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ANALYSIS

Finance, climate-change and radical uncertainty: Towards a precautionary approach to financial policy

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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 framework for dealing with them has largely focused on market-based solutions that seek to reduce perceived information gaps that prevent the accurate pricing of CRFR. These include disclosure, transparency, scenario analysis and stress testing. We argue this approach will be limited in impact because CRFR are characterised by radical uncertainty and hence 'efficient' price discovery is not possible. In addition, this approach tends to bias financial policy towards concern around avoiding short-term market disruption at the expense of longer-term, potentially catastrophic and irreversible climate risks. Instead, an alternative 'precautionary' financial policy approach is proposed that offers an intellectual framework for legitimizing more ambitious financial policy interventions in the present to better deal with these long-term risks. This framework draws on two existing concepts — the 'precautionary principle' and modern macroprudential policy — and justifies the full integration of CRFR into financial policy, including prudential, macroprudential and monetary policy frameworks.

1. Introduction

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, 2019a, 2019b; Bolton et al., 2020). Such recognition was a key catalyst in the creation of the Network for Greening the Financial System (NGFS), an international grouping of now 90[1] central banks, financial supervisors and observers focused on how financial policy[2] needs to adjust to the risks posed by climate change and the low-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 their far-reaching impact, unforeseeable nature and irreversibility. They are also endogenous and systemic in nature – with the potential to affect the entire economy and financial system (NGFS, 2019b).

But how to deal with such CRFRs — especially transition risks — is an emerging area of concern. One specific challenge is the measurement and forecasting of CRFR in a way that supports effective financial policy interventions. In particular, there are issues of urgency and capacity, whereby, as noted by the NFGS, 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*

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[1] 77 members and 13 observers as of November 23, 2020 (https://www.ngfs.net/en/about-us/membership).

[2] We use financial policy as shorthand to incorporate monetary policy, financial regulation, supervision 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.

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financial risk assessment information' (NGFS, 2018, p. 3).

The policy response 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 their exposures to CRFR, notably through the Task Force on Climate Related Financial Disclosures (TCFD) and, more recently, via encouraging scenario analysis and stress testing (TCFD, 2017; Vermeulen et al., 2018; Bank of England, 2019a; NGFS, 2019a).

Many questions remain open, however, around the assumptions that should be used to determine different scenarios and what the outcomes of scenario modelling as well as stress testing results actually mean for policy interventions, beyond sending useful signals to markets. In the NGFS' First comprehensive report — A call for action' (NGFS, 2019b), the primary policy proposal put 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).[3] The key implication of the current narrative, illustrated by these NGFS quotes, is that while action is needed 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. We argue that CRFR, in particular with regards to transition risks in the short to medium term and to physical risk in the long term, 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 problem of radical uncertainty in relation to environmental financial risks is also identified by the Bank of International Settlements (BIS) and Banque de France (Bolton et al., 2020).

Given this and the widely acknowledged fact that not acting in the short term will increase the severity of CRFR, we argue that a *precautionary,* market-shaping approach to financial policy and supervision is required. Such a framework draws on two regulatory traditions. The first is the 'precautionary principle' which encourages preventative policies that protect human health and the environment in the face of uncertainty and is well established in European and international law. The second is macroprudential policy, which has come back in to favour in the post-crisis period in recognition of the limitations of microprudential policy in dealing with systemic and endogenous risks to the financial system (Altunbas et al., 2018). This precautionary policy approach can be considered an alternative intellectual framework — or mindset — for legitimizing more ambitious financial policy interventions in the present to better deal with these long-term risks.

Two qualifications should be noted. Firstly, we do not attempt to elaborate detailed new policy instruments or interventions in this paper — a subject for future research and which has already been discussed elsewhere — but rather consider how existing policy might be shifted in light of a precautionary policy framework. In addition, the focus of this paper is on climate-related *financial* risks and not broader climate risks. This does not imply we consider financial risks as more important than social, political or economic risks; rather we focus on finance because this is an area which has gained significant policy traction in recent years with the emergence of the NGFS and the increasingly important macroeconomic role of central banks since 2007–08 (Tooze, 2019).

The remainder of th paper is structured as follows. 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 present the intellectual justification for a precautionary financial policy approach to CRFR and in Section 4 we consider how it might apply to existing financial policy – including both regulatory and monetary policy spheres. We then discuss the challenges created by this approach, including those posed by theories surrounding central bank and supervisory independence, mandates and time horizons (Section 5). Section 6 concludes with suggestions for further research.

2. Climate change and financial risk

2.1. The nature of CRFR

There are two main categories of CRFR (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); and *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 and litigation[4]).

Physical and transition risks can affect the financial system in multiple ways. Risk materialises at physical asset and company levels, either through their own operations or from others', via the market or the supply chain. These can impact the value of the assets, collateral and/or cash flows of the companies which then affect their credit risks, access to capital and financial values. The revenue losses of firms can lead to unemployment and income losses in the household sector — or a higher cost of goods and services, for example due to increased energy and food prices from supply side shocks. Physical risks can also manifest at the household sector, by threatening to reduce asset or collateral values, through direct damage on residential property or loss or write-offs in homes at high-risk locations (Monnin, 2018a; Armal et al., 2020; Baldauf et al., 2020; Murfin and Spiegel, 2020).

Having started at the company and household level, risk reaches financial market level, through the classic market, credit, liquidity and operational risks. Thereafter, risks can propagate through financial institutions' portfolios and potentially become systemic (Dow, 2000).[5] 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. The concomitant reactions between these market players would lead to a network of adverse cascade effects (e.g. large-scale fire-sale of assets or hoarding of cash), 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 constitutes a systemic risk to the financial system as a whole (Battiston et al., 2017; Naqvi and Monasterolo, 2019; NGFS, 2019b).

Finally, it is important to highlight that there are important trade-offs between physical risks and transition risks: rapid and deep decarbonisation involving high transition risks in the short-term should decrease medium to long-term physical risks, and vice-versa. A key

[3] These guidelines have been published in June 2020 (NGFS, 2020b).

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

[5] 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).

challenge for financial authorities is how to manage this trade off.

2.2. The policy response to CRFR

2.2.1. Disclosure and enhancing market efficiency

The financial policy framework for dealing with CRFR focuses on financial market actors mispricing or under-pricing risk and encourages greater transparency through risk disclosures (cf. Chenet, 2021 and references therein). 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, capital allocation optimised and the financial system made more resilient (Krogstrup and Oman (2019), pp. 22–26; see Christophers (2017) and Cullen (2018) for more detailed discussions).

Improvement of transparency and information sharing indeed lies at the centre of the TCFD framework, which is the major international policy effort by financial regulators to meet the challenge of climate-related financial risks (Carney, 2015; TCFD, 2017). Disclosure of risk and transparency is also central to Pillar 3 of the international Basel III regulatory framework and one of the key recommendations of the NGFS (NGFS, 2019b, p. 27).

The TCFD recommendations have been widely endorsed (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, 2019; BCAM, 2019; Christophers, 2019). A recent survey by HSBC bank of 2000 investors found that just 10% viewed the climate related disclosures as a relevant source of information (Hook and Vincent, 2020).

2.2.2. Scenario analysis and stress testing

Even if financial firms accept the need to disclose their CRFRs in theory, they face a further problem in accurately measuring such risks, as illustrated in a recent analysis from the European Central Bank (ECB, 2020c, p. 13): "*Despite the fact that the majority of institutions have implemented one or more sustainability policies, most of the institutions do not have the tools to assess the impact of climate-related and environmental risks on their balance sheet.*" Within the logic of the disclosure framework, firms are expected to publish precise measurements based upon 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, 2019a, 2019b).[6]

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, central banks, financialsupervisors and banks themselves (NGFS, 2019b).

Scenario analysis involves studying a financial security/portfolio/institution/group of institutions in a given realisation of the future (i.e. the 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 (individual firm) or macroprudential (system wide) levels.

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 an adverse one) 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.[7]

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 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.[8] These are simply the multiple scenarios of climate pathways, which have not even been mapped on to highly complex interconnected modern financial systems — that would engender yet more potential scenarios, which are somehow supposed to inform financial supervisors.

Whatever the arguments over the effectiveness of TCFD, scenario-analysis and stress testing, it seems clear that, until now, this approach has not yet led to a material shift in financial flows away from unsustainable forms of financing. Recent analysis found that the world's largest investment banks have provided more than $1.9tn of financing for the fossil fuel companies most aggressively expanding in new coal, oil and gas projects since the first launch of the TCFD in 2015 (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). A detailed review of equity markets by the IMF (IMF, 2020) concluded that aggregate equity valuations in 2019 did not "*reflect the predicted changes in physical risk under various climate change scenarios, which suggests that investors do not pay sufficient attention to climate change risks.*" In its latest Financial Stability Review, the ECB notes that Eurozone bank lending to carbon-intensive firms, as a percentage of total lending, has increased since 2015 (ECB, 2020b, p. 73). It also notes that whilst the market for green bonds has been expanding rapidly, there is no evidence of the yields on green bonds being lower than on conventional bonds of a similar risk profile, which 'may reflect the fact that investors do not fully price in climate-related risks' (ECB, 2020b, p. 93). Given these facts, the universally understood need for rapid adjustments in financing to meet the

[6] Barnett et al. (2020) propose a first "*simplistic*" (in fact not that mathematically simple) approach to consider the "*pricing uncertainty induced by climate change*".

[7] 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.

[8] Indeed, knowing precisely the regional or local variability of emissions is not absolutely essential for modelling the future climate state (e.g. 1 ton of CO_2 emitted in the UK is equivalent in terms of contribution to warming to 1 ton of CO_2 emitted in Namibia). However, such knowledge is necessary to understand the future state of the economy (1 unit of oil sold in the US does not have a similar economic impact as 1 unit of rice sold in Vietnam, even if they release the same amount of greenhouse gas (GHG)).

Paris 2050 targets, alternative approaches for dealing with CRFR merit consideration.

2.3. The need for a different approach: risk versus uncertainty

2.3.1. Conceptual framing: risk and uncertainty

As a starting point for a reconsideration of the appropriate conceptual framework for dealing with CRFR, its worth defining more precisely what is meant by 'risk'. 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 (Keynes, 1936): '*Uncertainty in this account arises when the probability relation is numerically indeterminate and non-comparable to other probability relations*' (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.[9] 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. We discuss these in turn in the next sections.

2.3.2. 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 (Randall et al., 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 – 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 or fed with (Randall et al., 2007). These cannot be known with infinite precision. 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.

The economic and financial impacts of a specific future climate realisation are also uncertain. Under a specific degree of warming with resulting long-run consequences (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, as well as second round effects. The same applies in terms of the impacts of climate change on local flora and fauna.

It is worth highlighting that the inertia of the climate system implies relatively limited divergence of warming trajectories in the medium term. Indeed, whatever high (e.g. RCP8.5)[10] or low (e.g. RCP2.6) emission scenario is taken, the resulting warming difference by 2030 still lies within a narrow interval ($\sim +0.7\ ^\circ$C) by 2050 compared to the divergence modelled after mid-century that reaches substantial warming differences by 2100 ($\sim +3\ ^\circ$C).[11] In other words, current mitigation action will have a material impact in the long-term, but the upcoming future state of the climate by typically 2050 is essentially determined by the GHG emissions of the last decades. This implies that the future state of the global climate is relatively well-known in the medium term (say up to 2 or 3 decades) — not including singularities and possible tipping points —, which gives sufficient certainty for large-scale adaptation planning and financing over that time horizon. This also opens the way to better risk assessment as new climate services and tools become available (Hubert et al., 2018; de Bruin et al., 2019). But this is not to say that *financial* risks at the system level are not highly uncertain, as they depend on the potentially contrasting actions and reactions interconnected economic agents will have in the meantime (cf. below).

2.3.3. Transition risk and uncertainty

As described above, the climate mitigation action now and during the decades to come will determine the level of climate change over the second half of the century. Therefore, the immediate and upcoming uncertainty is mainly about mitigation actions themselves, i.e. how do we conduct the transition to net-zero. Thus, transition risk is subject to considerable levels of uncertainty, notably due to the human and behavioural factors at stake.

Socioeconomic reactions cover a vast number of eventualities, from strictly no change to a globally profound transformation, with a quasi-infinite number of nuances in between spanning all the possible versions of how policy, industry, technology, geopolitics, society and individual behaviour can evolve over time (classically up to 2100 to cope with climate-relevant horizons, even if climate consequences can extend much longer). How will consumers and companies react and adapt is largely a matter of hypothesis, and the endmost financial impacts those may have are fundamentally unknowable. Transforming each of these socioeconomic scenarios into ultimate 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 subsystem (e.g. global emissions of the energy mix, transportation system, infrastructures, agriculture, and forests etc.).

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

[10] RCP: A Representative Concentration Pathway is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC, describing different climate futures. The RCPs are labelled after a possible range of radiative forcing values in the year 2100 (here 8.5 and 2.6 W/m2, respectively).

[11] See e.g. IPCC Assessement Report 5 (2013) FAQ 12.1, Figure 1https://www.ipcc.ch/report/ar5/wg1/long-term-climate-change-projections-commitments-and-irreversibility/fig-35/

A specific 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 or an emission regulation on car engines, 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.

2.3.4. Complexity, multiplicity, and uncertainty

These different 'spots' of uncertainty are exacerbated by the fact that they occur within a highly complex financial system involving unpredictable reactions and interactions between market players (including governments).[12] Those can create nonlinear 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 (Battiston, 2019). 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). This endogeneity of CRFR is unfortunately not well acknowledged by the NGFS reports,[13] despite the fact that it challenges current modelling approaches of CRFR focusing on transition risk.

In short, we see that 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 and its socioeconomic (and financial) impacts 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 (and what will be the impact on the market price of wheat). Whatever the final purpose of using any type of model, it is important to be cautious about the real meaning and extent of usefulness of the model. .

2.3.5. Uncertainty, time horizon, stress testing and scenarios

As mentioned, the emerging preferred approach to dealing with CRFR recognises to some extent the impossibility of accurate forecasting with its emphasis on scenario analysis and stress testing (e.g. Bank of England, 2019b). 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.

The recent Bank of England discussion paper "2021 biennial exploratory scenario on the financial risks from climate change" (2019b) is illustrative of this analytical challenge relative to the time dimension in stress testing. It proposes scenario analysis exercises with a 2050 (30 yrs) horizon, with a fixed 2020 balance sheet, without questioning the consequences of such an approach on the interpretation of the results. Moreover, the physical consequences of climate change are proposed to be explored on the same 2020 balance sheet, but with an impact level that is supposed to be material for a 2080 horizon (50 yrs). This constitutes an 'all else remaining equal' assumption of heroic proportions. For example, bank balance sheets in advanced economies have doubled in overall size relative to GDP since 1980 and their make-up has transformed completely with the majority of credit supporting households rather than firms (Jordà et al., 2017). A rapid low-carbon transition can potentially be more easily captured by shorter time windows and would certainly be more compatible with fixed current balance sheets, but at the moment such a feature seems highly unlikely. This raises questions over what extent fixed balance sheets are relevant assumptions for climate stress testing, but also raises challenges on the capacity and significance of modeling dynamic ones over long time periods.

Another key attribute stress testing relies on so far is the assessment of an explicitly limited number of scenarios. That is even its main advantage in the face of the multiplicity obstacle. But 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.

More broadly, it appears that approaches relying on scenarios could make sense on the condition that either; 1) the high number of scenarios considered represents an 'acceptable' variability of plausible futures (opening the way to Monte-Carlo[14] types of analysis), or 2) the limited number of scenarios taken into account are accepted as representative of the extreme bounds of plausible futures. Both cases require a definition of what such levels of acceptability can be.

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), one has to face 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). The build-up of these in financial institution portfolios and the interactions between financial institutions themselves are simply impossible to model accurately. While scenario approaches are explicitly conceived as a tool to circumvent the multiplicity issue behind radical uncertainty, they cannot per se solve this complexity issue. It is perhaps revealing that the Bank of England (2019b) discussion paper mentioned above does not mention the uncertainty issue as such[15] nor address the question of the capacity of models and modelers to capture complexity at stake.[16]

[12] 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).

[13] Endogeneity is discussed in the technical documentation of the NGFS (NGFS, 2020c) concerning climate scenarios but is absent in the main reports.

[14] "Monte-Carlo" refers here to mathematical approaches in numerical science where in the face of the complexity caused by very high number of variables, it is preferred to randomly explore the universe of potential solutions rather than trying to solve complex equations deterministically.

[15] The word "uncertainty" does not appear once in the document.

[16] While developing an advanced suite of complex models, the recent stress test exercise proposed by the French financial supervisor (ACPR, 2020; Allen et al., 2020) does not seem to solve this conundrum, Allen et al. recognizing in their discussion of the proposed method: "*since* [scenario-based approaches] *need to be quantified in order to be relevant to the targeted community (*i.e. *central banks and financial institutions), they then often rely on the very same models that they were supposed to provide an alternative approach to. All the extensive literature on climate-economy modelling limitations and sensibility to parameterization and calibration therefore applies as caveat to our results.*"

2.3.6. Materiality and expectations

The dominant risk disclosure and risk management paradigm implicitly bets on the eventual materiality of CRFR 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 impacts are 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 — indeed the longer it takes to decarbonise, the greater the threat from transition and physical risks. This opens a window of overlap with financial sector (short-term) time horizons, but here the intensity of the risk as of today is clearly not credible as we hardly see any significant transition starting. The lack of a strong risk signal means there is little chance that the financial sector will voluntarily shift its position if it does not believe transition risk to be material within its narrow time frame, as born out in a number of recent studies (Ameli, 2019; BCAM, 2019; Campiglio et al., 2019; Christophers, 2019).

2.3.7. Summary

CRFRs – both physical and transition risks – are subject to radical uncertainty and are not well suited to conventional ergodic and exogenous 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.

Thus, the existing approach to CRFR is not fit for purpose. Scenarios and stress testing are useful tools in the face of uncertainty, but the quantitative modelling they rely upon cannot compensate for the 'unknown unknowns' attached to underlying socio-economic phenomena and mechanisms. Therefore, they cannot act as the sole guide for actual decision-making. What is lacking is an alternative intellectual framework that might guide action now under conditions of symmetrical levels of imperfect information (Beckert and Bronk, 2018).

3. A precautionary financial policy approach to CRFR: theory and rationale

We argue that a *precautionary* approach to financial policy and regulation (henceforth precautionary financial policy (PFP)) helps to meet the challenge of radical uncertainty associated with the specificity of CRFR. The PFP framework is inspired by two regulatory traditions — the precautionary principle and macroprudential policy — but is not intended to be rigid applications of either of these ideas.

3.1. The precautionary principle and environmental protection

The precautionary principle that influences our PFP framework has its roots in the German *Vorsorgeprinzip*. This distinguishes between human activity that may result in catastrophic consequences to 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:

> '*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 Kyoto Protocol and 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)[17]). Across the EU, the precautionary principle has been applied to regulations throughout a range of different sectors beyond climate change, including; health and safety, biodiversity, consumer protection, chemicals, novel foods, pesticides, nanoproducts and pharmaceuticals.

Of course, these examples do not extend perfectly to CRFR where we are dealing with the potential systemic risk caused by the financing of a wide range of *existing*, *declining* or *incompatible* activities at the macro-financial level rather than the harms caused by new specific products or technologies at the sector specifc or microeconomic level. We use the term 'precautionary policy approach' rather than 'precautionary principle' to make clear this distinction — implying the development of a broad and more flexible policy framework, rather than a single principle upon which any individual regulatory intervention should be judged as either right or wrong. The justification for this focus on systemic risk has already been elaborated in the form of macroprudential policy.

3.2. Macroprudential policy as a tool for dealing with uncertainty

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 wider systemic risks. 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 safer financial system (Baker, 2015). Financial institutions developed complex 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 analysis of past behaviours (Chenet, 2021). The apparent sophistication of this approach partially convinced regulators that financial markets could largely self-regulate (Constancio, 2016).

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

[17] For further details see EUR-LEX 2019.

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). As such, macroprudential policy can be seen as taking a precautionary approach.[18]

A key feature of macroprudential policy is that it empowers central banks and supervisory authorities to reduce the likely emergence of instability *ex-ante*, i.e. before market participants recognize the emergence of risk and adjust their behaviours. The macroprudential policy maker is forward, not backward-looking and has an incentive to behave in a robust fashion, preparing for worst-case scenarios. This approach favours precautionary but active policies that avoid large losses across scenarios regardless of the likelihood of any given scenario (Taleb et al., 2014; Bahaj and Foulis, 2016). 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 (unforeseen) shocks (e.g. by increasing capital buffers or developing robust resolution procedures); and 3) reduce the contagion or shock propagation by e.g. increasing the diversity or modularity of financial network (Borio, 2011; Claessens et al., 2013; Altunbas et al., 2018).

Macroprudential policy is also intentionally not 'sector' or 'market-neutral'. It recognises that certain sectors (e.g. real estate, foreign exchange) are more prone to the creation of systemic risks than others (lending to small firms) and develops sector-specific tools accordingly. In the case of housing, macruprudential policy has included tighter loan-to-value (LTV), debt-to-income (DTI) and interest-coverage-ratios (ICR) for households and investors on the demand side, whilst on the supply side required banks to hold more capital against certain types of real estate lending.

Given it is now recognised by central banks that certain activities increase climate-related financial risks, and that these risks can become systemic, there is a strong case for macroprudential policy to be extended to ensure the financial system is also more resilient to hard to predict climate-change related financial shocks.

It is noticeable that the introduction of macroprudential tools in the aftermath of the 2007–08 financial crisis was not the end point of a long and sophisticated attempt to accurately model the optimal quantity of mortgage credit in the economy in terms of financial stability. It was more a simple recognition that that the previous intellectual framework – focused on microprudential risk – was not fit fur purpose (Borio, 2011). Furthermore, the decisions for when and how to intervene are equally not based upon sophisticated risk modelling but on observing a set of core indicators (e.g. mortgage credit to GDP ratios at the national level, debt-servicing ratios) as well as regulator discretion and judgement. As an example, the Bank of England's policy statement on macroprudential policy tools relating to housing (Bank of England, 2016) states:

> *"The FPC [Financial Policy Committee] will be more likely to adjust LTV, DTI or ICR limits when the degree of imbalance as measured by the core indicators is greater, when the different indicators convey a more uniform picture, and when that picture is supported by market and supervisory intelligence. Judgement will, however, play a material role in all FPC decisions and policy will not be mechanically tied to any specific set of indicators. The indicators may also be useful in judging whether or not policy has been effective."*

4. A precautionary financial policy approach to CRFR: application

Our central argument is that both the systemic magnitude and irreversibility of the threats associated with CRFR, and the radical uncertainty attached to them, justify the development of an explicit climate-related Precautionary Financial Policy (PFP). This would incorporate all aspects of financial policy, including macroprudential and monetary policy interventions.[19]

Financial policies and regulation can be used to mitigate CRFR by supporting a rapid and smooth decarbonisation of economic activity through both direct measures and 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.[20]

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,[21] the following policy areas would appear particularly promising for implementation to address CRFR mitigation in the short- to medium-term.

4.1. Integrating climate risk in to capital adequacy requirements

The current capital adequacy requirement framework (the ratio required by the regulator of a bank's capital over its risk-weighted assets) is misaligned with keeping the financial system resilient to CRFRs, failing both to price in the credit risks of financing of carbon-intensive economic activities whilst also prompting unfavorable conditions for green lending (Blundell-Wignall and Atkinson, 2010; Allen et al., 2012; Angelini et al., 2015; D'Orazio and Popoyan, 2019). In the face of the necessary rapid decarbonisation of the economy, a precautionary approach would be to increase capital adequacy requirements for 'dirty loans' — also known widely known as 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.

Reciprocally, a 'green supporting factor', reducing capital adequacy requirements, has gained popularity (D'Orazio and Popoyan, 2019). While aligned in principle with the objective of mitigating climate change, we believe this approach comes with too many counterproductive effects.

[18] While having different etymological roots, 'prudence/prudential' and 'precaution' are semantically close in their approach to the future, precaution being the preventative action resulting from a prudent stance.

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

[20] For the sake of completeness, it could be argued to some extent that a genuine mitigation of transition risk would consist in avoiding the transition itself. But this point is not taken here as it would shift a higher burden to future generations having to cope with catastrophic levels of climate change. Therefore, we consider such an argument to be either an irresponsible response or alternatively a pure negation of anthropogenic climate change.

[21] See e.g. Schoenmaker et al. (2015), D'Orazio and Popoyan (2019) and the recent INSPIRE Briefing Paper "A Toolbox for Sustainable Crisis Response Measures for Central Banks and Supervisors" (Dikau et al., 2020) for more extensive discussions of 'green macroprudential' policy-type interventions.

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 less agreement on what counts as 'green' given it is a very new 'sector',[22] but much more agreement on what counts as excessively carbon-intensive (i.e. undesirable) sectors. In other words, climate science clearly says what is undesirable: fossil fuels and in particular coal (Masson-Delmotte et al., 2018); but on the 'green' side there is less consensus and constant evolution with technological and societal changes over time, from renewable sources of energy to nuclear power to negative emission technologies to efficient consumption patterns. The focus of the European Union on the development of a 'green taxonomy' rather than a classification of carbon intensive assets suffers from the same drawback. For this reason, the dedicated EU technical expert group actually supported the extension of the taxonomy to carbon intensive activities in its recent report (EU TEG SF, 2020), following the NGFS (NGFS, 2019b). The previous Governor of the Bank of England suggested the Bank would consider imposing a higher capital adequacy requirement for carbon intensive types of loans or as one of the potential policy outcomes of the climate stress tests it is conducting (Carney, 2020a), as did the Governor of the Banque de France (Villeroy de Galhau, 2018).

More broadly, an argument can be made that at the present time — i.e. before the necessary net zero carbon transition has occurred — there is no strong evidence of higher/lower risk for dirty/green loans (NGFS, 2020a), nor perception of it from market participants which would translate into prices, as noted in Section 2.2. Indeed, the materialization of such a risk is based on the realisation of an effective transition. As of now, it is difficult to explain why a green company would be less prone to default than a carbon intensive company, given that the former corresponds to a potential growth sector carrying considerable uncertainty whilst the latter remains a key part of a mature industrial ecosystem based on the still-dominant fossil fuel energy. Thus, this materialization can only be scenario-dependent: green activities will be less risky only when we are truly on a transition pathway, and vice versa for the carbon intensive firms. The point is precisely to support the materialization of these risks in an orderly manner, i.e. to push the economy to shift to a low-carbon trajectory and in doing so address the time inconsistency problem that affects climate policy more broadly (Carney, 2015).

4.2. Climate-risk aligned credit controls and credit guidance

A more direct way to restrict financing to carbon intensive activities would be the use of quantitative restrictions on lending, for example ratios of fossil fuel to total lending or carbon intensive to green across a bank's asset portfolio. The dirtiest 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. Adopting a precautionary approach, 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.

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.

Of course, a first-best scenario would be that environmental legislation would also prohibit such activity in its entirety, but given the lack of such an intervention, a precautionary approach would advocate intervention now on the assumption that such legislative action may not occur (i.e. a worst-case scenario), or to accompany/anticipate it. 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.

'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 and ambitious industrial transitions (Bezemer et al., 2018). Furthermore, they 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 do monetary policy operations, including both asset purchase programmes and collateral frameworks to support refinancing. Current asset purchase criteria by both the Bank of England and the ECB are not market neutral (Colesanti Senni and Monnin, 2020; van t Klooster and Fontan, 2020) and support incumbent 'dirty' industrial sectors, including energy, manufacturing, automobiles and utilities (Matikainen et al., 2017; Monnin, 2018a; Dafermos et al., 2020) 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 BoE's collateral framework and haircut regime are similarly supportive of brown sectors (Gabor et al., 2019). Aligned with such diagnosis, the ECB itself is currently showing some will to review its approach related to monetary policy, in particular related to the 'market neutrality' principle, acknowledging long standing market failures (Arnold, 2020; ECB, 2020a; Schnabel, 2020).

It is important to notice that as of today the ECB bases its corporate sector purchase program (CSPP) and collateral framework criteria on current credit rating agency analytics, which globally fail to capture CRFR. Indeed, mainstream credit rating so far demonstrates no concrete forward-looking view on physical nor transition risk. It is worthwhile to notice that rating agencies increasingly take into account environmental risks to some extent, but rather after crises occur — i.e. when risk have already materialised (Mathiesen, 2018).[23]

The profession is currently trying to catch up on the challenge of measuring CRFR, as illustrated by the wave of acquisitions of extra-financial and alternative rating boutiques by leading ones (Nauman, 2019). A number of alternative credit scoring approaches attempt to

[22] 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 (EU TEG SF, 2019).

[23] While as of today climate risk is not integrated per se in the core of genuine credit rating, rating agencies and other financial intermediaries do make rapid progress on attempting to capture climate risk exposure, either at sectoral or regional level, providing additional metrics. 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.

account for CRFRs in the context of central banks operations. For example, a recent study of the ECB's CSPP using 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 above, there is no reason to think any particular metric 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 suggest that, in the absence of reliable scientific estimates of CRFR, focus should be on avoiding the type of worst-case yet plausible scenarios (i.e. that these transition risks will materialise abruptly in the short term or catastrophically in the longer run) and adjust financial policy accordingly (Dupuy, 2002; Dupuy and Grinbaum, 2005).

5. Discussion

What are the key challenges for central banks and supervisors in adopting a precautionary financial policy approach? We focus discussion here on time horizon, mandates and implementation issues.

5.1. Time horizons and mandates

Two principal challenges around central bank and supervisory mandates in regard to the issues of CRFR are that: 1) the time horizon of their mandate is too short to capture the significant materiality of CRFR today (the tragedy of the horizon problem (Carney, 2015)); and 2) 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 (Borio, 2014; Aikman et al., 2015).

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).[24] 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 an absence of explicit definitions, it is impossible to guarantee that action will not be postponed until it is too late. 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.

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[25] which such approaches rest on no longer applies. 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; Svartzman et al., 2019). 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. Also, following Dupuy (2002), considering the 'worst plausible scenario' — e.g. a + 6 °C world — is a good rationale to take all the relevant decisions for the future catastrophe not to occur (Dupuy and Grinbaum, 2005).

Concerning the object of the mandate itself, it is clear that each jurisdiction has its own laws and rules, and interpretations of those institutions. 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 (Krogstrup and Oman, 2019; Dikau and Volz, 2020). 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 and recently the new ECB president, Christine Lagarde, put forward the objective of fighting climate change as a priority in the ECB's agenda (Lagarde, 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.[26] 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). The aim was to push back against the tendency of incumbent governments to ramp up spending in the run up to elections and pressure central banks to ease monetary policy to stimulate growth and employment. This would generate inflation and inflationary expectations that only an independent central bank could credibly prevent and reverse.

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 CRFR. Politicians and ministers of finance are under significant political pressure not to regulate against large companies (e.g. energy companies) engaged in unsustainable activities, which will enhance both physical and long-term transition-related CRFR. 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,

[24] 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, chap. 1).

[25] Also known as ceteris paribus.

[26] 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.

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 to ameliorate CRFR could be accused of not being independent or at the very least of not justifying the privilege of independence.

Therefore, while at its roots a PFP framework may require strong political and popular support in democracies, we emphasize that being independent and purpose driven, central banks should be capable of taking 'unpopular' decisions. In addition, the recent central bank narrative change related to the market neutrality principle, driven by the ECB — one of its main traditional supporters (Arnold, 2020; Schnabel, 2020) — is suggestive that central banks may be open to a shift in this direction. But, such drastic moves from financial regulators may not be that 'unpopular', as they are anyway 'backed' by a broader societal stream on climate change: consensuses at both the international diplomacy (Paris Agreement), scientific (IPCC) and political (EU Taxonomy) levels are now joined by progressively stronger support for the decarbonisation of the economy, coming from both civil society and economic actors (Maibach et al., 2017; Urpelainen and Van de Graaf, 2018; Mooney and Temple-West, 2020). The most recent progress in that direction comes from fossil fuel majors themselves, some of which are adopting renewed strategies vis-à-vis climate change, thanks to this evolving regulatory environment and pressure from the financial sector (Diringer and Perciasepe, 2020; Pavlovic, 2020).[27]

None of this is to say that only central banks and financial supervisors should be mobilised and that governments should not also be going much further, faster, to address the risks from climate change (Bolton et al., 2020). 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.

5.2. Implementation challenges

How to implement climate-risk oriented macroprudential 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 (Kay and King, 2020). 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, chap. 4). This type of approach relies more on heuristics and general direction-setting for markets than sophisticated mathematical 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, based on 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), e.g. early policy action can bring useful additional information on the reaction properties of the system, allowing better decisions going forwards instead of waiting to learn-then-act without having a sense of the reality of the system's dynamics; or exploiting 'animal spirits' (Keynes, 1936), e.g. investment behaviour could quickly shift away from carbon if we can shift sentiment decisively. All these approaches can help taking decisions in situations of uncertainty, but the level of radical uncertainty coming from the complexity of the CRFR conundrum cannot be addressed without the contribution of economic institutions, which aim precisely at reducing such uncertainty (Boyer, 2018; Svartzman et al., 2019).

The first means of applying a precautionary approach 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; Webb et al., 2017). 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, and in terms of coordination with fiscal policy. 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 dirty company will contribute to greening it).

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 (Bolton et al., 2020), but the implementation details are context- and country-dependent, which opens the way to more rapid decision-making, as formal international agreement between all partners is not indispensable before taking action. In addition, given radical uncertainty, experimentation with different approaches to dealing with CRFR may be beneficial, with the most successful approaches hopefully emerging and being adopted other countries, emphasizing the need for leadership from a at least a few jurisdictions.

[27] Since Spanish fossil fuel company Repsol kicked off the move in Dec. 2019, European fossil fuel majors progressively commit to become carbon neutral by circa 2050. While being a priori consistent with the objectives of the Paris Agreement, such carbon neutrality engagement is nevertheless usually limited to scope 1 and 2 GHG emissions, i.e. direct emissions from their operations and consumptions, not the scope 3 emissions from the use phase of their sold (fossil fuel) products, which corresponds by far to the most significant emissions from fossil fuels. Therefore, even if those unprecedented moves clearly constitute significant progress in terms of business acceptance of the need to transition, they are not yet aligned with climate goals. Cf. e.g. https://www.transitionpathwayinitiative.org/publications/61.pdf; http://priceofoil.org/2020/09/23/big-oil-reality-check/

6. Conclusion

In this paper we have proposed the adoption of a 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. In particular, we show that the uncertainty attached to the short- and mid-term transition risks makes a PFP approach useful, as it can provide financial policy makers with a framework that allows them to trigger policy intervention today despite the fact that financial risks — as traditionally understood — have not yet materialised.

While scenario analysis and stress testing can in theory be seen as a step forward in this direction and certainly superior to simple voluntary disclosure approaches, they remain within the broad purview of a market-correcting framework which views efficient price discovery as the best way to ensure a smooth transition and require heroic ceteris paribus assumptions. Moreover, so far these stress test frameworks are used with the expectation that market participants will act, without a necessary move from policy makers. This approach creates a bias against the short-term market disruption and raised transition-risk that is in fact needed in order to avoid longer-term, potentially catastrophic financial and economic damages created by physical climate change.

In contrast, a PFP approach should help justify immediate preventative action and steer 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, which do not just 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 CRFR 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. A PFP framework should also help to justify strengthening existing dispositions such as risk disclosures, benchmarks and non/sustainable taxonomies to, among other enhancements, make them compulsory and standardized, in place of the current voluntary frameworks that a growing number of stakeholders aspire to make mandatory (PBoC and UNEP Inquiry, 2015; McDaniels and Robins, 2018; Carney, 2020b; HM Treasury, 2020; Shaw, 2020; Wheelan, 2020).

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.

Clearly shifting the intellectual framework used by financial policy makers is no small, nor short-term task. Nevertheless, it may be an opportune time given that some central bankers and supervisors are questioning their mandates and what more they can do in the face of clear market failures that threaten to slow down the objective of decarbonisation objectives[28] (Lagarde, 2019; Arnold, 2020; Cox, 2020; Pereira da Silva, 2020; Schnabel, 2020).

This paper is an exploration which attempts 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 research on the topic 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. We have focussed very much on central banks and financial supervisors in this paper but other parts of government, in particular ministries of finance, industrial policy and other public financial institutions (e.g. state development banks) will also have a role to play in coordinating their policies with financial supervisors (Bolton et al., 2020), especially in times of crisis such as the Covid-19 pandemic (Pereira da Silva, 2020).[29]

Whilst more knowledge on CRFR is certainly welcome, the feasibility of research, in particular on quantitative modelling of long-term CRFR, must be consistent with the timeline of the policy decisions this research is supposed to inform. In other words, it does not make sense to expect research outcomes in 10 years from now to support policy decisions that must be taken in the present to have any impact. This is especially the case when dealing with situations of radical uncertainty prevents which limit the usefulness of results derived from probabilistic modelling approaches.

Beyond climate change, we hope the PFP framework 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 resource depletion. Indeed, most of these areas have important interactions with climate change itself and so should as far as possible be incorporated in to CRFR policy approaches.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[28] Paraphrasing Isabel Schnabel from the European Central Bank, in her 28/9/2020 speech (Schnabel, 2020).

[29] See also "*Le Covid-19 d'abord et le climat après? Pas si simple – Liens entre risques sanitaires et environnementaux*" https://covid19-economie.banque-france.fr/comprendre/le-covid-19-dabord-et-le-climat-apres-pas-si-simple-liens-entre-risques-sanitaires-et-environnementaux/ [in French]

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