk outcomes can be vastly different depending on the various assumptions underlying these scenarios, such as around energy demand, technological innovation, or cost projections.

Policymakers, CBS and FIs should therefore test the resilience of financial investments across a wide range of different transition narratives to better understand the wide range of uncertainty – which is sometimes the "forgotten" purpose of scenario analysis anyway. As shown in paper II of this DPhil, the flexibility of the TRISK framework allows to simulate firm's asset values under such a rich set of different scenario pathways, which is an important contribution that enhances the framework's decision usefulness. As identified in Paper III, this further aims to prevent biased scenario selection or institutions cherry-picking design choices that lead to supporting existing strategies of financial institutions and hence increases the credibility of the scenario analysis. The TRISK model can be complemented with a more qualitative in-depth analysis of key scenario components following the framework laid out in Paper III to aid scenario selection and interpretation.

Beyond the methodological and empirical contribution of this DPhil around climate stress testing approaches, Paper I also aims to contribute to a better understanding of the wider institutional dynamics around the role of central banks and supervisors in the transition. We contribute to the academic literature and ongoing debate with an analysis on the evolving nature of financial regulation in the aftermath of the global financial crisis, discuss geographical differences around the independence and degree of control over financial dynamics by CB&S and present stylized scenarios that could avoid an institutional deadlock with governments. Using a novel conceptual framework that distinguishes policy motives, instruments and implementing authorities, we have argued that the ability of European countries and similar jurisdictions to introduce market-distorting climate-related financial regulation is limited by: (i) a weak public control on private financial markets; and (ii) the presence of strong independent technical authorities with delegations concerning financial markets. Consequently, CB&S have so far prominently focused on the risk dimension of climate change, with informational policies such as climate-related disclosures and the issuance of supervisory expectations to balance accountability, institutional legitimacy, and legal mandates. These are the political economy considerations that constraint financial policy and regulation aimed at supporting the transition. Or else, CB&S are at risk of

losing accountability and legitimacy that could impede the ability of regulators to act upon their broader objectives. This is less the case in emerging economies, where central banks and supervisors often align financial policies with governments' development and sustainability objectives.

We explore various scenarios that can emerge from the status quo. First, governments could introduce ambitious mitigation policies (e.g. carbon pricing), allowing delegated authorities (CB&S) to focus uniquely on price and financial stability, leaving the need for market-distorting "promotional" policies to governments. This promotional-prudential coordination would be welcome; however, several hurdles currently exist that prevent strong government action on climate. Second, in the face of timid political action, delegated authorities concerned about their output legitimacy might decide to go promotional 'by stealth' and without an appropriate underlying change in mandate. Recent changes by some European delegated authorities hint that this change may have begun. While scope for extending their actions within their current interpretation of mandates exist, this trend, if brought to its extreme, might result in a green technocratic setting or trigger a coercive repossession of policy functions by political authorities. Finally, political and delegated authorities could cooperate in making the necessary adjustments to achieve a new institutional setting, such as a revision of the mandate, or an ex-post validation of promotional drifts.

In a 2018 speech meaningfully titled 'Let's dance', the chair of the NGFS Frank Elderson, outlined the contributions that central banks and supervisors could make in the societal effort to address climate change (Elderson, 2018). Paper I shows that central banks cannot and should not dance alone. Either through strong action in the fiscal sphere or through new clear delegations of climate missions to delegated authorities, political authorities will have to step in at some point, as central banks and other delegated authorities cannot do it all. It will take two to dance: only through strong cooperation from early stages will it be possible to simultaneously achieve effective climate action and continued strong institutional legitimacy. The stylized scenarios can partially explain the remit changes for the Bank of England (BoE) - a case where the UK government and HM Treasury have issued clearer guidance around the mandate with respect to the wider net-zero strategy. But some of the scenarios were strongly informed by developments in the EU and around the ECBs prominent role in the climate sphere. The unique institutional setting and idiosyncrasies around EU's governance, the focus area of ECB senior management and the resulting increased confidence about the understanding of climate risk, may suggest only limited external validity if the framework is applied beyond the EU. Further, a stronger coordination was observed between the EU commission, the European Banking Authority and other supervisory institutions with respect to governance around risk management and climate change more generally. The stylised scenarios should therefore be seen as thought-provoking extreme forms of different possible evolutions. While debates and contentions around legitimacy and division of roles between CB&S and supervisors still remain

relevant, recent developments have shown that coordination has already improved significantly, positioning it in an intermediate stage between coordination, status quo and green financial technocracy.

As identified in paper I of this DPhil, a source of contention between CBS and policy makers is institutional in nature, centering around the appropriate division of roles. The rigorous use of climate scenario analysis has the potential to partially ease this contention. In some advanced economy jurisdictions, financial regulation needs to be first and foremost risk-based to ensure the stability of individual financial institutions and the system as a whole. Analysing transition risk and the impact various transition decarbonisation scenarios have on financial firms can therefore act as an attempt to quantify the range of risk that society is facing. Once such a range is identified through rigorous analysis and an attribution has been made which central underlying drivers may impact the risk distribution over time, then CBS can make an informed decision on their level of intervention, weighing potential unintended consequences with their risk appetite in mitigating that risk. An additional complexity however is that there needs to be an appreciation of the short- and medium term-impact of transition risk and the cost of inaction in relation to a more systemic risk build-up and irreversible climate damages that threaten financial stability in the long-term.

Ideally, a rigorous scenario analysis should capture how those two risk categories interact with each other across time. Far-reaching prudential action may then be justified either based on the long-term financial stability concerns of CBS due to climate damages or based on the desire to mitigate short- to medium-term transition risks. However, this remains a challenge to operationalise in modelling at this stage and goes beyond the contribution of this DPhil. Nevertheless, a discussion around the intertemporal implications of climate change and the net-zero transition on financial stability over time is critical to inform further research; and the findings from this DPhil can be useful in this context.

Importantly, when deciding on the level of intervention in financial markets through regulation by CBS, the analytical evidence should be balanced against the risk appetite of the society expressed through policy makers and the appropriate time horizon of the mandate. This confronts CBS with an additional complexity on how to discount and value financial stability concerns in the short term over financial stability in the more distanced future. These questions are partially fuelling the debate on the legitimacy of CBS action in the climate sphere and are not immediately solvable. A stronger coordination between policy makers and regulators to define the desired risk appetite with relation to financial stability and climate change would be beneficial. As shown in this DPhil, rigorous scenario analysis can be a powerful tool to guide such a debate, by providing financial risk estimates associated with different ways the transition plays out, conditional on the political and societal choices we make. Here, scenario analysis can

serve as an enabling tool to support more effective policies that are best place to mitigate the risk and balance costs and benefits weighted against societal and political preferences. For instance, as shown in paper II, simulating the transition risk distribution based on three different scenarios on the evolution of the energy system provides valuable insights into the respective financial risk consequences of different technological futures, conditional on varying levels of the speed of deployment (which partially can be influenced through regulation and policies). Most importantly, it is critical to scrutinise and understand which levers and assumptions are driving different scenarios to better inform the risk implications of different choices. This DPhil aimed to contribute to this discussion from different perspectives across all three papers. First, with a political economy framework that lays the foundation of the contention between CBS and policy makers. Second, with a methodological and empirical contribution in paper II that exhibits the required flexibility to test a variety of scenarios. Third, with the evaluative contribution in paper III that provides a framework and taxonomy for financial institutions and CBS to scrutinise the credibility of scenarios and aid interpretation of results from scenario analysis. All these perspectives need to be considered when deciding on the optimal level of regulation and intervention in financial markets. More rigorous evidence on the financial risk associated with the transition and climate damages will provide a solid foundation for regulators to make the most appropriate choices. But importantly, as this DPhil highlighted, the risk evidence needs to be interpreted and contextualised with a sufficient understanding of the underlying scenario and model limitations – including the fact that most stress testing exercises cannot yet provide estimates on the intertemporal risk trade-off between physical climate damages and transition risk. This should not encourage inaction until better models are available, but rather shows that most analytical results need to be complemented with a deeper and more qualitative understanding of the risk implications that are not immediately captured but may put the credibility of the scenario or result in question (paper III aims to guide such an analysis). As I argue throughout this DPhil, a systematic misuse of scenario analysis should be avoided at all costs.

However, overcoming the technical challenges only goes so far. While more rigorous analytical evidence on the drivers of risks to financial stability can better inform CBS on the magnitude of the risks over time, how concentrated it is and which regulations and action may be best place to mitigate such risk, it can only partially provide answers to the more fundamental questions around the societal risk appetite and intertemporal value of financial stability over a longer time horizon relevant for climate change. This ultimately influences CBS legitimacy and determines the degree to which both prudential and more promotional policies may be desired. Nevertheless, more rigorous scenario analysis, across multiple dimensions such as enhanced empirical grounding, more granularity, representation of interlinked transition and physical risks over longer time horizons and more forward-looking data on government strategies and corporate plans would provide a significant step towards enhancing the ability of CBS (but also

policy makers) to make effective decisions throughout the net-zero transition. This alone would ease some of the contention between policy makers and central banks, if such evidence would support that prudential as well as more promotional policies could go hand-in-hand due to their risk mitigating impact that safeguards long-term financial stability, as well as their impact on accelerating the net-zero transition in the short- and medium term.

Summary of Contribution. The research of this DPhil serves not only the academic community but also policy makers and financial practitioners with an enhanced understanding of the appropriate design of climate risk scenario analysis, a novel analytical approach to climate stress testing, and provides insights into the institutional drivers and dynamics in the political economy landscape to assess the varying degree of involvement by CB&S. The outputs of this DPhil contributed to a better understanding of the likelihood, the magnitude and heterogeneity of transition impacts, the advancements of forward-looking and granular bottom up risk frameworks. Further, the research communicated the limitations and challenges associated with currently available approaches to better inform CB&S and FIs about their reliability and usability and to identify avenues for further research.

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A Appendix

The Appendix gives additional descriptive analysis for paper II and provides a background analysis on the supervisory statement on which parts of the framework in paper III are building upon. Further Appendix A.1 provides the co-authorship statements.

Table 11: Firm and Asset Coverage

Sector	Number of Assets	Number of Firms	HQ countries	Share of global production (in %)[69]	Countries with Assets
Power	8025	135	29	29,7	92

Table 12: Sector Description

Sector	Segment	Production unit	Emission intensity scope	Technology and Business Unit Type
Power	Power Generation	Installed capcity (MW)[70]	Scope 1	Electricity generated from oil, gas, coal, nuclear, hydro and renewables

[69] Based on a global production in 2021 of 27.520 TW/h. Total Production of firm sample 8.181 TW/h.

[70] We transform installed capacity into power generation by applying regional capacity factors from (IEA, 2020): $h^{-1}(y)$: MW/year $\rightarrow$ MW/h

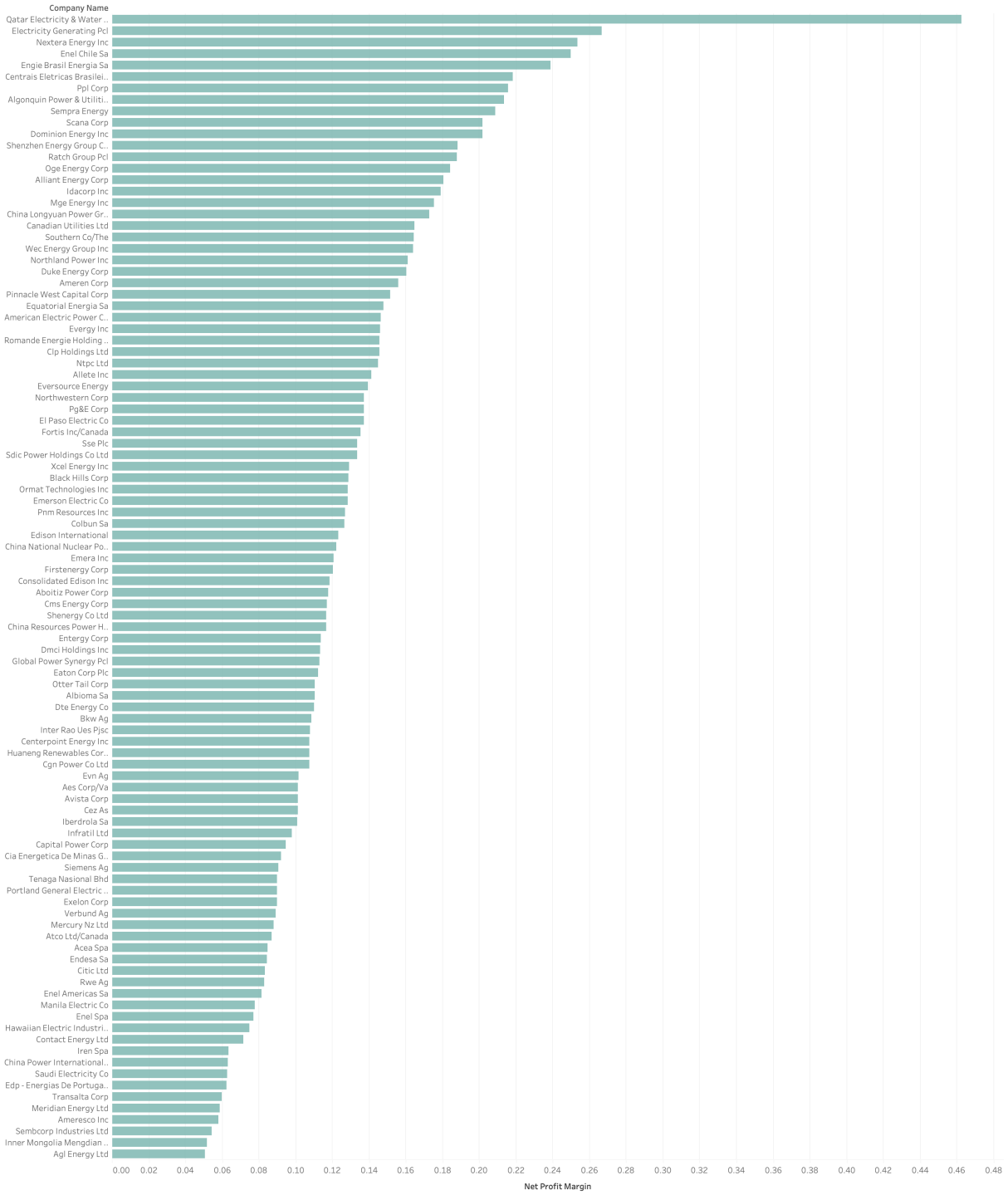


Figure 20: Top 100 firm profit margin

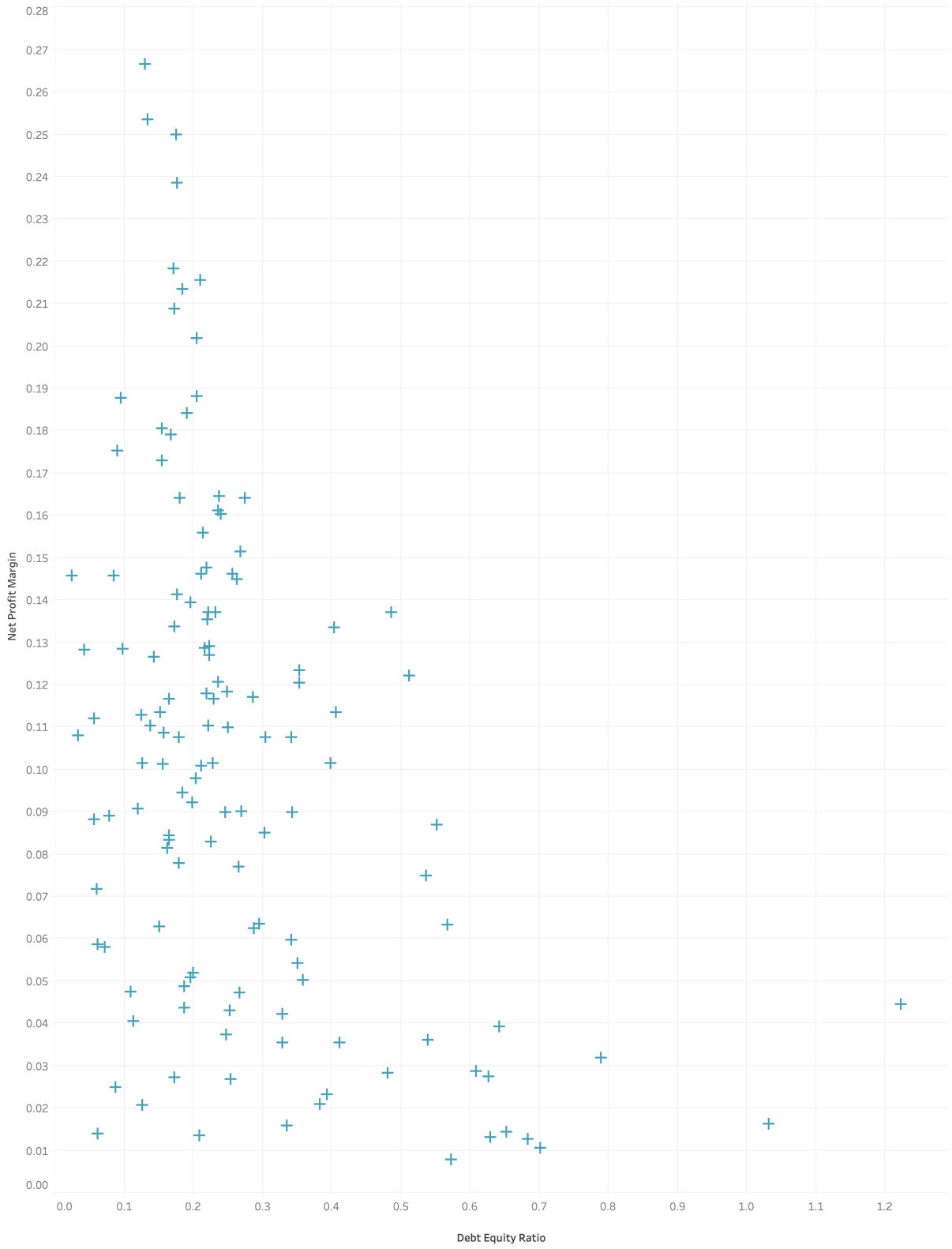


Figure 21: Debt-to-Equity Ratio and Net Profit Margin for Top 100 Firms

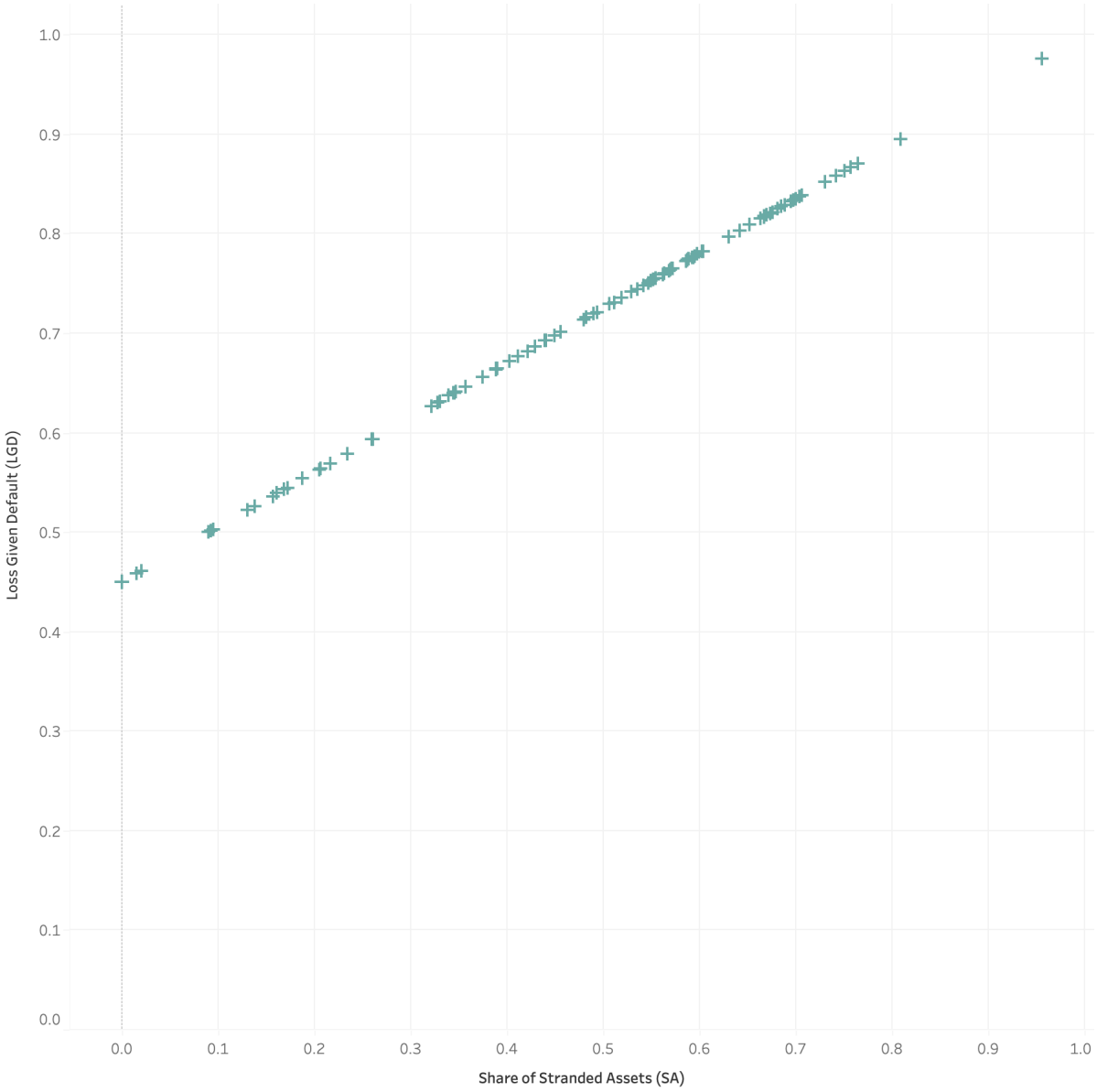


Figure 22: Stranded Assets and resulting LGD with 1.5° Carbon Budget

Figure 22 shows the calibration of firms' loss given default values (LGD) on outstanding debt to assess their credit risk on a counterparty level.

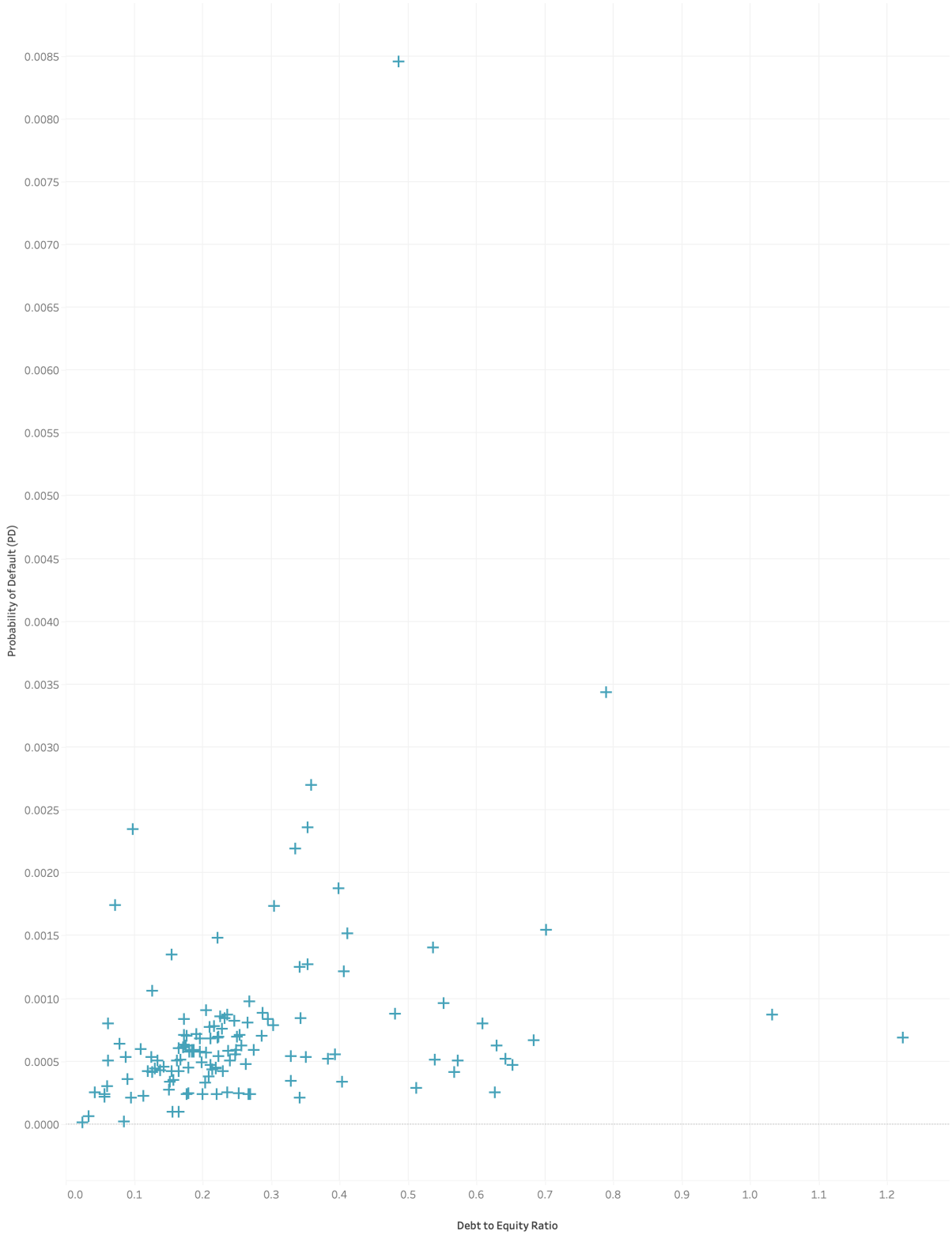


Figure 23: Debt-to-Equity Ratio and observed PDs for Top 100 Firms

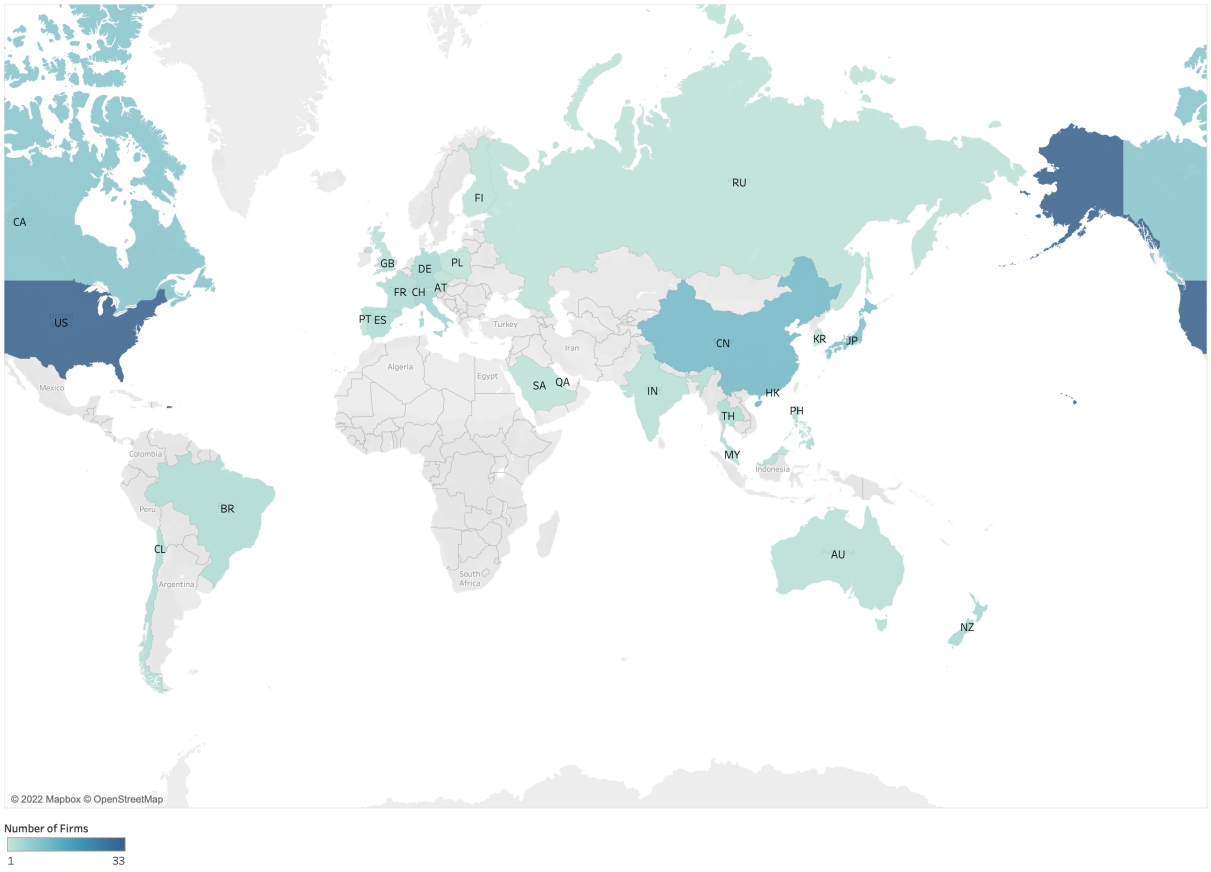


Figure 24: Firms Country of Domicile

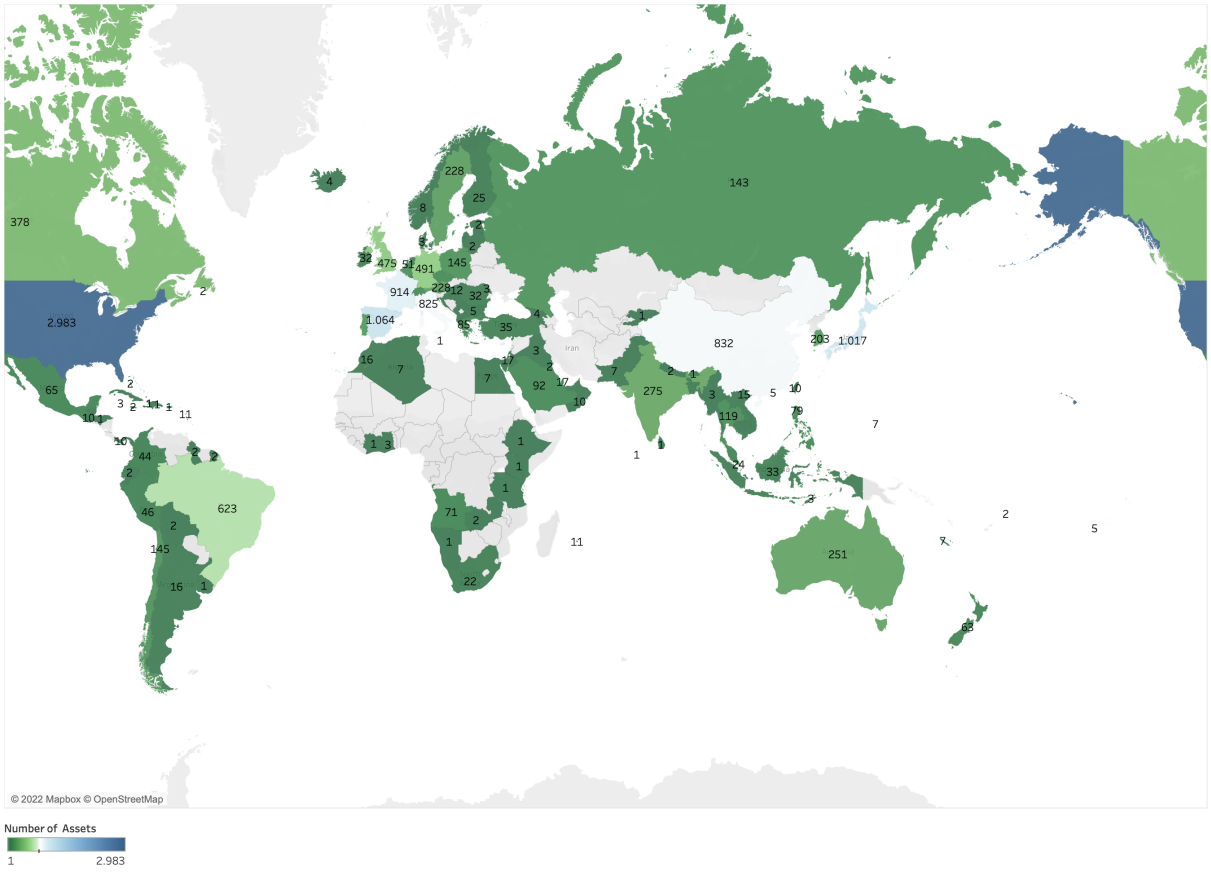


Figure 25: Firms Asset Location across Geographies

	Linked supervisory requirements relevant to scenarios	Requirements from SS3/19 and Letter to CEOs (1st July 2020) relevant to scenarios	*Implications for design of scenarios to inform requirement [authors analysis]*
Governance & Risk Management	Internal capital adequacy assessment Risk control Market risk and group risk systems SS5/16 Corporate governance SS21/15 internal governance	Understand and assess financial risks from climate change and be able to address and oversee these risks within overall business strategy and risk appetite. Demonstrate distinct elements of financial risks. Long-term review of the financial risks that can arise beyond standard business planning horizons Evidence on monitoring and managing risk in line with risk appetite statement [risk exposure limits and thresholds firm is willing to bear, taking account of: how decisions today affect future financial risks; results of stress and scenario testing on shorter and longer time horizons; uncertainty around the timing and channels through which financial risks from climate change may materialise; sensitivity of balance sheet to changes in risk drivers and external conditions]. Firms' oversight of climate-related financial risks could better demonstrate an appreciation of the far-reaching breadth and magnitude of the risks and a clearer understanding of their relationship to financial risks. This includes a clearer understanding of the physical and transition risk transmission channels and interactions between multiple lines of business, sectors and geographies. Medium and large sized firms, and firms with medium or large exposures to climate risk, should link business strategy changes to scenarios, identifying triggers to modify their strategies. Larger firms are expected to develop a range of stress scenarios designed to examine the particular risks inherent in their business models.	Distinct elements of financial risks Time horizon beyond standard business planning horizons Long- and short-term scenarios for stress testing and scenario analysis Analysis of uncertainty of timing through which financial risks materialise Analysis of the uncertainty in channels through which financial risks materialise Sensitivity to changes in risk drivers and external conditions – implies compound risks included
Risk Management	Internal capital adequacy assessment Risk control Market risk and group risk systems SS5/16 Corporate governance SS21/15 internal governance	Address financial risks from climate change through existing risk management frameworks in line with board-approved risk appetite, which recognising need for strategic approach. In a manner proportionate to their business, firms should identify, measure, monitor, manage, and report on their exposure to these risks. You should be able to explain what steps your firm has taken to ensure that, where appropriate, capital levels adequately cover the risks to which your firm is, or might be, exposed. Best practice lessons learnt: some firms managed uncertain and extended time horizons through using scenario analysis/stress tests; and differentiated the foreseeable nature of financial risks that arise from a combination of physical and transition risk factors from tail risks Understand the financial risks from climate change and how they will affect their business model. Firms should use scenario analysis and stress testing to inform the risk identification process and understand the short- and long-term financial risks to their business model from climate change. Firms are also expected to go beyond using only historical data to inform their risk assessment, for example by considering future trends in catastrophe modelling (scenarios). ICAAPs/ORSA – should include at a minimum all material exposures relating to financial risks of climate change and an assessment of how firms have determined material exposures in the context of their business. Metrics and quantification were identified as the most challenging aspect of assessing climate-related financial risks. We recognise that there are some areas where the science, data or tools are not yet sufficient to estimate the risks accurately. In these cases firms should ensure that identified risks are recognised through the use of reasonable proxies and assumptions. The nature of climate risk means firms will have to use long-term, forward-looking risk assessments (i.e. scenario analysis/stress tests). Where firms are reliant on third party information (e.g. climate scenarios and portfolio warming metrics) or outsourced providers, we expect them to have an understanding of the key assumptions and limitations inherent in the information they receive, and to use the information appropriately in their risk management frameworks. We recognise that there are some areas where the science, data or tools are not yet sufficient to estimate the risks accurately. In such cases, we expect you to use reasonable proxies and assumptions to work around these issues, and not leave known risks unrecognised. We expect firms to use risk management tools, which are appropriate for the speed of change that is necessary (e.g. early-warning indicators to engender prompt action where appropriate, or metrics to track a plan to pivot a firm's business model gradually over a number of years). Where the potential impacts of the financial risks are assessed to be material (for example as a result of scenario analysis), the PRA expects firms to evidence how they will mitigate these financial risks and to have a credible plan or policies in place for managing exposures. Plans should be reflective of the distinctive elements of the financial risks from climate change, so may differ from other risks. To inform their risk assessment and management, firms should seek to understand the potential current and future impacts of the physical and transition risk factors on their clients, counterparties, and organisations in which the firm invests or may invest.	Better understand likelihood of scenario materialisation to match with own risk appetite Understand analytical tools, limitations, and assumptions to ensure that identified risks are recognised Engage with counterparties to receive relevant forward-looking information on strategic transition plans to proxy for transition risk Have dynamic analytical risk monitoring in place to regularly update risk scenarios based on the rapid changes in policy and speed of transition
Scenario Analysis	Internal capital adequacy assessment (PRA rule book); SS31/15 ICAAP the Supervisory Review and Evaluation Process (SREP)	Where proportionate, the PRA expects firms to conduct scenario analysis to inform their strategic planning and determine the impact of the financial risks from climate change on their overall risk profile and business strategy. Scenario analysis should also be used to explore the resilience and vulnerabilities of a firm's business model to a range of outcomes The PRA expects a firm's scenario analysis to address a range of outcomes relating to different transition paths to a low-carbon economy, and a path where no transition occurs. The scenario analysis should, where appropriate, include: short-term assessment which sets out the firm's exposure to the financial risks from climate change within its existing business planning horizon; longer term assessment of the firm's exposure, based on its current business model, of a range of different climate-related scenarios. The PRA expects the time horizon of this long-term assessment to be in the order of decades. As with other types of scenario analysis, this is not intended to be a precise forecast, but a qualitative exercise used to inform strategic planning and decision making. Where a firm relies on management actions to mitigate the financial risks from a scenario, it should consider whether these are realistic, credible, consistent with regulatory expectations, and achievable. For example, it should not rely on the existence of a liquid market to sell the assets it has identified as being exposed. Firms should also consider whether any of the actions identified should be taken in advance as precautionary measures, or whether they would be relevant or desirable only if the scenario emerges. Firms should consider a range of scenarios covering both short-term (business planning horizon) and long-term (in the order of decades). Firms should select scenarios and timescales appropriate for their particular business model. When considering longer-term scenarios, firms should select a range of scenarios that reflect the range of climate outcomes (for example consistent with an average global temperature increase of less than or significantly less than 2°C) to a weak/no transition scenario (for example that results in continued growth in emissions and warming significantly in excess of 2°C by 2100). Firms may find it helpful to use a range of approaches. For example, evaluation of abrupt near-term transitional changes using detailed traditional static balance sheet stress tests, and longer-term physical climate and socio-economic changes using less granular analysis of the business model. We view it as useful for firms to differentiate between the central scenarios that shape their core business strategy and the tail risk scenarios that might be used to place a limit on their risk appetite or drive hedging activity and other possible actions Firms may wish to consider one or more central projections alongside other scenarios to explore tail risks. Some scenarios may be quite detailed and others more high-level. Firms should evaluate scenarios to a level of detail and accuracy appropriate to the uncertainty inherent in the scenario. Firms should consider how quickly their business might be able to react to the changes inherent in the scenarios, and not assume the business can respond faster than the changes in the scenario. Firms may wish to use standard, reference scenarios (such as those provided by the PRA as part of the BES, the Intergovernmental Panel on Climate Change or the NGFS) or tailor scenarios to their circumstances. Firms may wish to consider reverse stress tests as a method to assess what could cause the firm to fail, and the extent to which this could be driven by climate-related factors. Insurers, for example, might wish to consider robustness of reinsurance.	Short term scenarios for stress testing and scenario analysis Use realistic, credible scenarios, consistent with regulatory expectations Due to uncertainty and lack of applicability of past data, use innovative quantitative and qualitative tools to inform decision-making Sensitivity to changes in risk drivers and external conditions for scenario calibration as outlined in the proposed framework in this report

Table 13: SS3/19 – Focus on bank components only

A.1 Co-Authorship declaration

Bologna, Italy
15th of December 2021

Prof. Emanuele Campiglio
University of Bologna, Italy

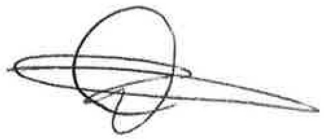
Contribution Statement - DPhil paper Moritz Baer, University of Oxford:

Baer, M., Campiglio, E., Deyris, J., 2021. It takes two to dance: Institutional dynamics and climate-related financial policies. Ecological Economics 190, 107210. https://doi.org/10.1016/j.ecolecon.2021.107210

The following contributions were made to the paper, following the Elsevier CRediT author statement[1]:

- Moritz Baer: Conceptualization; Methodology; Investigation; Writing – original draft; Writing – review & editing
- Emanuele Campiglio: Conceptualization; Methodology; Investigation; Writing – original draft; Writing – review & editing; Funding acquisition
- Jerome Deyris: Methodology; Investigation; Writing – original draft; Writing – review & editing

Emanuele Campiglio



[1] https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement

Bologna, Italy
17th of December 2021

Jérôme Deyris,
Université Paris Nanterre, France
jdeyris@parisnanterre.fr

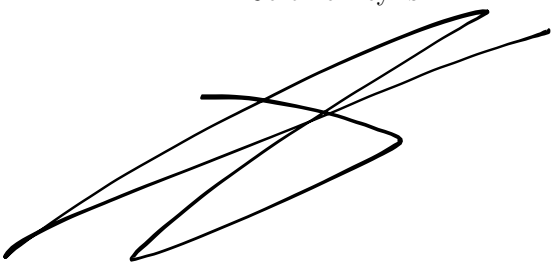
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Jérôme Deyris



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Contribution Statement - DPhil paper Moritz Baer, University of Oxford:

TRISK – A Climate Stress Test for Transition Risk. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4254114

The following contributions were made to the paper, following the Elsevier CRediT author statement[1]:

- Moritz Baer: Conceptualization; Methodology; Investigation; Formal analysis, Writing – original draft; Visualization, Writing – review & editing
- Jacob Kastl: Methodology; Formal Analysis; Writing – review & editing
- Alissa M. Kleinnijenhuis: Methodology; Writing – review & editing
- Nicola Ranger: Writing – review & editing
- Ben Caldecott: Writing – review & editing

Jacob Kastl (Date and Signature) 21 July 2023, 

Alissa M. Kleinnijenhuis (Date and Signature) 20 July 2023 

Nicola Ranger (Date and Signature)  21 July 2023

Ben Caldecott (Date and Signature)  15/07/2023

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Contribution Statement - DPhil paper Moritz Baer, University of Oxford:

"All scenarios are wrong, but some are useful"—Toward a framework for assessing and using current climate risk scenarios within financial decisions. Front. Clim., 14 July 2023
Sec. Climate and Decision Making. Volume 5 - 2023 |
https://doi.org/10.3389/fclim.2023.1146402

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- Moritz Baer: Conceptualization; Methodology; Investigation; Writing – original draft; Visualization, Writing – review & editing
- Matteo Gasparini: Investigation; Writing – review & editing
- Ryan Lancaster: Conceptualization; Investigation; Writing – review & editing
- Nicola Ranger: Conceptualization; Methodology; Writing – review & editing

Based on the contribution above, we declare that Moritz Baer has made a substantial contribution to this publication

Matteo Gasparini (Date and Signature) 15/07/2023 

Ryan Lancaster (Date and Signature) 15/07/2023 

Nicola Ranger (Date and Signature)  21st July 2023

[1] https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement