The green swan

Central banking and financial stability in the age of climate change

Patrick BOLTON - Morgan DESPRES - Luiz Awazu PEREIRA DA SILVA
Frédéric SAMAMA - Romain SVARTZMAN

January 2020

www.bis.org
email@bis.org

The views expressed in this publication are those of the authors and do not necessarily reflect those of their respective institutions.

ISBN 978-92-9259-325-4 (print)
ISBN 978-92-9259-326-1 (online)

Abstract

Climate change poses new challenges to central banks, regulators and supervisors. This book reviews ways of addressing these new risks within central banks' financial stability mandate. However, integrating climate-related risk analysis into financial stability monitoring is particularly challenging because of the radical uncertainty associated with a physical, social and economic phenomenon that is constantly changing and involves complex dynamics and chain reactions. Traditional backward-looking risk assessments and existing climate-economic models cannot anticipate accurately enough the form that climate-related risks will take. These include what we call "green swan" risks: potentially extremely financially disruptive events that could be behind the next systemic financial crisis. Central banks have a role to play in avoiding such an outcome, including by seeking to improve their understanding of climate-related risks through the development of forward-looking scenario-based analysis. But central banks alone cannot mitigate climate change. This complex collective action problem requires coordinating actions among many players including governments, the private sector, civil society and the international community. Central banks can therefore have an additional role to play in helping coordinate the measures to fight climate change. Those include climate mitigation policies such as carbon pricing, the integration of sustainability into financial practices and accounting frameworks, the search for appropriate policy mixes, and the development of new financial mechanisms at the international level. All these actions will be complex to coordinate and could have significant redistributive consequences that should be adequately handled, yet they are essential to preserve long-term financial (and price) stability in the age of climate change.

Acknowledgements

We acknowledge suggestions, comments and contributions by: Michel Aglietta, Thomas Allen, Nathalie Aufauvre, Lisa Biermann, Jean Boissinot, Antoine Boirard, Clément Bourgey, Régis Breton, Ben Caldecott, Emanuele Campiglio, Adam Cap, Pierre Cardon, Michel Cardona, Hugues Chenet, Valérie Chouard, Laurent Clerc, Benoît Cœuré, Stéphane Dees, Simon Dikau, Torsten Ehlers, Frank Elderson, Ulrike Elsenhuber, Etienne Espagne, Gauthier Faure, Ingo Fender, Antoine Godin, Ian Goldin, Sylvie Goulard, Kevin Hoskin, Kumar Jegarasasingam, Joaquim Levy, David Lunsford, Sabine Mauderer, Jean-François Mercure, Juliette Mollo, Xavier Musca, William Oman, Adrian Orr, Alban Pyanet, Fernando Restoy, Guilllaume Richet-Bourbousse, Dilyara Salakhova, Edo Schets, Nicholas Stern, Josué Tanaka, Jakob Thomä, Charlotte Vailles, Pierre-François Weber and Jeffery Yong. All errors are exclusively our own.

We also thank the BIS communications team (Maria Canelli, Emma Claggett, Krista Hughes, Nathalie Savary, Fanny Sorgato and Victoria Torrano), and Giulio Cornelli, Alan Villegas and Adam Cap for excellent research assistance.

Contents

Foreword by Agustín Carstens

A growing body of research by academics, central banks and international institutions including the BIS focuses on climate-related risks. These studies show that physical risks related to climate change can severely damage our economies, for example through the large cost of repairing infrastructure and coping with uninsured losses. There are also transition risks related to potentially disorderly mitigation strategies. Both physical and transition risks, in turn, can increase systemic financial risk. Thus their potential consequences have implications for central banks' financial stability mandate. All these considerations prompted central banks to create the Central Banks and Supervisors Network for Greening the Financial System (NGFS), which the BIS has been part of since its inception.

This book helps to trace the links between the effects of climate change, or global warming, and the stability of our financial sectors. It includes a comprehensive survey of how climate change has been progressively integrated into macroeconomic models and how these have evolved to better assess financial stability risks stemming from climate change (eg stress testing models using global warming scenarios). But the book also recognises the limitations of our models, which may not be able to accurately predict the economic and financial impact of climate change because of the complexity of the links and the intrinsic non-linearity of the related phenomena. Nevertheless, despite the high level of uncertainty, the best scientific advice today suggests that action to mitigate and adapt to climate change is needed.

Naturally, the first-best solution to address climate change and reduce greenhouse gas emissions is Pigovian carbon taxation. This policy suggests that fundamental responsibility for addressing issues related to climate change lies with governments. But such an ambitious new tax policy requires consensus-building and is difficult to implement. Nor can central banks resolve this complex collective action problem by themselves. An effective response requires raising stakeholders' awareness and facilitating coordination among them. Central banks' financial stability mandate can contribute to this and should guide their appropriate involvement. For instance, central banks can coordinate their own actions with a broad set of measures to be implemented by other players (governments, the private sector, civil society and the international community). This is urgent since climate-related risks continue to build, and negative outcomes such as what this book calls "green swan" events could materialise.

Contributing to this coordinating role is not incompatible with central banks doing their share within their current mandates. In this sense there are many practical actions central banks can undertake (and, in some cases, are already undertaking). They include enhanced monitoring of climate-related risks through adequate stress tests; developing new methodologies to improve the assessment of climate-related risks; including environmental, social and governance (ESG) criteria in their pension funds; helping to develop and assess the proper taxonomy to define the carbon footprint of assets more precisely (eg "green" versus "brown" assets); working closely with the financial sector on disclosure of carbon-intensive exposure to assess potential financial stability risks; studying more precisely how prudential regulation could deal with risks to financial stability arising from climate change; and examining the adequate room to invest surplus FX reserves into green bonds.

The BIS has been collaborating with the central bank community on all these aspects. In addition, in September 2019 it launched its green bond BIS Investment Pool Fund, a new vehicle that facilitates central banks' investments in green bonds. And with this book it hopes to steer the debate and discussions further while recognising that all these actions will require more research and be challenging, but nevertheless essential to preserving long-term financial and price stability in the age of accelerated climate change.

Agustín Carstens
BIS General Manager

Foreword by François Villeroy de Galhau

In the speech he delivered when receiving the Nobel Prize in Literature in 1957, the French writer Albert Camus said: "Each generation doubtless feels called upon to reform the world. Mine knows that it will not reform it, but its task is perhaps even greater. It consists in preventing the world from destroying itself". Despite a different context, these inspiring words are definitely relevant today as mankind is facing a great threat: climate change.

Climate change poses unprecedented challenges to human societies, and our community of central banks and supervisors cannot consider itself immune to the risks ahead of us. The increase in the frequency and intensity of extreme weather events could trigger non-linear and irreversible financial losses. In turn, the immediate and system-wide transition required to fight climate change could have far-reaching effects potentially affecting every single agent in the economy and every single asset price. Climate-related risks could therefore threaten central banks' mandates of price and financial stability, but also our socio-economic systems at large. If I refer to our experience at the Banque de France and to the impressive success of the Network for Greening the Financial System (NGFS) we launched in December 2017, I would tend to affirm that our community is now moving in the right direction.

But despite this growing awareness, the stark reality is that we are all losing the fight against climate change. In such times, the role our community should play in this battle is questioned. It is then important to clearly state that we cannot be the only game in town, even if we should address climate-related risks within the remit of our mandates, which may include considering options relating to the way we conduct monetary policy. On monetary policy, I have two strong beliefs, and we will have the opportunity to discuss them against the backdrop of the ECB strategic review led by Christine Lagarde. First, we need to integrate climate change in all our economic and forecasting models; second we need, instead of opening a somewhat emotional debate on the merits of a green quantitative easing, which faces limitations, to do an overhaul of our collateral assessment framework to reflect climate-related risks.

In order to navigate these troubled waters, more holistic perspectives become essential to coordinate central banks', regulators' and supervisors' actions with those of other players, starting with governments. This is precisely what this book does. If central banks are to preserve financial and price stability in the age of climate change, it is in their interest to help mobilize all the forces needed to win this battle. This book is an ambitious, carefully thought-out and therefore necessary contribution toward this end.

François Villeroy de Galhau
Governor of the Banque de France

Scientific knowledge is as much an understanding of the diversity of situations for which a theory or its models are relevant as an understanding of its limits.

Elinor Ostrom (1990)

Executive Summary

This book reviews some of the main challenges that climate change poses to central banks, regulators and supervisors, and potential ways of addressing them. It begins with the growing realisation that climate change is a source of financial (and price) instability: it is likely to generate physical risks related to climate damages, and transition risks related to potentially disordered mitigation strategies. Climate change therefore falls under the remit of central banks, regulators and supervisors, who are responsible for monitoring and maintaining financial stability. Their desire to enhance the role of the financial system to manage risks and to mobilise capital for green and low-carbon investments in the broader context of environmentally sustainable development prompted them to create the Central Banks and Supervisors Network for Greening the Financial System (NGFS).

However, integrating climate-related risk analysis into financial stability monitoring and prudential supervision is particularly challenging because of the distinctive features of climate change impacts and mitigation strategies. These comprise physical and transition risks that interact with complex, far-reaching, nonlinear, chain reaction effects. Exceeding climate tipping points could lead to catastrophic and irreversible impacts that would make quantifying financial damages impossible. Avoiding this requires immediate and ambitious action towards a structural transformation of our economies, involving technological innovations that can be scaled but also major changes in regulations and social norms.

Climate change could therefore lead to "green swan" events (see Box A) and be the cause of the next systemic financial crisis. Climate-related physical and transition risks involve interacting, nonlinear and fundamentally unpredictable environmental, social, economic and geopolitical dynamics that are irreversibly transformed by the growing concentration of greenhouse gases in the atmosphere.

In this context of deep uncertainty, traditional backward-looking risk assessment models that merely extrapolate historical trends prevent full appreciation of the future systemic risk posed by climate change. An "epistemological break" (Bachelard (1938)) is beginning to take place in the financial community, with the development of forward-looking approaches grounded in scenario-based analyses. These new approaches have already begun to be included in the financial industry's risk framework agenda, and reflections on climate-related prudential regulation are also taking place in several jurisdictions.

While these developments are critical and should be pursued, this book presents two additional messages. First, scenario-based analysis is only a partial solution to apprehend the risks posed by climate change for financial stability. The deep uncertainties involved and the necessary structural transformation of our global socioeconomic system are such that no single model or scenario can provide a full picture of the potential macroeconomic, sectoral and firm-level impacts caused by climate change. Even more fundamentally, climate-related risks will remain largely unhedgeable as long as system-wide action is not undertaken.

Second, it follows from these limitations that central banks may inevitably be led into uncharted waters in the age of climate change. On the one hand, if they sit still and wait for other government agencies to jump into action, they could be exposed to the real risk of not being able to deliver on their mandates of financial and price stability. Green swan events may force central banks to intervene as "climate rescuers of last resort" and buy large sets of devalued assets, to save the financial system once more. However, the biophysical foundations of such a crisis and its potentially irreversible impacts would quickly show the limits of this "wait and see" strategy. On the other hand, central banks cannot (and should not) simply replace governments and private actors to make up for their insufficient action, despite growing social pressures to do so. Their goodwill could even create some moral hazard. In short, central banks, regulators and supervisors can only do so much (and many of them are already taking action within their mandates), and their action can only be seen as enhancing other climate change mitigation policies.

To overcome this deadlock, a second epistemological break is needed: central banks must also be more proactive in calling for broader and coordinated change, in order to continue fulfilling their own mandates of financial and price stability over longer time horizons than those traditionally considered. We believe that they can best contribute to this task in a role that we dub the five Cs: **c**ontribute to **c**oordination to **c**ombat **c**limate **c**hange. This coordinating role would require thinking concomitantly within three paradigmatic approaches to climate change and financial stability: the risk, time horizon and system resilience approaches (see Box B).

Contributing to this coordinating role is not incompatible with central banks, regulators and supervisors doing their own part within their current mandates. They can promote the integration of climate-related risks into prudential regulation and financial stability monitoring, including by relying on new modelling approaches and analytical tools that can better account for the uncertainty and complexity at stake. In addition, central banks can promote a longer-term view to help break the "tragedy of the horizon", by integrating sustainability criteria into their own portfolios and by exploring their integration in the conduct of financial stability policies, when deemed compatible with existing mandates.

But more importantly, central banks need to coordinate their own actions with a broad set of measures to be implemented by other players (ie governments, the private sector, civil society and the international community). This coordination task is urgent since climate-related risks continue to build up and negative outcomes could become irreversible. There is an array of actions to be consistently implemented. The most obvious ones are the need for carbon pricing and for systematic disclosure of climate-related risks by the private sector.

Taking a transdisciplinary approach, this book calls for additional actions that no doubt will be difficult to take, yet will also be essential to preserve long-term financial (and price) stability in the age of climate change. These include: exploring new policy mixes (fiscal-monetary-prudential) that can better address the climate imperatives ahead and that should ultimately lead to societal debates regarding their desirability; considering climate stability as a global public good to be supported through measures and reforms in the international monetary and financial system; and integrating sustainability into accounting frameworks at the corporate and national level.

Moreover, climate change has important distributional effects both between and within countries. Risks and adaptation costs fall disproportionately on poor countries and low-income households in rich countries. Without a clear indication of how the costs and benefits of climate change mitigation strategies will be distributed fairly and with compensatory transfers, sociopolitical backlashes will increase. Thus, the needed broad social acceptance for combating climate change depends on studying, understanding and addressing its distributional consequences.

Financial and climate stability could be considered as two interconnected public goods, and this consideration can be extend to other human-caused environmental degradation such as the loss of biodiversity. These, in turn, require other deep transformations in the governance of our complex adaptive socioeconomic and financial systems. In the light of these immense challenges, a central contribution of central banks is to adequately frame the debate and thereby help promote the mobilisation of all capabilities to combat climate change.

Box A: From black to green swans

The “green swan” concept used in this book finds its inspiration in the now famous concept of the “black swan” developed by Nassim Nicholas Taleb (2007). Black swan events have three characteristics: (i) they are unexpected and rare, thereby lying outside the realm of regular expectations; (ii) their impacts are wide-ranging or extreme; (iii) they can only be explained after the fact. Black swan events can take many shapes, from a terrorist attack to a disruptive technology or a natural catastrophe. These events typically fit fat tailed probability distributions, ie they exhibit a large skewness relative to that of normal distribution (but also relative to exponential distribution). As such, they cannot be predicted by relying on backward-looking probabilistic approaches assuming normal distributions (eg value-at-risk models).

The existence of black swans calls for alternative epistemologies of risk, grounded in the acknowledgment of uncertainty. For instance, relying on mathematician Benoît Mandelbrot (1924–2010), Taleb considers that fractals (mathematically precise patterns that can be found in complex systems, where small variations in exponent can cause large deviation) can provide more relevant statistical attributes of financial markets than both traditional rational expectations models and the standard framework of Gaussian-centred distributions (Taleb (2010)). The use of counterfactual reasoning is another avenue that can help hedge, at least partially, against black swan events. Counterfactuals are thoughts about alternatives to past events, “thoughts of what might have been” (Epstude and Roese (2008)). Such an epistemological position can provide some form of hedging against extreme risks (turning black swans into “grey” ones) but not make them disappear. From a systems perspective, fat tails in financial markets suggest a need for regulation in their operations (Bryan et al (2017), p 53).

Green swans, or “climate black swans”, present many features of typical black swans. Climate-related risks typically fit fat-tailed distributions: both physical and transition risks are characterised by deep uncertainty and nonlinearity, their chances of occurrence are not reflected in past data, and the possibility of extreme values cannot be ruled out (Weitzman (2009, 2011)). In this context, traditional approaches to risk management consisting in extrapolating historical data and on assumptions of normal distributions are largely irrelevant to assess future climate-related risks. That is, assessing climate-related risks requires an “epistemological break” (Bachelard (1938)) with regard to risk management, as discussed in this book.

However, green swans are different from black swans in three regards. First, although the impacts of climate change are highly uncertain, “there is a high degree of certainty that some combination of physical and transition risks will materialize in the future” (NGFS (2019a), p 4). That is, there is certainty about the need for ambitious actions despite prevailing uncertainty regarding the timing and nature of impacts of climate change. Second, climate catastrophes are even more serious than most systemic financial crises: they could pose an existential threat to humanity, as increasingly emphasized by climate scientists (eg Ripple et al (2019)). Third, the complexity related to climate change is of a higher order than for black swans: the complex chain reactions and cascade effects associated with both physical and transition risks could generate fundamentally unpredictable environmental, geopolitical, social and economic dynamics, as explored in Chapter 3.

Box B: The five Cs – contribute to coordination to combat climate change: the risk, time horizon and system resilience approaches

Responsibilities / Paradigmatic approach to climate change	Measures to be considered[1] by central banks, regulators and supervisors	Measures to be implemented by other players[2] (government, private sector, civil society)
Identification and management of climate-related risks **>> Focus on risks**	Integration of climate-related risks (given the availability of adequate forward-looking methodologies) into: – Prudential regulation – Financial stability monitoring	Voluntary disclosure of climate-related risks by the private sector (Task Force on Climate-related Financial Disclosures) – Mandatory disclosure of climate-related risks and other relevant information (eg French Article 173, taxonomy of "green" and "brown" activities)
Limitations: – Epistemological and methodological obstacles to the development of consistent scenarios at the macroeconomic, sectoral and infra-sectoral levels – Climate-related risks will remain unhedgeable as long as system-wide transformations are not undertaken		
Internalisation of externalities **>> Focus on time horizon**	Promotion of long-termism as a tool to break the tragedy of the horizon, including by: – Integrating environmental, social and governance (ESG) considerations into central banks' own portfolios – Exploring the potential impacts of sustainable approaches in the conduct of financial stability policies, when deemed compatible with existing mandates	– Carbon pricing – Systematisation of ESG practices in the private sector
Limitations: – Central banks' isolated actions would be insufficient to reallocate capital at the speed and scale required, and could have unintended consequences – Limits of carbon pricing and of internalisation of externalities in general: not sufficient to reverse existing inertia/generate the necessary structural transformation of the global socioeconomic system		
Structural transformation towards an inclusive and low-carbon global economic system **>> Focus on resilience of complex adaptive systems in the face of uncertainty**	Acknowledgment of deep uncertainty and need for structural change to preserve long-term climate and financial stability, including by exploring: – Green monetary-fiscal-prudential coordination at the effective lower bound – The role of non-equilibrium models and qualitative approaches to better capture the complex and uncertain interactions between climate and socioeconomic systems – Potential reforms of the international monetary and financial system, grounded in the concept of climate and financial stability as interconnected public goods	– Green fiscal policy (enabled or facilitated by low interest rates) – Societal debates on the potential need to revisit policy mixes (fiscal-monetary-prudential) given the climate and broader ecological imperatives ahead – Integration of natural capital into national and corporate accounting systems – Integration of climate stability as a public good to be supported by the international monetary and financial system

[1] Considering these measures does not imply full support to their immediate implementation. Nuances and potential limitations are discussed in the book. [2] Measures which are deemed essential to achieve climate and financial stability, yet which lie beyond the scope of what central banks, regulators and supervisors can do.

Source: Authors' elaboration.

1. INTRODUCTION – "PLANET EARTH IS FACING A CLIMATE EMERGENCY"

Scientists have a moral obligation to clearly warn humanity of any catastrophic threat and to "tell it like it is." On the basis of this obligation […] we declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency.

Ripple et al (2019)

Climate change poses an unprecedented challenge to the governance of global socioeconomic and financial systems. Our current production and consumption patterns cause unsustainable emissions of greenhouse gases (GHGs), especially carbon dioxide (CO_2): their accumulated concentration in the atmosphere above critical thresholds is increasingly recognised as being beyond our ecosystem's absorptive and recycling capabilities. The continued increase in temperatures has already started affecting ecosystems and socioeconomic systems across the world (IPCC (2018), Mora et al (2018)) but, alarmingly, climate science indicates that the worst impacts are yet to come. These include sea level rise, increases in weather extremes, droughts and floods, and soil erosion. Associated impacts could include a massive extinction of wildlife, as well as sharp increases in human migration, conflicts, poverty and inequality (Human Rights Council (2019), IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Ripple et al (2019)).

Scientists today recommend reducing GHG emissions, starting immediately (Lenton et al (2019), Ripple et al (2019)). In this regard, the 2015 United Nations Climate Change Conference (COP21) and resulting Paris Agreement among 196 countries to reduce GHG emissions on a global scale was a major political achievement. Under the Paris Agreement (UNFCCC (2015)) signatories agree to reduce greenhouse gas emissions "as soon as possible" and to do their best to keep global warming "to well below 2 degrees" Celsius (2°C), with the aim of limiting the increase to 1.5°C. Yet global emissions have kept rising since then (Figueres et al (2018)),[1] and nothing indicates that this trend is reverting.[2] Countries' already planned production of coal, oil and gas is inconsistent with limiting warming to 1.5°C or 2°C, thus creating a "production gap", a discrepancy between government plans and coherent decarbonisation pathways (SEI et al (2019)).

Changing our production and consumption patterns and our lifestyles to transition to a low-carbon economy is a tough collective action problem. There is still considerable uncertainty on the effects of climate change and on the most urgent priorities. There will be winners and losers from climate change mitigation, exacerbating free rider problems. And, perhaps even more problematically, there are large time lags before climate damages become apparent and irreversible (especially to climate change sceptics): the most damaging effects will be felt beyond the traditional time horizons of policymakers and other economic and financial decision-makers. This is what Mark Carney (2015) referred to as "the tragedy of the horizon": while the physical impacts of climate change will be felt over a long-term horizon, with massive costs and possible civilisational impacts on future generations, the time horizon in which financial, economic and political players plan and act is much shorter. For instance, the time horizon of rating

[1] Ominously, David Wallace-Wells recently observed in *The Uninhabitable Earth* (2019), "We have done as much damage to the fate of the planet and its ability to sustain human life and civilization since Al Gore published his first book on the climate than in all the centuries – all the millenniums – that came before."

[2] The Agreement itself is legally binding, but no enforcement mechanisms exist and the GHG reduction targets set by each country through their Nationally Determined Contributions (NDCs) are only voluntary.

agencies to assess credit risks, and of central banks to conduct stress tests, is typically around three to five years.

Our framing of the problem is that climate change represents a green swan (see Box A): it is a new type of systemic risk that involves interacting, nonlinear, fundamentally unpredictable, environmental, social, economic and geopolitical dynamics, which are irreversibly transformed by the growing concentration of greenhouse gases in the atmosphere. Climate-related risks are not simply black swans, ie tail risk events. With the complex chain reactions between degraded ecological conditions and unpredictable social, economic and political responses, with the risk of triggering tipping points,[3] climate change represents a colossal and potentially irreversible risk of staggering complexity.

Carbon pricing and beyond

Climate change is widely considered by economists as an externality that, as such, should be dealt with through publicly imposed Pigovian carbon taxes[4] in order to internalise the climate externalities. Indeed, according to basic welfare economics, a good policy to combat climate change requires such a "price" to act as an incentive to reduce GHG emissions. A carbon tax, for example, creates an incentive for economic agents to lower emissions by switching to more efficient production processes and consumption patterns. The amount of this tax needs to reflect what we already know about the medium- to long-term additional costs of climate change. From a mainstream economist's perspective, a carbon tax that reflects the social cost of carbon (SCC) would make explicit the "shadow cost" of carbon emissions and would be sufficient to induce economic actors to reduce emissions in a perfect Walrasian world.

By this analytical framing, central banks, regulators and supervisors have little to do in the process of decarbonising the economic system. Indeed, the needed transition would mostly be driven by non-financial firms and households, whose decentralised decisions would be geared towards low-carbon technologies thanks to carbon pricing. From a financial perspective, using a carbon tax to correctly price the negative externality would be sufficient to reallocate financial institutions' assets from carbon-intensive towards greener capital. At most, central banks and supervisors should carefully scrutinise financial market imperfections, in order to ensure financial stability along the transition towards a low-carbon economy.

Yet the view that carbon pricing is the sole answer to climate change, and its corollary in terms of monetary and prudential policies (ie that central banks, regulators and supervisors should not really be concerned by climate change) suffers from three significant limitations, which contribute to overlooking potential "green swan" events.

First, even though conceptually carbon pricing has been recognised as the first best option for decades, in practice it has not been implemented at a level sufficient to drive capital reallocation from "brown" (or carbon-intensive) to "green" (or low-carbon) assets. The reality is that governments have failed to act and will continue to do so unless much broader pressure from civil society and business induces significant policy change. Given the current deficiency in global policy responses, it only becomes more likely that the physical impacts of climate change will affect the socioeconomic system in a rapidly warming world. Given that rising temperatures will unleash complex dynamics with tipping points, the impact of

3 A tipping point in the climate system is a threshold that, when exceeded, can lead to large changes in the state of the system. Climate tipping points are of particular interest in reference to concerns about global warming in the modern era. Possible tipping point behaviour has been identified for the global mean surface temperature by studying self-reinforcing feedbacks and the past behaviour of Earth's climate system. Self-reinforcing feedbacks in the carbon cycle and planetary reflectivity could trigger a cascading set of tipping points that lead the world into a hothouse climate state (source: Wikipedia).

4 From Arthur C Pigou (1877–1959), who proposed the concept and the solution to externality problems by taxation, an idea that is key to modern welfare economics and to the economic analysis of environmental impacts. Other economic instruments aimed at pricing carbon exist, such as emission trading schemes (ETS), also known as cap-and-trade systems. Unlike a tax, where the price is determined ex ante, the price of CO_2 in a cap-and-trade mechanism is determined ex post, as a result of the supply and demand of quotas to emit CO_2.

global warming will affect our economies in a disorderly yet cumulative manner that, in turn, could trigger unforeseeable negative financial dynamics.

These so-called physical risks will have financial consequences that are naturally of concern to central bankers and supervisors. They can threaten financial stability by causing irreversible losses, as capital is affected by climate change and as financial agents may be unable to protect themselves from such climate shocks. These risks can also threaten price stability by triggering supply shocks on various commodities, which could in turn generate inflationary or even stagflationary effects (Villeroy de Galhau (2019a)). It should also be noted that traditional policy instruments may be less effective at smoothing these shocks, to the extent that these are more or less permanent biophysical shocks, rather than transitory economic shocks (Cœuré (2018)).

Second, climate change is not merely another market failure but presumably "the greatest market failure the world has ever seen", as leading climate economist Lord Nicholas Stern puts it (Stern (2007)). Given the size of the challenge ahead, carbon prices may need to skyrocket in a very short time span towards much higher levels than currently prevail. Moreover, taking climate-related risks and uncertainty seriously (eg by including the possibility of tipping points leading to catastrophic and irreversible events) should lead to even sharper increases in the SCC (Ackerman et al (2009), Cai and Lontzek (2019), Daniel et al (2019), Weitzman (2009)). With this in mind, the transition may trigger a broad range of unintended consequences. For example, it is increasingly evident that mitigation measures such as carbon price adjustments could have dramatic distributional consequences, both within and across countries.

More to the point of actions by central bankers and supervisors, newly enforced and more stringent environmental regulations could produce or reinforce financial failures in credit markets (Campiglio (2016)) or abrupt reallocations of assets from brown to green activities motivated by market repricing of risks and/or attempts to limit reputational risks and litigations. All this could result in a "climate Minsky moment" (Carney (2018)), a severe financial tightening of financial conditions for companies that rely on carbon-intensive activities (so-called "stranded assets"; see Box 1), be it directly or indirectly through their value chains. These risks are categorised as transition risks; as with physical risks, they are of concern to central bankers and supervisors. Here, the "paradox is that success is failure" (Carney (2016)): extremely rapid and ambitious measures may be the most desirable from the point of view of climate mitigation, but not necessarily from the perspective of financial stability over a short-term horizon. Addressing this tension requires a broad range of measures, as extensively discussed in this book.

Third, the climate change market failure is of such magnitude that it would be prudent to approach it as more than just a market failure. It is a subject that combines, among other things, uncertainty, risk, potentially deep transformations in our lifestyles, prioritising long-term ethical choices over short-term economic considerations, and international coordination for the common good. With this in mind, recent and growing transdisciplinary work suggests that our collective inability to reverse expected climate catastrophes originates in interlocked, complex institutional arrangements, which could be described as a socio-technical system: "a cluster of elements, including technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks" (Geels et al (2004), p 3).

Given this institutional or sociotechnical inertia, higher carbon prices alone may not suffice to drive individual behaviours and firms' replacement of physical capital towards low-carbon alternatives, as economics textbooks suggest. For instance, proactive fiscal policy may be an essential first step to build adequate infrastructure (eg railroads), before carbon pricing can really lead agents to modify their behaviour (eg by switching from car to train). Tackling climate change may therefore require finding complex policy mixes combining monetary, prudential and fiscal instruments (Krogstrup and Oman (2019)) as well as many other societal innovations, as discussed in the last chapter. Going further, the fight against climate change is taking place at the same time when the post-World War II global institutional framework is under growing criticism. This means that the unprecedented level of international coordination required to address the difficult (international) political economy of climate change is seriously compromised.

Therefore, to guarantee a successful low-carbon transition, new technologies, new institutional arrangements and new cultural frameworks should emerge (Beddoe et al (2009)) towards a comprehensive reshaping of current productive structures and consumption patterns. The analogy one may use to envision the change ahead is that of engaging in a multidimensional combat against climate change (Stiglitz (2019)). Even for the sceptics who prefer a "wait and see" approach, a pure self-interested risk management strategy recommends buying the proper insurance of ambitious climate policies (Weitzman (2009)) as a kind of precautionary principle[5] (Aglietta and Espagne (2016)), "pari Pascalien"[6] or "enlightened doomsaying"[7] (Dupuy (2012)), ie as a hedging strategy against the possibility of green swan events.

For all these reasons, even if a significant increase in carbon pricing globally remains an essential step to fight climate change, other (second-, third- or fourth-best from a textbook perspective) options must be explored, including with regard to the financial system.

Revisiting financial stability in the age of climate change

The reflections on the relationship between climate change and the financial system are still in their early stages: despite rare warnings on the significant risks that climate change could pose to the financial system (Carbon Tracker (2013)), the subject was mostly seen as a fringe topic until a few years ago (Chenet (2019a)). But the situation has changed radically in recent times, as climate change's potentially disruptive impacts on the financial system have started to become more apparent, and the role of the financial system in mitigating climate change has been recognised.

This growing awareness of the financial risks posed by climate change can be related to three main developments. First, the Paris Agreement's (UNFCCC (2015)) Article 2.1(c) explicitly recognised the need to "mak[e] finance flows compatible with a pathway toward low greenhouse gas emissions and climate-resilient development", thereby paving the way to a radical reorientation of capital allocation. Second, as mentioned above, the Governor of the Bank of England, Mark Carney (2015), suggested the possibility of a systemic financial crisis caused by climate-related events. Third, in December 2017 the Central Banks and Supervisors Network for Greening the Financial System[8] (NGFS) was created by a group of central banks and supervisors willing to contribute to the development of environment and climate risk management in the financial sector, and to mobilise mainstream finance to support the transition toward a sustainable economy.

The NGFS quickly acknowledged that "climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks" (NGFS (2018), p 3).[9] The NGFS also acknowledged that these risks are tied to complex layers of interactions between the macroeconomic, financial and climate systems (NGFS (2019b)). As this book

[5] The precautionary principle is used to justify discretionary measures by policymakers in situations where there are plausible risks of harming the public through certain decisions, but extensive scientific knowledge on the matter is lacking.

[6] The French philosopher, mathematician and physicist Blaise Pascal (1623–62) used a game theory argument to justify faith as a "hedge": rational people should believe in God as a "pari" or bet. They would incur small losses of pleasure (by accepting to live a life without excessive pleasures), which would be more than offset by infinite gains (eternity in heaven) if God existed. In the same way, accepting some small inconveniences (adjusting one's lifestyle to climate imperatives) is compensated by a more sustainable earth ecosystem, if indeed global warming exists (from the climate change sceptic's perspective).

[7] The concept of "enlightened doomsaying" (catastrophisme éclairé) put forward by the French philosopher of science Jean-Pierre Dupuy (2012) involves imagining oneself in a catastrophic future to raise awareness and trigger immediate action so that this future does not take place.

[8] As of 12 December 2019, the NGFS is composed of 54 members and 12 observers. For more information, see www.ngfs.net.

[9] As acknowledged by the NGFS (2019a), the legal mandates of central banks and financial supervisors vary throughout the world, but they typically include responsibility for price stability, financial stability and the safety and soundness of financial institutions.

will extensively discuss, assessing climate-related risks involves dealing with multiple forces that interact with one another, causing dynamic, nonlinear and disruptive dynamics that can affect the solvency of financial and non-financial firms, as well as households' and sovereigns' creditworthiness.

In the worst case scenario, central banks may have to confront a situation where they are called upon by their local constituencies to intervene as climate rescuers of last resort For example, a new financial crisis caused by green swan events severely affecting the financial health of the banking and insurance sectors could force central banks to intervene and buy a large set of carbon-intensive assets and/or assets stricken by physical impacts.

But there is a key difference between green swan and black swan events: since the accumulation of atmospheric CO_2 beyond certain thresholds can lead to irreversible impacts, the biophysical causes of the crisis will be difficult, if not impossible, to undo at a later stage. Similarly, in the case of a crisis triggered by a rapid transition to a low-carbon economy, there would be little ground for central banks to rescue the holders of assets in carbon-intensive companies. While banks in financial distress in an ordinary crisis can be resolved, this will be far more difficult in the case of economies that are no longer viable because of climate change. Intervening as climate rescuers of last resort could therefore affect central bank's credibility and crudely expose the limited substitutability between financial and natural capital.

Given the severity of these risks, the uncertainty involved and the awareness of the interventions of central banks following the 2007–08 Great Financial Crisis, the sociopolitical pressure is already mounting to make central banks (perhaps again) the "only game in town" and to substitute for other if not all government interventions, this time to fight climate change. For instance, it has been suggested that central banks could engage in "green quantitative easing"[10] in order to solve the complex socioeconomic problems related to a low-carbon transition.

Relying too much on central banks would be misguided for many reasons (Villeroy de Galhau (2019a), Weidmann (2019)). First, it may distort markets further and create disincentives: the instruments that central banks and supervisors have at their disposal cannot substitute for the many areas of interventions that are needed to transition to a global low-carbon economy. That includes fiscal, regulatory and standard-setting authorities in the real and financial world whose actions should reinforce each other. Second, and perhaps most importantly, it risks overburdening central banks' existing mandates. True, mandates can evolve, but these changes and institutional arrangements are very complex issues because they require building new sociopolitical equilibria, reputation and credibility. Although central banks' mandates have evolved from time to time, these changes have taken place along with broader sociopolitical adjustments, not to replace them.

Outline

These considerations suggest that central banks may inevitably be led into uncharted waters in the age of climate change. Whereas they cannot and should not replace policymakers, they also cannot sit still, since this could place them in the untenable situation of climate rescuer of last resort discussed above. This book sets out from this analytical premise and asks the following question: what, then, should be the role of central banks, regulators and supervisors in preserving financial stability[11] in the age of climate change? It is organised as follows.

Chapter 2 provides an overview of how climate-related risks are threatening socioeconomic activities, thereby affecting the future ability of central banks and supervisors to fulfil their mandates of monetary and financial stability. Following the old adage "that which is measured can be managed" (Carney (2015)), the obvious task in terms of financial regulation and supervision is therefore to ensure

[10] See De Grawe (2019) and the current debate about green quantitative easing in the United States and Europe.

[11] The question of price stability is also touched upon, although less extensively than financial stability.

that climate-related risks become integrated into financial stability monitoring and prudential supervision. However, such a task presents a significant challenge: traditional approaches to risk management consisting in extrapolating historical data based on assumptions of normal distributions are largely irrelevant to assess future climate-related risks. Indeed, both physical and transition risks are characterised by deep uncertainty, nonlinearity and fat-tailed distributions. As such, assessing climate-related risks requires an "epistemological break" (Bachelard (1938)) with regard to risk management. In fact, such a break has started to take place in the financial community, with the development of forward-looking, scenario-based risk management methodologies.

Chapter 3 assesses the methodological strengths and limitations of these methodologies. While their use by financial institutions and supervisors will become critical, it should be kept in mind that scenario-based analysis will not suffice to preserve financial stability in the age of climate change: the deep uncertainty at stake and the need for a structural transformation of the global socioeconomic system mean that no single model or scenario can provide sufficient information to private and public decision-makers (although new modelling and analytical approaches will be critical to embrace the uncertain and non-equilibrium patterns involved). In particular, forward-looking approaches remain highly sensitive to a broad set of uncertain parameters involving: (i) the choice of a scenario regarding how technologies, policies, behaviours, macroeconomic variables and climate patterns will interact in the future; (ii) the translation of such scenarios into granular sector- and firm-level metrics in an evolving environment where all firms will be affected in unpredictable ways; and (iii) the task of matching the identification of a climate-related risk with the adequate mitigation action.

Chapter 4 therefore argues that the integration of climate-related risks into prudential regulation and (to the extent possible) into the relevant aspects of monetary policy will not suffice to shield the financial system against green swan events. In order to deal with this challenge, a second epistemological break is needed: there is an additional role for central banks to be more proactive in calling for broader changes. This needs not threaten existing mandates. On the contrary, calling for broader action by all players can only contribute to preserving existing mandates on price and financial stability. As such, and grounded in the transdisciplinary approach that is required to address climate change, this book makes four propositions (beyond the obvious need for carbon pricing) that are deemed essential to preserve financial stability in the age of climate change, related to: long-termism and sustainable finance; coordination between green fiscal policy, prudential regulation and monetary policy; international monetary and financial coordination and reforms; and integration of natural capital into national and corporate systems of accounting. Some potential obstacles related to each proposition are discussed.

Chapter 5 concludes by discussing how financial (and price) stability and climate stability can be considered as two public goods, the maintenance of which will increasingly depend on each other. Moreover, the need to ensure some form of long-term sustainability increasingly applies to prevent other human-caused environmental degradations such as biodiversity loss, and could require deep transformations in the governance of our socio-ecological systems. All this calls for new quantitative and qualitative approaches aimed at building system resilience (OECD (2019a), Schoon and van der Leeuw (2015)). At a time when policymakers are facing well known political economy challenges and when the private sector needs more incentives to transition to a low-carbon economy, an important contribution of central banks is to adequately frame the debate and thereby help promote the mobilisation of all efforts to combat climate change.

2. CLIMATE CHANGE IS A THREAT TO FINANCIAL AND PRICE STABILITY

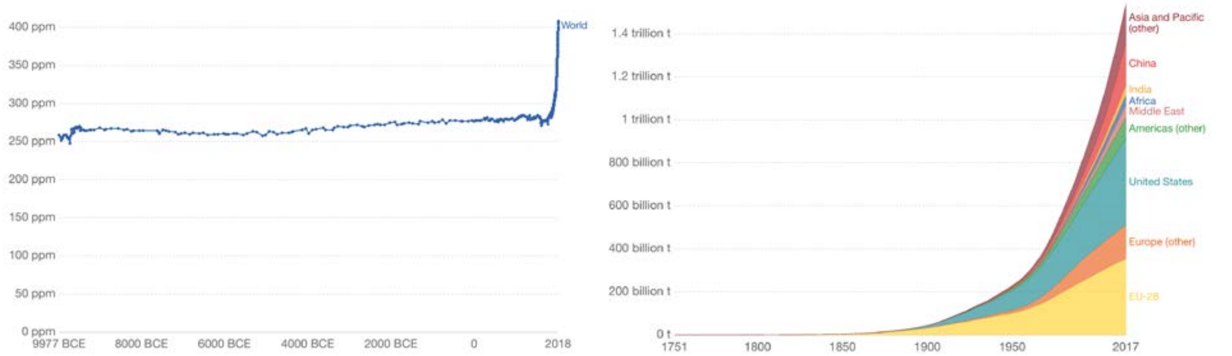
Climate change is the Tragedy of the Horizon. We don't need an army of actuaries to tell us that the catastrophic impacts of climate change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no direct incentive to fix.

Mark Carney (2015)

2.1 Climate change as a severe threat to ecosystems, societies and economies

At 415 parts per million (ppm),[12] Earth's concentration of CO_2 as of 11 May 2019 was higher than ever in human history, and far above the 270–280 ppm that had prevailed for millennia up to the Industrial Revolution (Graph 1, left-hand panel), guaranteeing stable climate conditions in which human societies were able to develop agriculture (Feynman and Ruzmaikin (2007)) and become more complex (Chaisson (2014)). The past decades, in particular, have shown a sharp increase in levels of atmospheric CO_2, from approximately 315 ppm in 1959 to 370 ppm in 1970 and 400 ppm in 2016 (right-hand panel).[12]

Evolution of atmospheric CO_2 concentration — Graph 1



Atmospheric CO_2 concentration over the past 12 millennia, measured in parts per million (left-hand panel); and annual total CO_2 emissions by world region since 1751 (right-hand panel).

Sources: Bereiter et al. (2015), NOAA, www.esrl.noaa.gov/gmd/ccgg/trends/data.html; Carbon Dioxide Information Analysis Center, http://cdiac.ornl.gov; and Global Carbon Project (2018). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

These increasing levels of atmospheric CO_2 concentration, caused by human activity (IPCC (2018)), primarily the burning of fossil fuels (Hansen et al (2013)) but also deforestation and intensive agriculture (Ripple et al (2017)), prevent the Earth's natural cooling cycle from working and cause global warming. Global warming has already increased by close to 1.1°C since the mid-19th century. Temperatures are currently rising at 0.2°C per decade, and average yearly temperatures are increasingly

[12] Based on the daily record of global atmospheric carbon dioxide concentration measured at Mauna Loa Observatory in Hawaii, and reported by the Scripps Institution of Oceanography at UC San Diego. See https://scripps.ucsd.edu/programs/keelingcurve/.

among the hottest ever recorded (IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Millar et al (2017), Ripple et al (2017)).

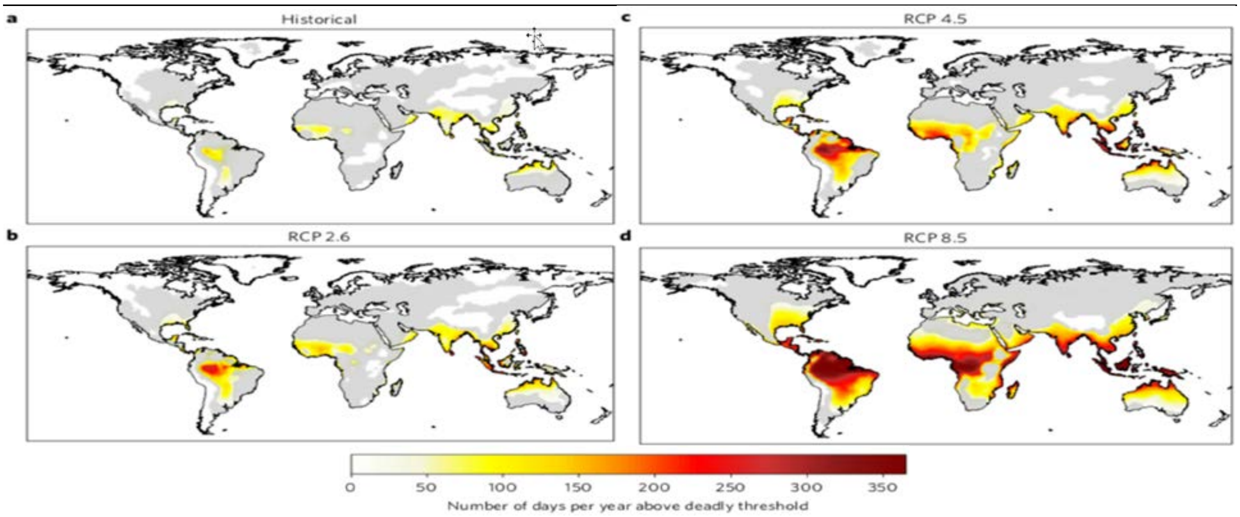
Current trends are on track to lead to systemic disruptions to ecosystems, societies and economies (Steffen et al (2018)). The continued increase in temperatures will lead to multiple impacts (IPCC (2018)) such as rising sea levels, greater intensity and incidence of storms, more droughts and floods, and rapid changes in landscapes. For instance, mean sea levels rose 15 centimetres in the 20th century, and the rate of rising is increasing. The impacts on ecosystems will be significant, potentially leading to species loss or even a massive extinction of wildlife (Ripple et al (2017)). Soil erosion could also accelerate, thereby decreasing food security and biodiversity (IPCC (2019)). Marine biodiversity, marine ecosystems and their ecological functions are also threatened (Masson-Delmotte and Moufouma-Okia (2019)).

The effects of climate change may be catastrophic and irreversible for human populations, potentially leading to "untold suffering", according to more than 11,000 scientists (Ripple et al (2019)). Sea levels could rise by several metres with critical impacts for small islands, low-lying coastal areas, river deltas and many ecological systems on which human activity depends. For instance, increased saltwater intrusion could lead to major agricultural losses, and flooding could damage existing infrastructure (Masson-Delmotte and Moufouma-Okia (2019)). A two-metre sea level rise triggered by the potential melting of ice sheets could displace nearly 200 million people by 2100 (Bamber et al (2019)). Even more worrisome, past periods in the Earth's history indicate that even warming of between 1.5°C and 2°C could be sufficient to trigger long-term melting of ice in Greenland and Antarctica and a sea level rise of more than 6 metres (Fischer et al (2018)).

Humans may have to abandon many areas in which they currently manage to sustain a living, and entire regions in South America, Central America, Africa, India, southern Asia and Australia could become uninhabitable due to a mix of high temperatures and humidity levels (Im et al (2017), Mora et al (2018); see Graph 2). About 500 million people live in areas already affected by desertification, especially in southern and East Asia, the Middle East and sub-Saharan Africa, which will only be under greater socioeconomic pressure due to climate change (IPCC (2019)).

Average temperature changes

Graph 2



Number of days per year above a deadly threshold by the end of the century in a business as usual scenario.

Source: Mora et al (2017).

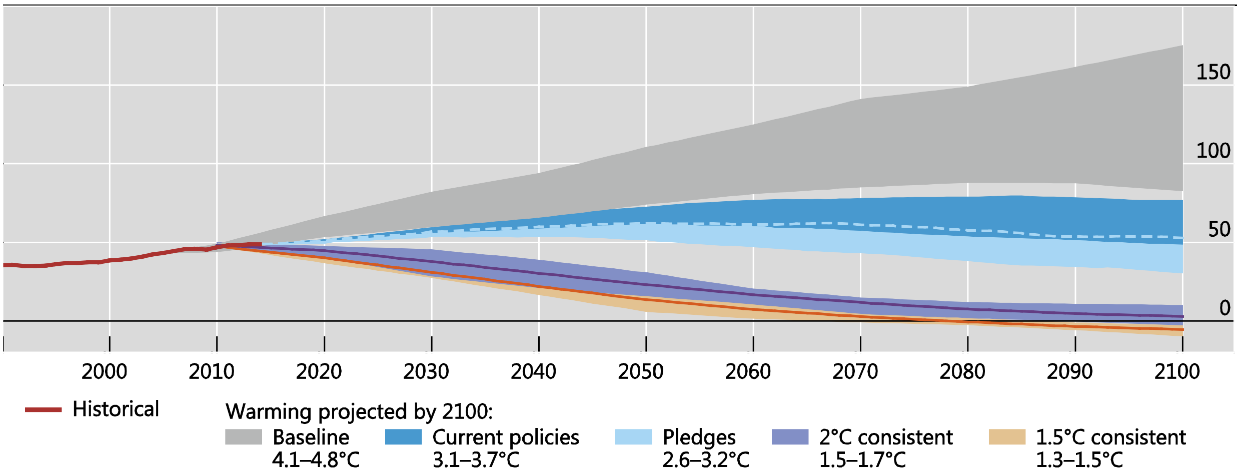
Climate change is not just a future risk: it has actually already started to transform human and non-human life on Earth,[13] although the worst impacts are yet to come. Crop yields and food supply are already affected by climate change in many places across the globe (Ray et al (2019)). Parts of India are undergoing chronic severe water crises (Subramanian (2019)). Heatwaves are becoming more frequent in most land regions, and marine heatwaves are increasing in both frequency and duration (Masson-Delmotte and Moufouma-Okia (2019)). Extreme weather events have increased significantly over the past 40 years (Stott (2016)). Large-scale losses of coral reefs have started to occur (Hughes et al (2018)). Even keeping global warming below 1.5°C could result in the destruction of 70–90% of reef-building corals (IPCC (2018)), on which 25% of all marine life depends (Gergis (2019)).

In turn, avoiding the worst impacts of climate change amounts to a massive, unprecedented, challenge for humanity. The planet is producing close to 40 gigatonnes (Gt) of CO_2 per year, and it is on track to double by 2050. We should reduce emissions to almost zero by then (Graph 3) in order to comply with the UN Paris Agreement of 2015 (UNFCCC (2015)), which set the goal of keeping global warming well below 2°C and as close as possible to 1.5°C above pre-industrial levels (defined as the climate conditions experienced during 1850–1900).

Nevertheless, the special report of the IPCC on the 1.5°C goal (IPCC (2018)) shows that the gap between current trends and emission reduction targets set by countries through their nationally determined contributions (NDCs) – which were already insufficient to limit global warming to 2°C – is widening and leading to somewhere between 3°C and 4°C of warming, which is consistent with a "Hothouse Earth" pathway (Steffen et al (2018)).

2100 warming projections: emissions and expected warming based on pledges and current policies

Global greenhouse gas emissions ($GtCO_2e$/year) Graph 3



Source: Climate Action Tracker.

The impacts on economic output could be significant if no action is taken to reduce carbon emissions. Some climate-economic models indicate that up to a quarter of global GDP could be lost (Burke et al (2015a)), with a particularly strong impact in Asia, although these predictions should be taken cautiously given the deep uncertainty involved (as discussed in Chapter 3). In any case, both the demand side and the supply side are affected (examples in Table 1).

13 A list of observed impacts, with links to relevant studies, can be found at: impact.gocarbonneutral.org/.

Climate change-related shocks and their effects on… Table 1

	Type of shock	From gradual global warming	From extreme weather events
Demand	Investment	Uncertainty about future demand and climate risks	Uncertainty about climate risk
	Consumption	Changes in consumption patterns, eg more savings for hard times	Increased risk of flooding to residential property
	Trade	Changes in trade patterns due to changes in transport systems and economic activity	Disruption to import/export flows due to extreme weather events
Supply	Labour supply	Loss of hours due to extreme heat. Labour supply shock from migration	Loss of hours worked due to natural disasters, or mortality in extreme cases. Labour supply shock from migration
	Energy, food and other inputs	Decrease in agricultural productivity	Food and other input shortages
	Capital stock	Diversion of resources from productive investment to adaptation capital	Damage due to extreme weather
	Technology	Diversion of resources from innovation to adaptation capital	Diversion of resources from innovation to reconstruction and replacement

Sources: NGFS (2019b), adapted from Batten (2018).

Demand-side shocks are those that affect aggregate demand, such as private (household) or public (government) consumption demand and investment, business investment and international trade. Climate damages could dampen consumption, and business investments could be reduced due to uncertainty about future demand and growth prospects (Hallegatte (2009)). Climate change is also likely to disrupt trade flows (Gassebner et al (2010)) and reduce household wealth. Even less exposed economies can have extensive interactions with global markets and be affected by extreme climate shocks.

Supply-side shocks could affect the economy's productive capacity, acting through the components of potential supply: labour, physical capital and technology. For instance, higher temperatures tend to reduce the productivity of workers and agricultural crops (IPCC (2019)). Moreover, climate change can trigger massive population movements (Opitz Stapleton et al (2017)), with long-lasting effects on labour market dynamics and wage growth. Supply-side shocks can also lead to a diversion of resources form investment in productive capital and innovation to climate change adaptation (Batten (2018)). Damages to assets affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol (2005)). Even if the relevant capital stocks might survive, efficiency might be reduced and some areas might have to be abandoned (Batten (2018)).

These economic shocks can have major impacts on the price and financial instability, as respectively explored next.

2.2 The redistributive effects of climate change

Climate change has important distributional effects both between and within countries. The geographical distribution of potential physical risks triggered by rising temperatures (Graph 2) clearly shows that they primarily affect poor and middle-income countries. Moreover, transition risks might also disproportionately impact the natural endowments, traditional carbon-intensive industries and consumption habits of poor countries and low-income households. The cost of mitigation and adaptation might also be prohibitive for both groups.

The degree of awareness about the risks posed by climate change is also unevenly shared within societies, following – and sometimes reinforced by – inequalities of wealth and income. In some cases, denial has been a convenient demagogic response to these issues, compounded by accusations of intrusion into national sovereignty. Another popular political stance has been to dismiss the challenges posed by climate change as merely a concern of the wealthy and well protected. The debate with climate change sceptics is a legitimate and necessary step towards improving the analytics on these issues while creating the sociopolitical conditions to start implementing policies to mitigate risks. There is a relatively old and large literature calling for fairness and social justice when designing adaptation and mitigation policies (eg Adger et al (2006), Cohen et al (2013)). All this will require a better understanding of the redistributive effects of climate change, of the policies to adapt our economies and of the associated costs of mitigation. Without a clear map for how the costs and benefits of climate change mitigation strategies will be distributed, it is almost certain – as we have been observing in many recent cases – that political backlashes will increase against a lower-carbon society. Thus, the sociopolitical viability of combating climate change depends on addressing its distributional consequences.

Indeed, the enormous challenges described above mean that the policies to combat climate change will be quite invasive and are likely to have significant collateral effects on our societies and our production and consumption processes, with associated distributional effects. Zachmann et al (2018) conduct a study of the distributional consequences of mitigation policies and point out that the intensity of these effects depends on the choice of the policy instrument used, the targeted sector, the design of the intervention and the country's degree of development and socioeconomic conditions. They study the impact of climate policies on households of different income levels (low to high) and assess policies addressing climate change as regressive, proportionate or progressive. They take into account households' budget and wealth constraints (eg their inability to quickly shift to lower carbon consumption baskets as well as investment in lower-carbon houses and durable goods). They conclude that the regressive distributional effects of many climate policies requires compensating lower-income households for their negative income effects as well as being gradual and progressive in the introduction of such policies.

Dennig et al (2015) also study regional and distributional effects of climate change policies. They use a variant of the Regional Integrated model of Climate and the Economy (RICE) – a regionally disaggregated version of the Dynamic Integrated model of Climate and the Economy (DICE) – and introduce economic inequalities in the model's regions. Their study confirm that climate change impacts are not evenly distributed within regions and that poorer people are more vulnerable, suggesting that this must be taken into account when setting the social cost of carbon. However, improving the poverty and inequality modelling in climate research requires more efforts as the current approaches are limited as argued by Rao et al (2017) because current models do not capture well household heterogeneity and proper representation of poor and vulnerable societal segments.

Finally, there is an extensive literature and numerous studies pointing to the distributional impact of climate change on poor countries and the need to scale up international mechanisms to finance their transition and reduce their vulnerability to climate change-related events with well known implications for massive migration. This has been a significant part of the discussions of the UN Conference of the Parties (COP) since its inception. For example, the Adaptation Fund was established at the COP 7 in 2001 but only set up under the Kyoto Protocol of the United Nations Framework Convention on Climate Change

(UNFCCC) and officially launched in 2007. The mechanism has revolved around the need for rich countries to contribute to the adaptation cost by developing countries. At COP 2015 in 2009, this resulted in the pledge by advanced economies to mobilise $100 billion in aid by 2020. So far, the practical implementation has remained limited.

2.3 Climate change as source of monetary instability

Although this book focuses on financial stability, it should be noted that climate-related shocks are likely to affect monetary policy through supply-side and demand-side shocks, and thereby affect central banks' price stability mandate. Regarding supply-side shocks (McKibbin et al (2017)), pressures on the supply of agricultural products and energy are particularly prone to sharp price adjustments and increased volatility. The frequency and severity of such events might increase, and impact supply through more or less complex channels. There are still relatively few studies analysing the impact of climate-related shocks on inflation, but some studies indicate that food prices tend to increase in the short term following natural disasters and weather extremes (Parker (2018), Heinen et al (2018), Debelle (2019)).

In addition to these short-term pressures on prices, supply shocks can also reduce economies' productive capacity. For instance, climate change could have long-standing impacts on agricultural yields, lead to frequent resource shortages or to a loss in hours worked due to heat waves. These effects, in turn, can reduce the stock of physical and human capital, potentially resulting in reduced output (Batten (2018), McKibbin et al (2017)). But climate change can also translate into demand shocks, for instance by reducing household wealth and consumption (Batten (2018)). Climate mitigation policies could also affect investment in some sectors, with various indirect impacts further discussed in the next chapter.

In sum, the impacts of climate change on inflation are unclear partly because climate supply and demand shocks may pull inflation and output in opposite directions, and generate a trade-off for central banks between stabilising inflation and stabilising output fluctuations (Debelle (2019)). Moreover, if climate-related risks end up affecting productivity and growth, this may have implications for the long-run level of the real interest rate, a key consideration in monetary policy (Brainard (2019)).

Traditionally, monetary policy responses are determined by looking at their impact on prices and expectations. If there is a presumption that the impact is temporary, the response can be to wait and see or "look through" the shock as it does not affect prices and expectations on a permanent basis. However, if the shock has more lasting effects, there could be motives to consider a policy reaction to adjust aggregate demand conditions. In the case of climate-related risks, the irreversibility of certain climate patterns and impacts poses at least three new challenges for monetary policy (Olovsson (2018)):

(i) While the use of cyclical instruments aims to stimulate or subdue activity in the economy over relatively short periods, climate change is expected to maintain its trajectory for long periods of time (Cœuré (2018)). This situation can lead to stagflationary supply shocks that monetary policy may be unable to fully reverse (Villeroy de Galhau (2019a)).

(ii) Climate change is a global problem that demands a global solution, whereas monetary policy seems, currently, to be difficult to coordinate between countries (Pereira da Silva (2019a)). As such, the case for a single country or even a monetary zone to react to inflationary climate-related shocks could be irrelevant.

(iii) Even if central banks were able to re-establish price stability after a climate-related inflationary shock, the question remains whether they would be able to take pre-emptive measures to hedge ex ante against fat-tail climate risks, ie green swan events (Cœuré (2018)).

It should nevertheless be admitted that studies on the impact of climate change on monetary stability are still at an early stage, and that much more research is needed. Far more evidence has been collected on the potential financial impacts of climate change, as discussed in the rest of this book.

2.4 Climate change as a source of financial instability

Even though a growing number of stakeholders has recognised the socioeconomic risks posed by climate change over the past decades, much of the financial sector seemed to remain unconcerned until a few years ago. The situation has changed radically over the past few years, as the potentially disruptive impacts of climate change on the financial system started to become more apparent (Carney (2015)). As further detailed in Chapter 4, some central banks, regulators and supervisors are already taking steps towards integrating climate-related risks into supervisory practices, and more could follow in the near future. The NGFS, created in December 2017, quickly recognised that "climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks" (NGFS (2018), p 3).

There are two main channels[14] through which climate change can affect financial stability:

Physical risks are "those risks that arise from the interaction of climate-related hazards [...] with the vulnerability of exposure to human and natural systems" (Batten et al (2016)). They represent the economic costs and financial losses due to increasing frequency and severity of climate-related weather events (eg storms, floods or heat waves) and the effects of long-term changes in climate patterns (eg ocean acidification, rising sea levels or changes in precipitation). The losses incurred by firms across different financial portfolios (eg loans, equities, bonds) can make them more fragile.

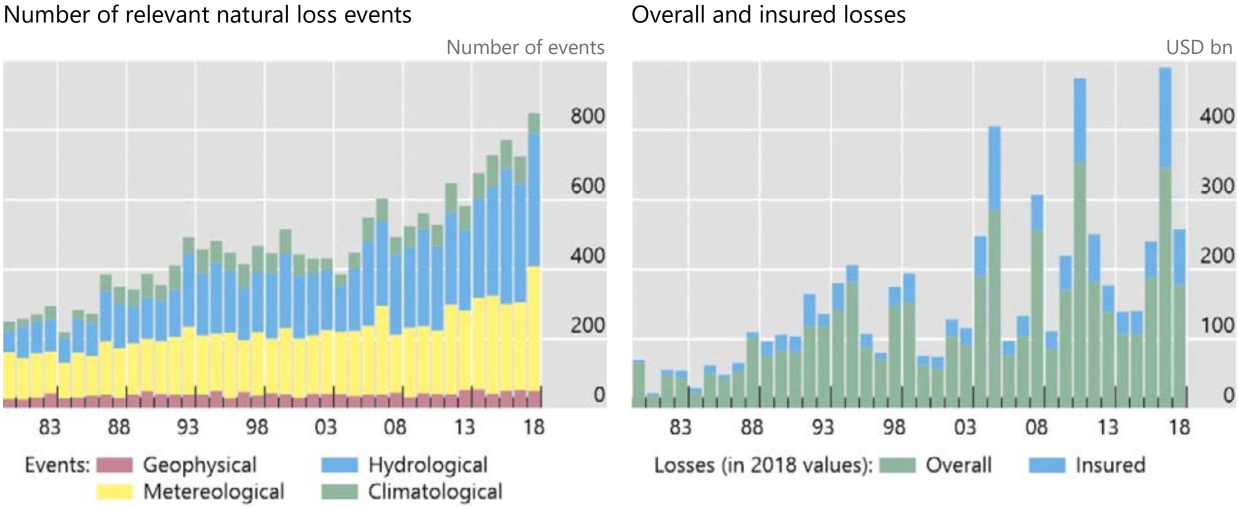
The destruction of capital and the decline in profitability of exposed firms could induce a reallocation of household financial wealth. For instance, rising sea levels could lead to abrupt repricing of real estate (Bunten and Kahn (2014)) in some exposed regions, causing large negative wealth effects that may weigh on demand and prices through second-round effects. Climate-related physical risks can also affect the expectation of future losses, which in turn may affect current risk preferences. For instance, homes exposed to sea level rise already sell at a discount relative to observationally equivalent unexposed properties equidistant from the beach (Bernstein et al (2019)).

As natural catastrophes increase worldwide (Graph 4), non-insured losses (which represent 70% of weather-related losses (IAIS (2018)) can threaten the solvency of households, businesses and governments, and therefore financial institutions. Insured losses, on their end, may place insurers and reinsurers in a situation of fragility as claims for damages keep increasing (Finansinspektionen (2016)). More broadly, damages to assets affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol (2005)).

[14] A third type of risk, liability risk, is sometimes mentioned. This refers to "the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible" (Carney (2015), p 6). However, such costs and losses are often considered to be part of either physical or transition risk.

Increase in the number of extreme weather events and their insurance,[15] 1980–2018

Graph 4



Includes copyrighted material of Munich Re and its licensors.

Source: MunichRe (2018).

Moreover, the fat-tailed probability distributions of many climate parameters are such that the possibility of extreme values cannot be ruled out (Weitzman (2009, 2011)). This could place financial institutions in situations in which they might not have sufficient capital to absorb climate-related losses. In turn, the exposure of financial institutions to physical risks can trigger contagion and asset devaluations propagating throughout the financial system.

Transition risks are associated with the uncertain financial impacts that could result from a rapid low-carbon transition, including policy changes, reputational impacts, technological breakthroughs or limitations, and shifts in market preferences and social norms. In particular, a rapid and ambitious transition to lower emissions pathways means that a large fraction of proven reserves of fossil fuel cannot be extracted (McGlade and Elkins (2015)), becoming "stranded assets", with potentially systemic consequences for the financial system (see Box 1). For instance, an archetypal fire sale might result if these stranded assets suddenly lose value, "potentially triggering a financial crisis" (Pereira da Silva (2019a)). As Mark Carney puts it: "too rapid a movement towards a low-carbon economy could materially damage financial stability. A wholesale reassessment of prospects, as climate-related risks are re-evaluated, could destabilise markets, spark a pro-cyclical crystallisation of losses and lead to a persistent tightening of financial conditions: a climate Minsky moment" (Carney (2016), p 2).

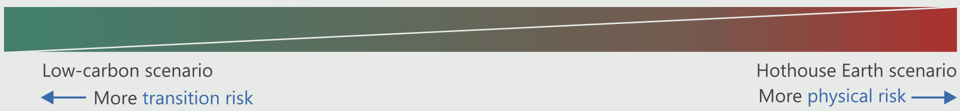
Moreover, the value added of many other economic sectors dependent on fossil fuel companies will probably be impacted indirectly by transition risks (Cahen-Fourot et al (2019a,b)). For instance, the automobile industry may be strongly impacted as technologies, prices and individual preferences evolve. Assessing how the entire value chain of many sectors could be affected by shocks in the supply of fossil fuels is particularly challenging, as will be further discussed in the next chapter.

Physical and transition risks are usually assessed separately, given the complexity involved in each case (as discussed in the next chapter). However, they should be understood as part of the same framework and as being interconnected (Graph 5). A strong and immediate action to mitigate climate change would increase transition risks and limit physical risks, but those would remain existent (we are already

[15] This figure does not allow them to be extrapolated into the future, and they should be interpreted carefully. For instance, some natural catastrophes, such as typhoons, could become less frequent but more intense.

experiencing some of the first physical risks of climate change). In contrast, delayed and weak action to mitigate climate change would lead to higher and potentially catastrophic physical risks, without necessarily entirely eliminating transition risks (eg some climate policies are already in place and more could come). Delayed actions followed by strong actions in an attempt to catch up would probably lead to high both physical and transition risks (not represented in Graph 5).

Framework for physical and transition risks — Graph 5



Scenario	Rapid Transition	Two-degree	Business-as-intended	Business-as-usual
Corrective transition response	Very strong	Strong	Substantial	Limited
Change in temperature, 2100 vs pre-industrial era	1.5°C	2°C	3°C	4°C

Source: adapted from Oliver Wyman (2019); authors' elaboration.

Box 1: Introduction to stranded assets

Limiting global warming to less than 1.5°C or 2°C requires keeping a large proportion of existing fossil fuel reserves in the ground (Matikainen (2018)). These are referred to as stranded assets. For instance, a study (McGlade and Elkins (2015)) found that in order to have at least a 50% chance of keeping global warming below 2°C, over 80% of current coal reserves, half of gas reserves and a third of oil reserves should remain unused from 2010 to 2050. As the risk related to stranded assets is not reflected in the value of the companies that extract, distribute and rely on these fossil fuels, these assets may suffer from unanticipated and sudden writedowns, devaluations or conversion to liabilities.

Estimates of the current value and scope of stranded assets vary greatly from one study to another. For instance, Mercure et al (2018) estimate that the discounted loss in global wealth resulting from stranded fossil fuel assets may range from $1 trillion to $4 trillion. Carbon Tracker (2018)[16] approximates the amount at $1.6 trillion, far below the International Renewable Energy Agency's (IRENA) (2017) estimate of $18 trillion, but the scope and definitions used by each of them differ. Therefore, as discussed more extensively in Chapter 3, it is critical to understand the models used by each of these studies to fully appreciate their respective outcomes and potential limitations.

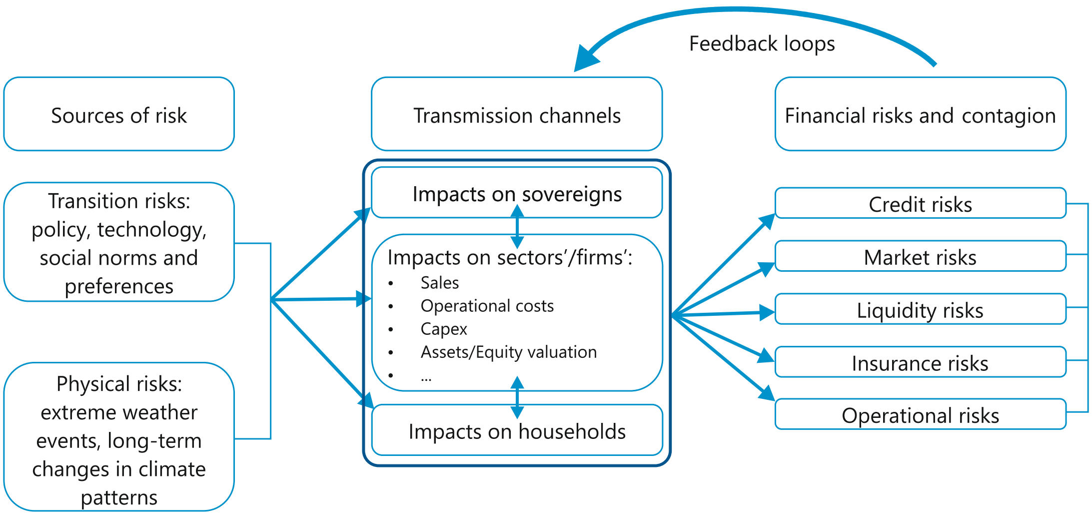
Physical and transition risks can materialise in terms of financial risk in five main ways (DG Treasury et al (2017)), with many second-round effects and spillover effects among them (Graph 6):

- ***Credit risk***: climate-related risks can induce, through direct or indirect exposure, a deterioration in borrowers' ability to repay their debts, thereby leading to higher probabilities of default (PD) and a higher loss-given-default (LGD). Moreover, the potential depreciation of assets used for collateral can also contribute to increasing credit risks.

[16] In a scenario with an increase in temperatures of 1.75°C.

- ***Market risk***: Under an abrupt transition scenario (eg with significant stranded assets), financial assets could be subject to a change in investors' perception of profitability. This loss in market value can potentially lead to fire sales, which could trigger a financial crisis. The concept of climate value-at-risk (VaR) captures this risk and will be further discussed in the next chapter.
- ***Liquidity risk***: although it is covered less in the literature, liquidity risk could also affect banks and non-bank financial institutions. For instance, banks whose balance sheet would be hit by credit and market risks could be unable to refinance themselves in the short term, potentially leading to tensions on the interbank lending market.
- ***Operational risk***: this risk seems less significant, but financial institutions can also be affected through their direct exposure to climate-related risks. For instance, a bank whose offices or data centres are impacted by physical risks could see its operational procedures affected, and affect other institutions across its value chain.
- ***Insurance risk***: for the insurance and reinsurance sectors, higher than expected insurance claim payouts could result from physical risks, and potential underpricing of new insurance products covering green technologies could result from transition risks (Cleary et al (2019)).

Channels and spillovers for materialisation of physical and transition risks — Graph 6



Sources: adapted from DG Treasury et al (2017); authors' elaboration.

2.5 The forward-looking nature of climate-related risks – towards a new epistemology of risk

The potentially systemic risks posed by climate change explain why it is in the interest of central banks, regulators and financial supervisors to ensure that climate-related risks are appropriately understood by all players (NGFS (2019a)). It is therefore not surprising that the first recommendation made by the NGFS in its first comprehensive report called for "integrating climate-related risks into financial stability monitoring and micro-supervision" (NGFS (2019a), p 4). This integration helps ensure that financial institutions and the financial system as a whole are resilient to climate-related risks (NGFS (2019a)).

Moreover, a systematic integration of climate-related risks by financial institutions could act as a form of shadow pricing on carbon, and therefore help shift financial flows towards green assets. That is, if investors integrate climate-related risks into their risk assessment, then polluting assets will become more costly. This would trigger more investment in green assets, helping propel the transition to a low carbon economy (Pereira da Silva (2019a)) and break the tragedy of the horizon by better integrating long-term risks (Aufauvre and Bourgey (2019)). A better understanding of climate-related risks is therefore a key component of Article 2.1.c of the Paris Agreement, which aims to "mak[e] finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (UNFCCC (2015)).

However, integrating climate-related risks into financial stability monitoring and prudential supervision presents a significant challenge: traditional approaches to risk management are based on historical data and assumptions that shocks are normally distributed (Dépoues et al (2019)). The fundamental financial concept of value-at-risk (VaR) captures losses that can be expected with a 95–99% level of confidence and over a relatively short-term horizon. Capital requirements are also typically calculated (through estimated PD, exposure at default and estimated LGD) on a one-year horizon and based on credit ratings that largely rely on historical track records of counterparties.

The problem is that extrapolating historical trends can only lead to mispricing of climate-related risks, as these risks have barely started to materialise: physical risks will become worse as global warming goes on, and transition risks are currently low given the lack of ambitious policies on a global scale. Moreover, climate-related risks typically fit fat-tailed distributions and concentrate precisely in the 1% not considered by VaR. Finally, climate change is characterised by deep uncertainty: assessing the physical risks of climate change is subject to uncertainties related to climate patterns themselves, their potentially far-reaching impacts on all agents in the economy, and complex transmission channels (NGFS (2019a,b)), especially in the context of globalised value chains; transition risks are also subject to deep or radical uncertainty with regard to issues such as the policies that will be implemented (eg carbon pricing versus command-and-control regulations), their timing, the unpredictable emergence of new low-carbon technologies or changes in preferences and lifestyles that could take place. All these issues are further discussed in Chapter 3.

As a result, the standard approach to modelling financial risk consisting in extrapolating historical values (eg PD, market prices) is no longer valid in a world that is fundamentally reshaped by climate change (Weitzman (2011), Kunreuther et al (2013)). In other words, green swan events cannot be captured by traditional risk management.

The current situation can be characterised as an "epistemological obstacle" (Bachelard (1938)). The latter refers to how scientific methods and "intellectual habits that were useful and healthy" under certain circumstances, can progressively become problematic and hamper scientific research. Epistemological obstacles do not refer to the difficulty or complexity inherent to the object studied (eg measuring climate-related risks) but to the difficulty related to the need of redefining the problem. For instance, as a result of the incompatibility between probabilistic and backward-looking risk management approaches and the uncertain and forward-looking nature of climate-related risks, "investors, at this stage, face a difficult task to assess these risks – there is for instance no equivalent of credit ratings for climate-related financial risks" (Pereira da Silva (2019a)).

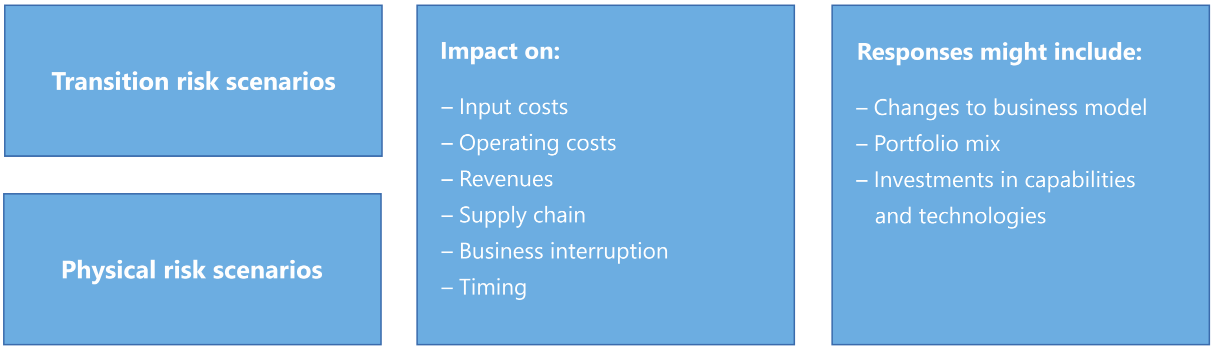
As scientific knowledge does not progress continuously and linearly but rather through a series of discontinuous jumps with changes in the meaning of concepts, nothing less than an epistemological break (Bachelard, 1938) or a "paradigm shift" (Kuhn (1962)) is needed today to overcome this obstacle and more adequately approach climate-relate risks (Pereira da Silva (2019a)).

In fact, precisely an epistemological break may be taking place in the financial sector: recently emerged methodologies aim to assess climate-related risks while relying on the fundamental hypothesis that, given the lack of historical financial data related to climate change and the deep uncertainty involved, new approaches based on the analysis of prospective scenarios are needed.[17] Unlike probabilistic approaches to financial risk management, they seek to set up plausible hypotheses for the future. This can help financial institutions integrate climate-related risks into their strategic and operational procedures (eg for the purpose of asset allocation, credit rating or insurance underwriting) and financial supervisors assess the vulnerability of specific institutions or the financial system as a whole.

A consensus is emerging among central banks, supervisors and practitioners involved in climate-related risks about the need to use such forward-looking, scenario-based methodologies (Batten et al (2016), DG Treasury et al (2017), TCFD (2017), NGFS (2019a), Regelink et al (2017)). As shown by the Task Force on Climate-related Financial Disclosures[18] (TCFD; Graph 7), managing climate-related risks through a forward-looking approach can lead financial institutions to test the resilience of corporations in their portfolios to potential materialisations of physical and transition risks, their impact on key performance indicators and the adaptive capacities of these firms.

Testing the resilience of corporations to potential materialisations of physical and transition risks

Graph 7



What scenarios (and narratives) are appropriate, given the exposures? Consider input parameters, assumptions, and analytical choices. What reference scenario(s) should be used?

Evaluate the potential effects on the organisation's strategic and financial position under each of the defined scenarios. Identify key sensitivities.

Use the results to identify applicable, realistic decisions to manage the identified risks and opportunities. What adjustments to strategic/financial plans would be needed?

Source: Adapted from TCFD (2017).

These methodologies may already be facilitating a more systematic integration of climate-related risks in the financial sector: some insurance companies are reassessing their cost of insuring physical risk; some rating agencies are increasingly re-evaluating credit risks in the light of growing climate-related risks; and some asset managers are becoming more selective and inclined to start picking green assets and/or ditching brown assets in their portfolio allocation (Bernardini et al (2019), Pereira da Silva (2019a)).

Hence, it is critical for central banks, regulators and supervisors to assess the extent to which these forward-looking, scenario-based methodologies can ensure that the financial system is resilient to climate-related risks and green swan events. The next chapter undertakes a critical assessment of these methodologies.

17 It is noteworthy that these methodologies have been produced by a variety of players including consulting firms, non-profit organisations, academics, international organisations and financial institutions themselves.

18 See www.fsb-tcfd.org/. The TCFD was set up in 2015 by the Financial Stability Board (FSB), to develop voluntary, consistent climate-related financial risk disclosures for use by companies, banks and investors in providing information to stakeholders.

3. MEASURING CLIMATE-RELATED RISKS WITH SCENARIO-BASED APPROACHES: METHODOLOGICAL INSIGHTS AND CHALLENGES

Thinking about future uncertainty in terms of multiple plausible futures, rather than probability distributions, has implications in terms of the way uncertainty is quantified or described, the way system performance is measured and the way future strategies, designs or plans are developed.

Maier et al (2016)

This chapter reviews some of the methodological challenges that financial institutions and supervisors face when conducting forward-looking, scenario-based analysis aimed at identifying and managing climate-related risks. It focuses on the main conceptual issues; a detailed discussion of the technical features of each existing methodology is beyond the scope of this book (for more exhaustive reviews see, for instance, Hubert et al (2018), UNEP-FI (2018a,b, 2019)). Also, our discussion is focused mostly on methodologies aimed at measuring transition risks,[19] although some challenges related to physical risks are mentioned.

Our key conclusion is that, despite their promising potential, forward-looking analyses cannot fully overcome the limitations of the probabilistic approaches discussed in the previous chapter and provide sufficient hedging against "green swan" events. That is, although the generalised use of forward-looking, scenario-based methodologies can help financial and economic agents to better grapple with the long-term risks posed by climate change, they will not suffice to "break the tragedy of the horizon" and induce a significant shift in capital allocation towards low-carbon activities. Two main limitations exist.

First, the materialisation of physical and transition risks depends on multiple nonlinear dynamics (natural, technological, societal, regulatory and cultural, among others) that interact with each other in complex ways and are subject to deep uncertainty. Climate-economic models are inherently incapable of representing all these interactions, and they therefore overlook many social and political forces that will strongly influence the way the world evolves. With this in mind, the outcomes of a scenario-based analysis should be assessed very cautiously and cannot suffice to guide decision-making. The broad range of results concerning the monetary value of stranded assets – one of the most prominent transition risks – are symptomatic of the complexity and uncertainty at stake (see Box 2 below).

In particular, the complex and multiple interactions between climate and socioeconomic systems are such that the task of identifying and measuring climate-related risks presents significant methodological challenges related to:

(i) The choice of scenarios describing how technologies, policies, behaviours, macroeconomic and even geopolitical dynamics and climate patterns may interact in the future (Chapter 3.2), especially given the intrinsic limitations of most equilibrium climate-economic models (Chapter 3.1);

(ii) The translation of such scenarios into granular sectoral and corporate metrics in an evolving environment where all firms and value chains will be impacted in largely unpredictable ways (Chapter 3.3).

19 This choice is notably informed by the fact that physical risks arising from a global warming beyond 2°C can be so systemic that aiming to measure them quickly becomes impossible. Transition risks can therefore be seen as those that must arise if we decide to remain within safer climate boundaries. In practice, physical and transition risks are interconnected, as discussed in Chapter 2.3. However, current climate-related risk methodologies generally fail to analyse physical and transition risks jointly, in spite of recent efforts in this direction.

Second, and more fundamentally, climate-related risks will remain largely uninsurable or unhedgeable as long as system-wide action is not taken (Chapter 3.4). In contrast to specific areas where scenario analysis can help financial institutions avoid undesirable outcomes (eg avoiding a dam collapse for a hydropower project), climate-related scenario analysis cannot by itself enable a financial institution or the financial system as a whole to avoid and withstand "green swan" events. For instance, a financial institution willing to hedge itself against an extreme transition risk (eg a sudden and sharp increase in carbon pricing) in the current context of weak climate policies may simply be unable to find adequate climate-risk-free assets if these are not viable in the current environment ("green" assets and technologies are still nascent and also present significant risks).

The first limitation can be partially resolved through better data (Caldecott (2019), NGFS (2019a)) and through the development of new models, in particular non-equilibrium models that can better account for nonlinearity, uncertainty, political economy considerations and the role of money and finance (Mercure et al (2019), Monasterolo et al (2019)). However, the second limitation is a reminder that only a structural transformation of our global socioeconomic system can really shield the financial system against "green swan" events. This calls for alternative epistemological positions that can fully embrace uncertainty and the need for structural transformations, including through more qualitative and politically grounded approaches (Aglietta and Espagne (2016), Chenet et al (2019a, 2019b), Ryan-Collins (2019)).

This does not mean that the development of forward-looking methodologies is not useful. On the contrary, non-financial and financial firms alike will increasingly need to rely on them to explore their potential vulnerabilities. But for central banks, regulators and supervisors concerned about the resilience of the system as a whole, the development of forward-looking, scenario-based methodologies should be assessed with a more critical stance. Much like a carbon price and other policies, they are a critical step that can become fully operational only if a system-wide transition takes place, as further discussed in Chapter 4.

Box 2: Methodological uncertainty surrounding the monetary value of stranded assets

As discussed in Chapter 2, limiting global warming to less than 1.5°C or 2°C requires keeping a large proportion of existing fossil fuel reserves in the ground (Matikainen (2018)). The case has often been made that risks related to stranded assets are not reflected in the value of the companies that extract, distribute and rely on these fossil fuels. This could lead to a significant and sudden drop in their value if ambitious climate policies are adopted.

However, estimating precisely the current value of fossil fuel assets that may be stranded in the future is an exercise replete with uncertainty. As such, the diverging estimates obtained (eg between $1 trillion and $4 trillion according to Mercure et al (2018); around $1.6 trillion as estimated by Carbon Tracker (2018);[20] and up to $18 trillion according to IRENA (2017)) should be carefully assessed as they are based on different geographical scopes, assumptions and valuation methods, among others. For instance, some estimates (eg IRENA (2017)) cover the stranded value of fossil fuel assets (eg the discounted cash flows of future revenues that will be lost) whereas others (eg IEA (2014)) focus on the stranded capital, ie the losses related to the capital invested in a project subject to stranding.

One source of uncertainty has to do with today's valuation of fossil fuel reserves. Some methodologies assume that these reserves significantly contribute to the current valuation of fossil fuel companies. In contrast, IHS Markit (2015) argues that oil and gas companies' market valuations are mostly driven by commercially proved reserves that will be monetised over the next 10 to 15 years, and not so much by the resources that would be likely to be stranded over a longer-term horizon. If this is true, the market mispricing of fossil fuel assets may not be as large as often expected. Some studies also suggest that investors are already reacting to climate-related risks: based on the

[20] In a scenario with an increase in temperatures of 1.75°C.

performance of high-emissions industries in the S&P 500 index before and after the Paris Agreement, Ilhan et al (2018) suggest that investors are actually already incorporating information about climate-related risks when assessing risk profiles. Other studies also find that the risk premium of fossil fuel firms has increased following the Paris Agreement (de Greiff et al (2018)) and that this rise in risk premium is due to increased awareness of transition risks (Delis et al (2018)). In short, the extent to which stranded assets are already valued remains unclear.

Estimating the impacts of stranding fossil assets with geographical granularity is essential to appreciate which companies can be hit, yet it also requires making uncertain choices with regard to which resources will actually be stranded (McGlade and Ekins (2015)). In this respect, Mercure et al (2018) conduct a precise geographical analysis of stranded assets based on the costs of extraction of fossil fuels around the world, assuming that resources in locations with higher extraction costs will be stranded first. They find that Saudi Arabia could keep selling oil in a low-carbon scenario given its competitive prices, whereas Canadian and US unconventional oils could be stranded much faster, with potential significant impacts on their GDPs. In practice, the most vulnerable countries (Canada and the United States in this case) would probably be tempted to subsidise their fossil fuel production to avoid such negative impacts.

Financial institutions can also be impacted indirectly through complex cascades of stranded assets (Cahen-Fourot et al (2019a,b)). For instance, in addition to the direct risk borne by investors exposed to stranded assets, financial assets can also suffer from the economic impacts of the transition triggered by a fall in corporate profits in different sectors that rely on stranded assets and (Caldecott (2017), Dietz et al (2016)). For jurisdictions where fossil fuel companies are state-owned (and therefore not valued by markets), the main financial impacts may only be indirect, eg through loss of revenues that could affect sovereign risk and/or GDP growth.

When mixing geographical with indirect impacts, it appears that stranding assets could have significant geopolitical repercussions and potentially deeply transform existing global value chains, but such considerations remain largely out of the scope of current assessments. For instance, the scenario developed by Mercure et al (2018) asks the question of how OPEC members would recycle their oil-related surpluses. Similarly, if all coal resources were to be stranded, the immediate impacts would fall significantly on China, which consumed 50% of the world's coal in 2018 (BP (2019)); yet this could also have system-wide impacts on global value chains, including potential sharp price increases in advanced economies.

Finally, estimating the value of stranded assets while relying on climate-economic models can lead to paradoxical assumptions. In particular, and as discussed in Chapter 3.2, some climate-economic models rely so much on negative emissions technologies and on carbon capture and storage (CCS) to meet the 1.5°C or 2°C targets that fossil fuels may no longer need to be stranded that rapidly. Under certain scenarios, these technologies can increase the remaining carbon budget to reach a 2°C world by up to 290% (Carbon Brief (2018)). This poses the question of the technological assumptions supporting each assessment of stranded assets and for transition risks in general, as discussed in this chapter.

3.1 Climate-economic models versus deep uncertainty – an overview

The very first step in conducting a scenario analysis is to determine a narrative of how climate and socioeconomic factors will interact, so that they can be translated into a sectoral and firm-level scenario. For instance, to embed a climate-related shock into existing stress test methodologies (see Borio et al (2014)), the first step is to assess how such a shock would impact the economy (eg through variables such as GDP or interest rates), which in turn translates into impacts to the financial system. In the case of transition risks, some critical elements of the narrative of a scenario refer to:

– What climate target is sought: as of today, most transition scenarios rely on limiting global warming to 2°C above pre-industrial temperatures by 2100, but more scenarios based on a 1.5°C limit may emerge as this latter target is increasingly understood as the more "acceptable" upper limit (eg IPCC (2018));

– When mitigation measures start (eg immediately and relatively smoothly, or with delay and more abruptly) and over which time horizon they take place;

– What kind of "shock" is applied: for instance a policy shock (such as a carbon tax, but other regulations can also be used) or a technological shock (eg a technological breakthrough leading to declining cost of renewable energy, or on the contrary a situation where substitution between carbon-intensive and low-carbon technologies is limited).

These initial inputs can then be translated into macroeconomic and/or sectoral outputs. In order to do this, most methodologies rely on climate-economic models such as Integrated Assessment Models (IAMs). For instance, Oliver Wyman's (2019) and Carbon Delta's (2019)[21] respective transition scenarios apply data from IAMs such as REMIND[22], GCAM[23] and IMAGE[24], and Battiston (2019) relies on IAMs to conduct system-wide climate stress tests.

IAMs cover a great range of methodological approaches and sectoral and regional disaggregation, but at their core they generally combine a climate science module linking greenhouse gas (GHG) emissions to temperature increases, and an economic module linking increases in temperatures to economic and policy outcomes. Some key variables serve to link the climate and economic modules, such as: the accumulation of GHGs in the atmosphere; the evolution of mean temperatures; a measure of well-being (GDP); a damage function linking increases in global temperatures to losses in GDP; and a cost function generated by the policies aimed at reducing GHG emissions (eg a carbon tax).

Although IAMs are used by the UN Intergovernmental Panel on Climate Change (IPCC)[25] to explore some of the relationships between society and the natural world, their limitations with regard to economic modelling are increasingly recognised. In particular, critical assumptions about the damage functions (impacts of climate change on the economy) and discount rates (how to adjust for climate-related risk) have been subject to numerous debates (Ackerman et al (2009), Pindyck (2013), Stern (2016)), as further discussed below. Other oft-mentioned limitations include: the absence of an endogenous evolution of the structures of production[26] (Acemoğlu et al (2012, 2015), Pottier et al (2014)); the choice of general equilibrium models with unrealistic assumptions on well-functioning capital markets and rational expectations (Keen (2019)); the emphasis on relatively smooth transitions to a low-carbon economy and the quick return to steady state following a climate shock (Campiglio et al (2018)); and the suppression of the critical role of financial markets (Espagne (2018); Mercure et al (2019)).

[21] See www.carbon-delta.com/climate-value-at-risk/.

[22] REMIND is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows for the analysis of technology options and policy proposals for climate mitigation. The REMIND model was developed by the Potsdam Institute for Climate Impact Research (PIK). www.pik-potsdam.de/research/transformation-pathways/models/remind/remind.

[23] The Global Change Assessment Model (GCAM) is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. The Joint Global Change Research Institute (JGCRI) is the home and primary development institution for GCAM. jgcri.github.io/gcam-doc/v4.2/.

[24] IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The IMAGE modelling framework has been developed by the IMAGE team under the authority of PBL Netherlands Environmental Assessment Agency. models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

[25] The IPCC is composed of three working groups. Working Group I assesses scientific aspects of the climate system and climate change; Working Group II assesses the vulnerabilities of socioeconomic and natural systems to climate change, as well as their consequences and adaptation options; Working Group III assesses the options for limiting greenhouse gas emissions and mitigating climate change.

[26] It should be noted that some IAMs feature endogenous technological change (IPCC (2014, p 423)).

For all these reasons, it is increasingly recognised that "today's macroeconomic models may not be able to accurately predict the economic and financial impact of climate change" (NGFS (2019a, p 4), Weyant (2017)). This does not mean that IAMs and climate-economic models in general are not useful for specific purposes and under specific conditions (Espagne (2018)). In particular, a new wave of models embracing uncertainty and complexity seems better able to account for heterogeneity and nonlinearities, as well as for cascade effects, policy path dependency and interactions between macroeconomic and financial dynamics (see Dafermos et al (2017), Espagne (2017), Mercure et al (2019), Monasterolo et al (2019)). The central bank community could gain from exploring these new modelling approaches, as discussed in Chapter 3.5.

Nevertheless, the deep uncertainty related to physical and transition risks means that both the neoclassical approach of most IAMs and alternative approaches such as demand-led and non-equilibrium models will remain unable to capture many forces triggered by climate change. A corollary is that the outcomes of such models should be interpreted cautiously by both financial practitioners and financial regulators and supervisors. Some of the key sources of uncertainty with respect to climate-related physical and transition risks are outlined below and further detailed in Annexes 1 and 2.

With regard to physical risks (see Annex 1), some of the main sources of modelling uncertainty relate to the following features:

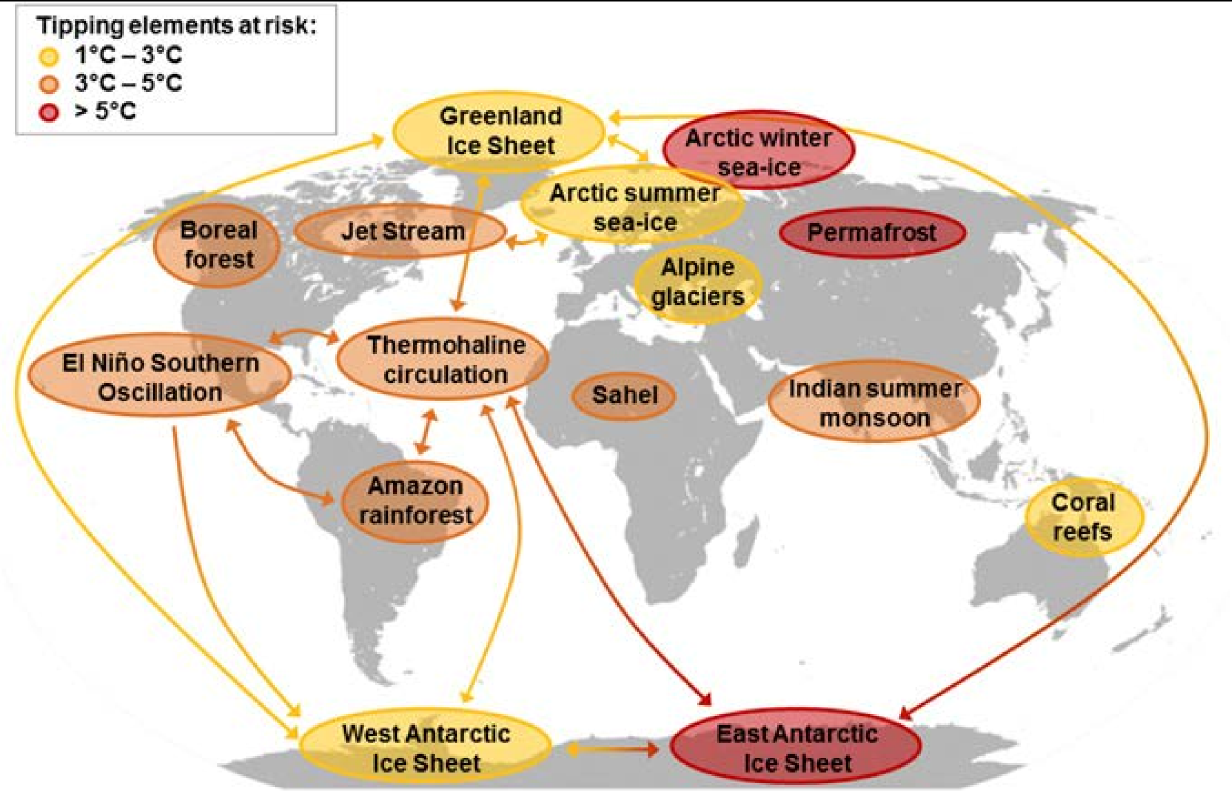
– Deep uncertainty exists with regard to the biogeochemical processes potentially triggered by climate change. Climate scientists have shown not only that tipping points exist but remain difficult to estimate with precision, but also that they could generate tipping cascades on other biogeochemical processes, as shown in Graph 8 below. Evidence is now mounting that tipping points in the Earth system such as the loss of the Amazon forest or the West Antarctic ice sheet could occur more rapidly than was thought (Lenton et al (2019));

– The impacts of such biogeochemical processes on socioeconomic systems can be highly nonlinear, meaning that small changes in one part of the system can lead to large changes elsewhere in the system (Smith (2014)) and to chaotic dynamics that become impossible to model with high levels of confidence. For instance, it seems that climate change will mostly impact developing economies, which could increase global inequality (Diffenbaugh and Burke (2019)) and generate mass migrations and conflicts (Abel et al (2019), Bamber et al (2019), Kelley et al (2015)). These could have major implications for development across the world (Human Rights Council (2019)) but their probability of occurrence and degrees of impact remain largely impossible to appropriately integrate into existing models. However, advanced economies are not exempt from significant impacts either. For instance, Dantec and Roux (2019) assess how climate change may affect different French territories and demand multiple adaptation strategies in areas such as urban planning, water management or agricultural practices;

– In the light of these considerations, it has been argued that the damage functions used by IAMs are unable to account for the tail risks related to climate change (Calel et al (2015)), and in some cases lead studies to suggest "optimal" warming scenarios that would actually correspond to catastrophic conditions for the future of human and non-human life on Earth: for instance, while DICE (Dynamic Integrated Climate-Economy) modellers find that a 6°C warming in the 22nd century would mean a decline of less than 0.1% per year in GDP for the next 130 years, in practice such a rise in global temperatures could mean extinction for a large part of humanity (Keen (2019)). Similarly, the social cost of carbon (which adds up in monetary terms all the costs and benefits of adding one additional tonne of CO_2), and the choice of a rate of discount of future damages can provide "almost any result one desires" (Pindyck (2013, p 5)) and lead to outcomes and policy recommendations that are "grossly misleading" (Stern (2016)). Climate modellers typically embrace uncertainty by showing the great range of outcomes that can result from a specific event or pattern (eg a specific CO_2 atmospheric concentration can translate into different increases in global temperature and different sea level rises, with respective confidence intervals), but this dimension tends be lost in climate-economic models based on benefit-cost analysis (Giampietro et al (2013), Martin and Pindyck (2015)).

Global map of potential tipping cascades

Graph 8



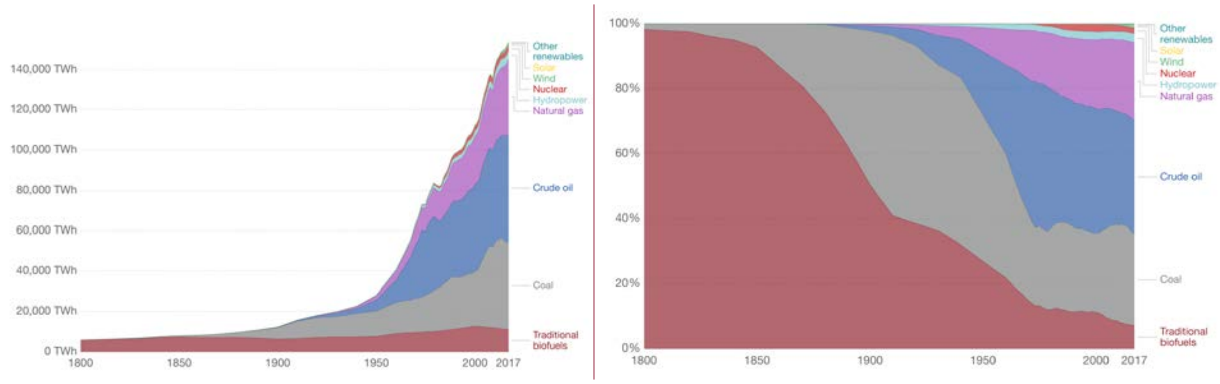
The individual tipping elements are colour-coded according to estimated thresholds in global average surface temperature. Arrows show the potential interactions among the tipping elements that could generate cascades, based on expert elicitation.

Source: Adapted from Steffen et al (2018).

With regard to transition risks (see Annex 2), one of the main sources of modelling uncertainty relates to the general use of economy-wide carbon prices as a proxy for climate policy in IAMs. This assumption tends to overlook many social and political forces that can influence the way the world evolves, as recognised by the IPCC itself (IPCC (2014, p 422)). As the history of energy and social systems shows (Bonneuil and Fressoz (2016), Global Energy Assessment (2012), Pearson and Foxon (2012), Smil (2010, 2017a)), the evolution of primary energy uses is deeply influenced by structural factors and requires deep transformations of existing socioeconomic systems (Graph 9, left-hand panel). Past transformations have responded to a variety of stimuli including relative prices but also many other considerations such as geopolitical (eg choice of nuclear energy by certain countries to guarantee energy independence) and institutional ones (eg proactive policies supporting urban sprawl and its related automobile dependency). Attempts to reverse these inertias through pricing mechanisms alone could be insufficient.

Moreover, all major energy transitions in the past (Graph 9, right-hand panel) have taken the form of energy additions in absolute terms (Graph 9, left-hand panel). That is, they were energy additions more than energy transitions. For instance, biomass (in green) has decreased in relative terms but not in absolute terms. This highlights the sobering reality that achieving a low-carbon transition in a smooth manner represents an unprecedented challenge with system-wide implications. With this in mind, estimating the social cost of carbon with confidence is all the more difficult "due to considerable uncertainties […] and [results that] depend on a large number of normative and empirical assumptions that are not known with any certainty" (IPCC (2007, p 173)).

Evolution of energy systems, in absolute and relative terms — Graph 9



Global primary energy consumption, measured in terawatt-hours (TWh) per year (left-hand panel) and in percentage by primary energy source (right-hand panel).

Note: "other renewables" are renewable technologies not including solar, wind, hydropower and traditional biofuels.

Source: Smil (2017b) and BP (2019). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy.

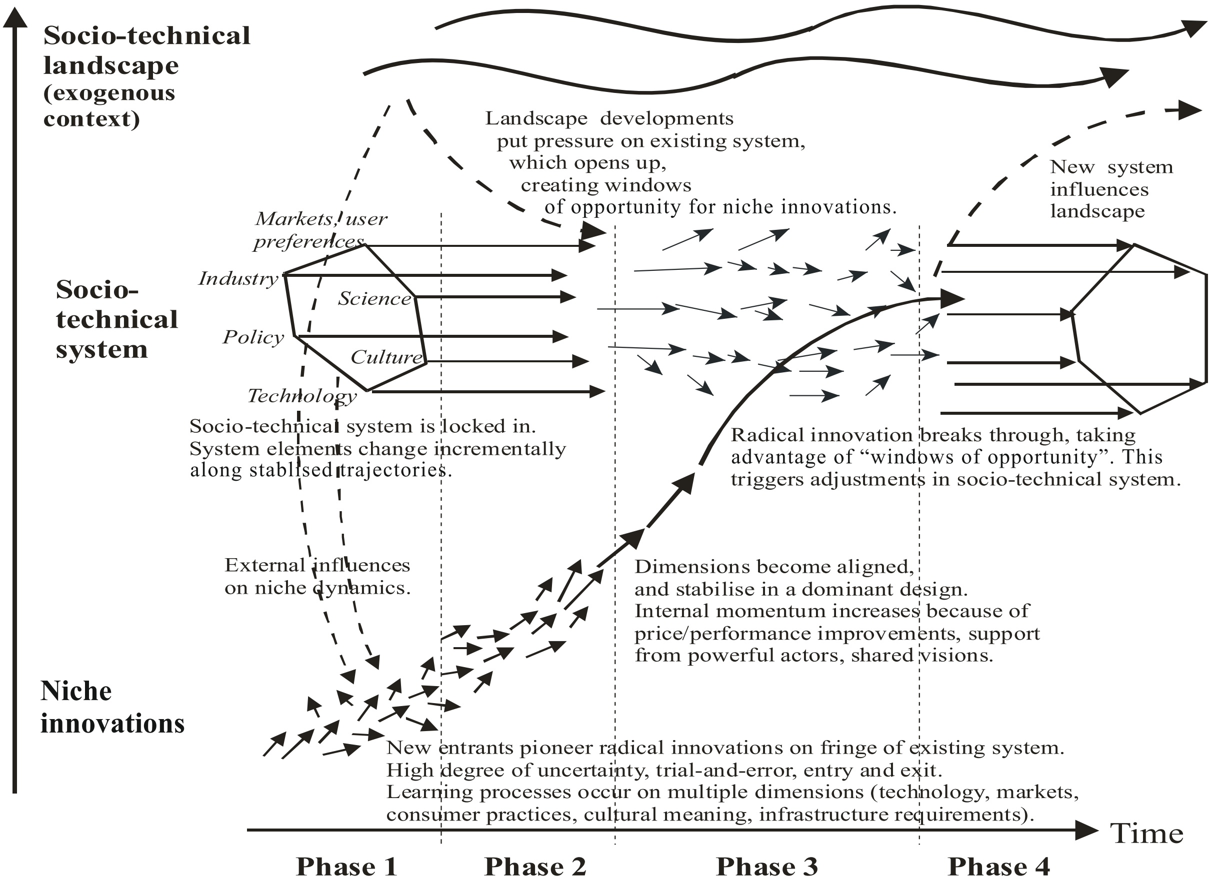
To account for this complexity, transdisciplinary approaches around concepts such as socio-technical systems and transitions (Geels et al (2017)) seem more appropriate to embrace the multiple dimensions involved in any climate change mitigation transition (Box 3). These approaches are concerned with "understanding the mechanisms through which socio-economic, biological and technological systems adapt to changes in their internal or external environments" (Lawhon and Murphy (2011, pp 356–7)). In particular, socio-technical transition scholars provide a framework for more sophisticated qualitative and quantitative approaches to three parameters that are essential to a low-carbon transition: technological niches, socio-technical regime, and socio-technical landscape (Graph 10).

In short, the physical and transition risks of climate change are subject to multiple forces (natural, technological, societal, regulatory and cultural, among others) that interact with each other and are subject to uncertainty, irreversibility, nonlinearity and fat-tailed distributions. Moreover, physical and transition risks will increasingly interact with each other, potentially generating new cascade effects that are not yet accounted for (Annex 3).

In the rest of this chapter, we discuss how to go beyond the limitations of climate-economic models as discussed above to better assess climate-related risks, especially with regard to: (i) the choice of scenarios regarding how technologies, policies, behaviours, and macroeconomic – and even geopolitical – dynamics will interact in the future (Chapter 3.2); (ii) the translation of such scenarios into granular sectoral and corporate metrics in an evolving environment where all firms and value chains will be impacted in unpredictable ways (Chapter 3.3); and (iii) the matching of climate-related risk assessments with appropriate financial decision-making (Chapter 3.4). One key finding is that alternative approaches are needed to fully embrace the uncertainty and the need for structural transformation at stake (Chapter 3.5).

Phases of transformations of existing socio-technical systems

Graph 10



Source: Adapted from Geels et al (2017).

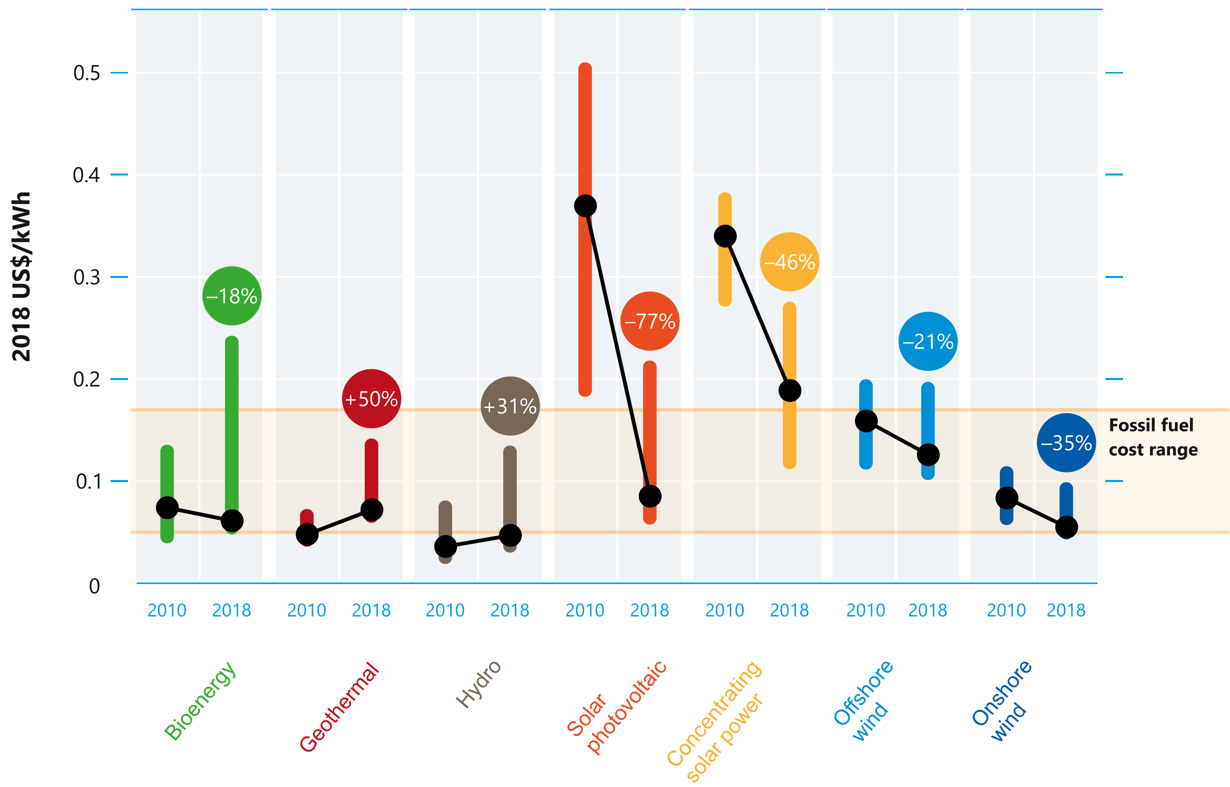
Box 3: A multi-layered perspective on socio-technical transition

Multi-layered perspectives on socio-technical transition can provide a framework for more sophisticated qualitative and quantitative approaches to the interactions between three layers that are essential to a low-carbon transition: technological niches, socio-technical regime, and socio-technical landscape (Graph 10).

First, technological niches and innovations will, unsurprisingly, be a key parameter of a successful transition. Yet their representation in existing models fails to reflect the unpredictable and disruptive nature of technological innovations. As an example, the sharp increase of usage and cost variation in many renewable energy technologies over the past few years (Graph 3.A) has outpaced most predictions, and this seems to have responded more to massive investments in R&D and targeted subsidies to solar energy than to any ambitious carbon pricing mechanism (Zenghelis (2019)). In contrast, the intermittency of renewable energy remains a considerable problem that tends to be overlooked (Moriarty and Honnery (2016), Smil (2017a)). Moreover, other sectors may be impossible to decarbonise in the medium term regardless of carbon pricing, as we can observe (so far) not only with aviation or cement, but also with parts of the energy sector. In short, the type of technological solution that will prevail in a low-carbon world is largely unpredictable. A case in point is the transportation sector: the most promising technological alternatives have varied greatly over short time horizons (Graph 3.B) and with new technologies such as hydrogen fuel (Morris et al (2019), Li (2019), Xin (2019)).

Changes in global levelised cost of energy for key renewable energy technologies, 2010–18

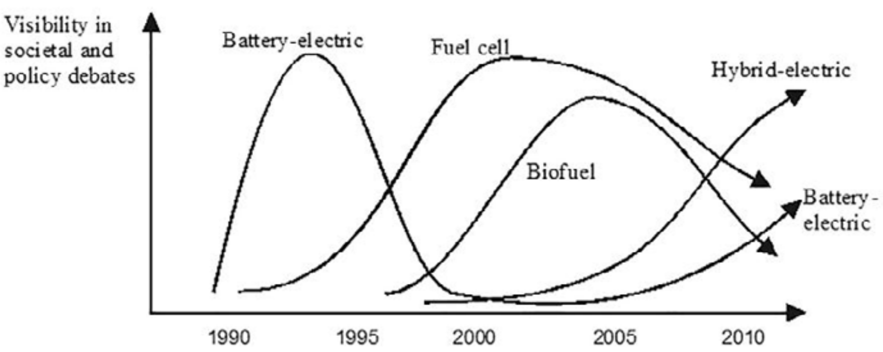
Graph 3.A



Source: UNEP (2019).

Changes in visibility of transportation technologies through time

Graph 3.B



Source: Geels et al (2017).

Second, the successful implementation of technologies does not depend only on their relative prices but also on the so-called socio-technical regimes in which they operate, ie the rules and norms guiding the use of particular technologies. For instance, once car-based transportation systems are set up in a city or country, they largely become self-sustaining "by formal and informal institutions, such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity, and individual identity; the skills and assumptions of transport planners; and the technical capabilities of car manufacturers, suppliers, and repair shops" (Geels et al (2017, p 465)). Although pricing mechanisms can surely contribute to overcoming this institutional inertia, other regulations may be needed such as rules on the weight of new cars (to avoid rebound effects[27]) and proactive support to the development of public transportation to limit the number of personal vehicles. More broadly, some solutions may depend not on new technologies but rather on shifting social norms towards the use of already existing technologies (Bihouix (2015)). For instance, the recent "flight shame" movement in Sweden and its negative impact on airline companies (Fabre (2019)), along with positive impacts for the national rail operator (Henley (2019)), are responses to a "Greta Thunberg effect" rather than a technological breakthrough.

Third, technological, behavioural and regulatory changes do not take place in a vacuum but in specific socio-technical landscapes, ie in contexts comprising "both slow-changing trends (eg demographics, ideology, spatial structures, geopolitics) and exogenous shocks (eg wars, economic crises, major accidents, political upheavals)" (Geels et al (2017, p 465)). In other words, assessing specific transition paths requires integrating many real-world considerations into the scope of the analysis, which is particularly difficult for modellers whose objective is precisely to simplify the representation of the world for reasons of tractability. Some features of the current "socio-technical landscape" that will prove essential to consider for the transition (further developed in Annex 2) include:

– A rather weakened multilateral order that is an important barrier to address the multiple trade-offs that a global low-carbon transition will generate. For instance, stranding fossil fuels may require the United States and Canada to immediately stop extracting unconventional oil, with potentially significant impacts on the output of their national economies (Mercure et al (2018)). Similarly, as China consumed half of the world's coal in 2018 (BP (2019)) and Asia has accounted for 90% of new coal plants over the past two decades (IEA (2019)), stranding such assets could have major impacts on global value chains, for example with sharp increases in the price of imports for advanced economies, sharp decreases in corporate profits in Asia, and potential relocations of certain economic activities. These could have significant implications for global imbalances. With this in mind, aiming to strand these assets rapidly and in a fair manner would probably require unprecedented international cooperation, including significant compensation mechanisms for countries that do not exploit fossil fuel reserves. However, past experiences such as the Yasuni-ITT initiative in Ecuador show the difficulty of reaching agreements on compensation for not polluting (Martin and Scholz (2014), Warnars (2010)). Finally, a low-carbon transition could trigger new geopolitical tensions and potential conflicts, including conflicts related to the quest for resources needed for renewable energy (IRENA (2019), Pitron (2018)). Hence, existing models still have a long way to go to account for the international political economy of climate change and for the principle of "common but differentiated responsibilities" enshrined in international climate negotiations (UNFCCC (2015)).

– Significant transformations of market economies have taken place over the past decades, including a decrease in growth rates in advanced economies but also at the global level (despite rapid growth in emerging and developing economies). Discussions are under way about the causes of this slowdown (eg a new "secular stagnation", whether structural and possibly related to a long-term decline in productivity (Gordon (2012)), or a more conjunctural slowdown in aggregate demand that can be addressed by new macroeconomic policies). Other transformations include a shift in corporate governance towards maximisation of shareholder value and short-termism (Mazzucato (2015)) and increased inequalities within nations (Piketty (2014)) despite a relative decrease in inequalities among nations (Milanovic (2016)). These features pose significant questions such as the social acceptability of a low-carbon transition. For

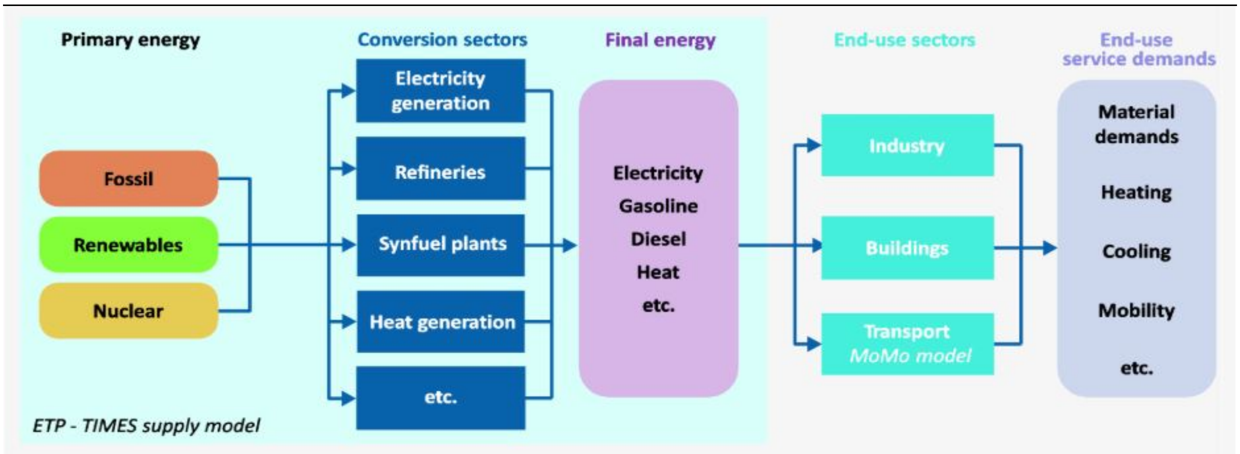
[27] In energy economics, rebound effects occur when initial energy efficiency gains are cancelled out by behavioural or systemic responses, for instance if a consumer uses the financial gains from increased housing energy efficiency to set higher temperatures or to increase energy use elsewhere. As a concrete example, increases in cars' energy efficiency over the past few years have been offset by the fact that households are buying larger cars and that the number of passengers per car is decreasing (IEA (2019)).

instance, given that such a transition requires "intensive public discussion" (Stern (2008, p 33)), it is unclear whether mechanisms such as revenue-neutral carbon taxes will be sufficient. Some argue that if inequalities were lower in the first place, it could become easier to reach consensus on difficult topics such as the burden-sharing efforts to mitigate and adapt to climate change (Chancel (2017), Otto et al (2019)). That is, without suggesting an optimal specific path, climate change needs to be considered as being embedded in a myriad of real-world socioeconomic challenges, not as an ad hoc challenge that should simply not interfere with other challenges.

3.2 Climate-related uncertainties and the choice of scenarios

Forward-looking approaches that are built around an IAM inevitably inherit all the limitations of the climate-economic models mentioned in the previous chapter. Here we focus mostly on technological uncertainties, given the difficulty of accounting for the other sources of uncertainty discussed above (eg international political economy uncertainties associated with the transition). It should also be noted that some methodology providers do not rely on IAMs but rather on "technologically-based" models. For instance, the ET Risk Project,[28] developed by a consortium of stakeholders, uses scenarios provided by the International Energy Agency (IEA) and adapts these based on bottom-up market analyses. The IEA produces scenarios on the development of energy technologies and the investments needed to upscale them under different climate pathways and policy tracks (regulations, carbon pricing, etc).[29] For instance, the IEA's 2017 *Energy Technology Perspectives* (ETP) report (Graph 11) seeks to offer a "technology-rich, bottom-up analysis of the global energy system" (IEA (2017)).

Structure of the ETP model Graph 11



Source: IEA (2017).

[28] http://et-risk.eu/.

[29] These include a "Current Policies Scenario" akin to a "business as usual" setup, a "New Policies Scenario" focused on the Nationally Determined Contributions (NDCs) set by each country following the Paris Agreement (UNFCCC (2015)), and a more ambitious "Sustainable Development Scenario".

Whether they rely on IAMs or "technology-based" models, it is critical to assess which choices inform the selected technological pathway (eg development of carbon capture and storage (CCS) technologies, nuclear energy, price of renewable energy, gains obtained from energy efficiency, etc) as these strongly determine which sectors and companies could benefit from it. However, the representation of clean technology diffusion rates in energy-systems models is inherently subject to much uncertainty (Barreto and Kemp (2008)). Some scenarios rely on the rapid development of existing technologies to respond to increasing demand for energy (eg IEA (2017)), while others focus on the potential reduction in energy demand to be achieved through energy efficiency and modification of existing behaviours (eg Negawatt (2018)). Other technology-based scenarios include BP's Rapid transition scenario, IRENA's REmap scenario, Greenpeace's Advanced Energy Revolution scenario (for a comprehensive review of scenarios, see Colin et al (2019), The Shift Project and IFPEN (2019)) or, with a different approach, the Science-Based Targets Initiative.[30]

An important source of technological uncertainty has to do with the role allocated to negative emissions and to CCS technologies.[31] Their relative importance varies widely across models: in a subset of 2°C scenarios, between 400 and 1,600 gigatonnes of carbon dioxide ($GtCO_2$) can be compensated through negative emissions and CCS, corresponding to 10–40 years of current emissions (Carbon Brief (2018)). This increases the size of the remaining carbon budget by between 72 and 290%, compared to scenarios where negative emissions and CCS do not occur. In practice, however, significant uncertainty exists with regard to CCS technologies due to technological constraints, potentially high costs and environmental and health risks (IPCC (2014)).

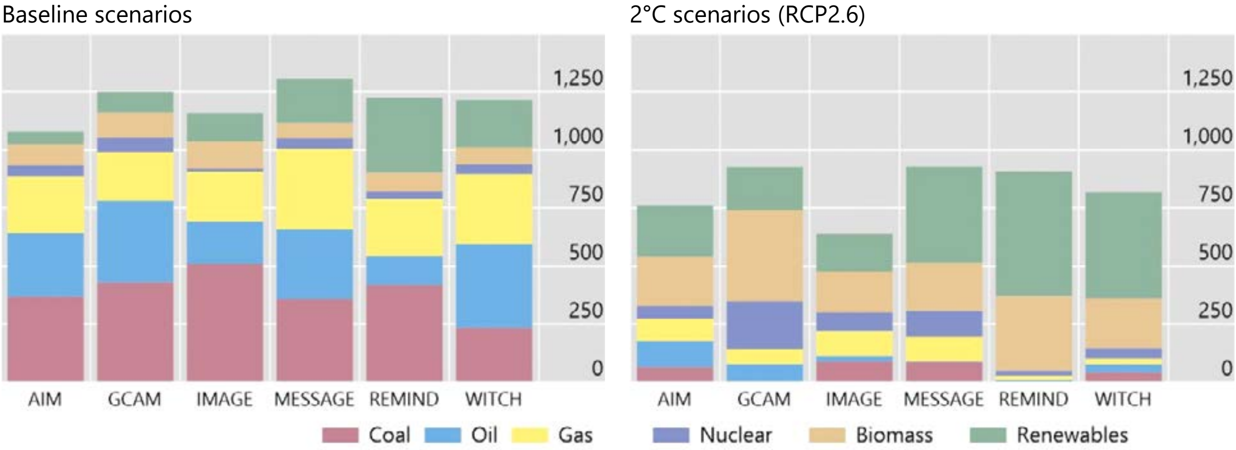
As a result, a scenario with a large role for negative emissions and CCS will naturally reduce the amount of assets that are stranded (eg the GCAM model in the graph below, for a 2°C scenario), whereas a scenario with less room for negative emissions will require a more massive development of renewables (as in the MESSAGE, REMIND and WITCH models) or considerable improvements in energy efficiency (as in IMAGE). This means that the financial impacts of a specific financial portfolio will be entirely different depending on which scenario is chosen.

30 The Science-Based Targets Initiative (sciencebasedtargets.org/) differs from the other listed scenarios. Instead of a comprehensive approach, it aims to provide companies with pathways to align their emissions to climate targets on a sectoral basis, based on current scientific knowledge.

31 CCS is technically not a "negative emissions" technology since it does not remove CO_2 from the atmosphere, but stores new emissions instead. That is, it avoids new emissions but does not capture past emissions. CCS is usually included in the category of BECCS (bioenergy with carbon capture and storage).

The 2100 primary energy mix

Exajoules of primary energy Graph 12



The 2100 primary energy mix according to six IAMs, for SSP2 ("middle of the road") RCP2.6 scenarios. The energy mix in a "baseline" scenario is shown on the left, and scenarios that limit global warning to 2°C are shown on the right. Fossil fuel categories include CCS and non-CCS use.

Sources: Carbon Brief (2018); IIASA SSP Database.

Partially as a result of these sources of technological uncertainty, the volume of investments needed (a critical element to assess the risk and opportunities related to a low-carbon transition) can vary significantly. The survey of six models estimating the additional annual average energy-related investments needed to limit global warming to 1.5°C (over the period 2016 to 2050, compared to the baseline) finds significant variations, with values ranging from $150 billion ($2010) to $1,700 billion ($2010). Total investments (ie not just additional ones) in low-carbon energy also vary greatly, from $0.8 trillion ($2010) to $2.9 trillion ($2010; IPCC (2018, p 153)). Estimated needed investments vary even over shorter time horizons. For instance, global investments needed in sustainable infrastructure for the period 2015–30 range from less than $20 trillion to close to $100 trillion (Bhattacharya et al (2016, p 27)).

These estimates depend significantly on initial assumptions and methodological choices. For instance, in MESSAGE (the energy core of IIASA's[32] IAM framework), emissions-reduction investments occur in the models' regions and at the time they are cheapest to implement (assuming full temporal and spatial flexibility), based on the cost assumptions of 10 representative generation technologies (Zhou et al (2019)). In contrast, the New Climate Economy project estimates the investments needed in infrastructure by using existing technologies and investment patterns, assuming an exogenous growth rate of 3% and no productivity gains (Bhattacharya et al (2016)). Other assumptions are also critical, eg supply side investments could be lowered by up to 50% according to some studies if strong policies to limit energy demand growth are implemented (Grubler et al (2018), in IPCC (2018)).

Therefore, scenarios "should be considered illustrative and exploratory, rather than definitive [...]. It is important to remember that scenarios represent plausible future pathways under uncertainty. Scenarios are not associated with probabilities, nor do they represent a collectively exhaustive set of potential outcomes or actual forecasts" (Trucost ESG Analysis (2019, p 39)). Their "results are subject to a

[32] The International Institute for Applied Systems Analysis (IIASA)'s model is composed of five different models: the two most important that represent the energy system (MESSAGE) and land-use competition (GLOBIOM), and three that represent the macroeconomic system (MACRO), the climate system (MAGICC) and air pollution and GHG emissions (GAINS). The MESSAGE framework divides the world into 11 regions. For an overview, see: https://message.iiasa.ac.at/projects/global/en/latest/overview/index.html.

high degree of uncertainty" (Zhou et al (2019, p 3)) and cannot be allocated probabilities of occurrence, ie they should be assessed with extreme caution by finance supervisors engaged in financial stability monitoring.

3.3 Translating a climate-economic scenario into sector- and firm-level risk assessments

To incorporate climate-related risks into financial institutions' risk management procedures and financial stability monitoring, the main challenge to determining a reasonable scenario consists in translating it into granular metrics at the sector (see Box 4 below) and firm level. A firm-level assessment is critical as it can distinguish how firms with a similar exposure to climate scenarios have different adaptive capacities, making them more or less vulnerable. Indeed, the climate vulnerability of a firm does not depend only on its exposure to climate-related risks (which can be relatively similar for different firms in the same sector) but also on its sensitivity and its adaptive capacity to a specific scenario (eg its ability to develop new low-carbon technologies in response to climate-related risks, or to pass through additional costs to its suppliers or customers). For instance, two oil and gas companies may fall under the same industry classification but be exposed to transition risks in very different ways, depending on factors such as the likelihood of owning stranded assets (as discussed above) or their degree of diversification into renewable energy.

Box 4: The Netherlands Bank's climate stress test

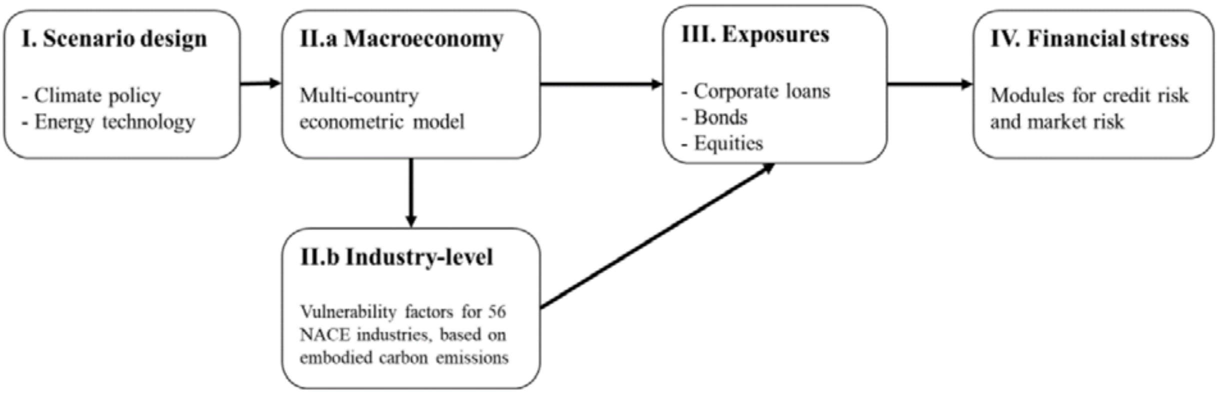
The Netherlands Bank's methodology (Vermeulen et al (2018, 2019)) first defines climate scenarios and shocks (mostly via carbon taxes and technological development paths) based on literature and validated by experts (block I in figure below). The policy shock consists in the abrupt implementation of a $100 carbon tax, and the technology shock in the rapid development of renewable energy, which leaves fossil fuel dependent technologies obsolete, resulting in capital stock write-offs. These shocks can be assessed separately or jointly (double shock); they can also lead to a negative confidence shock affecting the behaviour of consumers, producers and investors. These scenarios are translated into macroeconomic impacts on GDP, consumer prices, stock prices and interest rates through NiGEM (block II.a in Graph 4.A), a multi-country macroeconomic model. The central bank then estimates the vulnerability of each sector to transition risks, based on the embodied CO_2 emissions of 56 NACE industries[33] (ie including the emissions related to their value chain) weighted by their contribution to GDP (block II.b in the graph). The impact of the transition on each NACE industry is then connected to the national financial sector portfolios of corporate loans, bonds and equities (block III in the figure below). In the last step (block IV in Graph 4.A), the central bank calculates losses for financial institutions with the aid of traditional top-down approaches to stress testing. The results of the climate stress test indicate losses of up to 11% of assets for insurers and up to 3% for banks, potentially leading to a reduction of about 4 percentage points in Dutch banks' CET1 ratio[34].

[33] NACE is the industry standard classification system used in the European Union.

[34] Common Equity Tier 1 (CET1) is a component of Tier 1 capital that consists mostly of common stock held by a bank or other financial institution. It is the highest quality of regulatory capital, as it absorbs losses immediately when they occur. See: https://www.bis.org/fsi/fsisummaries/defcap_b3.pdf.

Overview of the stress test framework

Graph 4.A

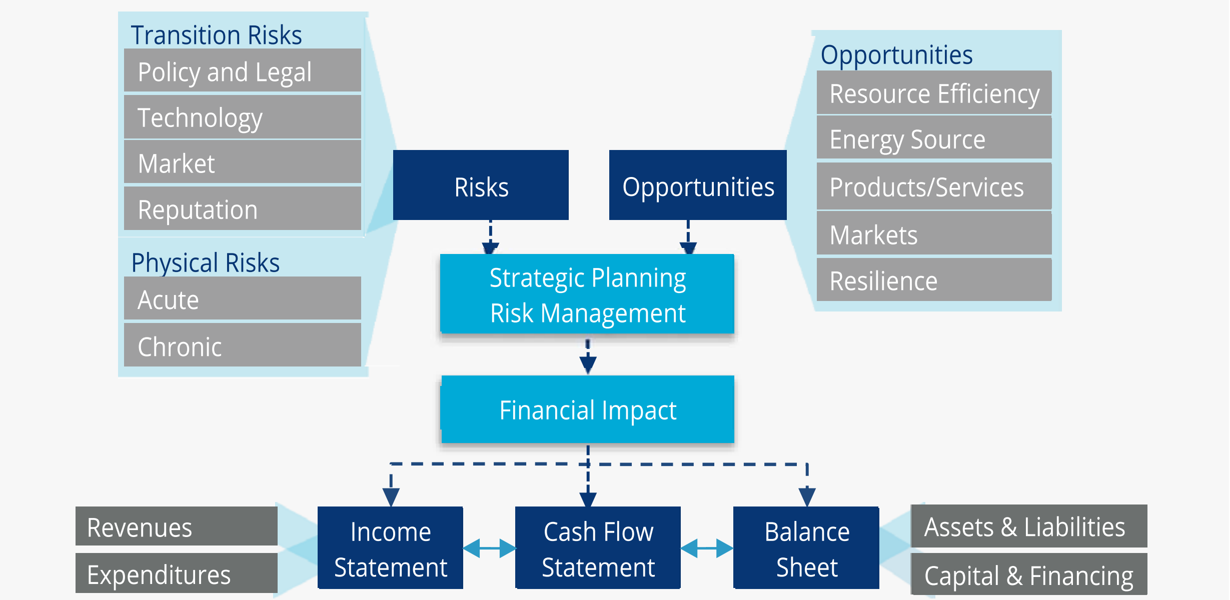


Source: Vermeulen et al (2019).

Climate change mitigation and adaptation also brings opportunities related to the development of low-carbon technologies and climate-friendly policies (see Graph 13), which are captured by several climate-related risk assessment methodologies (eg Mercer, Oliver Wyman and Carbon Delta). UNEP-FI (2019) estimates that profits generated by a 30,000-company universe in the transition to a 2°C world could amount to $2.1 trillion, although this number should be taken cautiously given the many sources of uncertainty discussed above. It is therefore important to assess how climate-related risks and opportunities will impact specific key performance indicators (KPIs) of a firm, such as its sales, operational and maintenance costs, capital expenditures, R&D expenditures, and potential impairment of fixed assets.

Climate-related risks, opportunities and financial impact

Graph 13



Source: TCFD (2017).

One of the main difficulties at this stage is determining how a firm is exposed to climate-related risks throughout its value chain. A firm can be exposed to these risks through: (i) direct, so-called "scope 1" emissions (particularly important in sectors such as mining, aviation or the chemical industry); (ii) indirect, so-called "scope 2" emissions resulting from purchased energy (eg real estate or energy-intensive industries); and (iii) other indirect emissions related to its entire upstream and downstream value chain, so-called "scope 3" emissions.[35] A case in point for scope 3 is the automotive industry, where the main exposure lies not so much with the sector's own emissions (scope 1) or its energy sources (scope 2), but with carbon combustion by end users (scope 3). For buildings, scope 3 emissions are twice as high as direct emissions (Hertwich and Wood (2018)). This is not to say that the emissions related to scopes 1, 2 and 3 are sufficient to assess the exposure of a firm. For instance, a firm with high emissions today could become decarbonised and seize many opportunities under specific transition paths. Still, focusing on scopes 1, 2 and 3 means that a comprehensive risk assessment should look at potential vulnerabilities throughout the entire value chain.

The assessment of a firm's exposure to its scope 1, 2 and 3 emissions and its translation into risk metrics can be conducted in quantitative or qualitative manners. The PACTA stress test model,[36] based on International Energy Agency (IEA) technological pathways up to 2050 compatible with a specific climate scenario (eg a 2°C or 1.75°C rise in temperatures) and on proprietary databases including existing investment plans at the firm level, determines how each firm within specific sectors may become aligned or misaligned with the scenario. This insight then informs a delayed stress test tool that calculates shocks based on alternative cash flows, discounted in a valuation or credit risk model. The assessment of the risk materiality by sector is a key dimension of this methodology, which involves technological, market and policy considerations.

Another methodology, developed by Carbon Delta (2019), proceeds by breaking down each country's emission reduction pledge (as indicated by its Nationally Determined Contribution, or NDC) into sector-level targets, and then assigning emission reduction quantities to a firm's production facilities based on its emission profile within each sector, using a proprietary asset location database. The costs relative to the transition are then obtained by multiplying the required GHG reduction amount by the price per tonne of carbon dioxide (tCO_2) obtained via IAMs for the scenario under analysis (eg for a 3°C, 2°C and 1.5°C rise in temperatures). In order to estimate the revenues that each firm could obtain from a low-carbon transition, Carbon Delta (2019) uses a database covering millions of low-carbon patents granted by authorities worldwide, and a qualitative assessment of each low-carbon patent portfolio as a proxy for firms' adaptive capacity.

Other approaches rely more extensively on qualitative judgments regarding the adaptive capacity of firms in each sector. For instance, Oliver Wyman (2019) resorts to experts' judgments to forecast how specific companies in the portfolio may adapt to climate-related risks, although it also includes quantitative tools to estimate impacts of scenarios on prices, volumes, cost, impairment and capital expenditure of counterparties. Carbone 4's (2016) bottom-up assessment considers firms' adaptive capacities to a low-carbon transition, relying on a mix of qualitative and quantitative indicators such as the investments made in R&D and the CO_2 reduction objectives of the firm related to its scope 1, 2 and 3 emissions. Allianz Global Investor integrates technological, regulatory and physical considerations qualitatively into its asset allocation procedures (IIGCC (2018)).

35 The GHG Protocol Corporate Standard classifies a company's GHG emissions into three "scopes". "Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions." Source: ghgprotocol.org/sites/default/files/standards_supporting/FAQ.pdf.

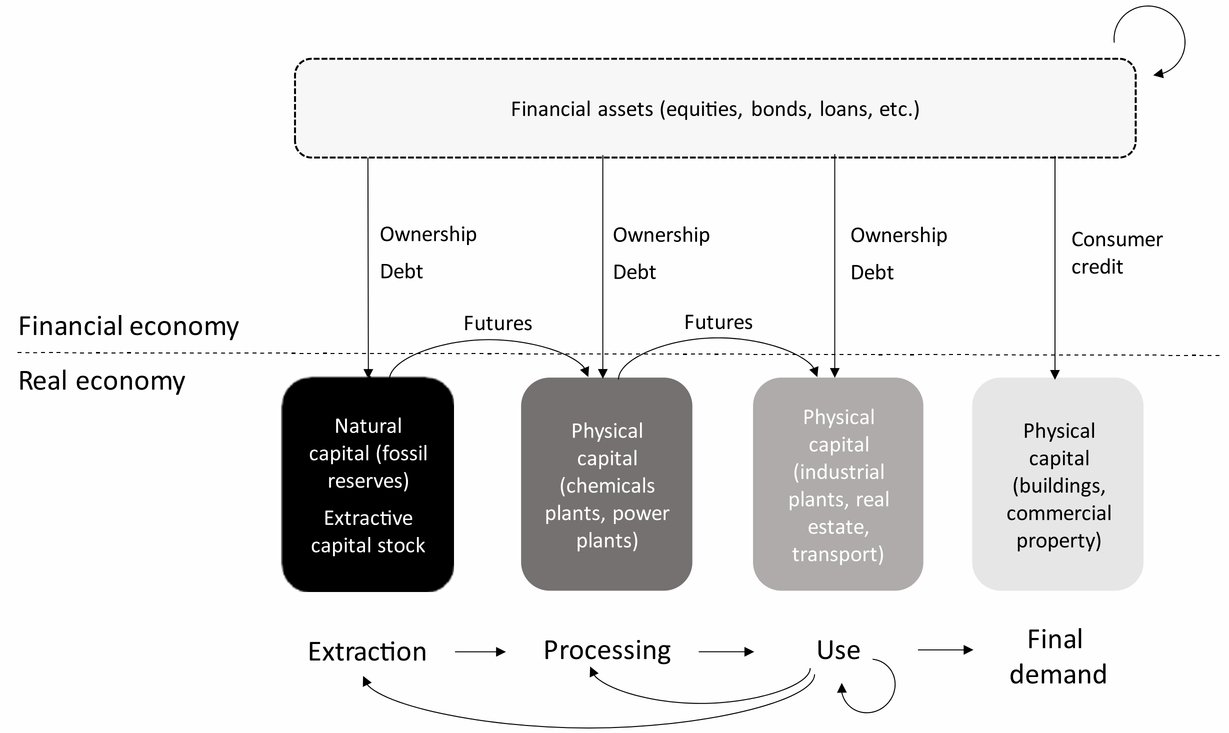
36 www.transitionmonitor.com/.

Other approaches have also emerged to better account for the indirect exposures to climate-related risks, without necessarily relying on scopes 1, 2 and 3. For instance, Battiston et al (2017) classify economic activities into six sectors (fossil-fuel, utility, energy intensive, transportation, housing, and finance) and twenty subsectors based on their relative vulnerability to climate transition risks (as a function of their emissions). They further map out the exposure of financial institutions (through equity and debt) to these different sectors, which enables them to capture potential knock-on effects within financial networks. When applying a sectoral shock (eg a carbon tax), the firms in sectors that have not adapted their business model to the energy transition face increased costs and reduced revenues, whereas the firms that have invested in alternative technologies are able to increase their profits. This methodology can be applied to the financial system as a whole or to specific financial institutions (Battiston et al (2017)), and to different asset classes such as equity, corporate and sovereign bonds (Battiston and Monasterolo (2019)), while capturing second-round effects related to the holding of financial assets.

Another way of estimating indirect exposures is to look at production networks, as suggested by Cahen-Fourot et al (2019a,b). Using input-output tables for 10 European economies and based on the monetary value of productive capital stocks (Cahen-Fourot et al (2019b)), the authors seek to provide a systemic perspective on how the reduction in production in one sector can cascade to physical stocks supporting the rest of the economic activity through chains of intermediate exchange. That is, as physical inputs stop flowing from one sector to another, more sectors along value chains are also impacted. For instance, the mining and quarrying sector (including the extraction of fossil fuels), although it accounts for a relatively low share of value added, tends to provide crucial inputs for many other downstream economic activities such as construction, electricity and gas, coke and refined petroleum products or land transport; in turn, these sectors are critical for the correct functioning of public administration, machinery and equipment and real estate activities; and so on. In short, stranding an asset in one specific sector can trigger a "cascade of stranded assets" affecting many other sectors of the economy.

While these two approaches bring critical insights into the interconnectedness among sectors and potential transmission channels of transition shocks and could greatly benefit from being combined (see Graph 14), applying them to future scenarios is not without its challenges. Indeed, relying on existing sectoral classifications and interconnections cannot be assumed to serve as a good proxy for future interconnectedness, given the need to change the very productive structures of the economy. In this sense, they are probably more tailored to the conduct of a climate stress test with a relatively short-term horizon (assuming a static portfolio) than as a tool to be used by financial institutions in a dynamic environment.

Natural, physical and financial assets at risk of stranding Graph 14



Source: Campiglio et al (2017).

Regardless of the approach chosen, some critical sources of uncertainty to keep in mind when conducting forward-looking risk assessments concern the ability to predict:

– *The development and diffusion of new technologies*: As new technologies that do not yet exist or are not yet widespread appear and scale up, they may reshape existing market structures in unpredictable ways. For instance, wholesale online distribution would have been unpredictable a few decades ago. With this in mind, it is difficult to predict how a specific firm will perform in a new environment that will be determined not only by its own strategy but also by multiple elements in its value chain;

– *Each firm's market power:* In response to climate regulations, some firms may be able to offset an increase in operating costs through their customers (by increasing final prices) or suppliers (by decreasing purchasing prices), while others may not have this market power. For instance, after the introduction of the EU Emissions Trading Scheme (ETS) in 2005, some electricity generators were able to pass through more than 100% of the cost increase to consumers (UNEP-FI (2019)). Determining each firm's market position and power and its related pass-through capacity in a dynamic environment remains a considerable task. Some methodologies (eg Oliver Wyman) aim to assess firms' ability to withstand a decrease in demand due to possible product substitutions and cost pass-through (based among other things on the estimated price elasticity of demand); others examine the adaptive capacity of firms based on the potential development of low-carbon and emissions abatement technologies (eg Carbone 4; ET Risk).

– *The exposure to liability risks that have not yet arisen:* Existing methodologies focus on physical and transition risks, but liability risks[37] may become increasingly important in the future. A case in point is PG&E (Baker and Roston (2019), Gold (2019)), the owner of California's largest electric utility, which filed for bankruptcy in early 2019 after wildfire victims sued the company for failing to adjust its grid to the risks posed by increasingly drier climate conditions. Several legal actions against energy and oil and gas companies (eg Drugmand (2019)) are also under way, often brought by cities or civil society organisations seeking compensation for climate-related disasters or the non-compliance of their business plans with the Paris Agreement (Mark (2018)). These examples show how in the future, firms may be exposed not only to the physical and transition risks of climate change, but also to legal risks. However, assessing liability risks is a major challenge not only because of their inherent uncertainty (eg predicting which lawsuits will be triggered by future uncertain events) but also because of variations in the legal framework of each jurisdiction. For instance, in some jurisdictions the government acts as reinsurer "of last resort" in the case of natural disasters; in this case the risks end up being borne by the government rather than the firm or insurer.

Overall, the outcomes provided by each methodology are therefore highly sensitive to the ways in which they account for specific scenarios and how they translate them into static or dynamic corporate metrics that take into account the scope 1, 2 and 3 emissions. Although the lack of data is commonly and rightly invoked as a barrier to the development of climate-related risk assessment, it is also important to emphasise that bridging the data gap will not fully "resolve" the sources of uncertainty discussed above.

3.4 From climate-related risk identification to a comprehensive assessment of financial risk

Once a scenario has been translated into specific metrics at the firm or sector level, there remains the challenging task of integrating such an analysis into a financial institution's internal risk management procedures/a supervisor's practices. In this respect, some methodologies provide a scorecard or climate risk rating and estimates of the carbon impact of a portfolio (eg Carbone 4). Other methodologies aim to calculate the specific impact on asset pricing or credit risks, for instance through the concept of climate value-at-risk (climate VaR), which compares a climate disaster scenario to a baseline scenario. For instance, Carbon Delta estimates future cash flows generated by each firm and discounts them to measure current values that can inform credit risk models (eg a Merton model).

Regardless of the method chosen, at least three main methodological challenges should be kept in mind when conducting such an exercise.

First, it is possible for investors to see the long-term risks posed by climate change, while remaining exposed to fossil fuels in the short term (Christophers (2019)), especially if they believe that hard regulations will not be put in place anytime soon. The identification of the risk is one thing; mitigation is entirely another. For instance, Lenton et al (2019) find that the emergency to act is not only a factor of the risk at stake but also the urgency (defined as reaction time to an alert divided by the intervention time left to avoid a bad outcome). In other words, even identifying all the risks (if even possible) would not necessarily suffice to "break the tragedy of the horizon". Accordingly, new approaches to risk such as MinMax rules (Battiston (2019)), where the economic agent takes a decision based on the goal of minimising losses (or future regrets) in a worst case scenario, may be needed. Other approaches to risk management such as real option analyses, adaptation pathways or robust decision analysis are also already used for specific projects such as infrastructure and large industrial projects (Dépoues et al (2019)).

[37] As described by Carney (2015): "the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible". It should be noted that in some approaches (eg TCFD (2017)), "legal" risks (which share similar features with liability risks) are captured under physical and/or transition risks.

However, there are no indications that financial institutions would naturally choose this approach (except in specific cases such as project finance), and it is unclear how regulators could promote its use by financial institutions. In other words, the question of how to adjust risk modelling approaches to allow for longer time horizons remains a challenging one (Cleary (2019, p 28)).

Second, it is possible for financial institutions to hedge individually against climate change, without reducing the exposure of the system as a whole as long as system-wide action is not taken. For instance, Kling et al (2018) find that climate-vulnerable countries exhibit a higher cost of debt on average. This means that as markets hedge against climate-related risks by increasing risk premiums, the risk is transferred to other players such as climate-vulnerable sovereigns, which also happen to be poorer countries on average. Carney (2015) had also noted that insurers' rational responses to physical risks can paradoxically trigger new risks: for instance, storm patterns in the Caribbean have left many households unable to get private cover, prompting "mortgage lending to dry up, values to collapse and neighbourhoods to become abandoned" (Carney (2015, p 6)). Another risk may have to do with the development of financial products in response to climate-related risks, such as weather derivatives: these may help individual institutions hedge against specific climate-related risks, but they can also amplify systemic risk (NGFS (2019b, p 14)). In short, reckoning climate-related risks can lead financial institutions to take rational actions that, while hedging them individually from a specific shock, do not hedge against the systemic risks posed by climate change. For central banks, regulators and supervisors, this poses difficult questions, such as the adequate prudential regulation that should be deployed in response.

Third, in order to fully appreciate the potential systemic dimension of "green swan" events or "climate Minsky moments", more work is still needed on how a climate-related asset price shock (eg stranded assets) could trigger other losses within a dynamic financial network, including contagion effects towards non-climate-related sectors. The 2007–08 Great Financial Crisis has shown how a shock in one sector, subprime mortgages, can result in multiple shocks in different regions and sectors with little direct exposure to subprimes (for instance, affecting German Landesbanken and southern Europe's banking systems and sovereign credit risks). In this respect, abrupt shifts in market sentiment related to climate change could affect all players, including those who were hedged against specific climate-related risks (Reynolds (2015)).

These challenges go a long way towards explaining the "cognitive dissonance" (Lepetit (2019)) between the increased acceptance of the materiality of climate-related risks by financial institutions, and the relative weakness of their actions in response. In short, accounting for the multiple transmission channels of climate-related risks across firms, sectors and financial contracts while reflecting a structural change of economic structures remains a task filled with uncertainty. As a result, the question of how much asset values are affected and how much credit ratings should be impacted today in the face of future uncertain events remains unclear for deeper reasons than purely methodological ones. Despite these limitations, scenario-based analysis will remain critical for financial and non-financial firms aiming to increase their chances of adapting to future risks. That is, these methodological obstacles should not be a pretext for inaction, since climate-related risks remain real.

3.5 From climate-related risk to fully embracing climate uncertainty – towards a second "epistemological break"

The previous analyses have highlighted that regardless of the approach taken, the essential step of measuring climate-related risks presents significant methodological challenges related to: (i) the inability of macroeconomic and climate scenarios to holistically capture a large range of climate, social and economic factors; (ii) their translation into corporate metrics within a dynamic economic environment; and (iii) the difficulty of matching the identification of a climate-related risk with the adequate mitigation action. Climate-economic models and forward-looking risk analysis are important and can still be improved, but they will not suffice to provide all the information required to hedge against "green swan" events.

As a result of these limitations, two main avenues of action have been proposed. We argue that they should be pursued in parallel rather than in an exclusive manner. First, central banks and supervisors could explore different approaches that can better account for the uncertain and nonlinear features of climate-related risks. Three particular research avenues (see Box 5 below) consist in: (i) working with non-equilibrium models; (ii) conducting sensitivity analyses; and (iii) conducting case studies focusing on specific risks and/or transmission channels. Nevertheless, the descriptive and normative power of these alternative approaches remain limited by the sources of deep and radical uncertainty related to climate change discussed above. That is, the catalytic power of scenario-based analysis, even when grounded in approaches such as non-equilibrium models, will not be sufficient to guide decision-making towards a low-carbon transition.

As a result of this, the second avenue from the perspective of maintaining system stability consists in "going beyond models" and in developing more holistic approaches that can better embrace the deep or radical uncertainty of climate change as well as the need for system-wide action (Aglietta and Espagne (2016), Barmes (2019), Chenet et al (2019a), Ryan-Collins (2019), Svartzman et al (2019)). The concept of "risk" refers to something that has a calculable probability, whereas uncertainty refers to the possibility of outcomes that do not lend themselves to probability measurement (Knight (2009) [1921], Keynes (1936)), such as "green swan" events. The question of decision-making under deep or radical uncertainty is making a comeback following the 2007–08 Great Financial Crisis (Webb et al (2017)). According to former governor of the Bank of England Mervyn King, embracing radical uncertainty requires people to overcome the belief that "uncertainty can be confined to the mathematical manipulation of known probabilities" (King (2017, p 87)) with alternative and often qualitative strategies aimed at strengthening the resilience and robustness of the system (see also Kay and King (2020)).

As such, a second "epistemological break" is needed to approach the role of central banks, regulators and supervisors in the face of deep or radical uncertainty. This demands a move from an epistemological position of risk management to one that seeks to build the resilience of complex adaptive systems that will be impacted in one way or another by climate change. What should then be the role of central banks, regulators and supervisors in this approach? In the next chapter, we argue that the current efforts aimed at measuring, managing and supervising climate-related risks will only make sense if they take place within an institutional environment involving coordination with monetary and fiscal authorities, as well as broader societal changes such as a more systematic integration of sustainability considerations into financial and economic decision-making.

Box 5: New approaches for forward-looking risk management: non-equilibrium models, sensitivity analysis and case studies

In order to better account for the specific features of climate-related risks (deep uncertainty, nonlinearity, multiple and complex transmission channels within and among transition and physical risks, etc), three complementary research avenues seem particularly promising. They consist in: (i) working with non-equilibrium models; (ii) conducting sensitivity analyses; and (iii) conducting case studies focusing on specific risks and/or transmission channels.

Non-equilibrium models:

Mercure et al (2019) find that "equilibrium" and "non-equilibrium" models tend to yield opposite conclusions regarding the economic impacts of climate policies. Equilibrium models (such as DSGE) remain the most widely used for climate policy, yet their central assumption that prices coordinate the actions of all agents (under constrained optimisation) so as to equilibrate markets for production factors fails to represent transition patterns (including some discussed above) in a consistent manner.

In this context, non-equilibrium models may be better positioned to address three critical features of the transition:

1. Path dependency: in non-equilibrium models, the state of the economy depends on its state in previous time steps. This approach seems particularly aligned with the purpose of scenario analysis, consisting as it does in describing the economy under different possible and diverging circumstances that are dependent on past and present decisions. For instance, it is easier to represent how socio-technical inertia shapes current behaviours, beyond and despite pricing mechanisms.

2. Role of money and finance: the need to better account for the dynamics of the financial sector has been widely discussed after the 2007–08 Great Financial Crisis, yet the discussion has only slightly permeated the field of climate economics so far (Mercure et al (2019)). A more central role is often attributed to finance in non-equilibrium models, particularly in the post-Keynesian school of thought through stock-flow consistent models: money is created by banks in response to demand for loans, and therefore investments are not constrained by existing savings (Graph 5.A). This may better represent the behavioural dynamics of financial institutions than DSGE (Dafermos et al (2017)), especially when merged with agent-based models (Monasterolo et al (2019)). For instance, financial institutions can expand lending and investments in times of economic optimism and restrict them when the perceived risk of default is too high, including because of climate-related issues.

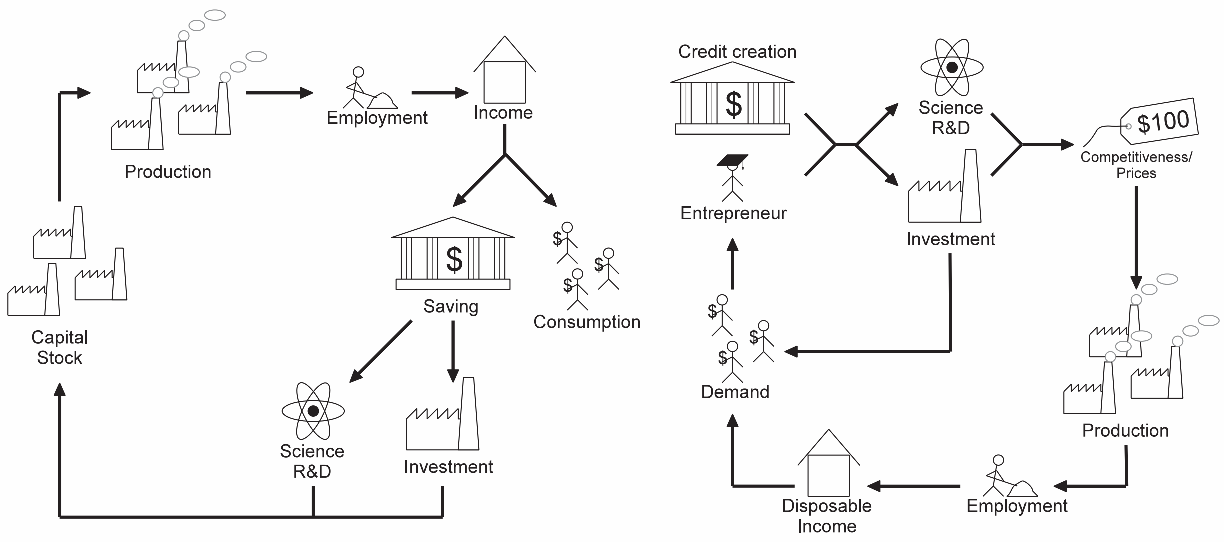
3. Role of energy: standard economic theory, based on the cost share of energy in GDP, implies that a decrease in energy use reduces GDP but only to a limited extent. For instance, as energy costs typically represent less than 10% of GDP, a 10% reduction in energy use would lead to a loss in GDP of less than 1% (Batten (2018, p 28)). However, a growing literature suggests that the role of energy in production should not be treated as a third input independently from labour and capital (as in three-factor Cobb-Douglas production functions) but through a different "epistemological perspective" (Keen et al (2019)): energy is an input to labour and capital, without which production becomes impossible (Ayres (2016)). In this view, an improvement in energy efficiency may paradoxically lead (all other things being equal) to a sharp decrease in GDP. Given the critical role of energy for the transition, non-equilibrium models that can account for the peculiar role of energy in economics (Ayres (2016), Keen et al (2019), The Shift Project and IFPEN (2019)) may be critical for future scenario-based analysis.

Alternative models

Graph 5.A

Supply-led / Equilibrium

Demand-led / Non-equilibrium



Source: Mercure et al (2019).

Sensitivity analysis:

Conducting relatively simple scenario-based risk assessments, also called sensitivity analyses, may be another approach to capture some features of climate-related risks, especially transition risks. Sensitivity analyses "represent a fast and easy method for assessing the sensitivity of a portfolio to a given risk" (DG Treasury et al (2017, p 67)) and they do not need to rely on complex scenarios. The methodological difficulties related to scenario-based models "argue in favor of sensitivity analyses that measure the impact of a shock without necessarily incorporating it into a comprehensive scenario" (DG Treasury et al (2017, p 6)).

An example of such sensitivity analysis is ICBC (2016): the bank subjected firms in two sectors of its portfolio, thermal power and cement, to a selection of heavy, medium and light environmental stresses (tighter atmospheric pollution emissions limits for thermal power; tighter atmospheric pollutant emissions and discharges for cement). The test was carried out assuming that all other things remain equal, ie without factoring in the macroeconomic effects of such measures (eg carbon leakage to neighbouring countries). It estimated:

– The impacts of these regulatory shocks on the firms' costs, prices and quantity sold under each scenario;

– How credit ratings would be impacted;

– The possible changes in the firm credit rating and probability of default, and derived the change in the non-performing loan (NPL) ratio.

The recent climate stress test conducted by the UK's Prudential Regulation Authority (PRA (2019a)) takes a similar approach. The PRA translated three broad categories of climate scenarios (sudden and disorderly transition; progressive and orderly transition; no transition) into impacts on the asset side of insurance companies' balance sheets by applying a negative shock to the value of some companies they have in their investment portfolios. For instance, as part of the sudden and disorderly scenario (see Scenario A in Table 5.A), general insurance companies are required to simulate the impact of a valuation shock on their power generation firms (–65% for the coal sector, –35% for oil, –20% for gas, and +10% for renewable energy). Different shocks are applied to several sectors, such as fuel extraction (see below) but also transport, utilities, agriculture and real estate.

The PRA recognises that "the development of hypothetical values affecting investments are based on the interpretation of available literature by the PRA and discussions with specialists in the field" (PRA (2019a, p 50)), including several of the methodologies mentioned above. That is, the valuation shocks correspond to a coherent narrative aimed at signalling potential risks to financial institutions, rather than an attempt at precise modelling of the valuation shock.

Sensitivity analysis

Table 5.A

Sector	% of investment portfolio in following sectors	Assumptions	Transition risk			Physical risk		
			Scenario			Scenario		
			A	B	C	A	B	C
Fuel extraction	Gas/coal/oil (incl crude)	Change in equity value for sections of the investment portfolio comprising material exposure to the energy sector as below						
		Coal	–45%	–40%				
		Oil	–42%	–38%				
		Gas	–25%	–15%				
							–5%	–20%
Power generation		Coal	–65%	–55%				
		Oil	–35%	–30%				
		Gas	–20%	–15%				
		Renewables (incl nuclear)	+10%	+20%				
							–5%	–20%

Source: PRA (2019a).

Case studies:

A third avenue for forward-looking analyses in the presence of climate uncertainty consists in assessing the potential impacts of a climate-related transition or physical shock on one specific sector or region. This can provide a level of analysis that stands in between scenario analysis (which lacks granularity and suffers from many sources of uncertainty) and sensitivity analysis (which lacks a systemic view).

Along these lines, Huxham et al (2019) assess the transition risks for the South African economy in a scenario consistent with temperature rises well below 2°C above pre-industrial levels, by examining potential impacts of a reduction in demand and price of energy sources such as coal (which provides 91% of South African electricity and significantly contributes to the country's export revenues). For instance, infrastructure that supports carbon-intensive activities such as power plants and port infrastructure may have to be replaced or retired early, companies (assessed on an individual basis) and investors could be hurt and could lay off workers, leading to reduced demand for certain products. Governments could face lower tax revenues while also having to deal with increasing expenditures related to industries and workers in transition.

One advantage of such studies is that they can explore the vulnerability of firms and sovereigns to potential economic policies within a limited perimeter, which enables greater transparency regarding the assumptions made and greater detail in the narratives chosen. For instance, the South African case study considers the impact of government policies shifting fiscal incentives from climate-vulnerable sectors to low-carbon activities, and the support from international development finance institutions in this process.

4. POLICY RESPONSES – CENTRAL BANKS AS COORDINATING AGENTS IN THE AGE OF CLIMATE UNCERTAINTY

Rien n'est plus puissant qu'une idée dont l'heure est venue ("There is nothing more powerful than an idea whose time has come").

Attributed to Victor Hugo

Acknowledging the limitations of risk-based approaches and embracing the deep uncertainty at stake suggests that central banks may inevitably be led into uncharted waters in the age of climate change. On the one hand, they cannot resort to simply measuring risks (hoping that this will catalyse sufficient action from all players) and wait for other government agencies to jump into action: this could expose central banks to the real risk that they will not be able to deliver on their mandates of financial and price stability. In the worst case scenario, central banks may have to intervene as climate rescuers of last resort or as some sort of collective insurer for climate damages. For example, a new financial crisis caused by such "green swan" events severely affecting the financial health of the banking and insurance sectors could put central banks under pressure to buy their large set of assets devalued by physical or transition impacts.

But there is a key difference from an ordinary financial crisis, because the accumulation of atmospheric CO_2 beyond certain thresholds can lead to irreversible impacts, meaning that the biophysical causes of the crisis will be difficult if not impossible to undo at a later stage. While banks in financial distress in an ordinary crisis can be resolved, this will be far more difficult in the case of economies that are no longer viable because of climate change. A potential intervention as climate rescuer of last resort would then expose in a painful manner the limited substitutability between financial and natural capital, and therefore affect the credibility of central banks.

On the other hand, central banks cannot succumb to the growing social demand arguing that, given the severity of climate-related risks and the role played by central banks following the 2007–08 Great Financial Crisis, central banks could now substitute for many (if not all) government interventions. For instance, pressures have grown to have central banks engage in different versions of "green quantitative easing" in order to "solve" the complex socioeconomic problems related to a low-carbon transition. However, the proactive use of central bank balance sheets is highly politically controversial and would at the very least require rethinking the role of central banks with a historical perspective. Goodhart (2010) argues that central banks have had changing functional roles throughout history, alternating between price stability, financial stability and support of the State's financing in times of crisis. Central bankers in advanced economies have grounded their actions around the first role (price stability) over the past decades, and increasingly around the second role (financial stability) since the 2007–08 Great Financial Crisis. Proposals concerning "green quantitative easing" could be seen as an attempt to define a third role through a more explicit and active support of green fiscal policy.

Without denying the reality of evolutionary perspectives on central banking (eg Aglietta et al (2016), Goodhart (2010), Johnson (2016), Monnet (2014)) and the fact that climate change could perhaps be the catalyst of new evolutions, the focus on central banks as the main agents of the transition is risky for many reasons, including potential market distortions and the risk of overburdening central banks' existing mandates (Villeroy de Galhau (2019a), Weidmann (2019)). More fundamentally, mandates can evolve but these changes in mandates and institutional arrangements are also very complex issues because they require new sociopolitical equilibria, reputation and credibility. Central bankers are not elected officials and they should not replace or bypass the necessary debates in civil society (Volz (2017)). From a much more pragmatic perspective, mitigating climate change requires a combination of fiscal, industrial and land planning policies (to name just a few) on which central banks have no experience.

To overcome this deadlock, we advocate a third position: without aiming to replace policymakers and other institutions, central banks must also be more proactive in calling for broader and coordinated change, in order to continue fulfilling their own mandates of financial and price stability over longer time horizons than those traditionally considered. The risks posed by climate change offer central banks a special perspective that private players and policymakers cannot necessarily adopt given their respective interests and time horizons. In that context, central banks have an advantage in terms of proposing new policies associated with new actions, in order to contribute to the societal debates that are needed. We believe that they can best contribute to this task in a role that we call the five Cs: **c**ontribute to **c**oordination to **c**ombat **c**limate **c**hange. This coordinating role would require thinking concomitantly within three paradigmatic approaches to climate change and financial stability: the "risk", "time horizon" and "system resilience" approaches (see Table 3).

Embracing deep or radical uncertainty therefore calls for a second "epistemological break" to shift from a management of risks approach to one that seeks to assure the resilience of complex adaptive systems in the face of such uncertainty (Fath et al (2015), Schoon and van der Leeuw (2015)).[38] In this view, the current efforts aimed at measuring, managing and supervising climate-related risks will only make sense if they take place within a much broader evolution involving coordination with monetary and fiscal authorities, as well as broader societal changes such as a better integration of sustainability into financial and economic decision-making.

Importantly, central banks can engage in this debate not by stepping out of their role but precisely with the objective of preserving it. In other words, even though some of the actions required do not fall within the remit of central banks and supervisors, they are of direct interest to them insofar as they can enable them to fulfil their mandates in an era of climate-related uncertainty.

This chapter explores some potential actions that are needed precisely to preserve the mandate and credibility of central banks, regulators and supervisors in the long term. The purpose here is not to provide an optimal policy mix, but rather to contribute to the emerging field of climate and financial stability from the perspective of deep or radical uncertainty. We suggest two broad ranges of measures. First, as detailed in Chapter 4.1, we recall that central banks, supervisors and regulators have a role to play through prudential regulation related to their financial stability mandate. However, while assessing and supervising climate-related risks is essential, it should be part of a much broader political response aimed at eliminating the economy's dependence on carbon-intensive activities, where central banks cannot and should not become the only players to step forward.

We then suggest and critically discuss four non-exhaustive propositions[39] that could contribute to guaranteeing system resilience and therefore financial stability in the face of climate uncertainty: (i) Beyond climate-related risk management, central banks can themselves and through their relationship with their financial sectors proactively promote long-termism by supporting the *values* or *ideals* of sustainable finance in order to "break the tragedy of the horizon" (Chapter 4.2); (ii) Better coordination of fiscal, monetary and prudential and carbon regulations is essential to successfully support an environmental transition, especially at the zero lower bound (Chapter 4.3); (iii) Increased international cooperation on environmental issues among monetary and financial authorities will be essential (Chapter 4.4); (iv) More systematic integration of climate and sustainability dimensions within corporate

[38] This system resilience view holds that: (i) new analytical frameworks are needed to represent the interactions between humans and their natural environment; (ii) these interactions need transdisciplinary approaches (rather than multidisciplinary ones where each discipline continues to adhere to its own views when approaching another discipline requiring a different paradigm); and (iii) open systems are generally not in equilibrium, ie their behaviour is adaptive and dependent upon multiple evolving interactions.

[39] In particular, "command and control" policies are not discussed (given that their implementation tends to depend on specific national and subnational factors), although they also probably have a critical role to play in the transition.

and national accounting frameworks can also help private and public players manage environmental risks (Chapter 4.5). Some potential obstacles related to each proposition are also discussed.

We do not touch on carbon pricing not because we think it is not important. On the contrary, we take it as given that higher and more extensive carbon pricing is an essential part of the policy mix going forward, and that it will become both more politically accepted and more economically efficient if the other measures outlined here are implemented.

The five Cs – contribute to coordination to combat climate change:
The "risk", "time horizon" and "system resilience" approaches

Table 3

Responsibilities / Paradigmatic approach to climate change	Measures to be considered[1] by central banks, regulators and supervisors	Measures to be implemented by other players[2] (government, private sector, civil society)
Identification and management of climate-related risks **>> Focus on risks**	Integration of climate-related risks (given the availability of adequate forward-looking methodologies) into: – Prudential regulation – Financial stability monitoring	– Voluntary disclosure of climate-related risks by the private sector (TCFD) – Mandatory disclosure of climate-related risks and other relevant information (eg French Article 173, taxonomy of "green" and "brown" activities)
Limitations: – Epistemological and methodological obstacles to the development of consistent scenarios at the macroeconomic, sectoral and infra-sectoral levels – Climate-related risks will remain unhedgeable as long as system-wide transformations are not undertaken		
Internalisation of externalities **>> Focus on time horizon**	Promotion of long-termism as a tool to break the tragedy of the horizon, including by: – Integrating ESG into central banks' own portfolios – Exploring the potential impacts of sustainable approaches in the conduct of financial stability policies, when deemed compatible with existing mandates	– Carbon pricing – Systematisation of ESG practices in the private sector
Limitations: – Central banks' isolated actions would be insufficient to reallocate capital at the speed and scale required, and could have unintended consequences – Limits of carbon pricing and of internalisation of externalities in general: not sufficient to reverse existing inertia/generate the necessary structural transformation of the global socioeconomic system		

Structural transformation towards an inclusive and low-carbon global economic system **>> Focus on resilience of complex adaptive systems in the face of uncertainty**	Acknowledgment of deep uncertainty and need for structural change to preserve long-term climate and financial stability, including by exploring: – "Green" monetary-fiscal-prudential coordination at the effective lower bound – The role of non-equilibrium models and qualitative approaches to better capture the complex and uncertain interactions between climate and socioeconomic systems – Potential reforms of the international monetary and financial system, grounded in the concept of climate and financial stability as interconnected public goods	– Green fiscal policy (enabled or facilitated by low interest rates) – Societal debates on the potential need to revisit policy mixes (fiscal-monetary-prudential) given the climate and broader ecological imperatives ahead – Integration of natural capital into national and corporate accounting systems – Integration of climate stability as a public good to be supported by the international monetary and financial system

[1] Considering these measures does not imply full support to their immediate implementation. Nuances and potential limitations are discussed in the book. [2] Measures deemed essential to achieve climate and financial stability, yet which lie beyond the scope of what central banks, regulators and supervisors can do.

Source: Authors' elaboration.

4.1 Integrating climate-related risks into prudential supervision – insights and challenges

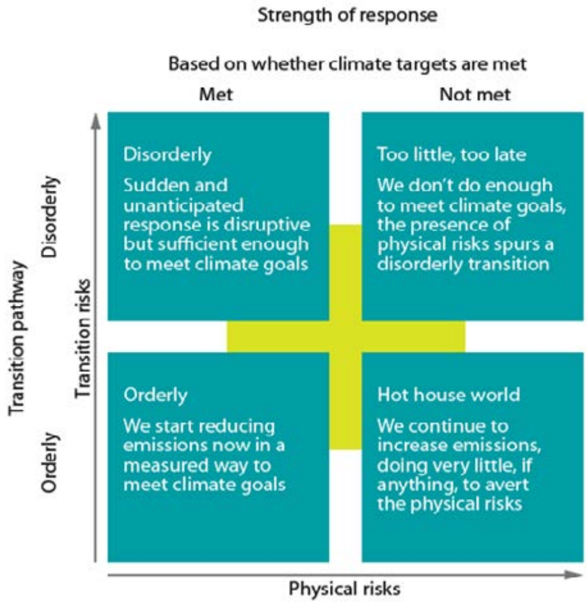
While acknowledging the methodological challenges associated with measuring climate-related risks and the need for alternative approaches (Chapter 3.5), central banks and supervisors should keep pushing for climate-related risks to be integrated into both financial stability monitoring and micro-supervision (NGFS (2019a, p 4)).

The first task, assessing the size of climate-related risks in the financial system, requires developing new analytical tools, for example by integrating climate scenarios into regular stress tests. In the same way that stress tests are conducted by regulatory authorities to assess the resilience of banking institutions in an adverse macro-financial scenario (Borio et al (2014)), proposals have been made over the past years to develop so-called "climate stress-tests" (eg ESRB (2016), Regelink et al (2017), Schoenmaker and Tilburg (2016), UNEP-FI (2019)). Some central banks, regulators and supervisors have already started to consider or develop climate risk scenario analyses for stress tests (Vermeulen et al (2018, 2019), EBA (2019), EIOPA (2019), PRA (2019a), Allen et al (2020)).

In practice, a stress test focusing on the physical risks of climate change (bottom-right scenario in Graph 15), which typically involves projections over several decades, seems particularly difficult to reconcile with the relatively short-term period considered under traditional stress tests (DG Treasury et al (2017, p 19)). In contrast, a climate stress test seems more adapted to manage abrupt transition risks (top-left scenario in Graph 15) that may occur over a relatively short-term horizon compatible with traditional stress tests.

In theory, if climate stress tests find that climate-related risks are material, systemic capital buffers could be applied to mitigate the exposure to climate-related risks (ESRB (2016)). In practice, the main use of these scenarios at this stage is to help financial institutions familiarise themselves with such exercises (Cleary (2019)) and to potentially create catalytic change as well as gaining experience through "learning by doing". A key task for supervisors is to establish a set of reference scenarios that could be used for climate stress tests, while identifying and disclosing the key sources of uncertainty attached to each scenario, as well as leaving flexibility for users to modify the assumptions and parameters of the scenario as deemed appropriate to their national and regional context.

Four representative high-level scenarios for climate stress tests — Graph 15



Source: NGFS (2019a).

The second task for central banks and supervisors consists in ensuring that climate-related risks are well incorporated into individual financial institutions' strategies and risk management procedures. In addition to initiatives based on the voluntary disclosure of climate-related risks such as the Task Force on Climate-related Financial Disclosures (TCFD), it is increasingly accepted that mandatory disclosure should be implemented to strengthen and systematise the integration of climate-related risks. Financial institutions should better understand climate-related risks and consider them in their risk management procedures and investment decisions, as well as in their longer-term strategies (NGFS (2019a)).

Discussions have emerged with regard to how the three pillars of the Basel Framework could integrate climate-related risks:[40]

[40] In the absence of a carbon price, it has also been suggested that the structure of capital of non-financial firms could be adjusted to reflect their exposure to climate-related risks (ESRB (2016), Bolton and Samama (2012)). If both financial institutions and non-financial firms need to align their capital requirements to their exposure to climate-related risks, the cost of capital could increase for non-financial firms and lead financial firms to assess risks differently. However, such an idea would necessitate much more careful analysis and would not necessarily fall under the remit of central banks and supervisors.

– *Pillar 1 on minimum capital requirements:* If being exposed to climate-related risks is seen as part of financial risks, then it might be appropriate to consider capital requirements to reflect such risks. In this respect, proposals have emerged in favour of either a "green supporting factor" (which would reduce capital requirements for banks with lower exposure to climate-related risks) or a "brown penalising factor", which would increase capital requirements for banks with higher exposure to exposed sectors (Thöma and Hilke (2018)). Although additional research is needed, it seems that discussions are evolving towards favouring a "brown penalising factor" as more appropriate. Exposure to "brown" assets can increase financial risks, but it is not obvious why being exposed to "green" sectors would necessarily reduce non-climate-related financial risks, and thereby justify lower capital requirements. In any case, regulations based on distinguishing "green" from "brown" assets require working on an agreed upon "taxonomy", defining which assets can be considered "green" (or "brown" if the goal is to penalise exposure to fossil fuels). China has already established a definition for green loans and the European Commission has tabled a legislative proposal to develop such a taxonomy (NGFS (2019a)). It is noteworthy that such a classification is not exempt from conflicting views over what is "green" (Husson-Traoré (2019)), and that classifications could differ significantly from one country or region to another.[41] Even more fundamentally, it should be recalled that the "greenness" or "brownness" of assets do not necessarily correspond to their vulnerability to climate-related risks. For instance, "green" assets are subject to both transition risks (eg because of the technological and regulatory[42] uncertainty related to the transition) and physical risks (eg a renewable power plant could be impacted by extreme weather events);

– *Pillar 2 on the supervision of institutions' risk management:* Regulators could prescribe additional capital on a case by case basis*, for instance* if a financial institution does not adequately monitor and manage climate-related risks. This would first require new expectations to be set in this regard. For instance, banks and insurers in the United Kingdom are now required to allocate responsibility for identifying and managing climate-related risks to senior management functions (PRA (2019b)). And Brazil's central bank requires commercial banks to incorporate environmental risks into their governance framework (FEBRABAN (2014));

– *Pillar 3 on disclosure requirements:* Supervisory authorities can contribute to improving the pricing of climate-related risks and to a more efficient allocation of capital by requiring more systematised disclosure of climate-related risks. As indicated in the NGFS first comprehensive report, "authorities can set out their expectations when it comes to financial firms' transparency on climate-related issues" (NGFS (2019a, p 27)). For this to happen, guidance is needed to ensure a more systematic, consistent and transparent disclosure of climate-related risks. Some regulators and supervisors have already paved the way for such systematic disclosure. Article 173 of the French Law on Energy Transition for Green Growth (*loi relative à la transition énergétique pour la croissance verte,* 2015) requires financial and non-financial firms to disclose the climate-related risks they are exposed to and how they seek to manage them.[43] In doing so, Article 173 encourages financial sector firms to become increasingly aware of how climate change can affect

41 For instance, "green coal" or nuclear energy are subject to diverging interpretations from one jurisdiction to another. Moreover, the fact that an activity is deemed "green" does not necessarily mean that it is less risky: as discussed in the previous chapter, the uncertainty regarding future technologies is such that some "green" sectors and technologies may not succeed in the transition. It is therefore important to keep in mind that taxonomies cannot replace or be conflated with a climate-related risk analysis, although the two topics are often discussed together.

42 For instance, renewable energy capacity can be affected by a change in feed-in tariffs. "Feed-in tariff" refers to a policy instrument offering long-term contracts to renewable energy producers (households or businesses).

43 Paragraph V of Article 173 requires banks to identify and disclose their climate-related risks and tasks the French government with providing guidance on the implementation of a scenario to conduct climate stress tests on a regular basis; paragraph VI requires institutional investors and asset managers to report on the integration of ESG (environmental, social and governance) criteria and climate-related risks into their investment decision processes (DG Treasury et al (2017)).

their risk management processes and supervising authorities to follow these developments closely (ACPR (2019)). And the European Commission has set up a Technical Expert Group (TEG) on sustainable finance that seeks, among other things, to provide guidance on how to improve corporate disclosure of climate-related risks (UNEP-FI (2019)).

Some developing and emerging economies have already started developing climate-related regulations (see D'Orazio and Popoyan (2019)), although no measures on capital requirements have yet been implemented. Different categories of intervention can be found across developing and emerging economies (Dikau and Ryan-Collins (2017)), such as credit guidance (Bezemer et al (2018)), which reflects the often broader mandate of central banks in these countries. For instance, commercial banks and non-bank financial institutions in Bangladesh are required to allocate 5% of their total loan portfolio to green sectors (Dikau and Ryan-Collins (2017)). Other countries such as China and Lebanon have established (or are in the process establishing) differentiated reserve requirements in proportion to local banks' lending to green sectors (D'Orazio and Popoyan (2019)).

The potential impacts of climate-related prudential regulation remain unclear. Most of the proposals discussed above remain subject to accurately assessing climate-related risks, as discussed in Chapter 3. More fundamentally, the role of prudential policy is to mitigate excessive financial risks on the level of individual financial institutions and the financial system as a whole, not to reconfigure the productive structures of the economy (ESRB (2016)); nevertheless, the latter is precisely what is needed to mitigate climate-related risks. The SME Supporting Factor introduced in the European Union in 2014 (reducing capital requirements for loans to small and medium-sized enterprises) does not seem to have generated major changes in bank lending to SMEs (EBA (2016), Mayordomo and Rodríguez-Moreno (2017)), although it demanded far less structural transformation than decarbonising our global economic system. Hence, adopting climate-related prudential regulations such as additional capital buffers may only very partially contribute to hedging financial institutions from "green swan" events.

Perhaps even more problematically, trade-offs could appear between short-term and long-term financial stability in the case of ambitious transition pathways. As stated by Bank of England Governor Mark Carney (Carney (2016)), the "paradox is that success is failure": extremely rapid and ambitious measures may be the most desirable from the point of view of climate change mitigation, but not from the perspective of financial stability over a short-term horizon. Minimising the occurrence of "green swan" events therefore requires a more holistic approach to climate-related risks, as discussed in the rest of this chapter.

4.2 Promoting sustainability as a tool to break the tragedy of the horizon – the role of values

Beyond approaches based strictly on risks, central banks and supervisors can help disseminate the adoption of so-called environmental, social and governance (ESG) standards in the financial sector, especially among pension funds and other asset managers.[44] The definition of ESG criteria and their integration into investment decisions can vary greatly from one institution to another, but it generally involves structuring a portfolio (of loans, bonds, equities, etc) in a way that aims to deliver a blend of financial, social and environmental benefits (Emerson and Freundlich (2012)). ESG-based asset allocation has grown steadily over the past years, and now funds that consider ESG in one form or another total $30.7 trillion of assets under management.[45]

[44] As stated by the NGFS, central banks and supervisors "may lead by example by integrating sustainable investment criteria into their portfolio management (pension funds, own accounts and foreign reserves), without prejudice to their mandates" (NGFS (2019a, p 28)).

[45] Estimated by the Global Sustainable Investment Alliance (2019).

Some central banks have also started to lead by example by integrating sustainability factors into their own portfolio management. For instance, the Banque de France and Netherlands Central Bank have adopted a Responsible Investment Charter for the management of own funds as well as pension portfolios, and are in the process of integrating ESG criteria into their asset management. Moreover, central banks are increasingly looking at "green" financial instruments as an additional tool for their foreign exchange (FX) reserve management. In a context of a prolonged period of low returns on the traditional safe assets (eg negative yields on a significant portion of government fixed income instruments), the requirements of liquidity, return and sustainability/safety need to be gauged against the properties of these new instruments. The eligibility of green bonds as a reserve asset will depend on several evolving factors such as their outstanding amount (still relatively small) and their risk-return profile. Fender et al (2019) suggest that the results of an illustrative portfolio construction exercise show that including both green and conventional bonds can help generate diversification benefits and hence improve the risk-adjusted returns of traditional government bond portfolios.

This being said, one should not confuse ESG- or green-tilted portfolios with hedging climate-related risks. As a general matter, ESG and green filters consider the impact of a firm on its environment rather than the potential impacts of climate change on the risk profile of the firm (UNEP-FI (2019)). Moreover, the integration of ESG metrics with pure risk-return considerations is far from straightforward. Some studies find that ESG and socially responsible investment (SRI) can enhance financial performance and/or reduce volatility (eg Friede et al (2015)), while others find that divesting from controversial stocks reduces financial performance (eg Trinks and Scholtens (2017)). Revelli and Viviani's (2015) meta-analysis of 85 papers finds that the consideration of sustainability criteria in stock market portfolios "is neither a weakness nor a strength compared with conventional investments", and that results vary considerably depending on the thematic approach or the investment horizon among other factors.

The main benefit of promoting a sustainable finance approach, including through ESG, may actually not lie in the greater impetus for asset managers to reduce their exposure to climate-related risks, but rather in broadening the set of values driving the financial sector. The financial industry has in recent decades mostly focused on financial risks and returns, and has often been criticised for its increased short-termism. By accepting potentially lower financial returns in the short run to ameliorate longer-term social and environmental results, time can be valued in a manner that better corresponds to environmental systems' "own patterns of time sequences for interactions among parts, abilities to absorb inputs, or produce more resources" (Fullwiler (2015, p 14)). This can promote long-termism in the financial sector and thereby contribute to overcoming the "tragedy of the horizon" (and therefore indirectly reduce climate-related risks). As such, the recent rise in the sustainable finance movement may offer "an opportunity to build a more general theory of finance" (Fullwiler (2015)) that would seek to balance risk-return considerations with longer-term social and environmental outcomes.

An additional ambitious and controversial proposal is to apply climate-related considerations to central banks' collateral framework. The goal of this proposal is not that central banks should step out of their traditional role when implementing monetary policies, but rather to recognise that the current implementation of market neutrality, because of its implicit bias in favour of carbon-intensive industries (Matikainen et al (2017), Jourdan and Kalinowski (2019)) could end up affecting central banks' very own mandates in the medium to long term. Honohan (2019) argues that central banks' independence will be more threatened by staying away from greening their interventions than by carefully paying attention to their secondary mandates such as climate change. Thus, and subject to safeguarding the ability to implement monetary policy, a sustainable tilt in the collateral framework could actually contribute to reducing financial risk, ie it would favour market neutrality over a longer time horizon (van Lerven and Ryan-Collins (2017)).

In this spirit, several proposals and initiatives have started to emerge. For instance, Monnin (2018) relies on a specific climate-related risks methodology to measure how the European Central Bank's corporate sector purchase programme (CSPP, which stood at €176 billion as of November 2018) could have differed from the current model if assessment of climate-related risks had been conducted. The study finds that about 5% of the issuers within the ECB's CSPP portfolio would fall out of the investment grade category if climate-related risks were factored in. The author suggests that the ECB could integrate such procedures not only into its unconventional monetary policies but also into its collateral framework. Following a simpler approach for the management of its FX reserves, the Swedish central bank recently decided to reject issuers with a "large climate footprint" (Flodén (2019)), for instance by selling bonds issued by a Canadian province and two Australian states.

Although legal opinions have yet to be issued on this matter, it appears that in many cases central banks already do have a legal mandate for considering the type of assets to use as collateral when implementing monetary policy. For instance, in the case of the Eurosystem the primary responsibility of central banks is to maintain price stability, with a secondary responsibility to support economic growth. In turn, the definition of economic growth by the European Union includes the sustainable development of Europe (Schoenmaker (2019)). The mandates of several central banks other than the ECB also include broader socioeconomic goals than price stability (Dikau and Volz (2019)).

However, the potential impact of such actions is still under debate and needs a cautious approach. It is true that a reweighting of eligible collateral towards low-carbon assets is likely to reduce the credit spread of newly eligible companies (Mésonnier et al (2017)) and to provide a powerful signalling effect to other financial market participants (Braun (2018), Schoenmaker (2019)). Nevertheless, the main challenge in the short run with regard to climate change is not the cost of credit of green projects but their insufficient number in the first place. It is therefore not entirely obvious how large an effect the greening of central banks' collateral framework could have. In fact, the ECB has already bought almost one quarter of the eligible public sector green bonds and one fifth of the eligible corporate green bonds (Cœuré (2018)). This may have already encouraged more issuers to sell green debt (Stubbington and Arnold (2019)), yet central bank monetary operations are clearly insufficient and do not even seek to trigger structural changes in the "real economy". Even if central bank actions could lead to downgrading of the price of carbon-intensive assets that are not compatible with a low-carbon trajectory, only climate policy can ensure that they simply disappear.

Governments could play a much more critical role in supporting sustainable investments. In this respect, it is noteworthy that the European Commission's (2018) action plan on sustainable finance also seeks to mainstream sustainability into investment decisions, and promote "long termism" among financial institutions. Many measures could be taken in this regard. For instance, the French Economic, Social and Environmental Council (ESEC (2019)) recommends that household savings should be channelled towards long-term sustainable investments through fiscal incentives (see also Aussilloux and Espagne (2017)). And Lepetit et al (2019) further recommend offering a public guarantee on all household savings channelled to long-term SRI vehicles (and certified as such). Therefore, even if investments in a low-carbon economy were to provide lower returns and/or returns over a longer time horizon than current market expectations (Grandjean and Martini (2016)), those could then be partially offset by a lower risk for households.

4.3 Coordinating prudential regulation and monetary policy with fiscal policy – Green New Deal and beyond

In addition to promoting sustainable investments, direct government expenditures will also be an opportunity to develop new technologies in a timely fashion and to regulate their use in ways that guarantee lower-carbon production and consumption patterns (eg by avoiding rebound effects in the transportation sector, as discussed above). This is not a reason for central banks not to address climate change; rather, it is a simple observation of the fact that fiscal policies are key to climate change mitigation and that prudential and monetary tools can only complement these policies (Krogstrup and Oman (2019)). Indeed, the public sector is usually in a better position to fund investments in R&D for early-stage technologies with uncertain and long-term returns. In a series of case studies across different sectors (eg nanotech and biotech), Mazzucato (2015) has shown how government investment in high-risk projects has proved essential to create the conditions for private investments to follow.

Sustainable public infrastructure investments are also fundamental as they lock in carbon emissions for a long time (Arezki et al (2016), Krogstrup and Oman (2019)). They can provide alternative means of production and consumption, which would then enable economic agents to change their behaviour more effectively in response to a carbon price (Fay et al (2015), Krogstrup and Oman (2019)). Indeed, carbon prices alone may not suffice to shift individual behaviour and firms' replacement of physical capital towards low-carbon alternatives until infrastructures suited for alternative energies are in place. For instance, building an efficient public transit system may be a precondition to effective taxation of individual car use in urban areas.

It is noteworthy that under this approach, government action would not seek to manage climate-related risks optimally but rather to steer markets "in broadly the right direction" (Ryan-Collins (2019)). In turn, such a proactive shift in policymaking could lead market players to reassess the risks related to climate change. Public investments in the low-carbon transition could "become the next big technological and market opportunity, stimulating and leading private and public investment" (Mazzucato and Perez (2015)), and potentially create millions of jobs that could compensate for those that might be lost due to the changes in labour markets caused by technological progress (Pereira da Silva (2019a)).

In spite of a rapidly growing literature pointing towards better coordination between fiscal, monetary and prudential regulation, arguments regarding the optimal climate policy mix remain scarce. However, and as a general matter, fiscal tools are critical to accelerate the transition, whereas prudential and monetary tools can mostly support and complement them (Krogstrup and Oman (2019)). Public banks may also have an important role to play in providing a significant part of the long-term funding needed for the transition (Aglietta and Espagne (2016), Campiglio (2016), Marois and Güngen (2019)). In this regard, the European Investment Bank (EIB (2019)) announcement that it will cease financing fossil fuel energy projects by the end of 2021 could be a major landmark.

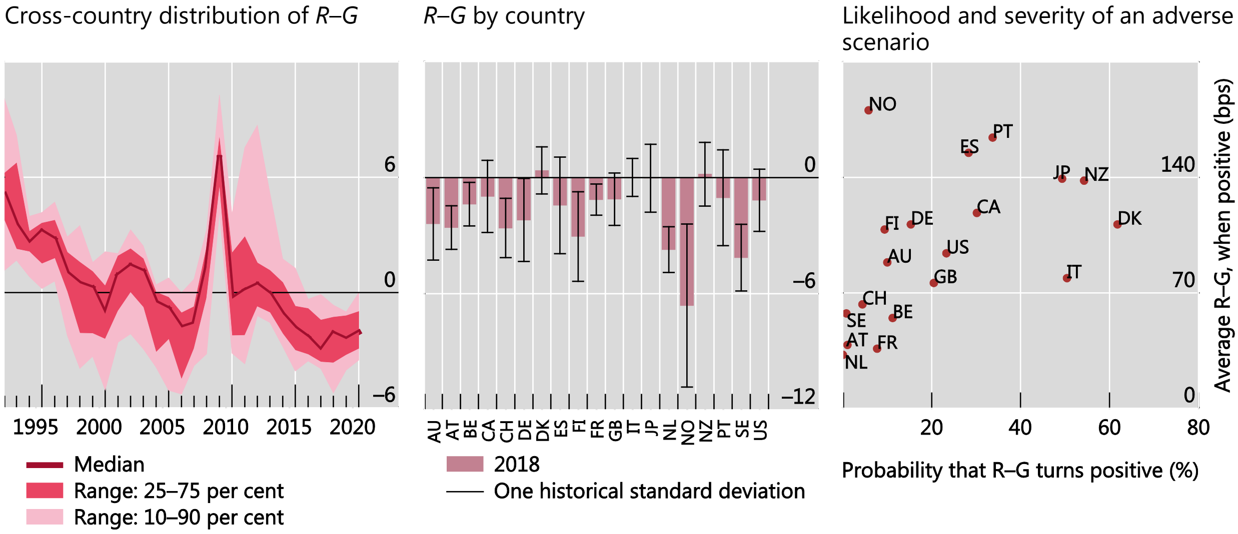
The key question that has arisen with regard to fiscal policy is that of how governments could fund such investments, and what kind of policy mix this could entail. Revisiting the nature of the interactions between fiscal and monetary policy (and prudential regulation) is precisely what has been suggested by some proponents of a Green New Deal in the United States (eg Kelton (2019), Macquarie (2019)), which partly relies on Modern Monetary Theory (MMT), also known as Neo-Chartalism. One key argument of MMT is that currency is a public monopoly for any government, as long as it issues debts in its own currency and maintains floating exchange rates. Following that reasoning, the sovereign could use money creation to achieve full employment (or a climate-related objective) by a straightforward financing of economic activity. The obvious risk of inflation can be addressed subsequently by raising taxes and issuing bonds as the policy goes to remove excess liquidity from the system. A government that by definition issues its own money cannot be forced to default on debt denominated in its own currency. The major underlying assumption is therefore that of "seigniorage without limits": governments can incur deficit spending "without" limits other than those imposed by biophysical scarcity, without automatically generating inflation (Wray (2012)). MMT scholars are generally considered to be outliers in the broader post-Keynesian school, and some of their claims related to the unlimited spending power of governments have been criticised by other post-Keynesian or closely related authors (Lavoie (2013), Palley (2019)). Some of them have suggested more traditional green countercyclical fiscal and monetary policy instead (Harris (2013), Jackson (2017)). Other commentators have pointed out (Summers (2019a), Krugman (since 2011, but more recently 2019)), that MMT poses significant problems. It would undermine the complex set of institutional and contractual arrangements that have maintained price and financial stability in our societies. Moreover, numerous experiments in the history of hyperinflation in advanced economies and mostly in developing countries show that, while outright default in a country's own central bank currency might be avoided, the value of domestic assets including money could be reduced to almost zero.

From a very different perspective, and without sharing the conceptual premises of MMT, several economists have recently argued that financing the low-carbon transition with public debt is both politically more feasible than through carbon taxation and economically more sustainable in the current low interest rate environment, which provides several countries with a larger than previously anticipated fiscal room for manoeuvre (Bernanke (2017), Borio and Song Shin (2019), DeLong and Summers (2012), Blanchard (2019), Summers (2019b)). McCulley and Pozsar (2013) suggest that what matters in times of crisis is not monetary stimulus per se but whether monetary policy helps the fiscal authority maintain stimulus. In this respect, the fact that central banks in advanced economies are globally setting interest rates near or even below zero at a time where massive investments are needed is probably the greatest contribution from central banks to governments' capability to play their role in combating climate change.

As zero or negative interest rates may remain in place for a long period (Turner (2019)), financing the transition to a low-carbon economy via government debt presents fewer risks and would not threaten the mandate of central banks, as long as private and public debt growth continues to be closely monitored and regulated (Adrian and Natalucci (2019)) and there is fiscal space. When it is measured by the cost of servicing debt (*R*) minus the output growth (*G*) rate or (*R* – *G*) to assess the sustainability of debt-to-GDP, there is room in many advanced economies. Over the last 25 years there has been a secular downward trend in government funding costs relative to nominal growth. Graph 16 shows that the difference between government effective funding costs and nominal growth became negative for the median advanced economy around 2013 (left-hand panel) and has since then gone deeper and deeper into negative territory. And, according to the most recent data available (2018), almost all advanced economies now pay an effective interest cost of debt that is below their nominal GDP growth rate. In particular, lower funding costs for the government mean that previously accumulated debts will be cheaper to refinance than previously expected. That is, lower government funding costs mean that the primary balance required to stabilise public debt as a ratio of GDP also falls, down to the point where governments could even run primary deficits while keeping public debt (as a share of GDP) constant.

Government interest burden and snapback risk

In percentage points | Graph 16



Using current government yields. AU = Australia; AT = Austria; BE = Belgium; CA = Canada; CH = Switzerland; DE = Germany; DK = Denmark; ES = Spain; FI = Finland; FR = France; GB = United Kingdom; IT = Italy; JP = Japan; NL = Netherlands; NO = Norway; NZ = New Zealand; PT = Portugal; SE = Sweden; US = United States.

Sources: OECD, *Economic Outlook*; BIS calculations.

Combating climate change and financing the set of policies with public debt could perhaps be the way out of the existing conundrum for policymakers in advanced economies (Pereira da Silva (2019b)): low unemployment coexisting with low inflation for a prolonged period of time despite low interest rates. Reigniting growth through investment in low-carbon technologies is most probably more sustainable from a macroeconomic and environmental perspective than any of the previous consumption-led and household debt-based recoveries (Pereira da Silva (2016)). Some of the investments that could foster productivity in the long run include long overdue infrastructure spending, including in projects that are necessary to develop a low-carbon economy. For example, this type of fiscal stimulus may help create the necessary new science/technology/engineering/maths (STEM) jobs in new green industries, services and infrastructure. These jobs might be able to compensate for the jobs that are very likely to be significantly curtailed by technological progress in the new digital economy. Finally, where fiscal space is available, financing the transition to a lower-carbon economy with public debt could build greater social consensus for eventually accepting carbon taxation.

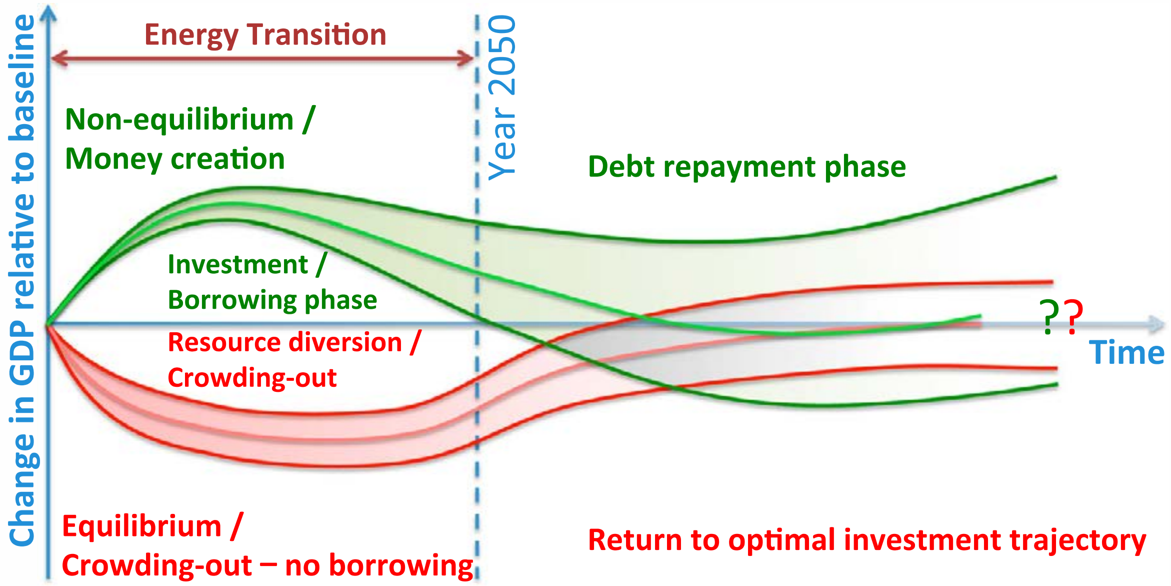
All this should not lead us to consider that there is a "silver bullet" and that the transition to a low-carbon economy can – under current financial circumstances – be easily funded through fiscal policy, as if we had a "free lunch". There could be a risk of a yield snapback. But there are other issues too. In particular, most of the literature calling for fiscal policy action assumes in a more or less explicit manner that it will have a positive impact on economic growth, employment and environmental outcomes, without paying attention to potential technical and institutional limitations and trade-offs between those goals. For instance, the strong reliance of a low-carbon economy on labour-intensive activities may strengthen the "Baumol's cost disease" effect and contribute to slowing down productivity and economic growth (Jackson (2017)). Moreover, the slowdown in productivity gains could be structural (Gordon (2012), Cette et al (2016)) and it is far from clear how the low-carbon transition will reverse it: most of the low-carbon investments needed in advanced economies aim to replace business-as-usual (more carbon-intensive) expected investments, without necessarily creating the conditions for a new boost in productivity. Some have gone further by casting doubt on whether it is even technically possible to decouple economic growth from environmental harm, including but not limited to CO_2 emissions (Jackson (2017), Hickel (2019), Macquarie (2019), OECD (2019b), Parrique et al (2019)).

These potential limitations, in turn, pose major questions for macroeconomic theory, such as estimating the size of the investment multiplier in a low-carbon transition. For instance, an improvement in energy efficiency could lead to a sharp decline in the supply side investments needed for the transition (Grubler et al (2018), in IPCC (2018)), and the latter could paradoxically lead (all other things being equal) to a decrease in GDP, especially if we rely on models where energy plays a critical and non-substitutable role in production (See Box 5 in Chapter 3.5). With this in mind, arguing that public investments will naturally crowd in private investments seems to rely on optimistic (or at least uncertain) assumptions regarding the nature of the transition. Moreover, a "crowding in" effect could paradoxically lead to undesirable (and still poorly accounted for) rebound effects (eg Gillingham et al (2016), Ruzzenenti et al (2019)): savings related to energy efficiency improvements can lead to an increase in the consumption of other fossil-intensive goods and services. In fact, assumptions about crowding out (in supply-led equilibrium models) or crowding in (in demand-led non-equilibrium models) may both (Graph 17) fail to discuss the specific technological, institutional and behavioural assumptions that specific transition paths entail.

These considerations suggest that the low-carbon transition consists in much more than just an investment plan, and that the socio-technical transition needed involves broader considerations than an optimal policy mix, including other ways of measuring system resilience and performance in the context of a low-carbon transition (Fath et al (2015), Ripple et al (2019), Svartzman et al (2019), UNEP (2019)). Without aiming for exhaustiveness, we discuss two of these broader considerations next: potential reforms of the international monetary and financial system in the light of climate considerations and the integration of sustainability into corporate and national accounting.

Impacts of the energy transition on GDP in non-equilibrium (demand-led) vs equilibrium (supply-led) models

Graph 17



Source: Mercure et al (2019).

4.4 Calling for international monetary and financial cooperation

Climate stability is a global public good, which raises difficult questions regarding international policy coordination and burden-sharing between countries at different stages of economic development. Unfair or poorly coordinated international action may simply incentivise some countries to free-ride (Krogstrup and Obstfeld (2018)). Achieving a smooth transition where all countries do their fair share means that a significant compensation mechanism must be agreed upon between developed and developing and emerging economies. As mentioned earlier, these economies need to see that their support for action combating climate change takes into account their stage of industrialisation.

Thus, climate change mitigation actions need to be built on international cooperation between advanced and developing countries (Villeroy de Galhau (2019b)) and recognition of the need for technology transfers and increases in official development assistance to developing countries. So far, developed countries have committed to jointly mobilise $100 billion per year by 2020 for climate action in developing countries (UNFCCC (2015)). But will this commitment be honoured, as current pledges are still far from this amount (OECD (2019c))? And will they suffice to trigger the massive investments needed in developing economies? If not, what are the implications and likely repercussions?

A sober assessment of international cooperation is that there has been uneven progress so far in mitigating climate change. On the one hand, collective action and stated commitments have flourished in multilateral conferences and internationally agreed commitments such as the Paris Agreement (UNFCCC (2015)). For instance, the recently created Coalition of Finance Ministers for Climate Action and the signing of the "Helsinki Principles"[46] could become a critical platform to articulate the need for fiscal policy and the use of public with prudential and monetary action and international coordination. The creation of the Network for Greening the Financial System (NGFS) is another success of such cooperation, possibly in the

[46] See www.cape4financeministry.org/coalition_of_finance_ministers.

very spirit of Bretton Woods (Villeroy de Galhau (2019c)). On the other hand, recent global debates have been dominated by a reaction against multilateralism (BIS (2017)). This mindset obviously does not help in combating climate change and delays collective action on the real problems. For instance, although coal, oil and gas are the central drivers of climate change, they are rarely the subject of ad hoc international climate policy and negotiations (SEI et al (2019)).

Inspiration for overcoming these limitations can be found in the literature on the commons and more precisely in Elinor Ostrom's (1990, 2010) principles for the governance of Common Pool Resources (CPRs). CPRs are "systems that generate finite quantities of resource units so that one person's use subtracts from the quantity of resource units available to others" (Ostrom (2002)). In this sense, the remaining stock of carbon that can be used while still having a fair chance of remaining below 1.5°C or 2°C can be considered as a CPR: burning fossil fuels in one place decreases the carbon budget available to others. One of Ostrom's key insights was to show that the over-exploitation of CPRs is due not so much to the lack of property rights, as often believed (Hardin (1968)), as to the lack of an adequate governance regime regulating the use of CPRs.

Building on Ostrom's insights, which are increasingly being adopted in both the climate and economic communities,[47] central banks along with other stakeholders could implement a governance regime based on CPRs by: (i) further identifying the risks to these resources (eg over-exploitation of the carbon budget); (ii) finding actions that reduce climate-related risks at the global and local levels; and (iii) monitoring these arrangements through the design and enforcement of rules for system stability. This implies coordination, local participation, some sense of fairness in burden-sharing, incentives and penalties, among others.

Given the difficulty of managing global commons (Ostrom et al (1999)), one concrete way of moving towards such a global joint governance of climate and financial stability would be to set up a new international agency (Bolton et al (2018)) that would play a role on two levels with: (i) a financial support mechanism between countries in case of severe climate events; and (ii) supervision of the climate policies being put in place. The theoretical justification of such an agency lies in the fact that, similarly to the creation of an international institutional framework after World War II to face the major global challenges of the time (such as postwar reconstruction), there is now a need for ad hoc institutions to tackle the new global challenges posed by climate change. In a similar spirit, Rogoff (2019) calls for the creation of a World Carbon Bank, which would constitute a vehicle for advanced economies to coordinate aid and technical transfers to developing countries.

Rather than creating new ad hoc institutions, other proposals have focused on embedding climate concerns within existing international institutions such as the International Monetary Fund (IMF), as part of their responsibilities to manage the international monetary and financial system. In particular, proposals have been made to issue "green" Special Drawing Rights (SDRs) through the IMF to finance green funds (Aglietta and Coudert (2019), Bredenkamp and Pattillo (2010), Ferron and Morel (2014), Ocampo (2019)). For instance, Aglietta and Coudert (2019, p 9) suggest creating "Trust Funds in which unused SDRs could be invested to finance the guaranteed low-carbon investment program. A more ambitious method consists of SDR loans to national and international public development banks being pledged to finance the national intentions of carbon emission reductions under the Paris Agreement".[48] Scaling up these "commons-based" mechanisms may require a major overhaul of the global governance system; yet they could become essential to build a "green" and multilateral financial system capable of channelling savings from all parts of the world to finance the low-carbon transition (Aglietta and Coudert (2019), Aglietta and Espagne (2018)).

[47] The third part of the IPCC (2014) report was dedicated to Elinor Ostrom, who was also awarded the Nobel Memorial Prize in Economic Sciences in 2009.

[48] A prerequisite to such a system would be for the IMF to take on the role of a "green" international lender of last resort, by issuing SDRs in exchange for excess reserves held by central banks and governments.

4.5 Integrating sustainability into corporate and national accounting frameworks

Beyond mechanisms aimed at financing the low-carbon transition, the severity of climate and other environmental crises has led a flourishing stream of research to reconsider how to account for economic value in an age of increasing ecological degradation. In particular, accounting standards at the corporate and national levels have increasingly been criticised for their incapacity to value the role of natural capital in supporting economic activity (see Costanza et al (1997)).

The concept of natural capital refers to "the stock of natural ecosystems on Earth including air, land, soil, biodiversity and geological resources … (which) underpins our economy and society by producing value for people, both directly and indirectly" (Natural Capital Coalition[49]). In turn, this stock of natural ecosystems provides a flow of services, called ecosystem services. These consist of provisioning, regulating, cultural and supporting services (Graph 18). For instance, a forest is a component of natural capital; the associated timber (provisioning service), climate regulation (regulating service) and touristic activities (cultural service) are examples of the ecosystem services it provides; and the forest nutrient cycle is a supporting service that enables all of the above.

Ecosystem services – an overview

Graph 18

Source: Millennium Ecosystem Assessment (2005).

Copyright holder: World Resources Institute.

Natural capital and ecosystem services are essential to economic activity in many forms and their degradation (eg soil erosion due to climate change) can have a major impact on human and produced capital (UN Environment (2018)). Important efforts and new frameworks have emerged in the past few years to integrate natural capital into accounting standards at the corporate level and into national accounts, as respectively outlined below.

With regard to corporate accounting, some suggest that a key step in getting companies to achieve a better trade-off between their financial objectives and their environmental and social impact is to transform corporate accounting, ie how companies report their performance to investors (de Cambourg (2019), Rambaud and Richard (2015)). A first encouraging development is the more systematic reporting of carbon emissions by companies under the standardised greenhouse gas protocol.[50] Another

[49] See www.naturalcapitalcoalition.org.

[50] See ghgprotocol.org/.

encouraging development is the creation of the Task Force on Climate-related Financial Disclosures (TCFD), which (as discussed above) seeks to coordinate and standardise reporting of company exposures to climate-related risks so as to allow investors to better manage their exposures to these risks. A third encouraging development is the rise of the integrated reporting movement (see Eccles et al (2015), UN Environment (2018)), which seeks to expand standardised accounting statements to include both financial and non-financial performance in a single integrated annual report. A particularly important initiative in this respect is the creation of the Sustainability Accounting Standards Board (SASB),[51] which already proposes standards for the reporting of non-financial ESG metrics.

In order to systematise integrated reporting approaches, regulatory action will be needed to induce or compel companies to systematically report their environmental and social performance according to industry-specific reporting standards. Few examples exist but some exceptions can be found, eg in the case of Article 173 of the French Law on Energy Transition for Green Growth (discussed above) and the recent support from French public authorities for the development of environmental and social reporting (de Cambourg (2019)). More debate will also be needed to streamline the reporting requirements. For instance, a specific question concerns whether natural capital should remain confined to extra-financial considerations or lead to changes in existing accounting norms, such as in the CARE/TDL model (see Rambaud (2015)).

Nevertheless, there is still a long way to go, as the fiduciary duties of CEOs and asset managers must be redefined and firms' non-financial performance metrics put on par with accounting measures of financial performance. An internationally coordinated effort to encourage the adoption of these standards would significantly accelerate the transition towards integrated reporting and/or new ways of accounting for natural capital. Such efforts would benefit central banks and supervisors as standardised accounting measures can allow investors to make relative comparisons across companies' respective exposure to environmental and social risks.

With regard to the integration of natural capital into national accounts, one of the main arguments put forward has to do with the fact that GDP accounts for only a portion of a country's economic performance. It provides no indication of the wealth and resources that support this income. For example, when a country exploits its forests, wood resources are identified in national accounts but other forest-related services, such as the loss in carbon sequestration and air filtration, are completely ignored. Several steps have been made towards better integration of natural capital into national accounts. The Inclusive Wealth Report (UN Environment (2018)) evaluates the capacities and performance of the national economies around the world, based on the acknowledgment that existing statistical systems are geared to measure flows of income and largely miss the fact that these depend upon the health and resilience of capital assets like natural capital. The World Bank Group has also spearheaded a partnership to advance the accounting of natural wealth and ecosystem services.[52]

Better accounting systems for natural capital are necessary to internalise climate externalities, but it should be recognised that the concepts of natural capital and ecosystem services are difficult to define precisely. For instance, pricing and payment mechanisms for ecosystem services can hardly account for the inherent complexity of any given ecosystem (eg all the services provided by a forest) and often lead to trade-offs by valuing a subset of services only, sometimes to the detriment of others (Muradian and Rival (2012)). They can also fail to provide the desired incentives if they are not designed in ways that recognise the complexity of socio-ecological systems (Muradian et al (2013)) and the need to strengthen cooperation in governing the local and global commons (Ostrom (1990, 2010), Ostrom et al (1999)). Hence, rather than envisaging it as an easy solution, accounting for natural capital and its related ecosystem services should constitute but one among a diverse set of potential solutions (Muradian et al (2013)).

[51] See www.sasb.org/.

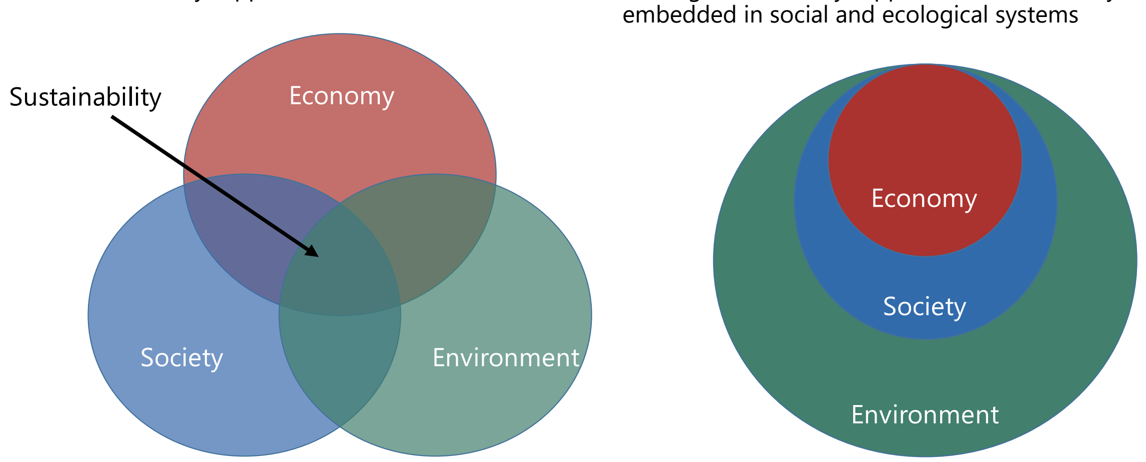
[52] See www.wavespartnership.org/.

Another significant limitation of the concept of natural capital has to do with the common assumption that it is substitutable for other forms of capital (Barker and Mayer (2017)). According to this assumption, what matters is that capital as a whole increase, not which components make up the increase. If, for example, an increase in manufactured capital (eg machines and roads) exceeds the depletion of natural capital, then the conclusion would be that society is better off. This view has been coined the "weak sustainability" approach. In contrast, proponents of an alternative "strong sustainability" argue that the existing stocks of natural capital and the flow of ecosystem services they provide must be maintained because their loss cannot be compensated by an increase in manufactured or human capital (Daly and Farley (2011)). For instance, the depletion of natural capital in a warming world cannot be compensated by higher income. In this view, the economy is embedded in social and biophysical systems (Graph 19, right-hand panel); it is not a separate entity as the traditional approach to sustainable development is framed (Graph 19, left-hand panel).

Two approaches to sustainability — Graph 19

"Weak sustainability" approach

"Strong sustainability" approach – economic system is embedded in social and ecological systems



Source: Authors' elaboration.

Instead of seeking to "internalise" external costs in order to correct market failures, proponents of the "strong sustainability" approach, including ecological economists, suggest "a more fundamental explanation" (OECD (2019b, p 13)) of the dependence of economic systems upon the maintenance of life support ecosystem services (such as climate regulation). Bringing the economic system back within Earth's "sustainability limits" therefore involves much more than marginal changes in the pricing and accounting systems, and could entail re-evaluating the notion of endless economic growth itself (Georgescu-Roegen (1971), Martinez-Alier (1987), Daly and Farley (2011), Jackson (2017), Spash (2017)). Rethinking macroeconomic and financial systems in the light of these considerations is still an underdeveloped area of research in most of the economic discipline, although great progress has been achieved in recent times towards mainstreaming this question (eg OECD (2019b)).

New approaches will be needed in the process of mainstreaming these questions (see Annex 4). In particular, the development of systems analysis has been identified as a promising area of research that should inform economic policies in the search for fair and resilient socio-ecological systems in the 21st century (Schoon and van der Leeuw (2015), OECD (2019a)). In contrast to risk management, a system resilience approach "accepts that transitions to new phases are part of its nature and the system will not return to some previous equilibrium. New normals are normal" (OECD (2019a, p 3)). Greater focus on institutional and evolutionary approaches and on political economy considerations may also be needed

(Gowdy and Erickson (2005), Vatn (2007)), as overcoming the roadblocks to sustainability can be seen as requiring an evolutionary redesign of worldviews, institutions and technologies (Beddoe et al (2009)).

Notwithstanding these important limitations, the ways in which accounting norms incorporate (or not) environmental dimensions remains critical: accounting norms reflect broader worldviews of what is valued in a society (Jourdain (2019)), at both the microeconomic and macroeconomic level. From a financial stability perspective, it therefore remains critical to integrate biophysical indicators into existing accounting frameworks to ensure that policymakers and firm managers systematically include them in their risk management practices over different time horizons.

5. CONCLUSION – CENTRAL BANKING AND SYSTEM RESILIENCE

Mitigating and adapting to climate change while honoring the diversity of humans entails major transformations in the ways our global society functions and interacts with natural ecosystems.

Ripple et al (2019)

Climate change poses an unprecedented challenge to the governance of socioeconomic systems. The potential economic implications of physical and transition risks related to climate change have been debated for decades (not without methodological challenges), yet the financial implications of climate change have been largely ignored.

Over the past few years, central banks, regulators and supervisors have increasingly recognised that climate change is a source of major systemic financial risks. In the absence of well coordinated and ambitious climate policies, there has been a growing awareness of the materiality of physical and transition risks that would affect the stability of the financial sector. Pursuing the current trends could leave central banks in the position of "climate rescuers of last resort", which would become untenable given that there is little that monetary and financial flows can do against the irreversible impacts of climate change. In other words, a new global financial crisis triggered by climate change would render central banks and financial supervisors powerless.

Integrating climate-related risks into prudential regulation and identifying and measuring these risks is not an easy task. Traditional risk management relying on the extrapolation of historical data, despite its relevance for other questions related to financial stability, cannot be used to identify and manage climate-related risks given the deep uncertainty involved. Indeed, climate-related risks present many distinctive features. Physical risks are subject to nonlinearity and uncertainty not only because of climate patterns, but also because of socioeconomic patterns that are triggered by climate ones. Transition risks require including intertwined complex collective action problems and addressing well known political economy considerations at the global and local levels. Transdisciplinary approaches are needed to capture the multiple dimensions (eg geopolitical, cultural, technological and regulatory ones) that should be mobilised to guarantee the transition to a low-carbon socio-technical system.

These features call for an epistemological break (Bachelard (1938)) with regard to financial regulation, ie a redefinition of the problem at stake when it comes to identifying and addressing climate-related risks. Some of this break is already taking place, as financial institutions and supervisors increasingly rely on scenario-based analysis and forward-looking approaches rather than probabilistic ones to assess climate-related risks. This is perhaps compounding a new awareness that is beginning to produce a repricing of climate-related risks. That, in turn, can contribute to tilting preferences towards lower-carbon projects and might therefore act, to some extent, as a "shadow price" for carbon emissions.

While welcoming this development and strongly supporting the need to fill methodological, taxonomy and data gaps, the essential step of identifying and measuring climate-related risks presents significant methodological challenges related to:

(i) The choice of a scenario regarding how technologies, policies, behaviours, geopolitical dynamics, macroeconomic variables and climate patterns will interact in the future, especially given the limitations of climate-economic models.

(ii) The translation of such scenarios into granular corporate metrics in an evolving environment where all firms and value chains will be affected in unpredictable ways.

(iii) The task of matching the identification of a climate-related risk with the adequate mitigation action.

In short, the development and improvement of forward-looking risk assessment and climate-related regulation will be essential, but they will not suffice to preserve financial stability in the age of climate change: the deep uncertainty involved and the need for structural transformation of the global socioeconomic system mean that no single model or scenario can provide sufficient information to private and public decision-makers. A corollary is that the integration of climate-related risks into prudential regulation and (to the extent possible) into monetary policy would not suffice to trigger a shift capable of hedging the whole system again against green swan events.

Because of these limitations, climate change risk management policy could drag central banks into uncharted waters: on the one hand, they cannot simply sit still until other branches of government jump into action; on the other, the precedent of unconventional monetary policies of the past decade (following the 2007–08 Great Financial Crisis), may put strong sociopolitical pressure on central banks to take on new roles like addressing climate change. Such calls are excessive and unfair to the extent that the instruments that central banks and supervisors have at their disposal cannot substitute for the many areas of interventions that are necessary to achieve a global low-carbon transition. But these calls might be voiced regardless, precisely because of the procrastination that has been the dominant modus operandi of many governments for quite a while. The prime responsibility for ensuring a successful low-carbon transition rests with other branches of government, and insufficient action on their part puts central banks at risk of no longer being able to deliver on their mandates of financial (and price) stability.

To address this latter problem, a second epistemological break is needed. There is also a role for central banks to be more proactive in calling for broader change. In this spirit, and grounded in the transdisciplinary approach that is required to address climate change, this book calls for actions beyond central banks that are essential to guarantee financial (and price) stability.

Central banks can also play a role as advocates of broader socioeconomic changes without which their current policies and the maintenance of financial stability will have limited chances of success. Towards this objective, we have identified four (non-exhaustive) propositions beyond carbon pricing:

(i) Central banks can help proactively promote long-termism by supporting the *values* or *ideals* of sustainable finance.

(ii) Central banks can call for an increased role for fiscal policy in support of the ecological transition, especially at the zero lower bound.

(iii) Central banks can increase cooperation on ecological issues among international monetary and financial authorities.

(iv) Central banks can support initiatives promoting greater integration of climate and sustainability dimensions within corporate and national accounting frameworks.

Financial and climate stability are two increasingly interdependent public goods. But, as we enter the Anthropocene (Annex 4), long-term sustainability extends to other human-caused environmental degradations such as biodiversity loss, which could pose new types of financial risks (Schellekens and van Toor (2019)). Alas, it may be even more difficult to address these ecological challenges. For instance, preserving biodiversity (often ranked second in terms of environmental challenges) is a much more complex problem from a financial stability perspective, among other things because it relies on multiple local indicators despite being a global problem (Chenet (2019b)).

The potential ramifications of these environmental risks for financial stability are far beyond the scope of this book. Yet, addressing them could become critical for central banks, regulators and supervisors insofar as the stability of the Earth system is a prerequisite for financial and price stability. In particular, the development of systems analysis has been identified as a promising area of research that should inform economic and financial policies in the search for fair and resilient complex adaptive systems in the 21st century (Schoon and van der Leeuw (2015), OECD (2019a)). Future research based on institutional, evolutionary and political economy approaches may also prove fundamental to address financial stability in the age of climate- and environment-related risks.

Faced with these daunting challenges, a key contribution of central banks and supervisors may simply be to adequately frame the debate. In particular, they can play this role by: (i) providing a scientifically uncompromising picture of the risks ahead, assuming a limited substitutability between natural capital and other forms of capital; (ii) calling for bolder actions from public and private sectors aimed at preserving the resilience of Earth's complex socio-ecological systems; and (iii) contributing, to the extent possible and within the remit of the evolving mandates provided by society, to managing these risks.

6. ANNEXES

ANNEX 1 – Uncertainties related to physical risks: Earth's climate as a complex, nonlinear system

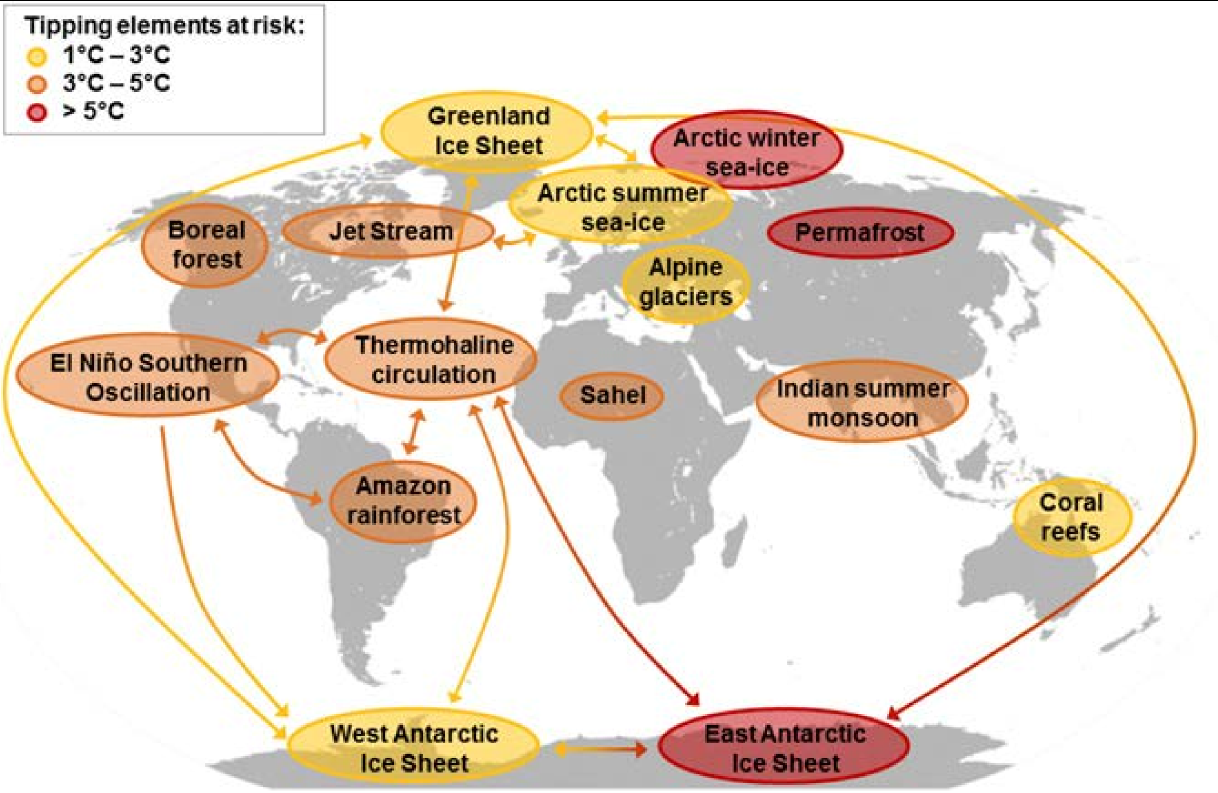
The Earth's climate system is a complex system, with multiple interacting subsystems that can give rise to so-called emerging properties, which refer to new endogenous collective responses. A fundamental (for the purpose of this book) source of emerging properties tied to climate change is irreversibility, ie changes that persist even when the original forcing (eg amount of atmospheric CO_2) is restored (Schneider (2003)). Moreover, the effects of climate change on the planet are "highly nonlinear, meaning that small changes in one part can lead to much larger changes elsewhere" (Smith (2014)).

Highly nonlinear systems can lead to chaotic dynamics, which are extremely difficult to model with any accuracy and confidence. As global warming continues, we face a situation of deep uncertainty related to the biogeochemical processes that can be triggered by climate change. The *IPCC Special Report on Global Warming of 1.5°C* (IPCC (2018)) indicates that beyond 2°C of global warming, the chances of reaching tipping points (such as a melting of the permafrost) become much more likely, which could in turn trigger multiple chain reactions between different ecosystems.

As shown in the graph below, some potential tipping cascades are more likely to occur if there is global warming of between 1°C and 3°C, whereas others are more likely to occur if global warming exceeds 3°C or 5°C. It is noteworthy that many tipping points may occur even if we manage to keep global warming below 2°C (Steffen et al (2018)). Indeed, climate change models predict significant and robust differences between a 1.5°C and a 2°C world. These include increases in intensity of extreme temperature events in most inhabited areas, with a higher frequency and intensity of heavy precipitation and drought events from one region to another (Masson-Delmotte and Moufouma-Okia (2019)).

Global map of potential tipping cascades

Graph A.1



The individual tipping elements are colour-coded according to estimated thresholds in global average surface temperature. Arrows show the potential interactions among the tipping elements based on expert elicitation that could generate cascades.

Sources: Adapted from Steffen et al (2018).

Estimates of when certain tipping point cascades could be triggered are regularly reassessed by the scientific community. For instance, a recent study (Bamber et al (2019)) found that due to accelerated melting in Greenland and Antarctica, global sea levels could rise far more than predicted by most studies so far, potentially leading to other tipping cascades that have not been anticipated. Other studies find that rainforests, which act as a critical climate stabiliser by absorbing and storing CO_2, may be losing their ability to do so faster than expected (eg Fleischer et al (2019)), which could trigger important increases in global warming and other cascades.

In the light of these challenges, the case has often been made that the damage functions used by IAMs are unable to capture the full uncertainty and complexity of the effects of climate change. In particular, they do not incorporate the high probabilities of extreme risks (or fat-tailed distribution of risks) relative to normal distributions (Calel et al (2015), Thomä and Chenet (2017)), especially those resulting from crossing tipping points that trigger knock-on effects on other biophysical subsystems (Curran et al (2019)). For instance, the DICE model (one of the most famous IAMs) assumes that damages are a quadratic function of temperature change, ie that there are no discontinuities and tipping points (Keen (2019)). This can lead to predictions at odds with all scientific evidence: while DICE modellers find that a 6°C warming in the 22nd century would mean a decline of less than 0.1% per year in GDP for the next 130 years, in practice such a rise in global temperatures could mean extinction for a large part of humanity (Keen (2019)).

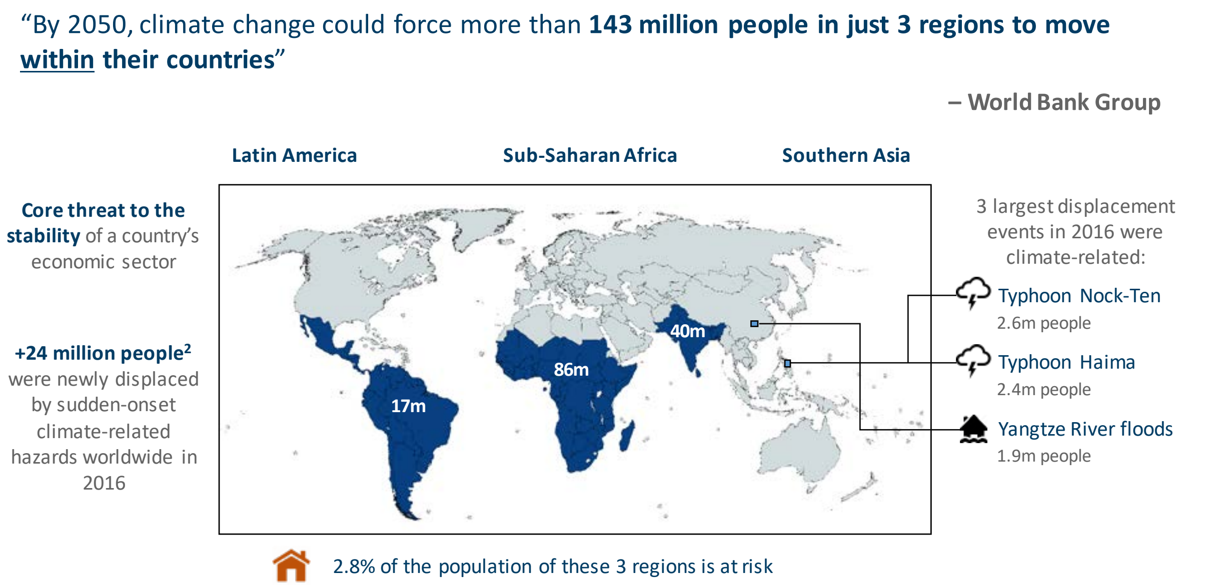
The physical impacts of climate change will also lead to complex social dynamics that are not only difficult to predict but also problematic to address from an ethical perspective, especially when it comes to translating them in economic terms. Climate change poses critical intergenerational equity issues as damages will tend to increase throughout time, thereby affecting people who are not yet born. Of particular importance for macroeconomic modelling of climate change is the choice of the discount rate applied to future damages, which are supposed to reflect our current economic valuation of the welfare of these future generations (Heal and Millner (2014)). But finding the "accurate" discount rate of future damages is subject to many interpretations. For instance, Nordhaus (2007) finds an optimal increase in temperatures of 3.4°C by using market-based discount rates. More recently, finance-based studies that take into account the pricing of risk and separate risk aversion from intertemporal substitution (eg Daniel et al (2019)) find lower risk-adjusted discount rates, meaning that immediate and drastic action is needed to avoid physical damages stemming from climate change.

Regardless of the rate of discount chosen, climate-economic models can hardly provide accurate responses to many intergenerational ethical issues posed by climate change. Climate change could lead to an increase in human migrations (see image below), conflicts (Abel et al (2019), Bamber et al (2019), Burke et al (2015b), Kelley et al (2015)) and deaths. For instance, the World Bank (2018) estimates that there could be at least 143 million migrants due to climate change by 2050 (taking into account only South America, Africa and India). These trends could also widen global inequality (Burke et al (2015a), Diffenbaugh and Burke (2019)). Although the top 10% wealthiest individuals generate 45% of greenhouse gas emissions while the 50% least affluent individuals generate 13% of them (Chancel (2017)), climate-related shocks will very likely have adverse consequences concentrated in countries with relatively hot climates, which include most low-income countries (IMF (2017)). A recent report commissioned by the United Nations (Human Rights Council (2019)) estimates that climate change could lead to the reversal of all the progress made in the last 50 years in terms of poverty reduction.

Migration risks of climate change

Environmental changes cause an increasing number of human displacements

Graph A.2



Sources: Adapted from World Bank Group (2018).

While these developments speak for themselves from an ethical perspective, their translation into economic variables is not obvious and can be dangerously misleading. From a mainstream economic perspective, the losses incurred due to climate-related physical impacts in low-income economies could be compensated, eg if economic agents in high-income economies show a strong willingness to pay for adaptation. However, this is at odds with scientific evidence: climate change can lead to irreversible patterns and impacts, which may be only very partially compensated by cash transfers, regardless of their amount.

As a result of these sources of uncertainty, the social cost of carbon (which attempts to quantify in monetary terms the costs and benefits of emitting one additional tonne of CO_2) varies considerably from one model to another (Pindyck (2013)). The selection of parameter values that inform the damage functions as well as the rate of discount rely on arbitrary choices, and IAMs "can be used to obtain almost any result one desires" (Pindyck (2013), p 5). Going further, Lord Nicholas Stern now argues that IAMs are "grossly misleading" (Stern (2016)). Rather than simply rejecting them, we need at least a more nuanced and contextualised support to IAMs (Espagne (2018)).

In any case, addressing climate change adequately requires that we consider it a moral issue (much like avoiding a war or any other major threat to human and non-human lives), not a purely economic one. Assessing these trends merely through discounted individual preferences and/or damage functions, all the more while using cost-benefit analysis, can hardly provide any meaningful insight into what matters most: finding socially fair solutions to guarantee that greenhouse gas atmospheric concentration remains as far as possible from any tipping point. Fighting climate change is therefore a paramount ethical issue that cannot be reduced to a calibration exercise of an IAM.

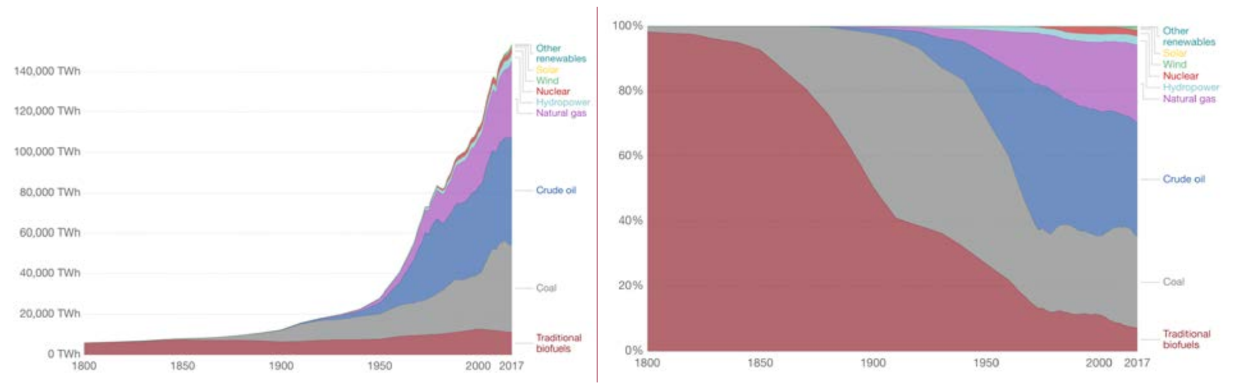
ANNEX 2 – Uncertainties related to transition risks: towards comprehensive approaches to socio-technical transitions

The textbook solution to mitigating climate change is a globally coordinated Pigovian carbon tax that reflects the shadow social cost of carbon emissions. However, as discussed in the Introduction, the prospects for an adequate carbon price as an effective, immediate policy intervention to combat climate change look dim, for the following reasons. First, it is far-fetched to assume that a significant global carbon tax will be implemented in the current political and economic environment, which is sufficient reason in itself to look for other interventions. Second, given the importance of the climate externality ("the greatest market failure ever seen", according to Stern (2007)), estimating the adequate level of a carbon tax and its potential impacts (eg its ability to elicit the desired behaviours and technological breakthroughs without unintended consequences) is a delicate exercise. And third, the decarbonisation paths we need to take may involve such a dramatic shift in the productive structures of the global economic system that climate change may be best understood as more than an externality.

Focusing on the last two points, it is increasingly understood that climate change is a source of structural change in the global economy (NGFS (2019a)). Mitigating climate change in order to avoid its worst physical impacts amounts to nothing less than an unprecedented socioeconomic challenge, requiring the replacement of existing technologies, infrastructure and life habits over a very short time frame. The scale and timing of this required transition has even led some to analyse it in terms of a war mobilisation or rapid urbanisation, rather than the typical transformation of modern economies (Stiglitz (2019)).

In support of the view that a low-carbon transition involves much more than just pricing mechanisms, the history of energy (eg Bonneuil and Fressoz (2016), Global Energy Assessment (2012), Pearson and Foxon (2012), Smil (2010, 2017a)) indicates that the evolution of primary energy uses is intricately related to deep transformations of human societies and economic systems (Graph A.3, left-hand panel. Today's challenge brings an additional layer of complexity, as it requires not only a reduction in the proportion of fossil fuels in the share of global primary energy (right-hand panel) but also a reduction in absolute terms, something that has never been done up to now: as the left-hand panel shows, the energy history of the past centuries has always involved adding new energy sources to old ones (energy additions), not in transitioning from one to another in absolute terms (energy transition). For instance, the share of biomass decreased from almost 100% to less than 10% of total primary energy use between 1850 and the 21st century, but its use in absolute terms has remained more or less constant.

Evolution of energy systems, in absolute and relative terms — Graph A.3



Global primary energy consumption, measured in terawatt-hours (TWh) per year (left-hand panel) and in percentage by primary energy source (right-hand panel).

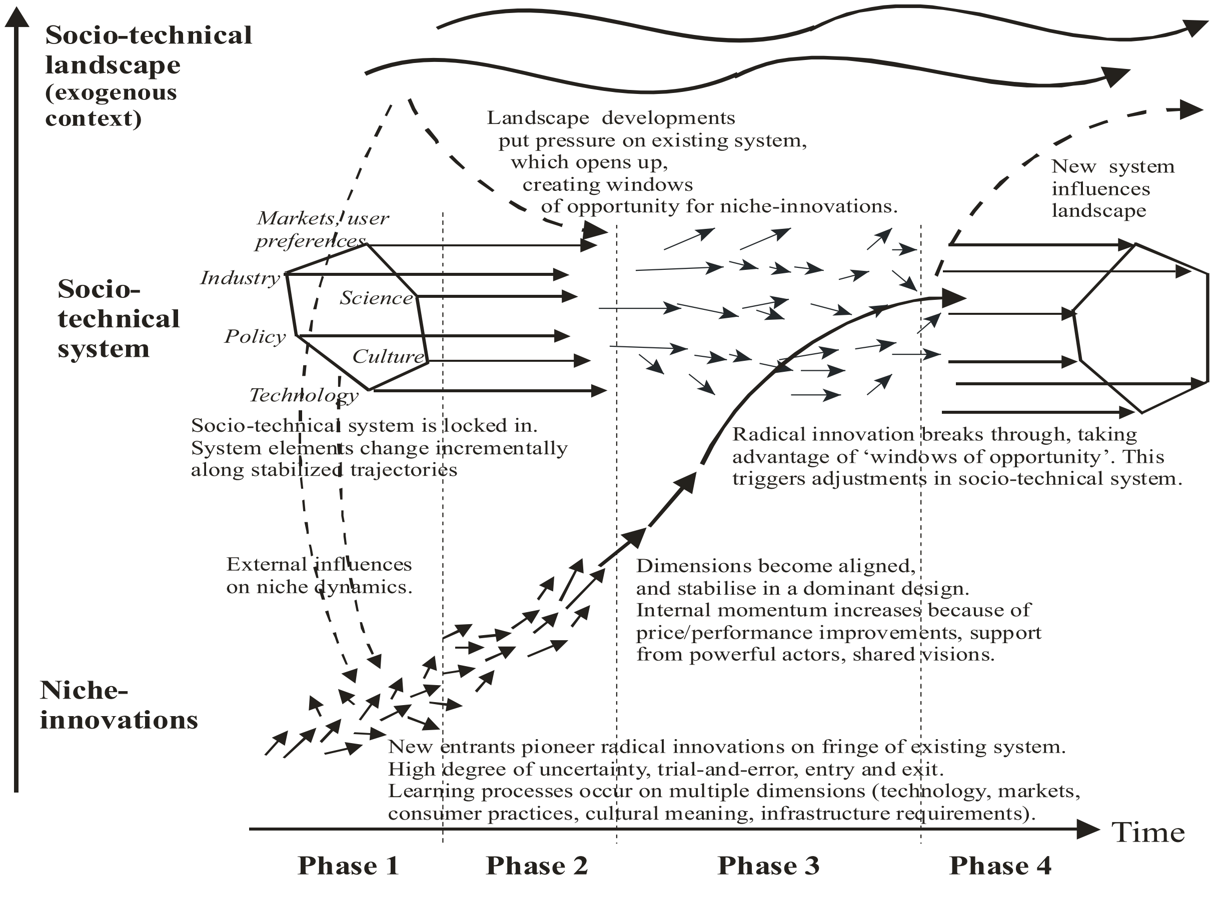
Note: "other renewables" are renewable technologies not including solar, wind, hydropower and traditional biofuels.

Source: Smil (2017b) and BP (2019). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy.

Hence, the use of a global, economy-wide carbon price as a proxy for climate policy in IAMs (Carbon Brief (2018)) tends to "not structurally represent many social and political forces that can influence the way the world evolves" (IPCC (2014), p 422). In particular, a low-carbon transition will probably involve a broad range of actions guided not only by cost-benefit calculations and revolving around carbon prices, as put forward by a transdisciplinary group of scholars using the concept of socio-technical transition (Geels et al (2017)). Socio-technical transition scholars are concerned with "understanding the mechanisms through which socio-economic, biological and technological systems adapt to changes in their internal or external environments" (Lawhon and Murphy (2011), p 356–7). Prices surely play a role in these processes, but a far more limited one than in most IAMs.

In the quest for more comprehensive accounts of how transitions may come about, socio-technical systems scholars show that a low-carbon transition could result from complex interactions within and between three levels (Graph A.4): technological niches, socio-technical regime and socio-technical landscape, as respectively discussed below.

Phases of transformations of existing socio-technical systems | Graph A.4

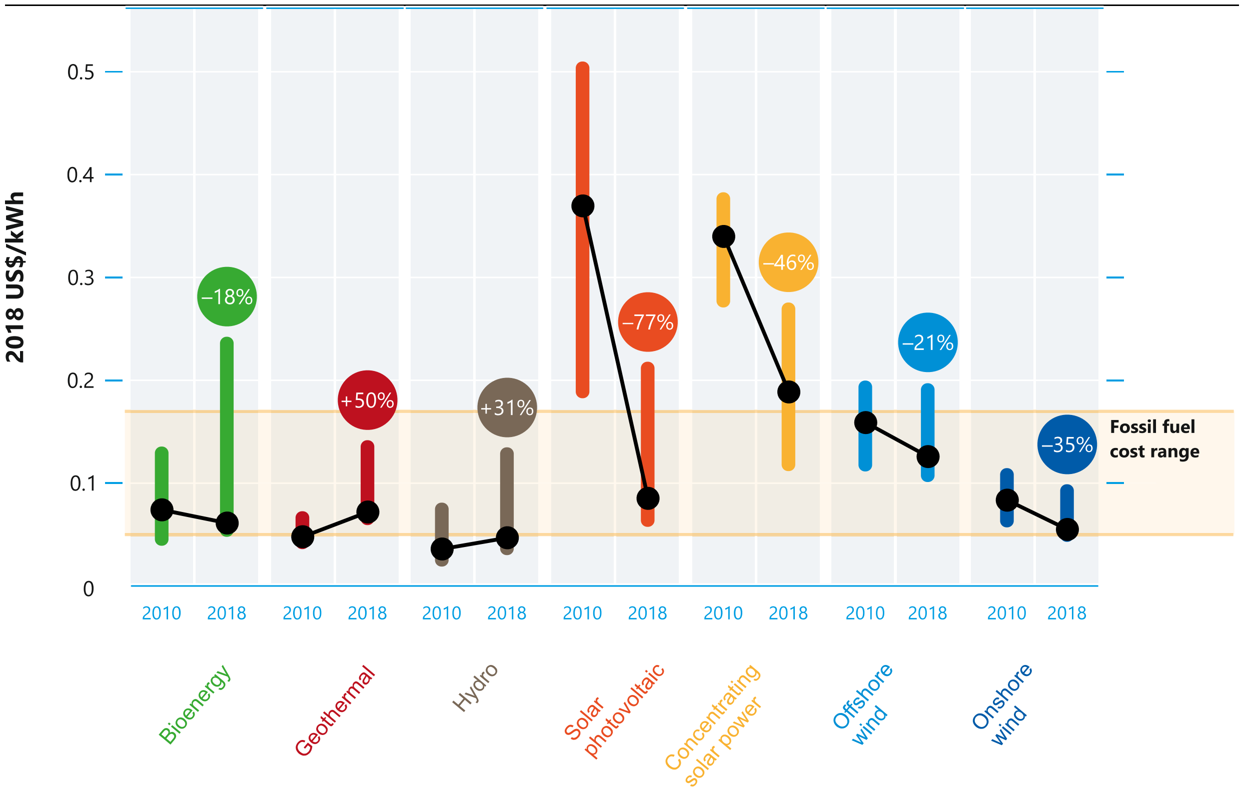


Source: adapted from Geels et al (2017).

First, at the lowest level, niche-innovations are innovations that "differ radically from the prevailing socio-technical system and regime, but are able to gain a foothold in particular applications, geographical areas, or markets" (Geels et al (2017), p 465). In this respect, the path of development of low-carbon technologies is unsurprisingly a key parameter for the transition. Yet it is also a significant source of uncertainty, with both potential barriers and breakthroughs to a rapid and smooth transition. The rapidly declining levelised costs of many renewable energy technologies (Graph A.5) is an example of unpredictable technological development. Moreover, technologies that are still unknown today may emerge and develop much more quickly than usually assumed in IAMs (Curran et al (2019)).

Changes in global levelised cost of energy for key renewable energy technologies, 2010–18

Graph A.5

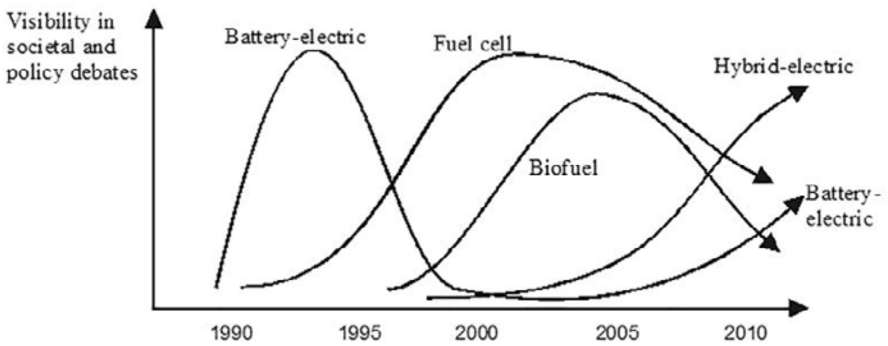


Source: UNEP (2019).

On the other hand, renewable energy is still subject to potential barriers to its development, such as intermittent and unpredictable power output (Moriarty and Honnery (2016)), which requires major improvements in current energy storage technologies (and/or maintaining backup conventional energy capacity). Developing renewable energy capacity may also demand transforming existing land uses, as energy sources such as solar and wind require larger land masses than oil, gas and coal (Smil (2017a)). In addition, the cost of hydropower (the main source of renewable energy so far) could increase because of the physical impacts of climate change (eg increased frequency in droughts could lead to water shortages). In short, many barriers could stand in the way of smooth development of renewable energy capacity.

Modelling technological development paths is a delicate exercise, which can greatly vary over time. For instance, with regard to transportation technologies (Graph A.6), biofuel-powered vehicles were seen as a technological alternative to fossil-powered vehicles more than a decade ago, while today it seems that electric vehicles are a more promising alternative, despite potentially significant limitations with regard to resources and pollution (Pitron (2018)). But these assessments could also be challenged by emerging solutions such as hydrogen (Morris et al (2019)), not represented in the graph below although countries such as China may already be moving towards hydrogen fuel (Li (2019), Xin (2019)). Biofuels could also be discussed again, with the development of third- and fourth-generation biofuels (Aro (2016)) that would not compete with food security in terms of use of land and resources. In short, predicting which technologies will prevail is far from obvious, regardless of the price on carbon. This calls for a very prudent use of IAMs and the technological assumptions informing them, as explained in Chapter 3.2.

Changes in visibility of transportation technologies throughout time — Graph A.6



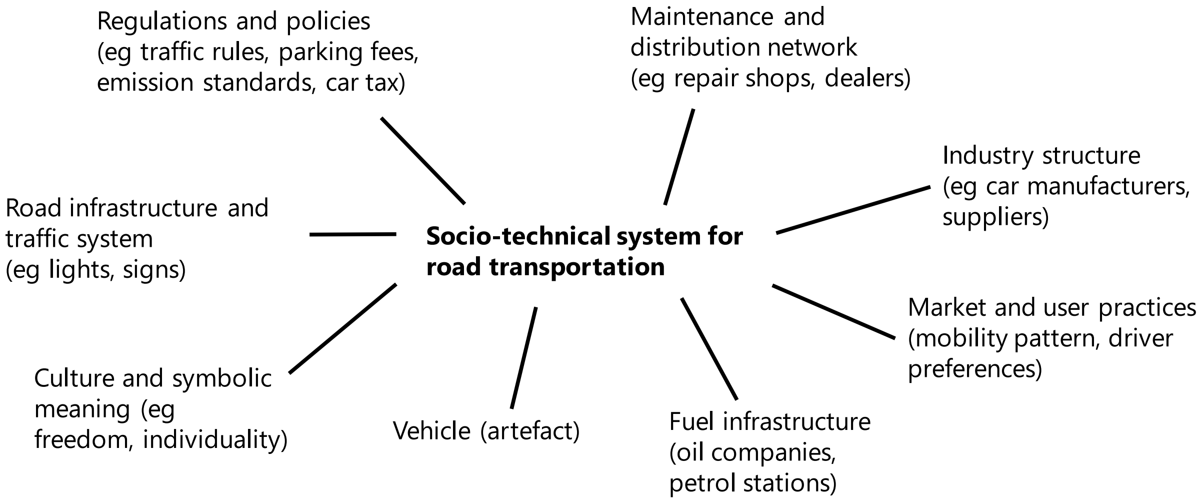
Source: Geels et al (2017).

Second, the middle level of Graph A.4 corresponds to socio-technical regimes, which are "constituted by the conventions, rules, and norms that guide the uses of particular technologies and the everyday practices of the producers, workers, consumers, state agencies, scientists, societal groups, and business people who participate in the regime" (Lawhon and Murphy (2011), p 357). This includes the process leading to the implementation of a carbon price or any other climate-related regulation, eg a feed-in tariff to accelerate the speed of renewable energy capacity installation.

Modelling a realistic transition may require better accounting for many dimensions of the current socio-technical system and the institutional inertia it generates. For instance, reducing the number of individual cars (which may be an important part of the solution along with developing cleaner fuels) is much more difficult once cities and suburbs have been planned on the basis of individual vehicle ownership. Indeed, once car-based transportation systems are institutionalised, they become self-sustaining (Graph A.7) "by formal and informal institutions, such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity, and individual identity; the skills and assumptions of transport planners; and the technical capabilities of car manufacturers, suppliers, and repair shops" (Geels et al (2017), p 465).

Although pricing mechanisms can contribute to addressing these issues, other regulations may be needed, such as rules on the weight of new cars and improved public transportation to limit the amount of personal vehicles (The Shift Project and IFPEN (2019)) and potential rebound effects. Other solutions may not even depend on new technologies but rather on shifting social norms towards the use of already existing technologies (Bihouix (2015)). For instance, the recent "flight shame" movement in Sweden and its negative impact on airline companies (Fabre (2019)) along with positive effects for the national rail operator (Henley (2019)) are responses to the so-called "Greta Thunberg effect" rather than a technological breakthrough.

Socio-technical system of auto-mobility Graph A.7



Source: Adapted from Geels et al (2017).

An additional element of the socio-technical regime has to do with the social acceptability of carbon taxes, which is closely tied to its perceived fairness, and more generally to the fairness of the current wealth distribution. Some argue that designing a carbon tax that varies with household income and between urban and rural areas will be critical to ensure that the worst off households are not disproportionately affected (Bureau et al (2019)). Others argue that the link between carbon pricing and inequalities is even deeper: reducing economic inequalities may be a pre-condition for an effective carbon tax, as it may be easier for a group to collectively reach a consensus on difficult topics (such as burden-sharing efforts for climate mitigation) when inequalities are considered to be within acceptable boundaries in the first place (Chancel (2017)). Alternatively, carbon mitigation efforts may need to focus first on the lifestyles of the wealthiest individuals, since they are the biggest emitters by far (Otto et al (2019)). These considerations suggest that the transformation of an existing socio-technical system requires an even deeper dive into the third level of socio-technical transitions.

Third, the upper level of socio-technical transitions refers to the socio-technical landscape, which considers "the broader contextual developments that influence the socio-technical regime and over which regime actors have little or no influence. Landscape developments comprise both slow-changing trends (e.g., demographics, ideology, spatial structures, geopolitics) and exogenous shocks (e.g., wars, economic crises, major accidents, political upheavals)" (Geels et al (2017), p 465). In particular, complex issues of coordination and well known collective action problems arise when there is a common pool of resources (such as the remaining stock or budget of carbon that can be used) to be administered. In a nutshell, there is a political economy of climate change. That is about who will pay for what, and, inter alia, when and how to share the burden of abatement and transition costs, and how climate-related considerations can be incorporated into practical decision-making processes in a way that is sustainable from a sociopolitical viewpoint.

Historically, advanced economies' emissions were responsible for a larger share of the depletion/consumption of the stock of carbon. They are now enjoying a higher standard of living, while climate change demands us to limit future GHG emissions. Thus, limiting emissions raises obvious issues of fairness in burden-sharing across nations (Millar et al (2017)). How should we respond to developing countries' claims for rights to emissions since they are now beginning to industrialise and thus are increasingly responsible for the new flows? Many textbook solutions (eg taxes and subsidies for carbon pricing and trading, even when adjusted for the respective levels of economic development) might create political economy difficulties and, if so, delay decisions and create inertia. The implementation of the principle of "common but differentiated responsibilities" (UNFCCC (2015)) enshrined in international climate negotiations is still an unresolved conundrum.

If no common but differentiated responsibilities or burden-sharing principles prevail on climate negotiations, ambitious climate action from one country could lead to free-riding behaviours from others and/or to outsourcing production to less stringent jurisdictions, potentially offsetting the gains in one country with an increase in GHG emissions elsewhere. One way of mitigating this would be to link trade agreements to climate change mitigation (Bureau et al (2019), German Council of Economic Experts (2019)). In particular, climate clubs (agreements between groups of countries to introduce harmonised emission reduction efforts and sanction non-participants through low and uniform tariffs on exports to countries in the club) could help limit free-riding behaviour by countries (Krogstrup and Oman (2019)). Yet this could lead to potential tensions between climate progress and gains from trade (Pisani-Ferry (2019)). For instance, as China consumed about 50% of the world's coal in 2018 (BP (2019)) and Asia contains 90% of coal plants built over the past two decades (IEA (2019)), it remains unclear how a rapid phase-out of coal would impact global value chains, and how it could take place without impinging on poorer countries' development path.

In this context, the geopolitical dimension of the socio-technical landscape is critical yet particularly difficult to grasp through climate-economic models. For instance, models aiming to estimate the amount of stranded assets need to make assumptions about which sources of fossil fuels will remain stranded, as discussed in the next chapter. While assuming that fossil fuels that are more expensive to extract will be stranded first makes sense from an economic standpoint (eg Canadian and US unconventional oil in Mercure et al (2018)), it is doubtful that countries sitting on these reserves will resort to exploiting them, at least not if major coordination and compensation schemes are designed at the international level. In this regard, the Yasuni-ITT initiative is a striking example of how difficult it can be to design compensation mechanisms: the Ecuadorian government proposed an innovative scheme in 2007, seeking $3.6 billion in contributions from foreign governments to maintain a moratorium on oil drilling in an Amazon rainforest preserve that is also home to indigenous people. The plan was abandoned in 2013 after actual donations and pledges barely exceeded $100 million (Martin and Scholz (2014), Warnars (2010)).

Still at the geopolitical level, it has been argued that a transition away from fossil fuels could significantly reshape geopolitical patterns. The International Renewable Energy Agency released a recent report (IRENA (2019)) arguing that the rise of renewable energy can affect the balance of power between states, reconfigure trade flows and transform the nature of conflicts, eg with fewer oil-related conflicts but possibly more conflicts related to access to minerals. Handling such transition risks smoothly (ie avoiding a conflict-prone transition) requires an unprecedented level of international cooperation, possibly requiring important international fiscal transfers. One step in this direction is the commitment by developed countries to jointly mobilise $100 billion per year by 2020 for climate change mitigation in developing countries (UNFCCC (2015)). However, this amount will surely fall short of being sufficient and, more importantly, current pledges are still far from this target (OECD (2019c)).

Going further into the assessment of the socio-technical landscape in which the low-carbon transition should take place, another major issue is the increasingly limited capabilities of governments to cope with the climate change challenge and the energy transition. Several disturbing developments in the current economic environment are worth mentioning briefly in this respect:

(i) Governments have not changed the way they operate much since the 1970s (Collier (2018)): they are still chasing a redistribution of growth that is now reduced and they must face widening inequalities, high levels of long-term unemployment and higher levels of debt. The transition to low carbon emissions adds an additional layer of complexity to this, as it is unclear whether climate change mitigation will represent a way out of current low growth rates[53] and therefore boost governments' power or, on the contrary, an additional drag toward the possibility of a secular stagnation (Gordon (2012)), as discussed in Chapter 4. In advanced economies in particular, most investments needed for the transition are expected to replace business-as-usual investments, not come as additional investments. Regardless of the price on carbon, the articulation between monetary, fiscal and prudential policy may be critical (as discussed in Chapter 4) to address these issues while fighting climate change.

(ii) Other major transformations of capitalism may also be worth considering when addressing the question of which strategy is realistically the most adequate to tackle climate change. For instance, the shift since the 1970s in the objectives of corporates with a narrow focus on shareholder value maximisation and the still-prevailing dominance of the efficient market hypothesis (Mazzucato (2015)) may lead to a situation where corporates are structurally unable to fully embrace the old and new responsibilities associated with their growing power. The "continued erosion of workers' bargaining power" (BIS (2019) p 9) is another, related major structural force that should not be forgotten when devising strategies for a socially fair low-carbon transition. Others argue that the evolution to societies driven more by passions than by reason (Dupuy (2013)) and by the pursuit of self-interest at the expense of the common good (Collier (2018)) is particularly disturbing as climate change demands social responsibility of all the players.

As a result, the fight against climate change must take place at a time when the global institutional framework established after World War II and some of the values it officially promotes (such as democracy and multilateralism) are increasingly under pressure. These patterns are significant institutional roadblocks to the low-carbon transition, which requires unprecedented participation and coordination. As Lord Nicholas Stern puts it, "it is intensive public discussion that will [...] be the ultimate enforcement mechanism" (Stern (2008), p 33). Or as David Pitt-Watson, the former Chair of the United Nations Environmental Program Finance Initiative (UNEP-FI) elegantly observed: "When it comes to climate change we are all players, we are not spectators" (cited in Andersson et al (2016), p 29). Climate-economic models still have a long way to go to grasp these fundamental international political economy dimensions. In order to embrace these features and the international and national political economy dimensions of a low-carbon transition discussed above, inspiration can be found in Elinor Ostrom's principles for governance of common pool resources (CPRs), as discussed in Chapter 4.

It is noteworthy that the Shared Socioeconomic Pathways (SSPs), a group of five narratives built by an international team of climate scientists, economists and energy systems modellers (Carbon Brief (2018)), aim precisely to capture some of these patterns. SSPs notably provide qualitative narratives describing alternative socioeconomic developments. They suggest, for instance, that a strong pushback against multilateralism would make ambitious climate targets almost impossible to achieve. SSPs still need to be fully coupled with Representative Concentration Pathways (RCPs), which describe different levels of greenhouse gases and other radiative forcings that might occur in the future. In spite of representing a significant step forward, it is unclear how simply considering the narratives put forth by the SSPs could lead climate-economic models to embrace the socio-technical patterns discussed above. It seems that SSPs could be better tailored to alternative analytical approaches and models such as those discussed in Chapter 3.5 (non-equilibrium models, case studies and sensitivity analyses) and in Chapter 4.

[53] Environmental policy can boost innovation, with positive spillover effects leading to increased competitiveness at the national scale (Porter (1991)). For instance, climate change mitigation and adaptation could lead to the creation of millions of jobs in green industries, services and infrastructure, which could even compensate for the jobs threatened by technological progress (Pereira da Silva (2019a)).

ANNEX 3 – Multiple interactions between physical and transition risks

Although physical and transition risks are usually treated separately, these are likely to interact with each other in practice. There could be multiple interactions and feedback loops within and among three subsystems: socio-ecological systems, socioeconomic systems and regulatory systems.[54] These interactions can generate new, complex cascade effects that cannot be captured by physical or transition risks separately. We present some examples below, which do not intend to be exhaustive but rather to exemplify the largely unpredictable patterns that can arise when the uncertain, complex and nonlinear patterns of Earth's systems and human ones are combined.

First, with regard to socio-ecological systems: climate change can have multiple impacts, as detailed in Annex 1. For instance, it can generate water scarcity, which in turn can trigger agricultural losses and cause food insecurity (IPCC (2019)). These knock-on effects, in turn, can feed back into climate patterns, as shown by the recent IPCC report on climate change and land use (IPCC (2019)). For instance, current land exploitation accounts for almost a quarter of GHGs emitted through human activity, but it is also responsible for soil erosion (due to intensive agricultural practices) that end up reducing the soil's ability to absorb carbon; the latter then contributes to accelerating climate change, which will further contribute to land degradation (eg increased rainfall can result in more surface run-off and subsequent losses in organic matter and nutrients (Lugato et al (2018)).

Second, with regard to socioeconomic systems, climate change can have multiple impacts such as increases in deaths due weather extremes (Mora et al (2018)), migrations (World Bank (2018)), inequalities within and between countries (Burke et al (2015a)) and violence and conflicts (Burke et al (2015b)). All these forces can generate emerging properties and chaotic forces such as asset destruction or reduction of economic growth. Conversely, they can trigger societal responses leading to new consumer behaviours and/or more investments in R&D in renewable energy, with potential nonlinear technological breakthroughs (eg utility-scale solar is now cheaper on a lifetime basis than the marginal cost of running nuclear or coal plants).

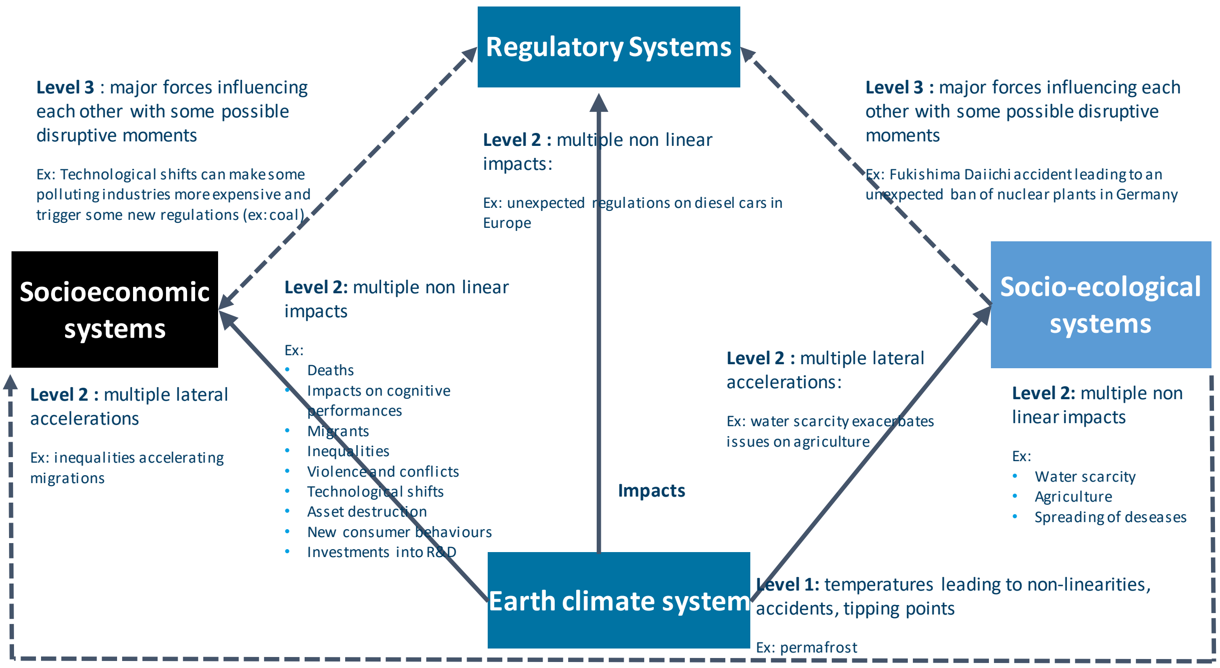
Third, with regard to regulatory and legal systems: climate change has already led to multiple but limited regulatory responses and laws. These can generate positive cascade effects, but they can also put some countries at risk if their economy is mainly based on fossil fuel reserves (McGlade and Ekins (2015)). For diesel cars, for example, the restrictive Corporate Average Fuel Economy (CAFE) regulation requires that EU fleet-wide average emissions be 95 g CO_2/km by 2020. This, in turn, will trigger many chain reactions within the industry; for instance, several large automobile groups are facing heavy potential fines as they are currently unable to meet these stringent new standards.

Lastly, these three subsystems (socio-ecological, socioeconomic and regulatory) interact with each other and generate new chain reactions (Graph A.8). For example, water scarcity could affect some corporates if water is allocated giving priority to basic human needs, or affect humans if it is allocated to corporates based on their ability to pay for it without any equity considerations. Similarly, extreme weather events could have major impacts on socioeconomic systems and lead to unexpected new regulations (such as the Fukushima Daiichi accident leading to an unexpected ban of nuclear plants in Germany). In turn, millennials' mobilisation against climate change (see the numerous climate marches across the world or the eruption of new social movements such as Extinction Rebellion) could increase the pressure on policymakers and lead to new rounds of unpredictable regulatory measures.

[54] We acknowledge that regulatory systems can be considered as part of socioeconomic systems. Nevertheless, we consider them as separate subsystems for the purposes of this annex.

Chain reactions at all levels

Graph A.8



Source: Authors' elaboration.

Box A1. Example of disruptive moment driven by regulation: the automotive industry

Today most changes are driven by consumers and technologies. The automotive industry is experiencing a crucial evolution driven by regulatory constraints and pressure from public opinion: the energy transition.

The Kyoto Protocol adopted by COP 3 in 1997 was the starting point of legally binding reduction targets in GHG emissions. However, the EU target was divided between its member states according to the burden-sharing agreement, while at the sectoral level the automobile sector was considered to not be doing enough to reduce emissions despite sectoral commitments set in 1998 by the ACEA (European Automobile Manufacturer's Association). However, forcing the automotive industry to reduce emissions drove the European Commission to pursue an integrated approach across the EU and pushed auto makers to achieve technological improvements in motor vehicle technology.

An example is the Volkswagen emissions scandal of September 2015, known as Dieselgate. It highlighted the weaknesses of an industry that had not sufficiently addressed the consequences of the technological revolution in relation to the energy transition pushed by regulators. On the financial side, while stock value collapsed, and credit spreads widened, residual value risk increased on captive finance units. This has changed the entire landscape for car makers. Europe has experienced less diesel use while seeing efforts to reduce CO_2 emissions hit by a boom of SUV commercialisation and a shift towards petrol engines. The additional pressure from public opinion and more stringent local regulators with the implementation of a diesel ban and ban on combustion engines in a mid-term horizon also contributed: car manufacturers had to adapt abruptly in order to propose new products and relevant technologies to address the EU's 2021 target of 95 g of CO_2/km.

Nevertheless, demand for electrified cars is still very low while capex and R&D investments remain very high, leading to pressure on company cash flow generation. Thus, uncertainty about the future profitability of electrified vehicles implies margin pressure for car manufacturers in a period of unfavourable timing due to the end of the cycle: more than 300 electric vehicle models are expected to be available on the European market by 2025.

The industry is at a time of change, driven by stronger regulation which will foster industry consolidation, alliance and M&A operations, for example PSA and FCA transactions. A key factor will be the cost of sector transition as operations driven by cost-sharing are increasing (eg the alliance between Ford and Volkswagen on vans and commercial vehicles).

At auto suppliers, the shift towards electric vehicles has led to lower valuations of their historical powertrain businesses and spin-off transactions. New entrants in the industry, like battery producers and mobility providers, will challenge traditional car manufacturers and suppliers by competing on multiple fronts, increasing the complexity of an already competitive landscape.

ANNEX 4 – From climate-related risk management to a systems view of resilience for the Anthropocene

Fighting climate change is paramount to preserve financial stability, but it should not be forgotten that climate change is only the "tip of the iceberg" (Steffen et al (2011)). Other biogeochemical cycles than the carbon cycle that are critical to life on Earth are also being altered, and may present even higher risks than climate change. For instance, the accelerating decline of the Earth's natural life support systems also poses significant risks to human societies (in addition to the ethical problems related to the erosion of non-human forms of life). The UN Global Assessment Report on Biodiversity and Ecosystem Services (IPBES (2019)) found that human activity caused a catastrophic decline in Earth's biodiversity, unprecedented in human history (for instance, the biomass of wild mammals fell by 82% since the pre-industrialisation era, and about a third of reef-building corals is threatened with extinction). Other risks include pressures on freshwater availability and soil erosion, which is becoming a vital stake for humanity according to the United Nations Convention to Combat Desertification (UNCCD).

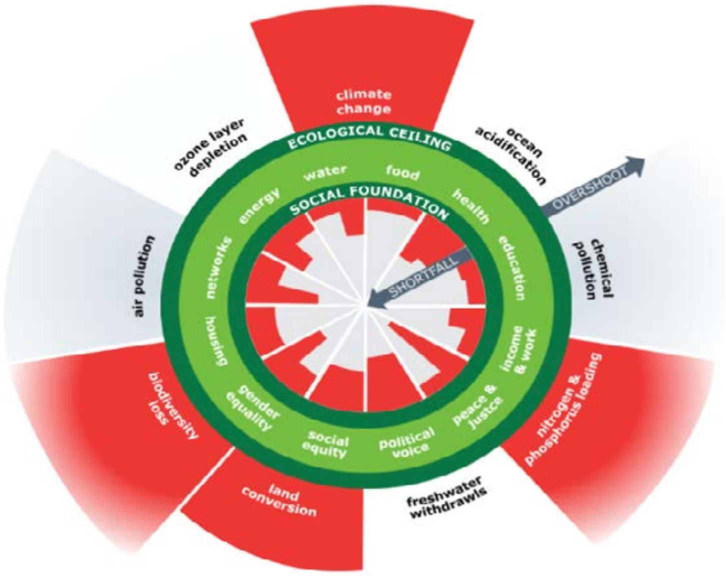
Rockström et al (2009) have identified and quantified nine planetary boundaries, which define the "safe operating space for humanity" associated with the planet's biophysical subsystems or processes. These subsystems are "particularly sensitive around threshold levels of certain key variables. If these thresholds are crossed, then important subsystems, such as a monsoon system, could shift into a new state, often with deleterious or potentially even disastrous consequences for humans" (Rockström et al (2009), p 472).

The dramatic and unprecedented changes in the Earth system caused by human activity have led many to consider that we have entered the Anthropocene,[55] an age in which "human impacts on essential planetary processes have become so profound that they have driven the Earth out of the Holocene epoch in which agriculture, sedentary communities, and eventually, socially and technologically complex human societies developed" (Steffen et al (2018)). In 2017, a group of 15,000 scientists (Ripple et al (2017)) issued a "warning to humanity", reminding that runaway consumption by a growing population in a world of limited resources and waste absorption capacity is now posing an existential threat.

In this context, avoiding the unmanageable risks that may arise if we cross different planetary boundaries requires nothing less than creating a stabilised Earth pathway, which "can only be achieved and maintained by a coordinated, deliberate effort by human societies to manage our relationship with the rest of the Earth System, recognizing that humanity is an integral, interacting component of the system" (Steffen et al (2017)). This requires finding an "environmentally safe and socially just space in which humanity can thrive", between social foundations and ecological ceilings (Raworth (2017); Graph A.9). Ecological ceilings map into nine planetary boundaries set out by Rockström et al (2015), while "the social foundations are derived from internationally agreed minimum social standards, as identified by the world's governments in the Sustainable Development Goals in 2015. Between social and planetary boundaries lies an environmentally safe and socially just space in which humanity can thrive" (Raworth (2017)).

[55] The term Anthropocene is used acknowledging that different societies around the world have contributed differently to pressures on the Earth system, as reminded by different authors critical of the narrative behind this term (eg Malm and Hornborg (2014)).

A comprehensive approach to social foundations and ecological ceilings Graph A.9



Source: Raworth (2017).

To be sure, such an approach raises difficult questions as to which "planetary stewardship strategies are required to maintain the Earth System in a manageable" state (Steffen et al (2018)), and which set of worldviews, institutions and technologies will be up to the task (Beddoe et al (2009), Vatn (2006)). Moreover, a systems approach would require shifting the focus from handling specific environmental crises (eg climate change) on a case by case basis to a much more holistic view that can better account for the cascading effects of system failure (OECD (2019a)).

It is noteworthy that the IPCC's Shared Socio-Economic Pathways (SSP) implicitly support revisiting GDP growth rates, as part of a broader socio-technical transition touching upon several points discussed in this book: the SSP1 "Sustainability" narrative, corresponding to the road towards a low-carbon world, strongly emphasises international cooperation and education to manage the global commons and the demographic transition, and shifts emphasis from economic growth towards other indicators such as human well-being and reduced inequalities (Carbon Brief (2018)).

7. REFERENCES

Abel, Guy J., Michael Brottrager, Jesus Crespo Cuaresma, and Raya Muttarak. 2019. "Climate, Conflict and Forced Migration." *Global Environmental Change* 54 (January): 239–49. https://doi.org/10.1016/J.GLOENVCHA.2018.12.003.

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. 2012. "The Environment and Directed Technical Change." *American Economic Review* 102 (1): 131–66. https://doi.org/10.1257/aer.102.1.131.

Acemoglu, Daron, Asuman Ozdaglar, and Alireza Tahbaz-Salehi. 2015. "Systemic Risk and Stability in Financial Networks." *American Economic Review* 105 (2): 564–608. https://doi.org/10.1257/aer.20130456.

Ackerman, Frank, Stephen J. DeCanio, Richard B. Howarth, and Kristen Sheeran. 2009. "Limitations of Integrated Assessment Models of Climate Change." *Climatic Change* 95 (3–4): 297–315. https://doi.org/10.1007/s10584-009-9570-x.

ACPR. 2019. "Le Changement Climatique : Quels Risques Pour Les Banques et Les Assurances ?" Analyses et synthèses. Available at : https://acpr.banque-france.fr/sites/default/files/medias/documents/as_risque_climatique_note_de_presentation_fr.pdf.

Adger, W. Neil, Jouni Paavola, Saleemul Huq, M. J. Mace. 2006. "Fairness in Adaptation to Climate Change" MIT Press.

Adrian, Tobias, and Fabio Natalucci. 2019. "Weak Spots in Global Financial System Could Amplify Shocks." IMF Blog, April 10. Available at: https://blogs.imf.org/2019/04/10/weak-spots-in-global-financial-system-could-amplify-shocks/

Aglietta, M., Ould Ahmed, P., Ponsot, J.F. 2016. La Monnaie, entre Dettes et Souveraineté. Odile Jacob, Paris.

Aglietta, Michel, and Virginie Coudert. 2019. "The Dollar and the Transition From Key Currency to Multilateralism." CEPII Working Paper 2019-26Available at :
http://www.cepii.fr/CEPII/en/publications/pb/abstract.asp?NoDoc=12245

Aglietta, Michel, and Étienne Espagne. 2018. "Le Système Monétaire International Face Aux Cycles Biogéochimiques." *Annales Des Mines - Responsabilité et Environnement* 92 (4): 64–68. https://doi.org/https://doi.org/10.3917/re1.092.0064.

Aglietta, Michel, and Étienne Espagne. 2016. "Climate and Finance Systemic Risks, More than an Analogy? The Climate Fragility Hypothesis." CEPII Working Paper No 2016-10. Available at: http://www.cepii.fr/PDF_PUB/wp/2016/wp2016-10.pdf

Allen, Thomas, Jean Boissinot, Carlos Mateo Caicedo Graciano, Valérie Chouard, Laurent Clerc, Stéphane Dees, Annabelle De Gaye, Marie-Elisabeth de la Serve, Morgan Despres, Antoine Devulder, Sophie Haincourt, Benoît Hallinger, Noëmie Lisack, Jean-Stéphane Mésonnier, Sylvain Peyron, Marie Rabaté, Romain Svartzman, Lucas Vernet. 2020. "Climate-Related Scenarios for Financial Stability Assessment: An Application to France." *Working Paper Banque de France.* Forthcoming.

Andersson, Mats, Patrick Bolton, and Frédéric Samama. 2016. "Hedging Climate Risk." *Financial Analysts Journal* 72 (3): 13–32. https://doi.org/10.2469/faj.v72.n3.4.

Arezki, Rabah, Patrick Bolton, Sanjay Peters, Frederic Samama, and Joseph Stiglitz. 2016. "From Global Savings Glut to Financing Infrastructure: The Advent of Investment Platforms." *IMF Working Papers* 16 (18): 1. https://doi.org/10.5089/9781475591835.001.

Aro, Eva Mari. 2016. "From First Generation Biofuels to Advanced Solar Biofuels." *Ambio* 45: 24–31. https://doi.org/10.1007/s13280-015-0730-0.

Aufauvre, Nathalie, and Clément Bourgey. 2019. "Le Rôle Des Banques Centrales et Des Autorités de Supervision Pour Inciter à Une Meilleure Prise En Compte Des Enjeux de Long Terme : Le Cas Du Changement Climatique." *Annales Des Mines - Réalités Industrielles*, no. 4: 60–63.

Aussilloux, Vincent, and Etienne Espagne. 2017. "Mettre La Fiscalité de l'Épargne Au Service d'une Croissance Durable." Note d'Analyse no. 2017-54, France Stratégie.

Ayres, Robert. 2016. *Energy, Complexity and Wealth Maximization*. *The Frontiers Collection*. Springer International Publishing. https://doi.org/10.1007/978-3-319-30545-5.

Bachelard, Gaston. 1938 (1967). *La Formation de l'Esprit Scientifique*. Librairie philosophique J. Vrin.

Baker, David R., and Eric Roston. 2019. "After PG&E's Climate-Driven Bankruptcy, Who's Next?" *Bloomberg*, January 22, 2019. https://www.bloomberg.com/news/articles/2019-01-22/why-a-pg-e-bankruptcy-could-change-climate-calculus-quicktake.

Bamber, Jonathan L., Michael Oppenheimer, Robert E. Kopp, Willy P. Aspinall, and Roger M. Cooke. 2019. "Ice Sheet Contributions to Future Sea-Level Rise from Structured Expert Judgment." *Proceedings of the National Academy of Sciences of the United States of America* 166 (23): 11195–200. https://doi.org/10.1073/pnas.1817205116.

Barker, Richard, and Colin Mayer. 2017. "How Should a 'Sustainable Corporation' Account for Natural Capital?" *Saïd Business School Research Papers* 2017–15.

Barmes, David. 2019. "Climate 'risk' vs ' Uncertainty' in Financial Policymaking." Positive Money. 2019. Available at: https://positivemoney.org/2019/10/climate-risk-vs-uncertainty-in-financial-policymaking/

Barreto, Leonardo, and René Kemp. 2008. "Inclusion of Technology Diffusion in Energy-Systems Models: Some Gaps and Needs." *Journal of Cleaner Production* 16 (1): S95–101. https://doi.org/10.1016/j.jclepro.2007.10.008.

Batten, Sandra. 2018. "Climate Change and the Macro-Economy: A Critical Review." Bank of England Working Paper no. 706. Available at: https://www.bankofengland.co.uk/working-paper/2018/climate-change-and-the-macro-economy-a-critical-review

Batten, Sandra, Rhiannon Sowerbutts, and Misa Tanaka. 2016. "Let's Talk about the Weather: the Impact of Climate Change on Central Banks". Bank of England Staff Working Paper no. 603.

Battiston, Stefano. 2019. "The Importance of Being Forward-looking: Managing Financial Stability in the Face of Climate Risk." *Banque de France Financial Stability Review*, no. 23: 39–48.

Battiston, Stefano, Antoine Mandel, Irene Monasterolo, Franziska Schütze, and Gabriele Visentin. 2017. "A Climate Stress-Test of the Financial System." *Nature Climate Change* 7 (4): 283–88. https://doi.org/10.1038/nclimate3255.

Battiston, Stefano, and Irene Monasterolo. 2019. "How Could the ECB's Monetary Policy Support the Sustainable Finance Transition?" https://www.finexus.uzh.ch/dam/jcr:0103ed7b-71e9-4e81-9941-ee61feefd851/ECB sustainable finance 22 MarchIM.pdf.

Beddoe, Rachael, Robert Costanza, Joshua Farley, Eric Garza, Jennifer Kent, Ida Kubiszewski, Luz Martinez, Tracy McCowen, Kathleen Murphy, Norman Myers, Zach Ogden, Kevin Stapleton, and John Woodward. 2009. "Overcoming Systemic Roadblocks to Sustainability: The Evolutionary Redesign of Worldviews, Institutions, and Technologies." *Proceedings of the National Academy of Sciences of the United States of America* 106 (8): 2483–89. https://doi.org/10.1073/pnas.0812570106.

Bereiter, Bernhard, Sarah Eggleston, Jochen Schmitt, Christoph Nehrbass-Ahles, Thomas F. Stocker, Hubertus Fischer, Sepp Kipfstuhl and Jerome Chappellaz. 2015. "Revision of the EPICA Dome C CO2 record from 800 to 600 kyr before present". *Geophysical Research Letters*. doi: 10.1002/2014GL061957.

Bernanke, Ben. 2017. “Monetary Policy in a New Era.” Brookings. 2017. The Brookings Institution. Available at: https://www.brookings.edu/research/monetary-policy-in-a-new-era/.

Bernardini, Enrico, Johnny Di Giampaolo, Ivan Faiella, and Riccardo Poli. 2019. “The Impact of Carbon Risk on Stock Returns: Evidence from the European Electric Utilities.” *Journal of Sustainable Finance and Investment*. https://doi.org/10.1080/20430795.2019.1569445.

Bernstein, Asaf, Matthew T. Gustafson, and Ryan Lewis. 2019. “Disaster on the Horizon: The Price Effect of Sea Level Rise.” *Journal of Financial Economics* 134 (2): 253–72. https://doi.org/10.1016/j.jfineco.2019.03.013.

Bezemer, Dirk, Josh Ryan-Collins, and Lu Zhang. 2018. “Credit Where It’s Due: A Historical, Theoretical and Empirical Review of Credit Guidance Policies in the 20th Century.” *Working Paper IIPP*, no. December. https://www.ucl.ac.uk/bartlett/public-purpose/wp2018-11.

Bhattacharya, Amar, Joshua P. Meltzer, Jeremy Oppenheim, Zia Qureshi, and Lord Nicholas Stern. 2016. “Delivering on Sustainable Infrastructure for Better Development and Better Climate.” The Brookings Institution. Available at: https://www.brookings.edu/wp-content/uploads/2016/12/global_122316_delivering-on-sustainable-infrastructure.pdf.

Bihouix, Philippe. 2015. “Les Low-Tech, Emplois de Demain.” In *Economie de l’après-Croissance: Politiques de l’Anthropocène II*, 197–212. Presses de Sciences Po.

BIS. 2019. “BIS Annual Economic Report 2019.” Bank for International Settlements. Available at: https://www.bis.org/publ/arpdf/ar2019e.pdf

BIS. 2017. “87th Annual Report, 2016/17.” Bank for International Settlements. Available at: https://www.bis.org/publ/arpdf/ar2017e.pdf

Blanchard, Olivier. 2019. “Public Debt: Fiscal and Welfare Costs in a Time of Low Interest Rates.” Washington, DC. Peterson Institute for International Economics. Available at: https://www.piie.com/publications/policy-briefs/public-debt-fiscal-and-welfare-costs-time-low-interest-rates.

Bolton, Patrick, Haizhou Huang, and Frédéric Samama. 2018. “From the One Planet Summits to the ‘Green Planet Agency.’” Working Paper.

Bolton, Patrick, and Frédéric Samama. 2012. “Capital Access Bonds: Contingent Capital with an Option to Convert.” *Economic Policy* 27 (70): 275–317. http://www.jstor.org/stable/41428855.

Bonneuil, Christophe, and Jean-Baptiste Fressoz. 2016. *L’évènement Anthropocène : La Terre, l’histoire et nous.* Editions du Seuil.

Borio, Claudio, Mathias Drehmann, and Kostas Tsatsaronis. 2014. “Stress-Testing Macro Stress Testing: Does It Live up to Expectations?” *Journal of Financial Stability* 12 (1): 3–15. https://doi.org/10.1016/j.jfs.2013.06.001.

Borio, Claudio, and Hyun Song Shin. 2019. “BIS Quarterly Review, September 2019 - Media Briefing.” Available at: https://www.bis.org/publ/qtrpdf/r_qt1909_ontherecord.htm

BP. 2019. “BP Statistical Review of World Energy Statistical Review of World.” *BP Statistical Review of World Energy*. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf.

Bradford Delong, J., and Lawrence H. Summers. 2012. “Fiscal Policy in a Depressed Economy.” *Brookings Papers on Economic Activity*, no. 1: 233–72. https://doi.org/10.1353/eca.2012.0000.

Brainard, Lael. 2019. “Why Climate Change Matters for Monetary Policy and Financial Stability.” Speech delivered at "The Economics of Climate Change", a research conference sponsored by the Federal Reserve

Bank of San Francisco, San Francisco, California, 8 November 2019. Available at: https://www.bis.org/review/r191111a.htm

Braun, Benjamin. 2018. "Central Banking and the Infrastructural Power of Finance: The Case of ECB Support for Repo and Securitization Markets." *Socio-Economic Review*. https://doi.org/10.1093/ser/mwy008.

Bredemkamp, Hugh, and Catherine Patillo. 2010. "Financing the Response to Climate Change." IMF Staff Position Note, March 25. Washington, DC.

Bryan, Dick, Michael Rafferty, and Duncan Wigan. 2017. "From Time-Space Compression to Spatial Spreads." *Money and Finance After the Crisis*, 41–67. https://doi.org/10.1002/9781119051374.ch2.

Bunten, Devin, and Matthew E. Kahn. 2014. "The Impact of Emerging Climate Risks on Urban Real Estate Price Dynamics." *National Bureau of Economic Research Working Paper Series* No. 20018: 1–21. https://doi.org/10.3386/w20018.

Bureau, Dominique, Fanny Henriet, and Katheline Schubert. 2019. "A Proposal for the Climate: Taxing Carbon Not People." *Notes du conseil d'analyse économique*, 2019/2 (No 50), p. 1-12. Available at : https://www.cairn.info/revue-notes-du-conseil-d-analyse-economique-2019-2-page-1.htm

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. 2015a. "Global Non-Linear Effect of Temperature on Economic Production." *Nature* 527 (7577): 235–39. https://doi.org/10.1038/nature15725.

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. 2015b. "Climate and Conflict." *Annual Review of Economics* 7: 577–617.

Caballero, Ricardo J., Emmanuel Farhi, and Pierre Olivier Gourinchas. 2008. "Financial Crash, Commodity Prices, and Global Imbalances." *Brookings Papers on Economic Activity*, no. 2: 1–55.

Cahen-Fourot, Louison, Emanuele Campiglio, Elena Dawkins, Antoine Godin, and Eric Kemp-Benedict. 2019a. "Looking for the Inverted Pyramid: An Application Using Input-Output Networks". *Ecological Economics* 169 (March 2020). https://doi.org/10.1016/j.ecolecon.2019.106554.

Cahen-Fourot, Louison, Emanuele Campiglio, Elena Dawkins, Antoine Godin, and Eric Kemp-Benedict. 2019b. "Capital Stranding Cascades: The Impact of Decarbonisation on Productive Asset Utilisation." *Ecological Economic Papers* 6854, WU Vienna University of Economics and Business.

Cai, Yongyang, and Thomas S Lontzek. 2019. "The Social Cost of Carbon with Economic and Climate Risks." *Journal of Political Economy* 127 (6): 2684-2734.https://doi.org/10.1086/701890.

Ben Caldecott. (2017) Introduction to special issue: stranded assets and the environment. *Journal of Sustainable Finance & Investment* 7 (1): 1-13.

Caldecott, Ben. 2019. "Viewpoint: Spatial Finance Has a Key Role." *IPE*, November 2019.

Calel, Raphael, David A Stainforth, and Simon Dietz. 2015. "Tall Tales and Fat Tails: The Science and Economics of Extreme Warming." *Climatic Change* 132 (1): 127–41. https://doi.org/10.1007/s10584-013-0911-4.

Campiglio, Emanuele. 2016. "Beyond Carbon Pricing: The Role of Banking and Monetary Policy in Financing the Transition to a Low-Carbon Economy." *Ecological Economics* 121: 220–30. https://doi.org/10.1016/j.ecolecon.2015.03.020.

Campiglio, Emanuele, Yannis Dafermos, Pierre Monnin, Josh Ryan-Collins, Guido Schotten, and Misa Tanaka. 2018. "Climate Change Challenges for Central Banks and Financial Regulators." *Nature Climate Change* 8 (6): 462–68. https://doi.org/10.1038/s41558-018-0175-0.

Campiglio, Emanuele, Antoine Godin, and Eric Kemp-benedict. 2017. "Papiers de Recherche | Research Papers Networks of Stranded Assets : A Case for a Balance Sheet Approach." Available at: https://www.afd.fr/en/ressources/networks-stranded-assets-case-balance-sheet-approach.

Carbon Brief. 2018. "Q&A: How 'Integrated Assessment Models' Are Used to Study Climate Change." 2018. Available at: https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change.

Carbon Delta. 2019. "Carbon Delta Methodologies Overview." Available at: https://www.tcfdhub.org/wp-content/uploads/2019/07/201711_Carbon_Delta_Methodologies.pdf

Carbon Tracker. 2018. "Mind The Gap: The $1.6 Trillion Energy Transition Risk." Available at: https://www.carbontracker.org/reports/mind-the-gap/

Carbon Tracker. 2013. "Unburnable Carbon 2013: Wasted Capital and Stranded Assets."

Carbone 4. 2016. "Carbon Impact Analytics - How to Measure the Contribution of a Portfolio to the Energy and Climate Transition." Available at: http://www.carbone4.com/wp-content/uploads/2016/08/CarbonImpactAnalytics.pdf

Carney, Mark. 2015. "Breaking the Tragedy of the Horizon – Climate Change and Financial Stability." Speech at Lloyd's of London, London, 29 September 2015. Available at: https://www.bis.org/review/r151009a.pdf

Carney, Mark. 2016. "Resolving the Climate Paradox." Text of the Arthur Burns Memorial Lecture, Berlin, 22 September 2016. Available at: https://www.bis.org/review/r160926h.pdf

Carney, Mark. 2018. "A Transition in Thinking and Action." Remarks at the International Climate Risk Conference for Supervisors, The Netherlands Bank, Amsterdam, 6 April 2018. Available at: https://www.bis.org/review/r180420b.pdf

Cette, Gilbert, John Fernald, and Benoît Mojon. 2016. "The Pre-Great Recession Slowdown in Productivity." *European Economic Review* 88: 3–20. https://doi.org/10.1016/j.euroecorev.2016.03.012.

Chaisson, Eric J. 2014. "Practical Applications of Cosmology to Human Society." *Natural Science* 06 (10): 767–96. https://doi.org/10.4236/ns.2014.610077.

Chancel, Lucas. 2017. *Insoutenables Inégalités : Pour Une Justice Sociale et Environnementale*. Les petits matins.

Chenet, Hugues. 2019a. "Climate Change and Financial Risk." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3407940.

Chenet, Hugues. 2019b. "Planetary Health and the Global Financial System." Rockefeller Foundation Economic Council on Planetary Health working paper.

Chenet, Hugues, Josh Ryan-Collins, and Van Lerven, Frank. 2019a. "Climate-Related Financial Policy in a World of Radical Uncertainty: Towards a Precautionary Approach." *UCL* Institute for Innovation and Public Purpose *Working Paper*, no 2019-13. Available at: https://www.ucl.ac.uk/bartlett/public-purpose/publications/2019/dec/climate-related-financial-policy-world-radical-uncertainty.

Chenet, Hugues, Luis Zamarioli, Bianca Kretschmer, and Rodrigo Narvaez. 2019b. "From Transformational Climate Finance to Transforming the Financial System for Climate." https://www.cop21ripples.eu/wp-content/uploads/2019/09/20190830_COP21-RIPPLES_D4-3a_Transforming-the-Financial-System.pdf.

Christophers, Brett. 2019. "Environmental Beta or How Institutional Investors Think about Climate Change and Fossil Fuel Risk." *Annals of the American Association of Geographers* 109 (3): 754–74. https://doi.org/10.1080/24694452.2018.1489213.

CISL. 2016. "Closing the Protection Gap: ClimateWise Principles Independent Review 2016." Cambridge, UK: Cambridge Institute for Sustainability Leadership.

Cleary, Patrick, William Harding, Jeremy McDaniels, Jean-Philippe Svoronos, and Jeffery Yong. 2019. "FSI Insights on Policy Implementation Turning up the Heat – Climate Risk Assessment in the Insurance Sector." https://www.bis.org/fsi/publ/insights20.pdf.

Cœuré, Benoît. 2018. "Monetary Policy and Climate Change." Speech at a conference on "Scaling up Green Finance: The Role of Central Banks", organised by the Network for Greening the Financial System, the Deutsche Bundesbank and the Council on Economic Policies, Berlin, 8 November 2018. Available at: https://www.bis.org/review/r181109f.pdf

Cohen Mark A., Don Fullerton, Robert H. Topel. 2013. "Distributional Aspects of Energy and Climate Policies", Edward Elgar Publishing.

Colin, Aurore, Charlotte Vailles, and Romain Hubert. 2019. "Understanding Transition Scenarios - Eight Steps for Reading and Interpreting These Scenarios." I4CE. Available at: https://www.i4ce.org/wp-core/wp-content/uploads/2019/11/I4CE-ScenariosTransition-Rapport-complet-VA.pdf

Collier, Paul. 2018. The Future of Capitalism: Facing the New Anxieties. Allen Lane UK.

Costanza, Robert, Ralph D'Arge, Rudolf De Groot, Stephen Farber, Monica Grasso, Bruce Hannon, Karin Limburg, et al. 1997. "The Value of the World's Ecosystem Services and Natural Capital." *Nature* 387 (6630): 253–60. https://doi.org/10.1038/387253a0.

Curran, Patrick, Nick Robins, and Nicholas Stern. 2019. "Unlocking the Strategic Economic Opportunity of Clean and Inclusive Growth." *Banque de France Financial Stability* 23: 29–38.

D'Orazio, Paola, and Lilit Popoyan. 2019. "Fostering Green Investments and Tackling Climate-Related Financial Risks: Which Role for Macroprudential Policies?" *Ecological Economics* 160: 25–37. https://doi.org/10.1016/j.ecolecon.2019.01.029.

Dafermos, Yannis, Maria Nikolaidi, and Giorgos Galanis. 2017. "A Stock-Flow-Fund Ecological Macroeconomic Model." *Ecological Economics* 131: 191–207. https://doi.org/10.1016/j.ecolecon.2016.08.013.

Daly, Herman E., and Joshua Farley. 2011. *Ecological Economics : Principles and Applications*. 2nd ed. Washington, DC: Island Press.

Daniel, Kent D., Robert B. Litterman, and Gernot Wagner. 2019. "Declining CO2 Price Paths." *Proceedings of the National Academy of Sciences of the United States of America* 116 (42): 20886–91. https://doi.org/10.1073/pnas.1817444116.

Dantec, Ronan, and Jean-Yves Roux. 2019. "Adapter La France Aux Dérèglements Climatiques à l'horizon 2050 : Urgence Déclarée." Rapport d'information - Sénat No511.

De Cambourg, Patrick. 2019. "Garantir La Pertinence et La Qualité de l'information Extra-Financière Des Entreprises : Une Ambition et Un Atout Pour Une Europe Durable." Rapport présenté au Ministre de l'Economie et des Finances.

De Grauwe, Paul. 2019. "Green Money without Inflation." Social Europe. 2019. https://www.socialeurope.eu/green-money-without-inflation.

De Greiff, Kathrin, T. Ehlers, and F. Packer. 2018. "The Pricing and Term Structure of Environmental Risk in Syndicated Loans. Mimeo." BIS (Bank for International Settlements).

Debelle, Guy. 2019. "Climate Change and the Economy." Speech at the Public Forum hosted by the Centre for Policy Development, Sidney, 12 March 2019. Available at: https://www.bis.org/review/r190313d.pdf.

Delis, Manthos D., Kathrin de Greiff, and Steven Ongena. 2018. "Being Stranded on the Carbon Bubble? Climate Policy Risk and the Pricing of Bank Loans." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3125017.

Dennig Francis, Mark B. Budolfson, Marc Fleurbaey, Asher Siebert, and Robert H. Socolow, "Inequality, climate impacts on the future poor, and carbon prices" PNAS, December 29, 2015, vol. 112, no. 52, 15827–15832

Dépoues, Vivian, Vincent Bouchet, Michel Cardona, and Morgane Nicol. 2019. "Pour Une Autre Approche Du Risque Climatique En Finance." I4CE. Available at : https://www.i4ce.org/wp-core/wp-content/uploads/2019/11/I4CE_Incertitudes_Pour-une-autre-approche-du-risque-en-finance_vf.pdf.

DG Treasury, Banque de France, and ACPR. 2017. "Assessing Climate Change- Related Risks in the Banking Sector." Directorate General of the Treasury. https://www.tresor.economie.gouv.fr/Ressources/File/433465.

Dietz, Simon, Alex Bowen, Charlie Dixon, and Philip Gradwell. 2016. "Climate Value at Risk' of Global Financial Assets." *Nature Climate Change* 6 (7): 676–79. https://doi.org/10.1038/nclimate2972.

Diffenbaugh, Noah S., and Marshall Burke. 2019. "Global Warming Has Increased Global Economic Inequality." *Proceedings of the National Academy of Sciences of the United States of America* 116 (20): 9808–13. https://doi.org/10.1073/pnas.1816020116.

Dikau, Simon, and Josh Ryan-Collins. 2017. "Green Central Banking in Emerging Market and Developing Country Economies." *New Economics Foundation*. http://neweconomics.org/2017/10/green-central-banking-emerging-market-developing-country-economies/.

Dikau, Simon, and Ulrich Volz. 2019. "Central Bank Mandates, Sustainability Objectives and the Promotion of Green Finance." Working Papers. Department of Economics, SOAS, University of London, UK. https://econpapers.repec.org/RePEc:soa:wpaper:222.

Drugmand, Dana. 2019. "Shell Faces Lawsuit in the Netherlands, a New Legal Front in the Climate Battle." Climate Liability News. 2019. https://www.climateliabilitynews.org/2019/02/12/shell-netherlands-lawsuit-climate-change/.

Dupuy, Jean Pierre. 2012. "The Precautionary Principle and Enlightened Doomsaying." *Revue de Metaphysique et de Morale* 74 (4): 577–92. https://doi.org/10.3917/rmm.124.0577.

Dupuy, Jean-Pierre. 2013. *The Mark of the Sacred*. Stanford: Stanford University Press.

EBA. 2019. "2020 EU-Wide Stress Test - Methodological Note." European Banking Authority, 25 June 2019.

EBA. 2016. "EBA Report on SMEs and SME Supporting Factor." European Banking Authority. https://eba.europa.eu/sites/default/documents/files/documents/10180/1359456/602d5c61-b501-4df9-8c89-71e32ab1bf84/EBA-Op-2016-04 Report on SMEs and SME supporting factor.pdf?retry=1.

Eccles, Robert G., Michael P. Krzus, and Sydney Ribot. 2015. "Meaning and Momentum in the Integrated Reporting Movement." *Journal of Applied Corporate Finance* 27 (2): 8–17. https://doi.org/10.1111/jacf.12113.

EIB. 2019. "EU Bank Launches Ambitious New Climate Strategy and Energy Lending Policy." European Investment Bank. 14 November 2019.

EIOPA. 2019. "Discussion Paper on Methodological Principles of Insurance Stress Testing - EIOPA-BoS-19/274." EIOPA. https://eiopa.europa.eu/Publications/Discussion paper/Methodological Principle of Insurance Stress Testing.pdf.

Emerson, Jed, and Tim Freundlich. 2012. "Invest with Meaning: An Introduction to a Unified Investment Strategy for Impact." Impact Assets. Issue Brief #1. https://www.impactassets.org/files/downloads/ImpactAssets_IssueBriefs_1.pdf

Epstude, Kai, and Neal J. Roese. 2008. "The Functional Theory of Counterfactual Thinking." *Personality and Social Psychology Review* 12 (2): 168–92. https://doi.org/10.1177/1088868308316091.

ESEC. 2019. "Demain, La Finance Durable : Comment Accélérer La Mutation Du Secteur Financier Vers Une plus Grande Responsabilité Sociale et Environnementale ?" Conseil Economique Social et Environnemental (CESE).

Espagne, Etienne. 2018. "Money, Finance and Climate: The Elusive Quest for a Truly Integrated Assessment Model." *Comparative Economic Studies* 60 (1): 131–43. https://doi.org/10.1057/s41294-018-0055-7.

Espagne, Étienne. 2017. "Climat, Finance et Croissance : L'introuvable Tango à Trois Des Modèles Économie-Climat ?" *Revue d'économie Financière* 127 (3): 237–252. https://doi.org/10.3917/ecofi.127.0237.

E Espagne, A Pottier, BP Fabert, F Nadaud, P Dumas. 2018. SCCs and the use of IAMs: Let's separate the wheat from the chaff. *International Economics, CEPII Research Center* 155, 29-47

ESRB. 2016. "Too Late, Too Sudden: Transition to a Low-Carbon Economy and Systemic Risk." ESRB Reports of the Advisory Scientific Committee No 6 / February 2016.

European Commission. 2018. "Communication from the Commission to the European Parliament, the European Council, the Council, the European Central Bank, the European Economic and Social Committee and the Committee of the Regions, Action Plan: Financing Sustainable Growth." *EUR-Lex*. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0097.

Fabre, Marina. 2019. "En Suède, Le 'Flygskam', La Honte de Prendre l'avion, Fait Chuter Le Trafic Aérien." Novethic. 2019.

Fankhauser, Samuel, and Richard Tol. 2005. "On Climate Change and Economic Growth." *Resource and Energy Economics* 27 (1): 1–17. https://econpapers.repec.org/RePEc:eee:resene:v:27:y:2005:i:1:p:1-17.

Fath, Brian D., Carly A. Dean, and Harald Katzmair. 2015. Navigating the adaptive cycle: an approach to managing the resilience of social systems. *Ecology and Society* 20 (2).

Fay, Marianne, Stephane Hallegatte, Adrien Vogt-Schilb, Julie Rozenberg, and Ulf Narloch. 2015. "Decarbonizing Development: Three Steps to a Zero-Carbon Future." *World Bank Group*. World Bank Group. https://doi.org/10.1596/978-1-4648-0479-3.

FEBRABAN. 2014. "The Brazilian Financial System and the Green Economy - Alignment with Sustainable Development." UNEP. https://www.greengrowthknowledge.org/resource/brazilian-financial-system-and-green-economy-alignment-sustainable-development

Fender, Ingo, Mike McMorrow, Vahe Sahakyan, and Omar Zulaica. 2019. "Green Bonds: The Reserve Management Perspective." *BIS Quaterly Review*, no. September 2019: 49–63. https://www.bis.org/publ/qtrpdf/r_qt1909f.pdf.

Ferron, Camille, and Romain Morel. 2014. "Smart Unconventional Monetary (SUMO) Policies: Giving Impetus to Green Investment." CDC Climat. http://www.cdcclimat.com/IMG/pdf/14-07_climate_report_no46__smart_unconventional_monetary_policies-2.pdf.

Feynman, Joan, and Alexander Ruzmaikin. 2007. "Climate Stability and the Development of Agricultural Societies." *Climatic Change* 84 (3–4): 295–311. https://doi.org/10.1007/s10584-007-9248-1.

Figueres, Christiana, Corinne Le Quéré, Anand Mahindra, Oliver Bäte, Gail Whiteman, Glen Peters, and Dabo Guan. 2018. "Emissions Are Still Rising: Ramp up the Cuts." *Nature* 564 (7734): 27–30. https://doi.org/10.1038/d41586-018-07585-6.

Finansinspektionen. 2016. "Climate Change and Financil Stability." Finansinspektionen. Available at: https://www.fi.se/contentassets/df3648b6cbf448ca822d3469eca4dea3/klimat-finansiell-stabilitet-mars2016_eng.pdf

Fischer, Hubertus, Katrin J. Meissner, Alan C. Mix, Nerilie J. Abram, Jacqueline Austermann, Victor Brovkin, Emilie Capron, et al. 2018. "Palaeoclimate Constraints on the Impact of 2 °c Anthropogenic Warming and Beyond." *Nature Geoscience* 11 (7): 474–85. https://doi.org/10.1038/s41561-018-0146-0.

Fleischer, Katrin, Anja Rammig, Martin G. De Kauwe, Anthony P. Walker, Tomas F. Domingues, Lucia Fuchslueger, Sabrina Garcia, et al. 2019. "Amazon Forest Response to CO2 Fertilization Dependent on Plant Phosphorus Acquisition." *Nature Geoscience* 12 (9): 736–41. https://doi.org/10.1038/s41561-019-0404-9.

Flodén, Martin. 2019. "Monetary Policy in a Changing World." Speech at the Örebro University and Kommuninvest, Örebro (November 13, 2019). Available at: https://www.bis.org/review/r191113c.pdf

Friede, Gunnar, Timo Busch, and Alexander Bassen. 2015. "ESG and Financial Performance: Aggregated Evidence from More than 2000 Empirical Studies." *Journal of Sustainable Finance and Investment* 5 (4): 210–33. https://doi.org/10.1080/20430795.2015.1118917.

Fullwiler, Scott T. 2015. "Sustainable Finance: Building a More General Theory of Finance." *Binzagr Institute for Sustainable Prosperity*, no. Working Paper No. 106.

Gassebner, Martin, Alexander Keck, and Robert Teh. 2010. "Shaken, Not Stirred: The Impact of Disasters on International Trade." *Review of International Economics* 18 (2): 351–68. https://doi.org/10.1111/j.1467-9396.2010.00868.x.

Geels, Frank W., Boelie Elzen, and Kate Green. 2004. "General Introduction: System Innovations and Transitions to Sustainability." In *System Innovation and the Transition to Sustainability - Theory, Evidence and Policy*, edited by Boelie Elzen, Frank W. Geels, and Kate Green, 19–47. Cheltenham: Edward Elgar.

Geels, Frank W., Benjamin K. Sovacool, Tim Schwanen, and Steve Sorrell. 2017. The Socio-Technical Dynamics of Low-Carbon Transitions. Joule 1 (3): 463–479. https://doi.org/10.1016/j.joule.2017.09.018

Georgescu-Roegen, Nicholas. 1971. *The Entropy Law and the Economic Process*. Harvard University Press.

Gergis, Joelle. 2019. "The Terrible Truth of Climate Change." *The Monthly*, August 2019. https://www.themonthly.com.au/issue/2019/august/1566136800/jo-lle-gergis/terrible-truth-climate-change.

German Council of Economic Experts. 2019. "Setting out for a New Climate Policy." 2019.

Giampietro, Mario, Kozo Mayumi, and Alevgül H. Sorman. 2013. *Energy Analysis for a Sustainable Future*. Routledge.

Gillingham, Kenneth, David Rapson, and Gernot Wagner. 2016. "The Rebound Effect and Energy Efficiency Policy." *Review of Environmental Economics and Policy* 10 (1): 68–88. https://econpapers.repec.org/RePEc:oup:renvpo:v:10:y:2016:i:1:p:68-88.

Global Carbon Project. 2018. "Global Carbon Budget 2018". *Earth System Science Data*. https://doi.org/10.5194/essd-10-2141-2018.

Global Energy Assessment. 2012. *Global Energy Assessment: Toward a Sustainable Future*. Cambridge University Press.

Global Sustainable Investment Alliance. 2019. "Global Sustainable Investment Review 2018." https://www.ussif.org/files/GSIR_Review2018_3_28(2).pdf%0Ahttp://www.gsi-alliance.org/trends-report-2018/.

Gold, Russell. 2019. "PG&E: The First Climate-Change Bankruptcy, Probably Not the Last." *Wall Street Journal*, 2019.

Gollier, Christian. 2012. *Pricing the Planet's Future: The Economics of Discounting in an Uncertain World*. Princeton University Press.

Goodhart, Charles A.E. 2010. "The Changing Role of Central Banks." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1717776.

Gordon, Robert J. 2012. "Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds." *National Bureau of Economic Research Working Paper Series* No. 18315.

Gowdy, John, and Jon D. Erickson. 2005. "The Approach of Ecological Economics." *Cambridge Journal of Economics* 29 (2): 207–22. https://doi.org/10.1093/cje/bei033.

Grandjean, Alain, and Mireille Martini. 2016. *Financer La Transition Énergétique - Carbone, Finance et Argent*. Les Editions de l'Atelier.

Grubler, Arnulf, Charlie Wilson, Nuno Bento, Benigna Boza-Kiss, Volker Krey, David L. McCollum, Narasimha D. Rao, et al. 2018. "A Low Energy Demand Scenario for Meeting the 1.5 °c Target and Sustainable Development Goals without Negative Emission Technologies." *Nature Energy* 3 (6): 515–27. https://doi.org/10.1038/s41560-018-0172-6.

Hallegatte, Stéphane. 2009. "Strategies to Adapt to an Uncertain Climate Change." *Global Environmental Change* 19 (2): 240–47. https://doi.org/10.1016/j.gloenvcha.2008.12.003.

Hansen, James, Pushker Kharecha, Makiko Sato, Valerie Masson-Delmotte, Frank Ackerman, David J. Beerling, Paul J. Hearty, et al. 2013. "Assessing 'Dangerous Climate Change': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature." *PLoS ONE* 8 (12). https://doi.org/10.1371/journal.pone.0081648.

Hardin, Garrett. 1968. "The Tragedy of the Commons." *Science* 162 (3859): 1243–48. https://doi.org/10.1126/science.162.3859.1243.

Harris, Jonathan M. 2013. "Green Keynesianism: Beyond Standard Growth Paradigms." GDAE Working Papers, Tufts University.

Heal, Geoffrey, and Antony Millner. 2014. "Uncertainty and Decision Making in Climate Change Economics." *Review of Environmental Economics and Policy* 8 (1): 120–37. https://doi.org/10.1093/reep/ret023.

Heinen, Andréas, Jeetendra Khadan, and Eric Strobl. 2018. "The Price Impact of Extreme Weather in Developing Countries." *Economic Journal* 129 (619): 1327–42. https://doi.org/10.1111/ecoj.12581.

Henley, Jon. 2019. "#stayontheground: Swedes Turn to Trains amid Climate 'Flight Shame.'" *The Guardian*, June 4, 2019.

Hertwich, Edgar G., and Richard Wood. 2018. "The Growing Importance of Scope 3 Greenhouse Gas Emissions from Industry." *Environmental Research Letters* 13 (10). https://doi.org/10.1088/1748-9326/aae19a.

Hickel, Jason. 2019. "The Limits of Clean Energy." *Foreign Policy*, September 2019. https://foreignpolicy.com/2019/09/06/the-path-to-clean-energy-will-be-very-dirty-climate-change-renewables/.

Honohan, Patrick. 2019. "Should Monetary Policy Take Inequality and Climate Change into Account?" *Peterson Institute for International Economics*, no. Working Paper. https://www.piie.com/sites/default/files/documents/wp19-18.pdf.

Hubert, Romain, Julie Evain, and Morgane Nicol. 2018. "Getting Started on Physical Climate Risk Analysis in Finance." I4CE. Available at: https://www.i4ce.org/wp-core/wp-content/uploads/2018/12/I4CE-ClimINVEST_2018_Getting-started-on-physical-climate-risk-analysis.pdf

Hughes, Terry P., James T. Kerry, Andrew H. Baird, Sean R. Connolly, Andreas Dietzel, C. Mark Eakin, Scott F. Heron, et al. 2018. "Global Warming Transforms Coral Reef Assemblages." *Nature* 556 (7702): 492–96. https://doi.org/10.1038/s41586-018-0041-2.

Human Rights Council. 2019. "Climate Change and Poverty - Report of the Special Rapporteur on Extreme Poverty and Human Rights." UN Human Rights - Office of the High Commissioner.

Husson-Traoré, Anne-Catherine. 2019. "The Great Battle over the European Classification System for Sustainable Activities Has Begun." *Novethic*, June 20, 2019.

Huxham, Matthew, Muhammed Anwar, and David Nelson. 2019. "Understanding the Impact of a Low Carbon Transition on South Africa." Climate Policy Initiative (CPI). https://climatepolicyinitiative.org/wp-content/uploads/2019/03/CPI-Energy-Finance-Understanding-the-impact-of-a-low-carbon-transition-on-South-Africa-March-2019.pdf.

IAIS (International Association of Insurance Supervisors). 2018. "Issues Paper on Climate Change Risks to the Insurance Sector." International Association of Insurance Supervisors c/o Bank for International Settlements.
https://naic-cms.org/sites/default/files/inline-files/cmte_c_climate_related_iais_sif_issues_ppr.pdf.

ICBC. 2016. "Impact of Environmental Factors on Credit Risk of Commercial Banks — Research and Application by ICBC Based on Stress Test." http://www.greenfinance.org.cn/upfile/upfile/filet/ICBC环境压力测试论文_2016-03-19_08-49-24.pdf.

IEA (International Energy Agency). 2015. "World Energy Outlook 2014." Paris: IEA.

IEA (International Energy Agency). 2017. "Energy Technology Perspectives 2017." Paris: IEA. https://www.iea.org/reports/energy-technology-perspectives-2017.

IEA (International Energy Agency). 2019. "World Energy Outlook 2019." Paris: IEA.

IHS Markit. 2015. "Deflating the 'Carbon Bubble.'" 2015. https://ihsmarkit.com/research-analysis/q22-deflating-the-carbon-bubble.html.

IIGCC. 2018. "Navigating Climate Scenario Analysis - A Guide for Institutional Investors." IIGCC. https://www.iigcc.org/download/navigating-climate-scenario-analysis-a-guide-for-institutional-investors/?wpdmdl=1837&refresh=5de922ef533fb1575559919.

Ilhan, Emirhan, Zacharias Sautner, and Grigory Vilkov. 2018. "Carbon Tail Risk." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3204420.

Im, Eun Soon, Jeremy S. Pal, and Elfatih A.B. Eltahir. 2017. "Deadly Heat Waves Projected in the Densely Populated Agricultural Regions of South Asia." *Science Advances* 3 (8). https://doi.org/10.1126/sciadv.1603322.

IMF. 2017. "The Effects of Weather Shocks on Economic Activity: How Can Low-Income Countries Cope?" *World Economic Outlook: October 2017*, no. October: 117–83.

IPBES. 2019. "Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services." Bonn, Germany: IPBES secretariat.

IPCC. 2007. "Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change." Geneva, Switzerland: IPCC. https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf.

IPCC. 2014. "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change." Geneva, Switzerland: IPCC.

IPCC. 2018. "Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response To the Threat of Climate Change." Geneva, Switzerland: IPCC.

IPCC. 2019. "Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems." IPCC.

IRENA. 2019. "A New World - The Geopolitics of the Energy Transformation."

IRENA. 2017. "Stranded Assets and Renewables: How the Energy Transition Affects the Value of Energy Reserves, Buildings and Capital Stock." Abu Dhabi: International Renewable Energy Agency (IRENA).

Jackson, Tim. 2017. *Prosperity without Growth*. 2nd edition. Routledge.

Juliet Johnson, *Priests of Prosperity. How Central Bankers Transformed the Postcommunist World*, Ithaca: Cornell University Press, 2016, 312 pages, ISBN 978-150170022-4

Jourdain, Edouard. 2019. *Quelles Normes Comptables Pour Une Société Du Commun ?* Editions Charles Léopold Mayer.

Jourdan, Stanislas, and Wojtek Kalinowski. 2019. "Aligning Monetary Policy with the EU's Climate Targets." Veblen Institute for Economic Reforms & Positive Money Europe.

Kay, John and Mervyn King. 2020 (forthcoming). Radical Uncertainty: Decision-Making Beyond the Numbers. W.W. Norton & Company. New York.

Keen, Steve. 2019. "The Cost of Climate Change - A Nobel Economist's Model Dismantled." Evonomics. 2019.

Keen, Steve, Robert U. Ayres, and Russell Standish. 2019. "A Note on the Role of Energy in Production." *Ecological Economics* 157: 40–46. https://doi.org/10.1016/j.ecolecon.2018.11.002.

Kelley, Colin P., Shahrzad Mohtadi, Mark A. Cane, Richard Seager, and Yochanan Kushnir. 2015. "Climate Change in the Fertile Crescent and Implications of the Recent Syrian Drought." *Proceedings of the National Academy of Sciences of the United States of America* 112 (11): 3241–46. https://doi.org/10.1073/pnas.1421533112.

Kelton, Stephanie. 2019. "How to Tell When Deficit Spending Crosses a Line." *Bloomberg*, March 7, 2019.

Keynes, John M. 1936. *The General Theory of Employment, Interest and Money*. 2013 Edition. Cambridge University Press.

King, Mervyn. 2017. The End of Alchemy: Money, Banking and the Future of the Global Economy. W.W. Norton & Company. New York.

Kling, Gerhard, Yuen C. Lo, Victor Murinde, and Ulrich Volz. 2018. Climate Vulnerability and the Cost of Debt. Available at SSRN: https://ssrn.com/abstract=3198093 or http://dx.doi.org/10.2139/ssrn.3198093

Knight, Frank H. 1921. *Risk, Uncertainty and Profit*. University of Illinois at Urbana-Champaign's Academy for Entrepreneurial Leadership Historical Research Reference in Entrepreneurship.

Knutti, Reto. 2010. "The End of Model Democracy?" *Climatic Change* 102 (3): 395–404. https://doi.org/10.1007/s10584-010-9800-2.

Krogstrup, Signe, and Maurice Obstfeld. 2018. "A Planet at Risk Requires Multilateral Action." IMF Blog. 2018. https://blogs.imf.org/2018/12/03/a-planet-at-risk-requires-multilateral-action/.

Krogstrup, Signe, and William Oman. 2019. "Macroeconomic and Financial Policies for Climate Change Mitigation: A Review of the Literature." *IMF*, no. Working Paper No. 19/185.

Krüger, Timmo. 2017. "Conflicts over Carbon Capture and Storage in International Climate Governance." *Energy Policy* 100: 58–67. https://doi.org/10.1016/j.enpol.2016.09.059.

Krugman, Paul 2019. "What's wrong with functional finance? (Wonkish): the doctrine behind MMT was smart but not completely right", The New York Times, 12 February.

Kuhn, Thomas. 1962. *The Structure of Scientific Revolutions*. University of Chicago Press.

Kunreuther, Howard, Geoffrey Heal, Myles Allen, Ottmar Edenhofer, Christopher B. Field, and Gary Yohe. 2013. "Risk Management and Climate Change." *Nature Climate Change* 3 (5): 447–50. https://doi.org/10.1038/nclimate1740.

Lavoie, Marc. 2013. "The Monetary and Fiscal Nexus of Neo-Chartalism: A Friendly Critique." *Journal of Economic Issues* 47 (1): 1–31. https://doi.org/10.2753/JEI0021-3624470101.

Lawhon, Mary, and James T. Murphy. 2011. "Socio-Technical Regimes and Sustainability Transitions: Insights from Political Ecology." *Progress in Human Geography* 36 (3): 354–78. https://doi.org/10.1177/0309132511427960.

Lenton, Timothy M., Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen, and Hans J. Schellnhuber. 2019. "Climate Tipping Points — Too Risky to Bet Against." *Nature* 575: 592–95.

Lepetit, Michel. 2019. "Deux Sons de Cloches Sur La Matérialité Du 'Risque Climat' Dans l'assurance Vie Française." The Shift Project. https://theshiftproject.org/wp-content/uploads/2019/07/2019-07_Observatoire-173_Deux-sons-de-cloche-sur-la-matérialité-du-risque-climat_The-Shift-Project.pdf.

Lepetit, Michel, Alain Grandjean, and Gaël Giraud. 2019. "Grand Débat : « Réorienter l'épargne Vers l'investissement Réellement Écologique et Socialement Responsable »." *Le Monde*, January 30, 2019.

Li, Olivia. 2019. "China's Electric Vehicle Industry Hit Hard by Policy Shift as Beijing Turns Toward Hydrogen Fuel." *The Epoch Times*, April 16, 2019. https://www.theepochtimes.com/chinas-electric-vehicle-industry-hit-hard-by-sudden-policy-shift-as-beijing-turns-toward-hydrogen-fuel_2865743.html.

Lugato, Emanuele, Pete Smith, Pasquale Borrelli, Panos Panagos, Cristiano Ballabio, Alberto Orgiazzi, Oihane Fernandez-Ugalde, Luca Montanarella, and Arwyn Jones. 2018. "Soil Erosion Is Unlikely to Drive a Future Carbon Sink in Europe." *Science Advances* 4 (11). https://doi.org/10.1126/sciadv.aau3523.

Macquarie, Rob. 2019. "Of Course We Can Pay for a Green New Deal, but We Can't Escape Hard Choices." *Open Democracy*, March 13, 2019.

Maier, H. R., J. H.A. Guillaume, H. van Delden, G. A. Riddell, M. Haasnoot, and J. H. Kwakkel. 2016. "An Uncertain Future, Deep Uncertainty, Scenarios, Robustness and Adaptation: How Do They Fit Together?" *Environmental Modelling and Software* 81: 154–64. https://doi.org/10.1016/j.envsoft.2016.03.014.

Malm, Andreas, and Alf Hornborg. 2014. "The Geology of Mankind? A Critique of the Anthropocene Narrative." *Anthropocene Review* 1 (1): 62–69. https://doi.org/10.1177/2053019613516291.

Mark, Jason. 2018. "Sue the Bastards - Climate Change Lawsuits Are Going Global." *Sierra Club*, December 2018. https://www.sierraclub.org/sierra/sue-bastards-international-climate-change-lawsuits.

Marois, Thomas, and Ali Rıza Güngen. 2019. "A US Green Investment for All: Democratized Finance for a Just Transition." The Next System Project.

Martin, Ian W.R., and Robert S. Pindyck. 2015. "Averting Catastrophes: The Strange Economics of Scylla and Charybdis." *American Economic Review* 105 (10): 2947–85. https://doi.org/10.1257/aer.20140806.

Martin, Pamela L., and Imme Scholz. 2014. "Policy Debate | Ecuador's Yasuní-ITT Initiative : What Can We Learn from Its Failure?" *Revue Internationale de Politique de Développement* 5 (2). https://doi.org/10.4000/poldev.1705.

Martinez-Alier, J. 1987. *Ecological Economics: Energy, Environment and Society*. Blackwell Publishers.

Masson-Delmotte, Valerie, and Wilfran Moufouma-Okia. 2019. "Climate Risks: Why Each Half-Degree Matters." *Banque de France Financial Stability Review*, no. 23: 17–27.

Matikainen, Sini. 2018. "What Are Stranded Assets?" The Grantham Research Institute on Climate Change and the Environment. 2018. http://www.lse.ac.uk/GranthamInstitute/faqs/what-are-stranded-assets/.

Matikainen, Sini, Emanuele Campiglio, and Dimitri Zenghelis. 2017. "The Climate Impact of Quantitative Easing." The Centre for Climate Change Economics and Policy (CCCEP) & The Grantham Research Institute on Climate Change and the Environment.

Mayordomo, Sergio, and Maria Rodriguez-Moreno. 2017. "'Support Is Appreciated': On the Effectiveness of the SME Supporting Factor." *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2870002.

Mazzucato, Mariana. 2015. *The Entrepreneurial State: Debunking Public vs. Private Myths in Risk and Innovation*. Public Affairs.

Mazzucato, Mariana, and Carlota Perez. 2015. “Innovation as Growth Policy.” *The Triple Challenge for Europe*, 229–64. https://doi.org/10.1093/acprof:oso/9780198747413.003.0009.

McCulley, Paul, and Zoltan Pozsar. 2013. “Helicopter Money: Or How I Stopped Worrying and Love Fiscal-Monetary Cooperation.” Global Society of Fellows.

McGlade, Christophe, and Paul Ekins. 2015. “The Geographical Distribution of Fossil Fuels Unused When Limiting Global Warming to 2°C.” *Nature* 517 (7533): 187–90. https://doi.org/10.1038/nature14016.

McKibbin, Warwick, Adele Morris, Augustus J. Panton, and Peter J. Wilcoxen. 2017. “Climate Change and Monetary Policy: Dealing with Disruption.” *CAMA Working Paper*, no. 77/201.

Mercure, J. F., H. Pollitt, J. E. Viñuales, N. R. Edwards, P. B. Holden, U. Chewpreecha, P. Salas, I. Sognnaes, A. Lam, and F. Knobloch. 2018. “Macroeconomic Impact of Stranded Fossil Fuel Assets.” *Nature Climate Change* 8 (7): 588–93. https://doi.org/10.1038/s41558-018-0182-1.

Mercure, Jean Francois, Florian Knobloch, Hector Pollitt, Leonidas Paroussos, S. Serban Scrieciu, and Richard Lewney. 2019. “Modelling Innovation and the Macroeconomics of Low-Carbon Transitions: Theory, Perspectives and Practical Use.” *Climate Policy* 19 (8): 1019–37. https://doi.org/10.1080/14693062.2019.1617665.

Mésonnier, Jean-Stéphane, Charles O’Donnell, and Olivier Toutain. 2017. “The Interest of Being Eligible.” *Banque de France Working Paper*, no. 636.

Milanovic, Branko. 2016. *Global Inequality - A New Approach for the Age of Globalization*. Harvard University Press.

Millar, Richard J., Jan S. Fuglestvedt, Pierre Friedlingstein, Joeri Rogelj, Michael J. Grubb, H. Damon Matthews, Ragnhild B. Skeie, Piers M. Forster, David J. Frame, and Myles R. Allen. 2017. “Emission Budgets and Pathways Consistent with Limiting Warming to 1.5 °c.” *Nature Geoscience* 10 (10): 741–47. https://doi.org/10.1038/NGEO3031.

Millennium Ecosystem Assessment. 2005. “Ecosystem and Human Well-Being: Synthesis.” Washington, DC: Island Press. Available at: https://www.millenniumassessment.org/documents/document.356.aspx.pdf

Monasterolo, Irene, Andrea Roventini, and Timothy Foxon. 2019. “Uncertainty of Climate Policies and Implications for Economics and Finance: An Evolutionary Economics Approach.” *Ecological Economics* 163 (C): 177–82. https://econpapers.repec.org/RePEc:eee:ecolec:v:163:y:2019:i:c:p:177-182.

Monnet, Eric. 2014. “Monetary Policy without Interest Rates: Evidence from France’s Golden Age (1948 to 1973) Using a Narrative Approach.” *American Economic Journal: Macroeconomics* 6 (4): 137–69. http://www.jstor.org/stable/43189942.

Monnin, Pierre. 2018. “Integrating Climate Risks into Credit Risk Assessment.” CEP Discussion Note 2018/4. https://www.cepweb.org/wp-content/uploads/2019/02/CEP-DN-Integrating-climate-risks-into-credit-risk-analysis.pdf.

Mora, Camilio, Bénédicte Dousset, Iain R. Caldwell, Farrah E. Powell, Rollan C. Geronimo, Coral R. Bielecki, Chelsie W. W. Counsell, Bonnie S. Dietrich, Emily T. Johnston, Leo V. Louis, Matthew P. Lucas, Marie M. McKenzie, Alessandra G. Shea, Han Tseng, Thomas W. Giambelluca, Lisa R. Leon, Ed Hawkins, and Clay Trauernicht. 2017. "Global risk of deadly heat". Nature Climate Change 7: 501-506. doi:10.1038/nclimate3322

Mora, Camilo, Daniele Spirandelli, Erik C. Franklin, John Lynham, Michael B. Kantar, Wendy Miles, Charlotte Z. Smith, et al. 2018. “Broad Threat to Humanity from Cumulative Climate Hazards Intensified by

Greenhouse Gas Emissions." *Nature Climate Change* 8 (12): 1062–71. https://doi.org/10.1038/s41558-018-0315-6.

Moriarty, Patrick, and Damon Honnery. 2016. "Can Renewable Energy Power the Future?" *Energy Policy* 93: 3–7. https://doi.org/10.1016/j.enpol.2016.02.051.

Morris, Leah, James J. Hales, Michel L. Trudeau, Peter Georgiev, Jan Peter Embs, Juergen Eckert, Nikolas Kaltsoyannis, and David M. Antonelli. 2019. "A Manganese Hydride Molecular Sieve for Practical Hydrogen Storage under Ambient Conditions." *Energy and Environmental Science* 12 (5): 1580–91. https://doi.org/10.1039/c8ee02499e.

MunichRe. 2018. "The Natural Disasters of 2018 in Figures." https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/the-natural-disasters-of-2018-in-figures.html.

Muradian, R., M. Arsel, L. Pellegrini, F. Adaman, B. Aguilar, B. Agarwal, E. Corbera, et al. 2013. "Payments for Ecosystem Services and the Fatal Attraction of Win-Win Solutions." *Conservation Letters* 6 (4): 274–79. https://doi.org/10.1111/j.1755-263X.2012.00309.x.

Muradian, Roldan, and Laura Rival. 2012. "Between Markets and Hierarchies: The Challenge of Governing Ecosystem Services." *Ecosystem Services* 1 (1): 93–100. https://doi.org/10.1016/j.ecoser.2012.07.009.

Negawatt. 2018. Scénario négaWatt 2017-2050. Hypothèses et résultats. Available at : https://negawatt.org/IMG/pdf/scenario-negawatt_2017-2050_hypotheses-et-resultats.pdf

NGFS. 2018. "NGFS First Progress Report." October 2018. Available at: https://www.ngfs.net/en/first-progress-report

NGFS. 2019a. "NGFS First Comprehensive Report. A Call for Action - Climate Change as a Source of Financial Risk." April 2019. Available at: https://www.ngfs.net/en/first-comprehensive-report-call-action.

NGFS. 2019b. "Macroeconomic and Financial Stability: Implications of Climate Change". NGFS Technical Supplement to the First Comprehensive Report." July 2019. Available at: https://www.ngfs.net/en/first-comprehensive-report-call-action

Nordhaus, William. 2007. *The Challenge of Global Warming: Economic Models and Environmental Policy*. New Haven, Connecticut USA: Yale University.

Ocampo, José Antonio. 2019. "The SDR's Time Has Come." *Finance & Development* 56 (4): 62–63.

OECD. 2019a. "Systemic Thinking for Policy Making - The Potential of Systems Analysis for Addressing Global Policy Challenges in the 21st Century." Paris: OECD Publishing.

OECD. 2019b. "Beyond Growth: Towards a New Economic Approach - Report of the Secretary General's Advisory Group on a New Growth Narrative." Paris: OECD Publishing. https://www.oecd.org/naec/averting-systemic-collapse/SG-NAEC(2019)3_Beyond Growth.pdf.

OECD. 2019c. "Climate Finance Provided and Mobilised by Developed Countries in 2013-17." Paris: OECD Publishing.

Oliver Wyman. 2019. "Climate Change - Managing a New Financial Risk." https://www.oliverwyman.com/content/dam/oliver-wyman/v2/publications/2019/feb/Oliver_Wyman_Climate_Change_Managing_a_New_Financial_Risk1.pdf.

Olovsson, Conny. 2018. "Is Climate Change Relevant for Central Banks?" Sveriges Riksbank Economic Commentaries. https://doi.org/10.2307/2551631.

Opitz Sapleton, Sarah, Rebecca Nadin, Charlene Watson, and Jan Kellett. 2017. "Climate Change, Migration, and Displacement: The Need for a Risk-Informed and Coherent Approach." *The Encyclopedia of Global Human Migration*. https://doi.org/10.1002/9781444351071.

Ostrom, Elinor. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press.

Ostrom, Elinor. 2002. "Common-Pool Resources and Institutions: Toward a Revised Theory." In: Handbook of Agricultural Economics, edited by B L Gardner and G C Rausser, 2, Part 1:1315-1339 BT-Handbook of Agricultural Economics. Elsevier. https://econpapers.repec.org/RePEc:eee:hagchp:3-24.

Ostrom, Elinor. 2010. "Beyond Markets and States: Polycentric Governance of Complex Economic Systems." *American Economic Review* 100: 641–72.

Ostrom, Elinor, Joanna Burger, Christopher B. Field, Richard B. Norgaard, and David Policansky. 1999. "Revisiting the Commons: Local Lessons, Global Challenges." *Science* 284 (5412): 278–82. https://doi.org/10.1126/science.284.5412.278.

Otto, Ilona M., Kyoung Mi Kim, Nika Dubrovsky, and Wolfgang Lucht. 2019. "Shift the Focus from the Super-Poor to the Super-Rich." *Nature Climate Change* 9 (2): 82–84. https://doi.org/10.1038/s41558-019-0402-3.

Palley, Thomas. 2019. "Macroeconomics vs Modern Money Theory: Some Unpleasant Keynesian Arithmetic." *Post-Keynesian Economics Society Workin Papers*, no. 1910.

Parker, Miles. 2018. "The Impact of Disasters on Inflation." *Economics of Disasters and Climate Change* 2 (1): 21–48. https://doi.org/10.1007/s41885-017-0017-y.

Parrique, Timothée, Jonathan Barth, François Briens, Joachim H. Spangenberg, and Alejo W. Kraus-Polk. 2019. "Decoupling Debunked. Evidence and Arguments against Green Growth as a Sole Strategy for Sustainability." Brussels: European Environmental Bureau.

Pearson, Peter J.G., and Timothy J. Foxon. 2012. "A Low Carbon Industrial Revolution? Insights and Challenges from Past Technological and Economic Transformations." *Energy Policy* 50: 117–27. https://doi.org/10.1016/j.enpol.2012.07.061.

Pereira da Silva, Luiz A. 2016. "Rethinking Development Finance: Towards a New 'Possible Trinity' for Growth?" Remarks at The Atlantic Dialogues 2016, Marrakesh, December 2016. Available at: https://www.bis.org/speeches/sp170221.htm

Pereira da Silva, Luiz A. 2017. "Green Finance: Can It Help Combat Climate Change?" Remarks at the conference organised by the BIS, OMFIF, the Deutsche Bundesbank and the World Bank Group, Frankfurt, 13 July. Available at: https://www.bis.org/speeches/sp170713.htm

Pereira da Silva, Luiz A. 2019a. "Research on Climate-Related Risks and Financial Stability: An Epistemological Break?" Based on remarks at the Conference of the Central Banks and Supervisors Network for Greening the Financial System (NGFS), Paris, 17 April. Available at: https://www.bis.org/speeches/sp190523.htm

Pereira da Silva, Luiz A. 2019b. "The Inflation Conundrum in Advanced Economies and a Way Out." Based on remarks at the University of Basel, May 5 2019. with Enisse Kharroubi, Emanuel Kohlscheen and Benoît Mojon. Available at: https://www.bis.org/speeches/sp190905a.htm

Piketty, Thomas. 2014. *Capital in the Twenty-First Century*. Harvard University Press.

Pindyck, Robert S. 2013. "Climate Change Policy: What Do the Models Tell Us?" *Journal of Economic Literature* 51 (3): 860–72. https://doi.org/10.1257/jel.51.3.860.

Pisani-Ferry, Jean. 2019. "The Coming Clash Between Climate and Trade." Bruegel. 2019. https://bruegel.org/2019/08/the-coming-clash-between-climate-and-trade/.

Pitron, Guillaume. 2018. *La Guerre Des Métaux Rares*. Paris: Les Liens qui Libèrent.

Porter, Michael E. 1991. "America's Green Strategy." *Scientific American* 264 (4): 168.

Pottier, Antonin, Jean Charles Hourcade, and Etienne Espagne. 2014. "Modelling the Redirection of Technical Change: The Pitfalls of Incorporeal Visions of the Economy." *Energy Economics* 42: 213–18. https://doi.org/10.1016/j.eneco.2013.12.003.

PRA (Bank of England Prudential Regulation Authority). 2019a. "Life Insurance Stress Test 2019 - Scenario Specification, Guidelines and Instructions." Bank of England Prudential Regulation Authority. Available at : https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/letter/2019/life-insurance-stress-test-2019-scenario-specification-guidelines-and-instructions.pdf

PRA (Bank of England Prudential Regulation Authority). 2019b. "Supervisory Statement SS3/19 - Enhancing Banks' and Insurers' Approaches to Managing the Financial Risks from Climate Change." Bank of England Prudential Regulation Authority. https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/supervisory-statement/2019/ss319.pdf?la=en&hash=7BA9824BAC5FB313F42C00889D4E3A6104881C44.

Rambaud, Alexandre. 2015. "Le Modèle Comptable CARE/TDL : Une Brève Introduction." *Revue Française de Comptabilité, Ed. Comptables-Malesherbes,* 483.

Rambaud, Alexandre, and Jacques Richard. 2015. "The 'Triple Depreciation Line' Instead of the 'Triple Bottom Line': Towards a Genuine Integrated Reporting." *Critical Perspectives on Accounting* 33: 92–116. https://doi.org/10.1016/j.cpa.2015.01.012.

Rao N. D., van Ruijven B. J., Riahi K., and Bosetti V. "Improving the poverty and inequality modelling in climate research" Nature Climate Change 7, 857-862 (2017).

Raworth, Kate. 2017. "What on Earth is the Doughnut?". https://www.kateraworth.com/doughnut/.

Ray, Deepak K., Paul C. West, Michael Clark, James S. Gerber, Alexander V. Prishchepov, and Snigdhansu Chatterjee. 2019. "Climate Change Has Likely Already Affected Global Food Production." *PLoS ONE* 14 (5). https://doi.org/10.1371/journal.pone.0217148.

Regelink, Martijn, Henk Jan Reinders, Maarten Vleeschhouwer, and Iris van de Wiel. 2017. "Waterproof? An Exploration of Climate-Related Risks for the Dutch Financial Sector." De Nederlandsche Bank. Available at: https://www.dnb.nl/en/binaries/Waterproof_tcm47-363851.pdf.

Revelli, Christophe, and Jean Laurent Viviani. 2015. "Financial Performance of Socially Responsible Investing (SRI): What Have We Learned? A Meta-Analysis." *Business Ethics* 24 (2): 158–85. https://doi.org/10.1111/beer.12076.

Reynolds, Jake. n.d. "Unhedgeable Risk: How Climate Change Sentiment Impacts Investment." Cambridge Institute for Sustainability Leadership. Accessed December 8, 2019. https://www.cisl.cam.ac.uk/news/blog/unhedgeable-risk.

Ricke, Katharine, Laurent Drouet, Ken Caldeira, and Massimo Tavoni. 2018. "Country-Level Social Cost of Carbon." *Nature Climate Change* 8 (10): 895–900. https://doi.org/10.1038/s41558-018-0282-y.

Ripple, William J, Christopher Wolf, Thomas M Newsome, Phoebe Barnard, and William R Moomaw. 2019. "World Scientists' Warning of a Climate Emergency." *BioScience*. https://doi.org/10.1093/biosci/biz088.

Ripple, William J., Christopher Wolf, Thomas M. Newsome, Mauro Galetti, Mohammed Alamgir, Eileen Crist, Mahmoud I. Mahmoud, and William F. Laurance. 2017. "World Scientists' Warning to Humanity: A Second Notice." *BioScience* 67 (12): 1026–28. https://doi.org/10.1093/biosci/bix125.

Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, Eric F. Lambin, Timothy M. Lenton, et al. 2009. "A Safe Operating Space for Humanity." *Nature* 461 (7263): 472–75. https://doi.org/10.1038/461472a.

Rogoff, Kenneth. 2019. "The Case for a World Carbon Bank." *Project Syndicate*, July 2019.

Ruzzenenti, Franco, David Font Vivanco, Ray Galvin, Steve Sorrell, Aleksandra Wagner, and Hans Jakob Walnum. 2019. "Editorial: The Rebound Effect and the Jevons' Paradox: Beyond the Conventional Wisdom." *Frontiers in Energy Research* 7. https://doi.org/10.3389/fenrg.2019.00090.

Ryan-Collins, Josh. 2019. "Beyond Voluntary Disclosure: Why a 'Market-Shaping' Approach to Financial Regulation Is Needed to Meet the Challenge of Climate Change." *SUERF Policy Note*, no. 61. https://www.suerf.org/policynotes/4805/beyond-voluntary-disclosure-why-a-market-shaping-approach-to-financial-regulation-is-needed-to-meet-the-challenge-of-climate-change/html.

Schellekens, Guan, and Joris van Toor. 2019. "Values at Risk? Sustainability Risks and Goals in the Dutch Financial Sector." De Nederlandsche Bank.

Schneider, Stephen H. 2003. "Abrupt Non-Linear Climate Change, Irreversibility and Surprise." OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers.

Schoenmaker, Dirk. 2019. "Greening Monetary Policy." *Bruegel Working Paper*, no. 2. https://bruegel.org/wp-content/uploads/2019/02/Greening-monetary-policy.pdf.

Schoenmaker, Dirk, and Rens Van Tilburg. 2016. "Financial Risks and Opportunities in the Time of Climate Change." *Bruegel Policy Brief*, no. 2. http://www.mejudice.nl/docs/default-source/bronmaterialen/pb-2016_02.pdf%5Cnhttp://aei.pitt.edu/74986/.

Schoon, Michael, and Sander Van Der Leeuw. 2015. "The Shift toward Social-Ecological Systems Perspectives: Insights into the Human-Nature Relationship." *Natures Sciences Societes* 23 (2): 166–74. https://doi.org/10.1051/nss/2015034.

SEI, IISD, ODI, Climate Analytics, CICERO, and UNEP. 2019. "The Production Gap: The Discrepancy between Countries' Planned Fossil Fuel Production and Global Production Levels Consistent with Limiting Warming to 1.5°C or 2°C." http://productiongap.org/wp-content/uploads/2019/11/Production-Gap-Report-2019.pdf.

Smil, Vaclav. 2010. *Energy Transitions: History, Requirements, Prospects*. Santa Barbara, CA: Praeger.

Smil, Vaclav. 2017a. *Energy and Civilization: A History*. MIT Press Scholarship Online.

Smil, Vaclav. 2017b. Energy Transitions: Global and National Perspectives. Praeger, 2nd edition. ISBN 144085324X.

Smith, H. J. 2014. "Climates Conspire Together to Make Big Changes." *Science* 345 (6195): 413–14. https://doi.org/10.1126/science.345.6195.413-o.

Spash, Clive L. 2017. *Routledge Handbook of Ecological Economics*. Routledge.

Steffen, Will, Jacques Grinevald, Paul Crutzen, and John Mcneill. 2011. "The Anthropocene: Conceptual and Historical Perspectives." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369 (1938): 842–67. https://doi.org/10.1098/rsta.2010.0327.

Steffen, Will, Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, et al. 2018. "Trajectories of the Earth System in the Anthropocene." *Proceedings of the National Academy of Sciences of the United States of America* 115 (33): 8252–59. https://doi.org/10.1073/pnas.1810141115.

Stern, Nicholas. 2007. "The Economics of Climate Change: The Stern Review." *The Economics of Climate Change: The Stern Review* 9780521877: 1–692. https://doi.org/10.1017/CBO9780511817434.

Stern, Nicholas. 2008. "The Economics of Climate Change." *American Economic Review* 98 (2): 1–37. https://doi.org/10.1257/aer.98.2.1.

Stern, Nicholas. 2016. "Economics: Current Climate Models Are Grossly Misleading." *Nature* 530 (7591): 407–9. https://doi.org/10.1038/530407a.

Stiglitz, Joseph. 2019. "The Climate Crisis Is Our Third World War. It Needs a Bold Response." *The Guardian*, June 4, 2019. https://www.theguardian.com/commentisfree/2019/jun/04/climate-change-world-war-iii-green-new-deal?CMP=share_btn_fb&fbclid=IwAR2USlPJHRp-W276QIGTR1zRgx1Ek7kf6E5XHbuqqNJIOB_EFrQsOm9q0ZI.

Stott, Peter. 2016. "How Climate Change Affects Extreme Weather Events: Research Can Increasingly Determine the Contribution of Climate Change to Extreme Events Such as Droughts." *Science* 352 (6293): 1517–18. https://doi.org/10.1126/science.aaf7271.

Stubbington, Tommy, and Martin Arnolrd. 2019. "Pushback and Practicalities Limit Hopes for 'Green QE' from ECB." *Financial Times*, November 5, 2019.

Subramanian, Meera. 2019. "India's Terrifying Water Crisis." *The New York Times*, July 15, 2019.

Summers, Lawrence H. 2019a. "The left's embrace of modern monetary theory is a recipe for disaster", Washington Post, op-ed, 4 March.

Summers, Lawrence H. 2019b. "Global Economy Is at Risk from a Monetary Policy Black Hole." *Financial Times*, October 11, 2019. https://www.ft.com/content/0d585c88-ebfc-11e9-aefb-a946d2463e4b.

Svartzman, Romain, Dominique Dron, and Etienne Espagne. 2019. "From Ecological Macroeconomics to a Theory of Endogenous Money for a Finite Planet." *Ecological Economics* 162: 108–20. https://doi.org/10.1016/j.ecolecon.2019.04.018.

Taleb, Nassim N. 2010. "Fat Tails, Asymmetric Knowledge, and Decision Making: Essay in Honor of Benoit Mandelbrot's 80th Birthday." *Willmott*, 2010.

Taleb, Nassim N. 2007. *The Black Swan*. New York: Penguin Random House.

TCFD (Task Force on Climate-related Financial Disclosures). 2017. "The Use of Scenario Analysis in Disclosure of Climate-Related Risks and Opportunities Technical Supplement - Technical Supplement." TCFD. Available at: https://www.fsb-tcfd.org/wp-content/uploads/2017/06/FINAL-TCFD-Technical-Supplement-062917.pdf

The Shift Project, and IFPEN. 2019. "Comprendre Les Enjeux de La Modélisation Du Lien Complexe Entre Énergie, Climat et Économie - Etat Des Lieux et Limites de La Modélisation Énergie-Climat-Économie Au Niveau Mondial."

Thomä, Jakob, and Hugues Chenet. 2017. "Transition Risks and Market Failure: A Theoretical Discourse on Why Financial Models and Economic Agents May Misprice Risk Related to the Transition to a Low-Carbon Economy." *Journal of Sustainable Finance and Investment* 7 (1): 82–98. https://doi.org/10.1080/20430795.2016.1204847.

Thomä, Jakob, and Anuschka Hilke. 2018. "The Green Supporting Factor: Quantifying the Impact on European Banks and Green Finance." 2 Degrees Investing Initiative.

Trinks, Pieter Jan, and Bert Scholtens. 2017. "The Opportunity Cost of Negative Screening in Socially Responsible Investing." *Journal of Business Ethics* 140 (2): 193–208. https://doi.org/10.1007/s10551-015-2684-3.

Trucost ESG Analysis. 2019. "Connecting the Dots: Energy Transition Scenarios and Credit Quality." http://et-risk.eu/wp-content/uploads/2019/01/Trucost-Connecting-the-Dots-08.pdf.

Turner, Adair. 2019. "What If Zero Interest Rates Are the New Normal?" *Project Syndicate*, March 2019.

UN Environment. 2018. "Inclusive Wealth Report 2018." UN Environment. https://wedocs.unep.org/bitstream/handle/20.500.11822/27597/IWR2018.pdf?sequence=1&isAllowed=y

UNEP. 2019. "Emissions Gap Report 2019. Executive Summary." Nairobi: United Nations Environment Programme. Available at:
https://wedocs.unep.org/bitstream/handle/20.500.11822/30798/EGR19ESEN.pdf?sequence=13

UNEP-FI. 2018. "Navigating a New Climate: Assessing Credit Risk and Opportunity in a Changing Climate." https://www.unepfi.org/wordpress/wp-content/uploads/2018/07/NAVIGATING-A-NEW-CLIMATE.pdf.

UNEP-FI. 2019. "Changing Course: A Comprehensive Investor Guide to Scenario-Based Methods for Climate Risk Assessment, in Response to the TCFD." https://www.unepfi.org/wordpress/wp-content/uploads/2019/05/TCFD-Changing-Course-Oct-19.pdf.

UNFCCC. 2015. "Paris Agreement." United Nations. Available at: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

Lerven, Frank van, and Josh Ryan-Collins. 2017. "Central Banks, Climate Change and the Transition to a Low-Carbon Economy." *The New Economics Foundation*, 1–16. [w5].

Vatn, Arild. 2006. *Institutions and the Environment*. Edward Elgar.

Vermeulen, Robert, Edo Schets, Melanie Lohuis, Barbara Kölbl, David-Jan Jansen, and Willem Heeringa. 2018. "An Energy Transition Risk Stress Test for the Financial System of the Netherlands." *De Nederlandsche Bank Occasional Studies* 16–7. Available at: https://www.dnb.nl/binaries/OS_Transition risk stress test versie_web_tcm46-379397.pdf.

Vermeulen, Robert, Edo Schets, Melanie Lohuis, Barbara Kölbl, David-Jan Jansen, and Willem Heeringa. 2019. "The Heat Is on: A Framework Measuring Financial Stress under Disruptive Energy Transition Scenarios." *De Nederlandsche Bank Working Paper*, no. 625. Available at: https://www.dnb.nl/binaries/Working%20paper%20No.%20625_tcm46-382291.pdf

Villeroy de Galhau, François. 2019a. "Climate Change: Central Banks Are Taking Action." *Banque de France Financial Stability Review*, no. 23: 7–16.

Villeroy de Galhau, François. 2019b. "Climate Risk – A Call for Action - Paris." Introductory remarks at the Network for Greening the Financial System conference, Paris, 17 April 2019. https://www.banque-france.fr/en/intervention/climate-risk-call-action.

Villeroy de Galhau, François. 2019c. "Bretton Woods: 75 Years Later – Thinking about the next 75 - Paris." Welcome Address at the G7 high-level conference – Paris, 16 July 2019. https://www.banque-france.fr/en/intervention/bretton-woods-75-years-later-thinking-about-next-75-paris.

Volz, Ulrich. 2017. "On the Role of Central Banks in Enhancing Green Finance." *UNEP Inquiry: Design of a Sustainable Fininancial System*. http://unepinquiry.org/wp-content/uploads/2017/02/On_the_Role_of_Central_Banks_in_Enhancing_Green_Finance.pdf.

Wallace-Wells, David. 2019. *The Uninhabitable Earth - Life After Warming*. Penguin Random House.

Warnars, Lavinia. 2010. "The Yasuni-ITT Initiative : A New Model to Implement Human Rights and Biological Diversity Conventions and Frameworks ?" *Policy Matters*, no. 17: 55–77. https://doi.org/10.1371/journal.pone.0008767.11.

Webb, Ian, David Baumslag, and Rupert Read. 2017. "How Should Regulators Deal with Uncertainty? Insights from the Precautionary Principle." *Bank Underground*. https://bankunderground.co.uk/2017/01/27/how-should-regulators-deal-with-uncertainty-insights-from-the-precautionary-principle/.

Weidmann, Jens. 2019. "Jens Weidmann : Climate Change and Central Banks - Welcome Address at the Deutsche Bundesbank's Second Financial Market Conference, Frankfurt Am Main, 29 October 2019." Bank for International Settlements (BIS).

Weitzman, Martin L. 2009. "On Modeling and Interpreting the Economics of Catastrophic Climate Change." *Review of Economics and Statistics* 91 (1): 1–19. http://dx.doi.org/10.1162/rest.91.1.1.

Weitzman, Martin L. 2011. "Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change." *Review of Environmental Economics and Policy* 5 (2): 275–92. https://doi.org/10.1093/reep/rer006.

Weyant, John. 2017. "Some Contributions of Integrated Assessment Models of Global Climate Change." *Review of Environmental Economics and Policy* 11 (1): 115–37. https://doi.org/10.1093/reep/rew018.

World Bank. 2018. Rigaud, Kanta Kumari; Alex de Sherbinin; Bryan Jones; Jonas Bergmann; Viviane Clement; Kayly Ober; Jacob Schewe; Susana Adamo; Brent McCusker; Silke Heuser; Amelia Midgley. "Groundswell - Preparing for Internal Climate Migration." *Washington, DC: The World Bank*. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/29461/WBG_ClimateChange_Final.pdf.

Wray, Randall L. 2012. *Modern Money Theory - A Primer on Macroeconomics for Sovereign Monetary Systems*. Palgrave macmillan.

Xin, Zheng. 2019. "Hydrogen Vehicles on Their Way." *China Daily*, April 11, 2019. http://global.chinadaily.com.cn/a/201904/11/WS5cae817fa3104842260b5819.html.

Zachmann Georg, Gustav Fredriksson and Grégory Claeys. 2018. "The distributional effects of climate policies", Bruegel Blueprint series 28.

Zenghelis, Dimitri. 2019. "Securing Decarbonisation and Growth." *National Institute Economic Review* 250 (1): R54–60. https://doi.org/10.1177/002795011925000118.

Zhou, Wenji, David L. McCollum, Oliver Fricko, Matthew Gidden, Daniel Huppmann, Volker Krey, and Keywan Riahi. 2019. "A Comparison of Low Carbon Investment Needs between China and Europe in Stringent Climate Policy Scenarios." *Environmental Research Letters* 14 (5). https://doi.org/10.1088/1748-9326/ab0dd8.

Biography of the authors

Patrick Bolton is the Barbara and David Zalaznick Professor of Business at ***Columbia University*** and visiting Professor at Imperial College London. He is a Co-Director of the Center for Contracts and Economic Organization at the Columbia Law School, a past President of the American Finance Association, a Fellow of the Econometric Society (elected 1993), the American Academy of Arts and Sciences (elected 2009), and a Corresponding Fellow of the British Academy (elected 2013).

His areas of interest are in contract theory, corporate finance, corporate governance, banking, sovereign debt, political economy, law and economics and sustainable investing.

He has written a leading graduate textbook on *Contract theory* with Mathias Dewatripont, MIT Press (2005) and among the books he has co-edited are *Sovereign wealth funds and long-term investing*, with Frederic Samama and Joseph E Stiglitz, Columbia University Press (2011); and *Coping with the climate crisis: mitigation policies and global coordination,* with Rabah Aretzki, Karim El Aynaoui and Maurice Obstfeld, Columbia University Press (2018).

Morgan Després is Deputy Head of the Financial Stability Department at the ***Banque de France*** and also serves as the Head of the Network for Greening the Financial System (NGFS) Secretariat. He joined the Banque de France in 2005 and served in the Payment and Settlement Systems Department and as Deputy Head of the Macroprudential Division.

Other professional experience includes a secondment as Deputy Head of the Financial Stability Unit within the French Treasury Department and technical assistance missions for the IMF.

Morgan holds an MBA from ESSEC business school, graduated from the Institut d'Etudes Politiques de Paris and studied at the Harvard Extension School.

Luiz Awazu Pereira da Silva is Deputy General Manager of the ***Bank for International Settlements***.

Prior to that, he was Deputy Governor at the Central Bank of Brazil, in charge of Economic Policy, International Affairs, and Financial Regulation.

He also served as Deputy Finance Minister, in charge of International Affairs at the Ministry of Finance and as Chief Economist of the Ministry of Budget and Planning. He is also a former Regional Country Director and Advisor to the Chief Economist at the World Bank and, in Japan, worked at the Institute of Fiscal and Monetary Policy of the Ministry of Finance and as Country Risk Director at the Japan Bank for International Cooperation (JBIC).

He has published on development economics, macroeconomic modelling and poverty reduction and is the co-editor with François Bourguignon of "*The impact of macroeconomic policies on poverty and income distribution: macro-micro evaluation techniques and tools*" (Palgrave Macmillan World Bank), and with Pierre-Richard Agénor of "*Integrated Inflation Targeting*", BIS 2019.

Frédéric Samama is Head of Responsible Investment at ***Amundi***.

He is the founder of the SWF Research Initiative, co-edited a book on long-term investing alongside Nobel Prize Laureate Joseph Stiglitz and Professor Patrick Bolton, and has published numerous papers on green finance.

Formerly, he oversaw Corporate Equity Derivatives within Crédit Agricole Corporate Investment Banking in New York and Paris. During his tenure, he developed and implemented the first international leveraged employee share purchase programme, a system now widely used among French companies.

He has advised the French government in different areas (employee investing mechanisms, market regulation, climate finance, etc) and has a long track record of innovation at the crossroads of finance and government policy.

In recent years, he has focused on climate change with a mix of financial innovation, research and policymaking recommendations, advising central banks, sovereign wealth funds and policymakers.

Romain Svartzman works as an economist on sustainable finance and climate-related issues at the ***Banque de France***.

He previously worked for the International Finance Corporation (World Bank Group) as an environmental and social consultant, and as an investor in clean technologies for a French venture capital firm. He also has experience in asset management, corporate social responsibility for the banking sector and the assessment of business regulations for small businesses.

He is completing a PhD in ecological macroeconomics at ***McGill University (Canada)***. He holds a master's degree in Finance and International Business from the Institut d'Etudes Politiques de Paris (Sciences Po), as well as a degree in Economics and Law of Climate Change from FLACSO Argentina.