Climate-related financial policy in a world of radical uncertainty:

Towards a precautionary approach

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Hugues Chenet, Josh Ryan-Collins and Frank van Lerven

Abstract

Climate-related financial risks (CRFR) are now recognised by central banks and supervisors as material to their financial stability mandates. But while CRFR are considered to have some unique characteristics, the emerging policy agenda for dealing with them has largely focused on conventional market-based solutions. Current policy emphasises information gaps that prevent the accurate assessment of market risk. The assumption is that these gaps can be remedied via disclosure, transparency, scenario analysis and stress testing, which will enable markets to self-correct. We argue this approach is misguided as CRFR are characterised by radical uncertainty and hence 'efficient' price discovery is not possible. Instead, a 'precautionary' policy approach is proposed. Since climate change poses a severe and potentially irreversible threat, lack of scientific certainty as to its exact nature or timing should not prevent regulatory action to mitigate its impact. Such an approach justifies fully integrating CRFR into financial policy, including both prudential and monetary policy frameworks. Central banks and financial supervisors can and should actively steer market actors in a clear direction — towards a managed transition — to ensure a scenario that minimises harm to the financial system and the wider economy in the future.

Keywords: Financial stability, financial regulation, macroprudential policy, central banks, climate-related financial risks, climate change, sustainable finance, systemic risk, low carbon transition

JEL codes: Q54, E44, E58, G28, G18, G14

1. Introduction

> 'If there is greater uncertainty about the effectiveness of tools for easing than tightening, then the monetary policy implication is clear: more should be done to cushion the effects of negative shocks, the like of which we have just seen, than positive ones… Put differently, I would rather run the risk of taking a sledgehammer to crack a nut than taking a miniature rock hammer to tunnel my way out of prison.'
>
> Andrew Haldane (2016)

It is now widely accepted that climate change poses serious threats to financial stability and as such is material to central banks' and financial supervisors' mandates (see, *inter alia*, Carney 2015; Gros et al. 2016; TCFD 2017; Campiglio et al. 2018; NGFS 2019b). Such recognition was a key catalyst in the creation of the Network for Greening the Financial System (NGFS), an international grouping of 63 central banks, financial supervisors and observers focused on how financial policy[1] needs to adjust to support a smooth net-zero carbon transition. A consensus is now emerging as to the nature of climate-related financial risks (hereafter CRFR) involving physical, transition and liability risks (Carney 2015; NGFS 2019b). CRFR are unique in that they are characterised by far-reaching impact, unforeseeable nature and irreversibility. They are also systemic as they have the potential to affect the entire economy and financial system (NGFS 2019b).

But how to deal with such risks — especially transition risks involving structural changes to the economy on the path towards net-zero carbon emissions — is an emerging area. One specific challenge is the measurement and forecasting of CRFR in a way that supports effective interventions. In particular, there is a timing problem, whereby, as noted in the first NFGS policy report, while '…the risks call for action in the short-term to reduce impact in the long-term […] there is a need to build intellectual capacity in translating the science into decision-useful financial risk assessment information' (NGFS 2018a, p. 3).

The emerging policy framework for dealing with CRFR has so far focused mainly on market-correcting strategies. CRFR are perceived to be under-priced in existing financial markets — or not priced at all — and financial markets are viewed as too short-termist in their outlook (Thomä and Chenet 2017). Hence policy has focused on encouraging financial institutions to examine and disclose CRFR — most notably through the Task Force on Climate Related Financial Disclosures (TCFD) — and, more recently, encouraging scenario analysis and stress testing (Vermeulen et al. 2018; Bank of England 2019; NGFS 2019a). However, many questions remain open around the assumptions that should be used to determine different scenarios and what the outcomes of scenario modelling and stress testing results actually mean for policy interventions,

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[1] We use financial policy as shorthand to incorporate monetary policy, financial regulation and credit policies carried out by both central banks and financial supervisory authorities. It should be noted that monetary policy and financial supervision can be carried out by separate institutions depending on the country in question.

beyond sending useful signals to markets. In the 'First comprehensive report' NGFS (2019b), the only concrete policy proposal going forward is to 'develop voluntary guidelines on scenario-based risk analysis' that individual central banks and supervisors may use to inform their policy frameworks (NGFS 2019b, p. 37). In other words, while it is preferable to act now, it may not be possible to do so since there is insufficient 'intellectual capacity' to understand the nature of CRFR and how policy interventions may affect their development.

In this paper, we challenge this assertion, arguing that CRFR are subject to radical or 'Knightian' uncertainty (Knight 1921; Christophers 2017) whereby the probabilities of different outcomes are impossible to calculate. This means sufficient 'intellectual capacity' for policy action will potentially never be reached in advance. The radical uncertainty attached to CRFR is a consequence of the endogenous interaction of policy and regulatory change, technological innovation, changing consumer preferences in the real economy and the highly interconnected global financial system which propagates and amplifies such risks rather than containing it within particular institutional, sectoral or spatial domains. Being endogenous and systemic means CRFR cannot be treated as conventional financial risks to which probabilities can be assigned based on previous data or hypothesised scenarios to inform climate financial policy and supervisory decision making.

Given this and given the widely acknowledged fact that not acting in the short term will increase the severity of CRFR, we argue that a *precautionary,* market-shaping (Mazzucato 2016) approach to financial policy and supervision is required. Financial supervisors can and should actively steer market actors in a clear *direction* — towards a managed transition — to ensure that a scenario that minimises harm to the financial system and wider economy in the future is the scenario that actually occurs. This requires some self-reflexivity on the part of policy makers. They should recognise the key role of regulation and supervision in determining the nature of emerging CRFR. They, together with ministries of finance and other relevant parts of government, must view themselves as helping to *create their preferred scenario* rather than spending years gathering sufficient information attempting to understand and predict *a priori* what scenario is occurring and then acting accordingly.

The 'precautionary principle' encourages preventative policies that protect human health and the environment in the face of uncertainty. It is well established in the environmental protection sphere, but was less well accepted in the sphere of financial regulation up until the global financial crisis (GFC) of 2007-08 (Cullen 2018). However, the crisis made clear the limitations of conventional microprudential financial risk-modelling approaches that attempt to forecast future risks based upon previous data. In its aftermath, regulatory innovations — in particular macroprudential policy, resolution planning and stress testing — can be seen as a shift in the direction of a precautionary approach. The starting point of macroprudential policy is to take preventative action to increase the resilience of the financial system to hard-to-predict-shocks, including rare events such as financial crises (Altunbas et al. 2018). Post-crisis monetary policy has also taken a precautionary turn with liquidity easing policies enacted on a massive scale to avoid financial crisis and stimulate growth.

The application of the precautionary policy intuition to the climate transition is clear. The transition creates significant uncertainty over future financial stability and raises the risk of a rare, highly catastrophic event (e.g. a financial crisis); under such conditions, the precautionary policy maker has a strong incentive to act to insure the economy against such events, even if there are no available models that can predict the probability of such an event happening (Weitzman 2012; Svartzman et al. 2019; Bolton et al. forthcoming 2020). A precautionary policy approach to CRFR also means rethinking how regulatory interventions are appraised and evaluated. Conventional cost-benefit analysis which seeks to quantitatively weigh outcomes to determine the best policy option at a given point in time (or with some kind of discount rate) are not appropriate because the well-established irreversible nature of climate change risk gives rise to potentially infinite costs (Taleb. et al 2014). Instead of optimising (short-term) market efficiency and focusing on prices, the focus should be on avoiding tipping points and thresholds, and building system resilience.

The remainder of the paper is structured as followed. In section 2 we review the existing academic and policy literature on financial risk and uncertainty, and then move on to examine how these notions apply to CRFR. In section 3 we introduce the precautionary financial policy approach, drawing on examples from environmental, financial and monetary policy to illustrate our argument. Section 4 focuses on the implementation of a precautionary financial policy approach, reviewing both existing and new policy tools in both regulatory and monetary policy spheres. Section 5 examines the potential challenges for central banks and supervisors in adopting a precautionary approach and section 6 concludes with suggestions for further research.

2. Climate change and financial risk

2.1 The nature of climate-related financial risks (CRFR)

There are two main categories of climate-related financial risks (e.g. Chenet et al. 2015; TCFD 2017): *Physical risks* – resulting from the changes in climate conditions themselves and their direct impacts, through either acute or trend variations (e.g. global warming, heatwaves, droughts, sea level rise, extreme weather events); *transition risks* – coming from the socioeconomic reaction to climate change, either through mitigating or adapting to the effects of climate change (e.g. the introduction of climate-change related policies such as carbon taxes, new regulations or rules around production of certain goods, technological development and deployment, evolution of consumer preferences, litigation[2]).

Physical and transition risks can affect the financial system in multiple ways. First, risk materialises at physical asset and company levels, either through their own operations or from others', via the market or the supply chain. These impact the revenues and expenditures of the companies which then affect their access to capital and financial values. Having started at the company level, risk can then materialise at financial market level, through the classic market, credit, liquidity and operational risks. Thereafter, risks can propagate through financial institutions' portfolios and

[2] Litigation and liability risk can also be considered as an independent category of climate-related risk (Carney 2015).

potentially become systemic (Dow 2000).[3] While the banking system in most advanced countries has only low direct exposures to firms engaged in fossil fuel extraction, it has much wider exposures to other fossil-fuel dependent sectors, not least real estate and transport (Battiston et al. 2017; Regelink et al. 2017; Cahen-Fourot et al. 2019). Some banks also have large equity exposures to institutional investors and asset managers who have more direct fossil fuel exposures (Battiston et al. 2017).

Uneven, unplanned and drastic policy reforms aimed at catalysing a net-zero carbon transition compatible with the 1.5°C target, or alternatively spontaneous and radical changes triggered by technology or consumer behaviour, could abruptly impact on the actions of market players, whose concomitant reactions would lead to a network of adverse cascade effects (e.g. large-scale fire-sale of assets or hoarding of cash) between market players, creating a potentially unanticipated redistribution of economic resources across multiple sectors (Cahen-Fourot et al. 2019). Such an upheaval of our current economies and propagation to the deeply interlinked network of financial intermediaries thus constitute ultimately a systemic risk to the financial system as a whole (Battiston et al. 2017; Naqvi and Monasterolo 2019; NGFS 2019b).

There are important trade-offs between physical risks and transition risks (Campiglio et al. 2018; NGFS 2019a). Rapid and deep decarbonisation involving high transition risks in the short-term should decrease medium- to long-term physical risks. Conversely, adopting a path of more gradual transition naturally reduces transition risk, but heightens physical risk. While it is impossible to forecast the policy decisions that will be taken in the immediate and long-term future, there is consensus that the physical manifestations of climate change are expected to increase dramatically if the current slow pace and ambition of adjustment continues (IEA 2019b, 2019a).

2.2 The policy response to CRFR

Disclosure and enhancing market efficiency

The financial policy framework for dealing with CRFR has focused on financial market actors mispricing or under-pricing risk and encouraged greater risk disclosure (e.g. Carney 2015; French Republic 2015; TCFD 2017; California Senate 2018; European Commission 2018; HLEG 2018). By encouraging corporations to disclose their actual or perceived exposures and plans to deal with these exposures (e.g. via governance, risk assessment frameworks and scenario analysis), financial supervisors expect more effective price discovery can occur, 'market discipline' can be imposed and capital allocation optimised (Krogstrup and Oman 2019, pp. 22-26; see Christophers 2017 and Cullen 2018 for more detailed discussions).

Improvement of transparency indeed lies at the centre of the major international policy effort – the Task Force on Climate-related Financial Disclosures (TCFD) — by financial regulators to meet the challenge of climate change financial risks (Carney 2015; TCFD 2017). Disclosure of risk and

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[3] We consider systemic risk as the risks that threaten to destabilise the financial system as whole, which bring significant costs to the real economy – meaning the destruction of economic value and leading to losses in terms of economic growth (Constâncio 2016).

transparency is also central to Pillar 3 of the international Basel III regulatory framework and one of the key recommendations of the NGFS in its first comprehensive report is that:

> '…authorities can set out their expectations when it comes to financial firms' transparency on climate-related issues. Through the promotion of climate-related disclosure via Pillar 3, for example in line with the Task Force on Climate-related Financial Disclosures (TCFD) recommendations […] authorities can contribute to an improvement of the pricing mechanisms for climate-related risks and a more efficient allocation of capital.' (NGFS 2019b, p. 27)

The TCFD recommendations have been widely embraced, with many large banks, asset managers, pension funds, credit rating agencies and accountancy firms having signed up to them, in addition to the official support of governments and financial regulators (TCFD 2019). However, while many firms have published information about their exposures, fewer have disclosed their views on the forward-looking financial risks they face or considered the longer-term strategic resilience of their business models to the reality of the massive structural change needed to shift to a net-zero carbon economy. Notably the NGFS (NGFS 2019b, p. 33) goes on to say that, 'The NGFS is also mindful of the remaining challenges, including the current lack of data, the scope of reporting and methodological issues.'

Moreover, the evidence suggests that a voluntary approach to risk disclosure may not be sufficient to generate a step change in investment and bank lending behaviour (Ameli et al. 2019; BCAM 2019; Christophers 2019). Recent analysis shows that the world's largest investment banks have provided more than $700bn of financing for the fossil fuel companies most aggressively expanding in new coal, oil and gas projects since the 2015 Paris Climate Change Agreement (Greenfield 2019a). Meanwhile, the thermal coal, oil and gas reserve holdings of the 'big three' asset managers (Blackrock, Vanguard and State Street) have surged 34.8% since 2016 (Greenfield 2019b).

The creation by the NGFS of a dedicated 'macrofinancial workstream' illustrates that the issue of climate change-triggered financial instability at a systemic level is now considered seriously by central banks and supervisors. However, it is still not demonstrated *per se* that the physical risk to financial stability is material in the self-defined time horizons of central banks and supervisors (Tooze 2018; Christophers 2019). Indeed, the key challenge is that initiating a transition now inevitably raises short-term financial market transition risks in order to ameliorate longer-term physical risks. Without doing so, it will become impossible to achieve the internationally agreed goal of limiting global warming to 'well below 2°C' (UNFCCC 2015; Masson-Delmotte et al. 2018).

Scenario analysis and stress testing

Even if financial firms accept the need to disclose the CRFRs, they face a further problem in accurately measuring such risks. Within the logic of the disclosure framework, companies and financial institutions are expected to publish precise measurements resulting from diverse types of modelling and quantitative assessments in order to inform financial decisions. This trend reflects the last four decades of mathematization of finance in general and financial risks in particular (e.g. Bouleau 2011). Indeed, the vast majority of financial risk management approaches are purely quantitative and rely on sophisticated statistical and stochastic modelling tools. Yet, as has been recognised by supervisors, CRFR are not well suited to conventional risk management tools and indicators, because of the high level of uncertainty around both their severity and time frames (NGFS 2019b, 2019a). In order to cope with the multiplicity of climate change outcomes, the main risk management approach being currently promoted is scenario analysis and stress testing. This is the case for the TCFD (TCFD 2017), central banks and supervisors (French Republic 2015; Batten et al. 2016; Regelink et al. 2017; California Department of Insurance 2018; NGFS 2018b, 2019a, 2019b; Vermeulen et al. 2018; Bank of England 2019) and banks themselves (BBVA et al. 2018; Knight and Ganguly 2018; UNEP-FI 2019).

Scenario analysis involves studying a financial security/portfolio/institution/group of institutions in a given realisation of the future (i.e. a scenario) for a number of parameters, such as liquidity, capital adequacy ratios or valuation (Chenet *et al.* 2015). Stress tests involve analysing the impact on financial actors of a range of scenarios, usually testing extreme, rare or adverse shocks (or trends) on these parameters. Under current regulation, stress tests are commonly undertaken at either micro- or macroprudential levels. The purpose of microprudential stress tests is to prevent the failure of individual financial entities, estimating the behaviour of balance sheets under specific adverse scenarios. In contrast, macroprudential stress testing involves assessing all, or a subset of, financial institutions in a given jurisdiction, with the same stress scenario. This enables supervisors to estimate the impact of an adverse shock on the financial system's capital and profitability, its ability to support economic activity as a whole and systemic contagion effects (Anderson et al. 2018).

Scenario analysis and in particular stress testing in finance usually rely on a comparison of a limited set of scenarios (typically one business-as-usual versus one adverse) over short time periods (generally one to three years), with the reaction function of the agents based upon historical data. This inevitably limits the range of possible outcomes (Beckert and Bronk 2018; Pilmis 2018). Some future realisations may appear impossible or so improbable that they are not worth considering, but even with realistic scenarios it is difficult, if not impossible, to deal with unprecedented events on the basis of historical events in the absence of any equation of state.[4]

This is problematic when it comes to CRFR. Climate change involves a situation where many options are 'possible' or 'plausible'. The IPCC, for example, considers a set of 222 scenarios that are compatible with the 1.5°C or 2°C global warming target, plus 189 scenarios representing a

[4] Equations of state in physics and thermodynamics give the relations between state variables that describe the state of the matter under given physical conditions (e.g. pressure, volume, temperature). The absence of a fixed relationship between an economic agent and its environment prevents its behaviour being described in a deterministic way.

variety of non-desirable warmer futures (Masson-Delmotte et al. 2018). And those only represent *global* emission pathways, not the multiple variations at regional and national levels that interact with each other and are the responsibility of local and national governments, central banks and supervisors. Indeed, knowing precisely the regional or local variability of emissions is not absolutely essential for modelling the future climate state (one ton of CO_2 emitted in the UK is equivalent in terms of contribution to warming to one ton of CO_2 emitted in Namibia). However, such knowledge is necessary to understand the future state of economy (one unit of oil sold in the US does not have a similar economic impact as one unit of rice sold in Vietnam, even if they release the same amount of greenhouse gas (GHG)).

2.3 The need for a different approach: risk versus uncertainty

Conceptual framing: risk and uncertainty

The issue of whether central banks and supervisors have yet to embrace macroprudential policy frameworks when dealing with CRFR may relate to an inability or unwillingness to distinguish risk from uncertainty. Risk is generally approached in economics and financial modelling to mean 'probabilistic or stochastic risk', implying random outcomes with knowable probabilities (Knight 1921). Assessing risk predominantly involves employing probabilistic density functions in statistical or econometric analyses, based on forward-looking projections of past data, to make predictions about the economy (e.g. Chenet et al. 2015; Thomä and Chenet 2017). As such, the future is essentially conceptualised as a replication of the past (Davidson 1988; Daníelson 2003).

In contrast, 'uncertainty' refers to a situation where there is no basis whatsoever upon which to form any calculable probability: 'Uncertainty in this account arises when the probability relation is numerically indeterminate and non-comparable to other probability relations' (Keynes 1936; Lawson 1985, p. 914). Under situations of uncertainty, the future is unknowable and unpredictable, and thus non-ergodic.

In financial markets the pricing of an asset is mainly a function of its risk probability distribution. As risk probability distributions provide market actors with knowable information about the future, capital portfolios can be adjusted to maximise profits and mitigate possible risks. In case it is not possible to assign an event a probability, the financial risk associated with this event is non-quantifiable and non-insurable. For greater precision, in much of the economic and finance literature a 'Knightian risk' refers to a risk that can be priced, because there is enough knowledge about the implicit or explicit probability distribution. In contrast, a situation of 'radical uncertainty' implies such a 'risk' (sic) cannot be priced. Thus, the more one considers a situation involving complex, unpredictable, unprecedented and long-term factors, the more one is exposed to radical uncertainty rather than Knightian risk.

Under the efficient market hypothesis (EMH), security prices are supposed to fully reflect the available information about the underlying risks affecting those securities (Fama 1970; Basu 1977), i.e. to represent the 'real' risk situation as far as it is known.[5] Within the EMH framework, a price variation reflects a modification of risk or a modification of risk perception by market players. In the presence of radical uncertainty, markets cannot efficiently price such exposed securities. Nobel laureate Robert Lucas suggested that 'in cases of uncertainty, economic reasoning (e.g. efficient markets hypothesis) would be of no value' (Lucas 1981, p. 224). In other words, market prices are always *incorrect* for securities affected by significant radical uncertainty; or, to put it another way, markets are blind to such radical uncertainty.

CRFR demonstrate a number of specificities that make them different from usual financial risks (Chenet et al. 2015; Thomä and Chenet 2017; NGFS 2019b). CRFR cover time horizons much longer than the usual ones considered in financial markets (normally three to five years); they are unprecedented and offer no past record of similar events or trends; they may have consequences that are irreversible; they may be endogenous by nature and unlike the macroeconomic shocks typically used in benchmark Dynamic-Stochastic-General-Equilibrium (DSGE) models that incorporate finance (Danielsson and Shin 2003); CRFR are also interlinked and systemic, involving non-linearity and tipping points, which requires them to be considered with macro approaches rather than the usual micro approaches that prevail for 'classical' risks. We examine these issues in more detail below.

Physical risks and uncertainty

First, the physics of climate change is inherently complex because it describes the dynamics of a multidimensional non-linear system, involving a multiplicity of subsystems where the current scientific approach is unable to capture all the parameters and mechanisms taking place (IPCC 2007). The interactions between solar radiations and the atmosphere are not the only relationships needed to model the future state of the climate and, more broadly, the environment. The ocean, biosphere, cryosphere, pedosphere and lithosphere also interact together, and are both sensitive to and influence climate and the environment.

On top of this, human — and particularly industrial — activity acts as a major force. Each single element of this system comes with its own level of uncertainty, which relies both on physical laws to model the phenomena, and the related observations models are compared with (IPCC 2007). Such types of uncertainty can be considered as 'error bars' rather than radical uncertainty as framed in the previous section, i.e. probability functions are attributable to future events with a certain level of confidence. Nevertheless, this does not mean that the future climate is predictable in a deterministic way: such predictions are conditional, i.e. under certain assumptions of future social and economic realisations (scenarios or pathways) it is possible to describe what the future climate will be, with a specific likelihood.

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[5] 'Market prices reflect the 'known information set', which comprises all information, all knowledge and all experience available at the time' (Slovik 2010).

Then, the impact of a specific future climate realisation is also uncertain. Under a specific degree of warming and the resulting consequences in the long run (e.g. on sea level), the exact effect on, and potential damage to, for example, a specific building or infrastructure, is highly uncertain, as are the associated cost, adaptation and anticipation of such impacts. The same applies in terms of the impacts of climate change on local flora and fauna.

Transition risk and uncertainty

Transition risk is subject to considerable levels of uncertainty, notably due to the human and behavioural factors at stake. To understand the level of transition risk involved requires answering the questions, 'What will the reaction of governments, companies and people be to climate change?' and 'What effect will this reaction have on climate change?' Socioeconomic reactions cover a vast number of eventualities, from strictly no change to a globally profound transformation, with a quasi-infinity of nuances in between spanning all the possible visions of how policy, industry, technology, geopolitics, society and individuals can evolve over time (classically up to 2100 to cope with climate-relevant horizons, even if climate consequences extend much longer). Transforming each of these socioeconomic scenarios into effects on climate requires a translation of all the choices, at a global scale, into GHG trajectories. These global predictions come with significant uncertainty for each sub-system (e.g. global emissions of the energy mix, transportation system, infrastructures, agriculture, forests).

A further layer of uncertainty arises from the impact of policy tool(s) that may be activated to realise some of the transformations above. When a government decides to put in place, for example, a carbon tax, an emission regulation on car engines, or a climate-aligned financial or monetary policy, it has only a vague idea of the final outcome, especially if it is a new policy tool in a new geo-/economic-/socio-political environment. In other words, new policies can increase complexity and uncertainty.

These different 'spots' of uncertainty are exacerbated by the fact that they occur within a complex network involving unpredictable reactions and interactions between market players (i.e. humans).[6] Those can create non-linear dynamics with high potential for positive feedback loops, covariance of risk probabilities and 'fat tails' (Thomä and Chenet 2017). Such features, inherently associated with radical uncertainty, constitute a typical characteristic of CRFR being endogenous to the financial system. Climate-related shocks can emanate from inside the financial system, and individual market participants' reactions will have an impact on price fluctuations and market outcomes that will in turn influence agents' decisions, and so on. Standard statistical approaches in finance, for example Value at Risk (VaR) evaluation, are unable to deal with these kinds of dynamics, and this endogeneity further adds uncertainty as the complex and nonlinear mechanisms at stake cannot be easily modelled in a deterministic or probabilistic way (Walter 2000; Daníelson 2003; Balint et al. 2017; Lamperti et al. 2018).

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[6] Mervyn King, when about predictions and referring to Halley's comet, said: 'But Halley was able to rely on scientific laws; economic predictions are inherently less reliable because they depend upon human behaviour' (King 2016).

There are two main categories of uncertainty at stake when dealing with CRFR: an uncertainty about the realisation of a specific event and how we understand it, due to intricate mechanisms that are not modelled in all their **complexity**; and another uncertainty about which specific realisation of the future will occur, which reflects the **multiplicity** of possible futures. Dealing with climate change involves a combination of the two.

With such a coupling of complexity and multiplicity, it becomes impossible to assign a probability to what is going to happen in the future, especially in the long term, as both phenomena grow exponentially in their uncertainty with time. Based on a good knowledge of the past, one can predict with good reliability the number of loaves of bread that the bakery around the corner will sell tomorrow morning. In contrast it is impossible to predict how many breads will be sold in, say, Europe in January 2049. Whatever the final purpose of using any type of model, it is important to be cautious about the real meaning and extent of validity of the model.

In summary, CRFRs – both physical and transition risks – are subject to radical uncertainty and are not well suited to conventional ergodic and exogeneous financial risk analysis, which makes the quest for accurate 'measurement' particularly difficult. Radical uncertainty prevents the generation of reliable ('efficient') prices and as such prevents financial system participants from having the deterministic or probabilistic vision of the future that they are looking for.

Uncertainty, stress testing and scenarios

As mentioned, the emerging preferred approach to dealing with CRFR recognises to some extent the difficulty of accurate forecasting with its emphasis on scenario analysis and stress testing. But problems still arise even within this more flexible framework. In particular, the time horizon at stake with physical climate change appears inconsistent with the time approach of traditional stress tests, based on current balance sheets. Admittedly, a rapid low-carbon transition can be more easily compatible with such time constraints, but at the moment such an outcome seems highly unlikely. In addition, as detailed above, the coupling of multiplicity and complexity in the possible outcomes related to climate change over the next decades makes it a challenge to robustly interpret their potential effect on the financial system. Stress testing relies so far on an assessment of an explicitly limited number of scenarios. That is even its main advantage: being a 'what-if' analysis under one specific adverse scenario. But, as seen earlier, it is difficult, if not impossible, to assess the representativeness and the robustness of a particular socioeconomic scenario, in particular if the aim is to generate detailed outcomes at a global scale. This significantly limits the validity and extent of its interpretation, unless the entity willing to undertake the test has good reasons to consider one specific scenario rather than another.

But beyond the multiplicity issue, the problem of complexity is more inextricable. Even after the quite subjective step of selecting one specific (set of) scenario(s), the multiple propagation mechanisms that run from climate-related factors (whether physical or transitional) to the heterogeneous agents along the value chain of a company, to the company's own internal operations, to its financial results, to its interpretation by financial markets, and to the countless possible interactions with all the other financial assets (at project, company, government etc. levels) that build up a financial institution portfolio and the interactions between financial institutions themselves at the financial system scale, are impossible to be modelled accurately.

This tends to demonstrate the non-suitability of the *ceteris paribus* assumption that is needed in any scenario analysis or stress test that would not pretend to be global and exhaustive. In such situations, all other things indeed cannot be considered equal. Each single process sketched here is complex and subject to a growing uncertainty as time horizons increase. Additionally, the future state of the system at the date of the shock is unknown. To bastardise former US Secretary of State Donald Rumsfeld's famous dictum, this is tantamount to analysing an unknown process applied to an unknown object.

The dominant risk disclosure and risk management paradigm implicitly bets on the eventual materiality of CRFR risks for financial institutions and that this market signal is both appropriate in timing and credible in intensity. These assumptions are questionable. The reality of climate change is met with much less scepticism than it used to be a few years ago, even in the financial community, but the severest impact is still expected to be in the long term, i.e. not material now to the shorter-term time horizons of financial actors and policy makers — cf. the tragedy of the horizon concept (Carney 2015).

However, transition risks emerging from the decarbonisation of the economy *need* to occur in the short term, ideally now. This opens a window of overlap with financial sector time horizons, but here the intensity of the risk is clearly not credible as we hardly see any significant transition starting whereas a profound revolution is expected and needed. Focusing on risk in terms of climate policy priority for the financial sector implies that there must be a strong signal showing that the transition is starting immediately. A lack of such signal prevents the activation of the finance sector. There appears little chance that the financial sector will voluntary shift its position if it does not believe transition risk to be material, as born out in a number of recent studies (Campiglio et al. 2019; Ameli et al. 2019; BCAM 2019; Christophers 2019). Financial markets themselves therefore cannot trigger the transition, they can only facilitate it.

In summary, the existing approach to CRFR is not fit for purpose. Uncertainty makes conventional, backward-looking, financial risk-modelling approaches inefficient. Scenarios and stress testing are useful tools in the face of this uncertainty, but they are not forecasters and cannot act as the sole guide for actual decision-making. What is lacking is a framework that might guide action now under conditions of imperfect information. We argue that an ontologically different understanding of financial regulation is needed to solve this conundrum. Financial policy should be understood as shaping financial markets towards contributing to the mitigation of climate change, rather than an instrument for addressing calculable risks.

3. A precautionary financial policy approach to climate-related financial risk: theory and rationale

We argue that a *precautionary* approach to financial policy and regulation — henceforth precautionary financial policy (PFP) — can help to meet the challenge of radical uncertainty associated with CRFR. This draws on the concept of the 'precautionary principle' which encourages preventative policies that protect human health and the environment in the face of uncertainty, and is well established in the environmental protection sphere (Kriebel et al. 2001; Cullen 2018).[7] But our notion of PFP also draws on recent developments in financial policy and monetary policy outside the sphere of environmental protection.

Macroprudential policy,[8] resolution planning, large-scale asset purchases and related liquidity interventions by central banks can be considered as forms of PFP as, in all cases, the future is highly uncertain, but there are concerns over the build-up of financial-sector risks that could lead to potentially catastrophic outcomes (financial crises) that necessitate preventative intervention. Climate-financial, risk-aligned macroprudential and monetary policy would appear an obvious direction for policy makers seeking a framework for a precautionary approach to climate-related financial risks. In this section we explore in more depth the origins of both these policy frameworks and then go on to consider how they could be applied in practice in section 4.

3.1 The precautionary principle and environmental protection

The precautionary principle has its roots in the German *Vorsorgeprinzip* which distinguishes between human activity with dangers of catastrophic consequences which must be prevented at all costs and human activity with potentially harmful consequences where preventative measures should be assessed using a more conventional assessment of costs and benefits (Henry and Henry 2002). Thus, a precautionary approach is suited to 'ruin' problems, in which a system is at risk of total failure; with such problems, '…what appear to be small and reasonable risks accumulate inevitably to certain irreversible harm' (Taleb et al. 2014).

Given the difficulties in quantifying the risks posed by climate change, the precautionary principle is particularly warranted to address it, as noted in Article 3.3 of the United Nations Framework Convention on Climate Change (UNFCCC 1992), signed by 153 countries and European communities:

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[7]Treaties using the precautionary principle Include the Montreal Protocol on the ozone layer (1987), the Rio Declaration on Environment and Development (1992) and the Kyoto Protocol on climate change (1997). The precautionary principle is also one of the core principles of EU law (EU 2000a), which aims to ensure '*a higher level of environmental protection through preventative decision-taking in the case of risk. However, in practice, the scope of this principle is far wider and also covers consumer policy, EU legislation concerning food and human, animal and plant health*' (EU 2000b).

[8] While having different etymological roots, 'prudence/prudential' and 'precaution' are semantically close in their approach to the future.

> 'The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures...'

Commitments within the Paris Climate Agreement to keep global warming temperatures well below 2°C are prime examples of the precautionary principle applied in practice. The precautionary component involved establishing a well-defined threshold in the face of ongoing scientific uncertainty surrounding the effects of climate change, as well as the costs and feasibility of a significant cut in greenhouse emissions (Gee et al. 2013).

Indeed, the precautionary principle acts as a cornerstone for multilateral organisations such as the IPCC (2014) and World Health Organisation (2004). It was further endorsed by the EU Commission and formally adopted in an EU treaty (Article 191 of the Treaty on the Functioning of the European Union (TFEU)[9]). Across the EU, the precautionary principle has been applied to regulations across a range of different sectors beyond climate change including health and safety, biodiversity, consumer protection, chemicals, novel foods, pesticides, nanoproducts and pharmaceuticals.

To take one example, the precautionary principal is a central tenet of legislation known as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)[10]. For new chemicals, where there is the possibility of social or environmental harm and the extent of the risks of such are scientifically uncertain, legislation requires companies to prove to the regulator (the European Chemicals Agency) that their products are safe prior to being made available on the market. Under previous legislation, the burden of proof lay on the regulatory authority, which was required to empirically exhibit that the chemical was unsafe before it could remove the chemical from the market.

The Cartagena Protocol on Biosafety to the Convention on Biological Diversity, endorsed by 180 countries in 2000, is another example of the precautionary principle. Its aim is to safeguard biological diversity and human welfare from potential hazards posed by biotechnological innovation.[11] An explicit objective is to certify the safe handling, transport and uses of living modified organisms, in particular relating to the exportation/importation of genetically modified organisms (GMOs). The protocol requires exporting parties to provide sufficient scientific evidence that its products do not cause irreparable harm to biological diversity and human safety. In the face of uncertain scientific evidence adequately demonstrating the safety of a product, importing countries may ban such products.

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[9] For further details see EUR-LEX (2019).

[10] This regulation is based on the principle that it is for manufacturers, importers and downstream users to ensure that they manufacture, place on the market or use such substances that do not adversely affect human health or the environment. Its provisions are underpinned by the precautionary principle. For further details see EUR-LEX (2006).

[11] Cf. Article 4: https://www.cbd.int/doc/legal/cartagena-protocol-en.pdf.

3.2 The emergence of the precautionary approach in financial policy

In the aftermath of the 2007-08 global financial crisis (GFC) central banks and financial supervisors faced criticism for not doing more to prevent rapid credit growth in undesirable sectors (especially real estate) and the emergence of systemic risks from new financial innovations, in particular the complex and opaque derivatives that spread risks rapidly across the global financial system. At the same time, monetary policy was used actively and in unorthodox fashion via large scale asset purchases and the creation of various forms of liquidity to the global banking system to prevent the crisis worsening. Thus, post-crisis financial policy can be seen to have adjusted towards a more precautionary approach.

Macroprudential policy

Up until the GFC, financial regulation focused on enhancing transparency and evaluating the risk management practices of individual institutions (microprudential policy) to encourage greater information sharing and price discovery. It was assumed that supervising the safety of individual institutions would combine in such a way as to produce a collectively optimal result – a safe financial system (Baker 2015). Financial institutions developed sophisticated approaches to managing financial risks with the expansion of computer capacity and the globalisation of finance aiding their ability to hedge and spread risk across a range of geographies and sectors. The modelling of risk was based on a probabilistic approach based on past behaviours (Chenet 2019). The apparent sophistication of this approach convinced regulators that financial markets could largely self-regulate.

The crisis demonstrated the weakness of this approach. Systemic risks to the financial system were created endogenously, due to a principal market failure in financial intermediation: what might be prudent behaviour from the perspective of an individual financial institution may be imprudent from a macro perspective if financial institutions engage in similar — herd-like — behaviour (Haldane and May 2011; Nijskens and Wagner 2011). In the case of the GFC, rising house prices led to increased confidence in mortgage lending and the emergence of new financial innovations to derive greater profits from such lending: the 'origination and distribution' of residential mortgage-backed securities and related derivatives. A classic bubble emerged, but a lack of monitoring of systemic risk build-up as increasingly low-quality housing debt was spread through the global financial system meant that the authorities failed to foresee the crisis.

Post-crisis, central banks and financial regulators developed a set of tools to deal with the aforementioned types of systemic and endogenous financial risks: macroprudential policy. Instead of regulating the soundness of individual institutions, macroprudential policy focuses on the stability of the *system as a whole* by mitigating the systemic financial risks to the macroeconomy through pre-emptive interventions (De Nicoló et al. 2012; Favara and Ratnovski 2014).

A key feature of macroprudential policy is that it empowers central banks and supervisory authorities to reduce the likely emergence of instability *in the first place*. The policy maker has an incentive to behave in a robust fashion, preparing for the worst-case scenario. This approach favours precautionary but active policies that avoid large losses across scenarios *regardless of how likely any given scenario is* (Bahaj and Foulis 2016; Taleb et al 2014). It encourages policy-makers to 1) 'lean against the wind' and make interventions in the opposite direction of the lending and investment activity of the market to dampen the cycle; 2) ensure that the financial system is resilient enough to withstand and recover from a shock (e.g. by increasing capital buffers or developing robust resolution procedures); and 3) reduce the contagion or shock propagation (Borio 2011; Claessens et al. 2013; Altunbas et al. 2018).

In the case of housing, this included tighter loan-to-value and loan-to-income ratios and required banks to hold more capital against certain types of real estate lending. Bank bailouts, bank resolution and restructuring techniques are examples of financial regulators and policy makers taking corrective action consistent with the intents of the precautionary principle (McEldowney 2011). Thus, post-crisis resolution planning 'seeks to manage the failure of a financial institution and thus reduce its impact, even where such failure appears highly improbable' (Webb et al. 2017).

Monetary policy

Pre-crisis monetary policy was focused on price stability rather than the management and prevention of financial risks. However, the GFC made clear the links between these two domains, with low interest rates seen to contribute to the excessive lending in the lead up to crisis. Post-crisis, monetary policy has come to play a larger role in macroeconomic crisis management, going well beyond narrow inflation targeting and implicitly following a more precautionary approach in the face of uncertainty (e.g. Evans et al. (2015) for the Fed; and Haldane (2016) for the Bank of England).

So called 'unconventional' monetary policies, including large-scale asset purchases (or quantitative easing (QE)) and related liquidity-enhancing policies, are a case in point. From a policy-making perspective, the precise effects of QE are highly uncertain and there is evidence that it creates negative side-effects, including asset-price inflation and the build-up of excessive private debts (Ryan-Collins et al. 2013; Evans et al. 2015; van Lerven 2016; Heise 2019). Neither is there a consistent institutional framework that sets out under what exact conditions such policies should be deployed, nor the quantity or type of financial assets that should be purchased and how/when to unwind these programmes. These are all matters of discretion for the boards of central banks or monetary policy committees rather than being driven by forecasting or modelling.

But the uncertainty attached to QE and related policies has not prevented their enactment on a massive scale. As former Chairman of the Fed, Ben Bernanke, noted (2014), 'The problem with quantitative easing is that it works in practice, but it doesn't work in theory.' On balance, policy makers have viewed the policy's potential benefits to prevent crisis and stimulate growth to considerably outweigh the costs, making it the correct preventative course of action. The most recent round of QE in the UK in the summer of 2016 is a case in point, with the chief economist of the Bank of England noting the need to take a highly activist and precautionary approach to monetary policy as stated in the quote on the first page of this paper (Haldane 2016).

The US response to the GFC was also characterised by the use of unconventional precautionary policies, with the Fed buying up billions of dollars of mortgage-backed securities from bank balance sheets. Prior the crisis, such action would have been unthinkable, but it was justified in the light of the catastrophic potential losses the banking system faced. In response to the GFC, the US Treasury Secretary, Tim Geithner, stated that, 'A basic rule of financial crises management is you want to make sure you have a level of resources that are larger than the potential need you face', (Cox 2011).

Given its strong adherence to price stability, the European Central Bank's embracing of QE involved an even more ambitious stretching of its mandate than that of the Fed or the Bank of England. Nevertheless, Mario Draghi's commitment to 'do whatever it takes' to save the Eurozone (Draghi 2012) — an implicit commitment to unlimited ECB liquidity for the Eurozone's sovereign debt-dependent banks — was effective in doing so. However, it should be noted that QE-type policies have not just been used in the face of financial crises. Rather, they have been used consistently since 2007–08 in the UK, US, Japan and the Eurozone as a means to prevent the economy slowing down and to pre-empt deflation. Whether the policy has been effective is, of course, another question, but for our purposes the point is that a monetary policy has adopted a distinctive approach to the prevention of risks.

4. A precautionary financial policy approach to climate-related financial risk: application

Our central argument is that both the magnitude and irreversibility of the threats associated with CRFR, and the radical uncertainty attached to them, justify the development of an explicit climate-related PFP. This would incorporate all aspects of financial policy, including macroprudential and monetary policy interventions.[12] In the following we distinguish two main domains for PFP, echoing the binary distinction traditionally used in the field of climate change: mitigation of climate-related financial risks and adaptation to their materialisation.

There is a clear case for PFP to justify macroprudential policy for the mitigation of CRFR by supporting the decarbonisation of economic activity through changing the incentive structures of financial institutions' and market players' decisions. This could involve 1) penalising or even prohibiting financing and investing in economic activities that are incompatible with a transition to a below 2°C warming planet (e.g. fossil fuels); and 2) supporting economic activities that are climate-desirable, both in the sense of efficiency and renewability. There are already a number of useful contributions as to what 'green macroprudential policy' might look like (Schoenmaker et al. 2015; Dikau and Ryan-Collins 2017; Volz 2017; D'Orazio and Popoyan 2019). Adaptation to CRFR takes two forms: adapting to physical risks because complete mitigation is certainly impossible; or adapting to transition risks because ambitious and rapid decarbonisation, and thus mitigation, will be implemented.

[12] Cullen (2018) has argued that precautionary principle as a justification for preventing the financing of GHG-intensive activities in a Eurozone context, but we argue the approach has much wider use and framing.

While it is not within the scope of this paper to develop a comprehensive analysis of policy instruments that could be used by central banks and supervisors as part of a PFP framework, the following policy areas would appear particular promising for implementation to address both CRFR mitigation and adaptation in the short- to medium-term.

4.1 Integrating climate risk in to capital adequacy requirements

The current capital requirement framework is misaligned with the objectives of a green transition, in that it could make banks more hesitant towards financing green loans (D'Orazio and Popoyan 2019) and may result in longer-term loans (to mainly non-financial business) being penalised (Blundell-Wignall and Atkinson 2010; Allen et al. 2012; Angelini et al. 2015). It is within this context that a 'green supporting factor', reducing capital adequacy requirements (the ratio required by the regulator of a bank's capital over its risk-weighted assets), has gained popularity (D'Orazio and Popoyan 2019). While aligned in principle with the objective of mitigating climate change, we believe this is the wrong approach for three reasons.

First, there are insufficient levels of capital in the banking system generally so further reducing it for some types of loans may increase overall systemic risk (van Lerven and Ryan-Collins 2018). Second, there is sufficient reason to believe that a green supporting factor will not actually lead to a noticeable increase in green lending (Cullen 2018; van Lerven and Ryan-Collins 2018; Collins 2018; Thomä and Gibhardt 2019). Third, there is less agreement on what counts as 'green' given it is a very new 'sector'[13], but much more agreement on what counts as excessively 'brown' or carbon-intensive (i.e. undesirable) sectors. The focus of the European Union on the development of a 'green taxonomy' rather than a classification of brown assets suffers from the same drawback.

For these reasons a precautionary approach would be to increase capital requirements for 'brown loans' – a 'brown penalising factor'. A sufficiently high capital requirement (a higher risk weight) for loans carrying carbon risk, or entities that are severely reliant on fossil fuels, would reflect the real and growing systemic risk of investing in carbon-intensive activities and could discourage further investment that contributes to climate change. It would also give banks a greater buffer to withstand losses related to climate-related transition risks (Cullen 2018; van Lerven and Ryan-Collins 2018) and potential sudden value losses due to the repricing of assets. An argument can be made that lower capital requirements for green assets could be justified if these loans are deemed less risky than others, but there is currently no evidence of lower risk for green loans. Moreover, even if this were the case, our suggestion would be to interpret the evidence as suggesting that brown loans are more risky than green ones, thus further justifying a brown penalising factor. There are already some tentative steps in this direction via a stress test being proposed by the NGFS (2019b), which may go some way to increasing, for example, bank capital vis-à-vis CRFR exposures.

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[13] Actually 'green' should not be considered as a 'sector' per se, as green activities can be present in many different industries. This is actually a considerable issue as one cannot approach 'green' activities through the use of classical industry classifications (e.g. EU TEG SF 2019).

4.2 Climate-risk aligned credit controls and credit guidance

A more direct way to restrict financing to brown activities would be the use of quantitative restrictions on lending, for example ratios of brown to total lending or brown to green across a bank's asset portfolio. The brownest forms of lending (e.g. thermal coal) could be prohibited completely within a relatively short space of time (e.g. one to two years), which would send a strong market signal to investors. This would naturally heighten short-term transition risks and supervisors would need to see through this, having in mind the longer-term catastrophic losses arising from physical risks associated with a more drawn out transition. Of course, a first best scenario would be that environmental legislation would also prohibit such activity in its entirety, but in the short term cutting down on the financing of such activity would seem an important first step. Currently, as noted in section 2.2., financing for GHG industries continues unabated and is even expanding, despite national and international agreements on reducing carbon emissions.

A related approach might be to introduce a cap on the level of debt financing of companies exceeding a certain carbon threshold (Schoenmaker et al. 2015). The cap could be in the form of a maximum part of debt finance (and thus a minimum amount of equity finance) for carbon-intensive firms, using an evolving threshold over time to accompany a smooth transition along each country's planned decarbonisation pathway. This would boost the resilience of the banking sector against transition risk while relatively favouring green activities and firms.

Given the urgency of the climate crisis, central banks and supervisors should also be considering how they can more directly support the massive increase in sustainable finance that is required to meet the transition to a net-zero carbon economy, beyond purely financial stability considerations. 'Credit guidance' — policy tools aimed at steering credit flows (encouraging or discouraging) towards particular sectors of the economy — has fallen somewhat out of fashion in advanced economies since the 1980s. However, they were commonly used in the post-war period and in East Asia during the 1980s to support rapid economic growth, transition and industrialisation (Bezemer et al. 2018), and are currently used in many emerging market economies to support green finance, including in China, India and Bangladesh (Dikau and Ryan-Collins 2017; Campiglio et al. 2018; D'Orazio and Popoyan 2019). Use of such tools may require greater coordination between central banks and governments, in particular ministries of finance and industrial policy. This is certainly a field where further research is needed to examine what types of policies will be effective in a world where market-based finance (or 'shadow-banking') also plays an important role and is often not within the purview of central bank regulators.

4.3 Integrating climate risk in to monetary policy operations

In just the same way that capital adequacy frameworks neglect CRFR, so monetary policy operations, including both asset purchase programmes and collateral frameworks, do the same. Current asset purchase criteria by both the Bank of England and the ECB support incumbent 'brown' industrial sectors, including energy, manufacturing, automobiles and utilities (Matikainen et al. 2017; Monnin 2018a; Jourdan and Kalinowski 2019). For example, a recent study found that 63% of assets bought through the ECB's corporate sector purchase program (CSPP) were issued by businesses operating within the most carbon-emitting sectors (Jourdan and Kalinowski

2019). The ECB's collateral framework and haircut regime are similarly supportive of brown sectors (Dafermos et al. forthcoming 2020).

The ECB bases its CSPP and collateral framework criteria on current credit rating agency analytics, but there are a number of alternative credit scoring approaches in existence that do attempt to account for CRFRs. For example, a recent study of the ECB's corporate bond purchase program (CSPP) using Carbon Delta's analytics (which attempt to incorporate transition risk) found that eight issuers would fall out of the ECB's investment grade criteria and hence no longer be eligible for the CSPP, representing almost 5% of the issuers analysed (Monnin 2018b). For the reasons outlined in this paper, there is no reason to think this or any other criteria should be relied upon to try and predict the medium- to long-term impact of climate change, but a precautionary approach to monetary policy would focus on the worst-case scenario (i.e. that these transition risks will materialise) and adjust policy accordingly.

4.4 Enhancing financial system climate resilience

The objective of adaptation of the financial system in the face of CRFR requires a precautionary approach for both physical and transition risks. As discussed in section 2.3, CRFR are endogenous and systemic by nature, which make their impact difficult to isolate from the usual financial risks considered by macroprudential policy. The appropriate response is then to strengthen the resilience of the financial system by enhancing financial institutions' individual capacity to cope with a (climate-triggered) crisis. Increasing general capital and liquidity buffers being the most obvious actions.

There is a trade-off between climate mitigation and adaptation policies — the more that is done to mitigate, the less adaptation may be required and vice-versa. Therefore, regulators should adjust resilience enhancements relative to the levels of mitigation implemented globally and by respective jurisdictions. For example, if a country implements an ambitious transition policy, stricter counter-crisis buffers will be required for financial institutions exposed to the GHG-dependent sectors and companies of that country. If such transition policies are weak at the global level, the focus of the regulators worldwide should be less on brown sectors, but rather on the longer-term adaptation to physical risk. Attention should be focused first on the physically exposed countries, sectors and companies, and second on the economy in general, due to systemic propagation effects.

In particular, physical risk parameters must be introduced, considering the location and resilience capacity of infrastructures and underlying assets, as well as the companies' and sectors' dependence on other industries that are most sensitive to climate impacts. Such indicators can be based on the rapidly evolving analysis of rating agencies and other financial intermediaries attempting to capture such physical risk exposure, either at sectoral or regional level.[14]

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[14] For example: FTSE Climate Risk-adjusted World Government Bond Index: https://www.ftserussell.com/index/spotlight/climate-wgbi; Moody's: Credit impact from environmental issues varies widely across sectors globally: https://www.moodys.com/research/Moodys-Credit-impact-from-environmental-issues-varies-widely-across-sectors--PR_339980; Mercer: Investing in a time of climate change: https://www.mercer.com/our-thinking/wealth/climate-change-the-sequel.html.

5. Discussion

What are the potential challenges for a PFP framework for CRFR? We have argued that this approach can be seen as a continuation of the post-crisis turn in financial policy, with greater emphasis on proactive intervention in financial markets to prevent financial shocks and increase system-wide resilience. However, PFP does pose some questions in terms of central bank mandates, time horizons and implementation.

Time horizons and mandate

Two principal challenges around central bank and supervisors mandates in regard to the challenge of CRFR are: 1) that the time horizon of their mandate is too short (typically one to three years) to capture the significant materiality of CRFR today (the tragedy of the horizon problem (Carney 2015)); and 2) that the strong economic and distributional policy consequences of such actions is beyond their mandates, limited as it is to price and financial stability, and is instead the domain of elected governments. We deal with these in turn.

For monetary policy (i.e. interest-rate setting), the focus of central banks is normally on the 'business cycle' – typically two to three years (Carney 2015). This certainly does seem too short to deal with the long-term risks posed by climate change (in particular the physical risks discussed in section 2.3). However, it is worth noting that with the acceptance of a much stronger financial stability mandate since the GFC, central banks have started to think in longer time horizons themselves, in particular focusing on the 'credit' or 'financial cycle', which is typically estimated to be anywhere between 10 and 16 years (Aikman et al. 2014; Borio 2014). Macroprudential policy encourages 'leaning against the wind': action should be taken in the present to prevent future damaging build-up of systemic risks, even quite far in to the future.

The increasingly clear evidence of the climate science further supports the adoption of a much longer time horizon in regard to CRFR: delaying action implies escalating costs and risks (Masson-Delmotte et al. 2018). As noted in the IPCC's report *Global warming of 1.5 degrees*, 'Every year's delay before initiating emission reductions decreases by approximately two years the remaining time available to reach zero emissions on a pathway still remaining below 1.5°C' (Masson-Delmotte et al. 2018, chapter 1). The policy approach of 'wait until we have better understanding' currently fails to justify and compensate for the potentially catastrophic and irreversible effects of delay. Indeed, regulators currently do not define what such an acceptable level of knowledge is or can be, nor which specific elements would allow them to trigger action and ensure the benefit of waiting. Under such absence of explicit definitions, it is impossible to guarantee that action will not be postponed forever. In the face of emergency and irreversibility, stated by science and not contradicted by the financial regulation community, it appears therefore that there is no scientific rationale to justify postponing strong mitigation action.

Given the radical uncertainty around CRFR, we argue that climate science provides financial policy makers with enough evidence of the level of threat and emergency to guide immediate decisions on a mitigation pathway that will anyway be safer than acting late. Conventional economic decision-making based on static efficiency models and cost-benefit analysis (CBA) in order to determine the most efficient mitigation pathway are of little use under a situation where the 'all else remaining equal' assumption which such approaches rest on no longer applies (Kattel et al. 2019). Climate change is a 'ruin' problem — i.e. it will result in a system exposed to irreversible harm that can eventually lead to a risk of total failure — which means negative outcomes may have infinite costs (Weitzman 2011; Taleb et al. 2014). In the absence of relevant CBA, it makes more sense to think in terms of insurance, where strong mitigation action would represent a collective strategy against the catastrophic outcomes of climate change (Weitzman 2009, 2012; Aglietta and Espagne 2016). This now famous approach to address climate change in general, popularised by Weitzman's (2009) dismal theorem, can be applied exactly in the same way to financial policy interventions.

Concerning the object of the mandate itself, it is clear that each jurisdiction has its own laws and rules, and interpretations of those. The Bank of England, Federal Reserve, ECB, People's Bank of China (PboC), Bank of Brazil, Bank of Bangladesh or Bank of Nigeria typically have very different mandates related to how far they support national economic priorities beyond price and financial stability (e.g. Dikau and Ryan-Collins 2017; D'Orazio and Popoyan 2019; Dikau and Volz 2019). Indeed, in addition to price stability, the mandates of central banks often cover general economic welfare, which would appear to be compatible with consideration of climate change (Dikau and Volz 2019; Krogstrup and Oman 2019). To quote just a few, the PBoC has a 'structural changes' objective in its mandate and the Chinese government views this as a tool for the implementation of national economic priorities, which now includes the environment (Chenet et al. 2019). In Europe, Article 2 of the E(S)CB statutes mentions explicitly the objective of supporting economic policies in the Community[15] and recently the new ECB president, Christine Lagarde, put forward the objective of fighting climate change as a priority in the ECB's agenda (Committee on Economic and Monetary Affairs 2019).

One argument against a PFP of the type described in this paper is that it is the job of the government, not the independent central bank or financial supervisor, to impose policies to repress or support particular sectors of the economy.[16] This argument may have had some force pre-crisis. However, post-crisis it is less convincing. Central banks in most advanced economies have taken on a clear financial stability mandate, along with their traditional focus on price stability. If a precautionary policy approach is viewed as reducing financial risks, then it would not appear to be stretching a mandate or reducing independence.

Indeed, the inverse argument could be made. Central bank independence was originally justified on the existence of a 'time-inconsistency problem' (Kydland and Prescott 1977) whereby politicians would tend to ramp up spending in the run up to elections and pressure central banks

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[15] Protocol on the Statute of the European System of Central Banks and of the European Central Bank: 'In accordance with Article 105(1) of this Treaty, the primary objective of the ESCB shall be to maintain price stability. Without prejudice to the objective of price stability, it shall support the general economic policies in the Community with a view to contributing to the achievement of the objectives of the Community as laid down in Article 2 of this Treaty. The ESCB shall act in accordance with the principle of an open market economy with free competition, favouring an efficient allocation of resources, and in compliance with the principles set out in Article 4 of this Treaty': https://www.ecb.europa.eu/ecb/pdf/orga/escbstatutes_en.pdf.

[16] It should be noted that, as of 2018, macroprudential policy is only uniquely controlled by a central bank in 41 of 141 countries (IMF 2018). In many countries the financial supervisor is in charge of such policies and is itself not independent of government or the respective ministry of finance.

to ease monetary policy to stimulate growth and employment. This would generate inflation and inflationary expectations that only an independent central bank could credibly reverse. And in the aftermath of the GFC, many advanced economy central banks and supervisors were given (or asked for) greater responsibility for interventions in the mortgage market using macroprudential policy, precisely because, given political pressures, it was felt politicians, ministries of finance and the market itself would find it harder to 'take away the punchbowl'. For example, in countries where the majority of voters are home-owners or would like to become so, policies that restrict mortgage credit or reduce house price growth in the upturn are likely to be highly unpopular, and the electoral cycle often dictates the time horizons of governments (Carney 2014; Holmes 2018).

The same issues apply to the problem of stranded assets. Politicians and ministers of finance are under significant political pressure not to regulate against large companies locked in to unsustainable industries. The lobbying power of these organisations is evident in the still enormous subsidies they receive, which far outweigh the subsidies flowing in to renewable energy. There is, as with house prices, also pressure from voters. The introduction of a carbon tax, for example, would almost certainly push up the cost of the majority of households' energy bills. In these circumstances, a central bank that did not act could be accused of not being independent or at the very least of not justifying the privilege of independence.

None of this to say that governments should not also be going much further, much faster, to address the risks from climate change. It is rather to say, as we learned from the last GFC, that financial policy makers have a duty to take systemic financial stability risk seriously, whatever sector of the economy it is coming from, and not wait until the crisis arrives before taking action.

Implementation challenges

So, how to implement climate-risk oriented macroprudential and monetary policy tools when there is a lack of indicators to fine tune them? This is an area where further research is needed, but here we can say that, in opposition to the common approach governing financial regulation in non-crisis periods, which is based on sophisticated modelling striving for precision and unique solutions, conditions of radical uncertainty require a more qualitative approach. Being rational in a world of radical uncertainty involves ignoring information that is of little help, using experience (rather than data) and discretion, developing coping strategies and thinking about the future in qualitative terms (King 2016, chapter 4). Discussing the complicated models used by commercial banks to calculate their own capital adequacy ratios, former Bank of England governor Mervyn King argued that 'If the nature of the uncertainty is unknown … It is better to be roughly right than precisely wrong, and to use a simple but more robust measure of required capital' (King 2016, chapter 4).

This type of approach relies more on heuristics and general direction-setting for markets than models. As noted by Boyer (2018), 'The higher the uncertainty and complexity, the more urgent the need for simple narratives.' In our case, the precautionary framework for CRFR can and must be used to guide urgent decision making. Concepts such as: 'rules of thumb' (Heiner 1983), e.g. we know in general we need to stop financing GHG-intensive sectors even though we don't know the exact effects this will have; bounded rationality (Simon 1997), e.g. we know and accept that our understanding of CRFR is inherently limited, but we can still make decisions within these limits; learning by doing (Gollier 2001); or exploiting 'animal spirits' (Keynes 1936), e.g. investment behaviour could quickly shift away from brown if we can shift sentiment decisively. All of these approaches can help us deal with complex decisions with intertemporal consequences (Boyer 2018).

The first means of applying the precautionary principle to mitigate CRFR could be to apply preventative measures related to undesirable economic activities. One specific way to implement this could aim at shifting the burden of proof (of non-harm) to financial market participants. Such an approach was proposed in the aftermath of the GFC as a means of dealing with complex new financial products (Epstein and Crotty 2009; Omarova 2012). By financing activities that raise CRFR, i.e. carbon-intensive undertakings, the financial sector creates a number of negative externalities that can exacerbate climate change (Campiglio 2016; Volz 2017). The existence of such externalities leads notably to credit market failures, as they allow banks to allocate excessive credit to carbon-intensive activities. The same reasoning can apply for issuing or owning securities related to such undesirable economic activities. These environmental 'market failures' create a strong argument for central banks to implement preventative or corrective policies in line with a precautionary approach.

An obvious place to start in implementing negative screening would be new lending that enables fossil fuel extraction (including tar sands, Arctic and ultra-deep-water oil, liquefied natural gas (LNG) export, coal mining, and coal power) (also proposed by Cullen 2018). Of course, such an approach opens many questions relative to the choice of those precise activities to penalise or, respectively, to favour, for reciprocal approaches. Such an approach can also be applied to existing assets (ongoing loans or securities), which makes sense for the technologies and industries that are already overexposed relative to climate targets. The situation of existing assets is potentially much more sensitive in terms of legal feasibility and acceptability. But in both cases, the reversal of the onus of the proof can be a way to be not overly prescriptive: the regulator can issue and regularly update a list of a priori undesirable activities that financial institutions must then cease, or demonstrate to the supervisors' satisfaction that they do not reduce the chances of following a net-zero carbon pathway (typically by demonstrating that lending to a specific brown company will contribute to greening).

The precautionary approach justifies the use of heuristics instead of deterministic or probabilistic models when such models are not available. Central banks and supervisors now need to adopt such a mindset and apply the approach to their decisions, defining the concrete options of implementation. Dealing with both finance and climate together calls for international coordination, but the implementation details are context- and country-dependent, which opens the way to more rapid decision-making, skipping the need for international agreement before taking action.

6. Conclusion

In this paper we have proposed the adoption of a Precautionary Financial Policy (PFP) approach to deal with the financial stability risks created by climate change. This approach is justified because CRFR, both transition and physical, are characterised by radical uncertainty, meaning conventional backwards-looking probabilistic financial risk modelling is not fit for purpose in dealing with them. While scenario analysis and stress testing to some extent recognise the uncertainty problem, they remain based upon assumptions that are subject to significant uncertainty and do not sufficiently justify action in the short term, despite widespread recognition of the risks posed by inaction.

In contrast, a PFP approach helps justify preventative actions now to mitigate the potentially catastrophic financial and economic damages created by climate change, and shape financial markets in a clear direction towards a preferred net-zero carbon future. In particular, because of the global, deep, long-term, systemic and endogenous characteristics of CRFR, the proper way to envisage financial regulation must be through macroprudential-type rules and discretion. These do not only consider an aggregation of individual financial institutions and markets but the financial system as a whole in the way it shapes the macroeconomy. In terms of implementation, we propose the comprehensive integration of climate risk into capital adequacy requirements, monetary policy operations (including asset purchases and collateral criteria), quantitative credit controls and credit guidance, and the enhancing of financial system resilience.

Policy makers adopting a precautionary approach should be aware of the likely short-term trade-off between efficiency and resilience, and likely resistance from market actors with shorter-term time horizons. There is a need to 'learn by doing' in this new environment, just as policy makers are learning from the success and failures of macroprudential policy interventions over the past few decades (Lim et al. 2011). Not all precautionary-type interventions will be successful. But, on balance, we would argue that more valuable information can be learnt from intervening and studying the (endogenous) reactions that follow a particular intervention than can be gleaned from non-interventionist analysis, modelling and forecasting.

This paper is an exploration and attempt to lay out a new policy framework for dealing with CRFR rather than a turn-key solution for financial regulation in the face of such risks. Future streams of research would involve deeper analyses of the possible tools and policies that can be activated, which we have discussed only at a high level in this paper. In parallel, objective evaluations of which CRFR challenges are priorities in terms of (further) data and modelling effort, aiming to establish appropriate policy actions for each time horizon considered, i.e. distinguishing the level of knowledge that can be expected in six months, one year, three years, ten years, etc. and those policy actions that, since they address challenges that will remain subject to radical uncertainty, can be taken much sooner.

Beyond climate change, the approach developed in this paper could be extended to other complex environmental challenges characterised by radical uncertainty, including biodiversity loss, water and air pollution, and natural resources depletion. Indeed, most of these areas have important interactions with climate change itself and so should as far as possible be incorporated into a PFP framework.

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