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L’emergenza climatica come “tragedia dei commons” o “tragedia dell’orizzonte”

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The green swan

Central banking and financial stability in the age of climate change

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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.

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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

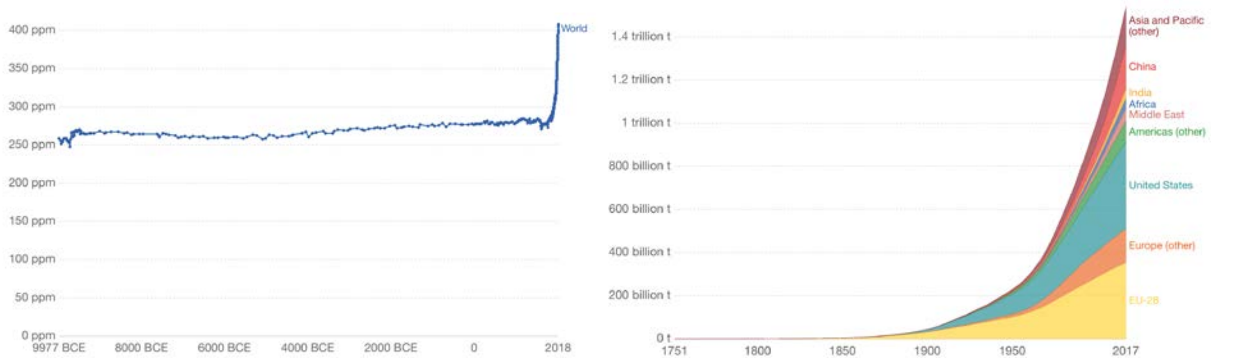
Climate change is the Tragedy of the Horizon. We don't need an army of actuaries to tell us that the catastrophic impacts of climate change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no direct incentive to fix.

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/.

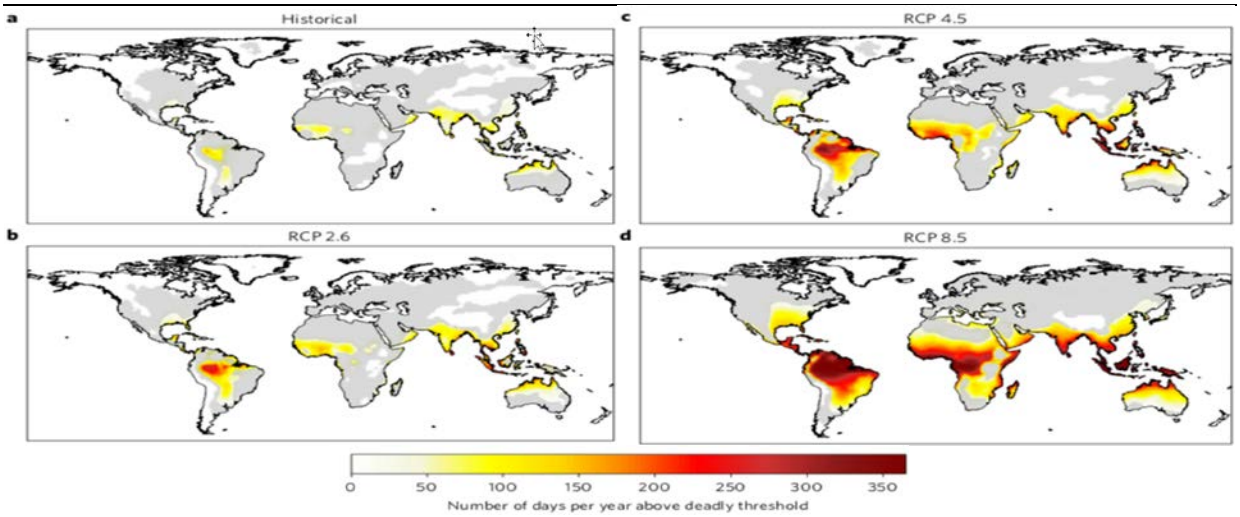
among the hottest ever recorded (IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Millar et al (2017), Ripple et al (2017)).

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).

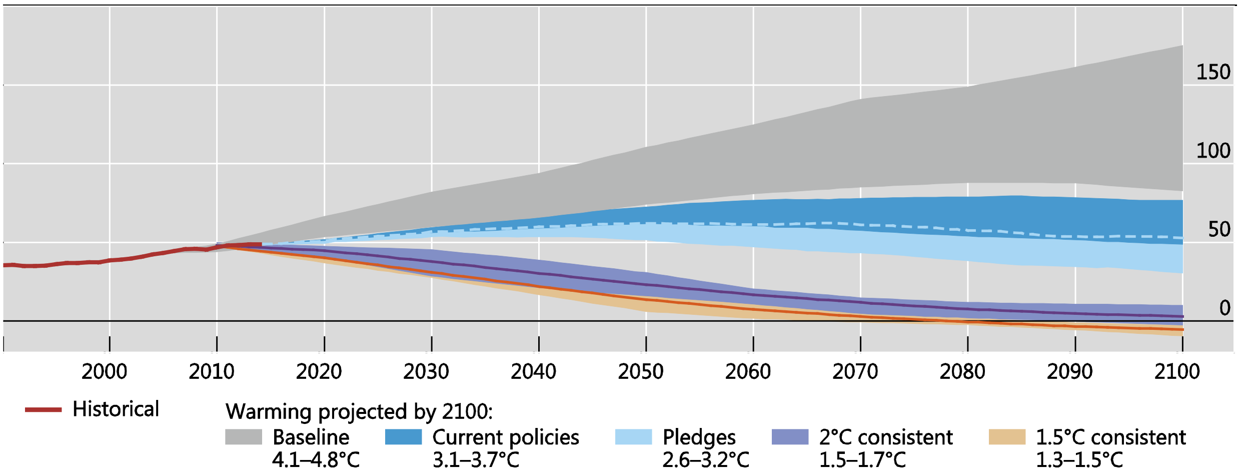
Climate change is not just a future risk: it has actually already started to transform human and non-human life on Earth,[13] although the worst impacts are yet to come. Crop yields and food supply are already affected by climate change in many places across the globe (Ray et al (2019)). Parts of India 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)).

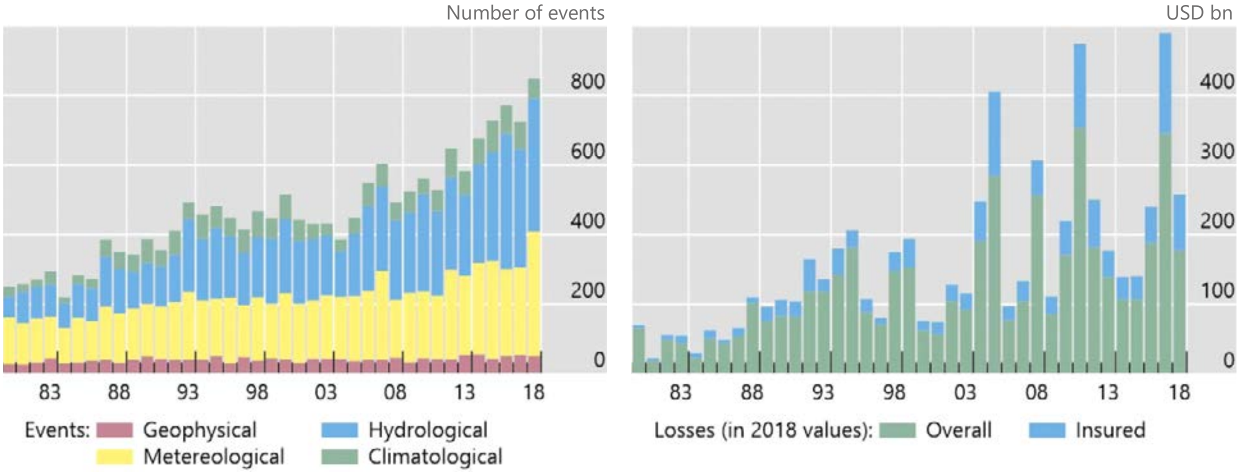
As natural catastrophes increase worldwide (Graph 4), non-insured losses (which represent 70% of weather-related losses (IAIS (2018)) can threaten the solvency of households, businesses and governments, and therefore financial institutions. Insured losses, on their end, may place insurers and reinsurers 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

Number of relevant natural loss events | Overall and insured losses



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).

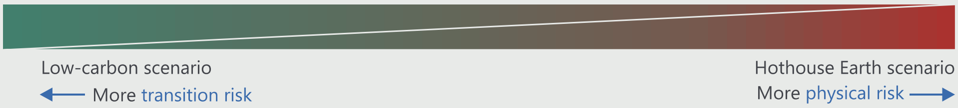
Moreover, the value added of many other economic sectors dependent on fossil fuel companies will probably be impacted indirectly by transition risks (Cahen-Fourot et al (2019a,b)). For instance, the automobile industry may be strongly impacted as technologies, prices and individual preferences evolve. 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.

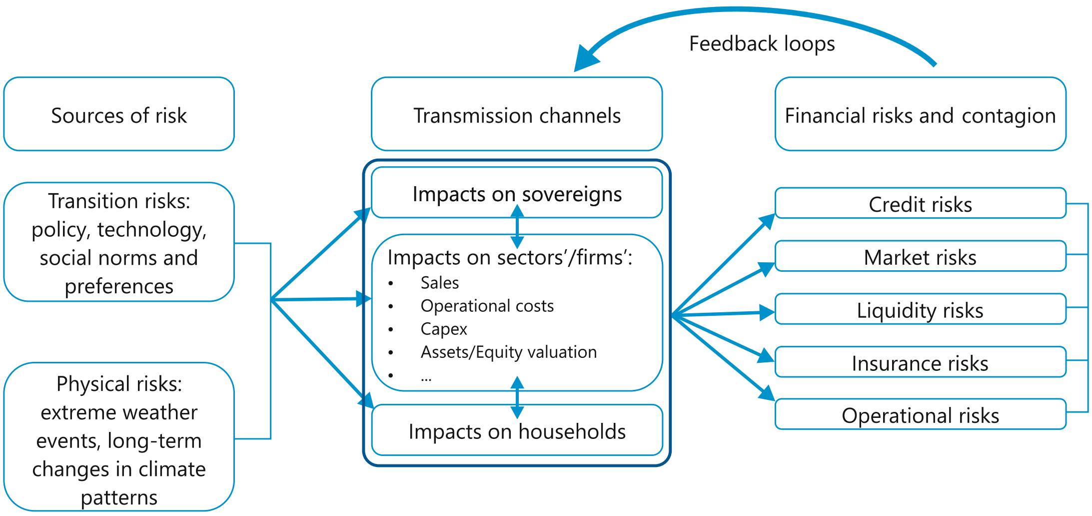
Physical and transition risks can materialise in terms of financial risk in five main ways (DG Treasury et al (2017)), with many second-round effects and spillover effects among them (Graph 6):

- ***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.

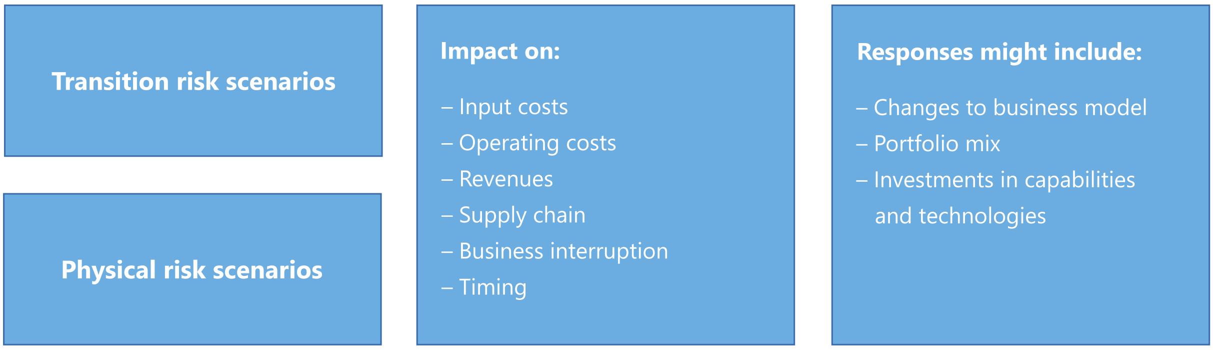
The current situation can be characterised as an "epistemological obstacle" (Bachelard (1938)). The latter refers to how scientific methods and "intellectual habits that were useful and healthy" under certain circumstances, can progressively become problematic and hamper scientific research. Epistemological 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.

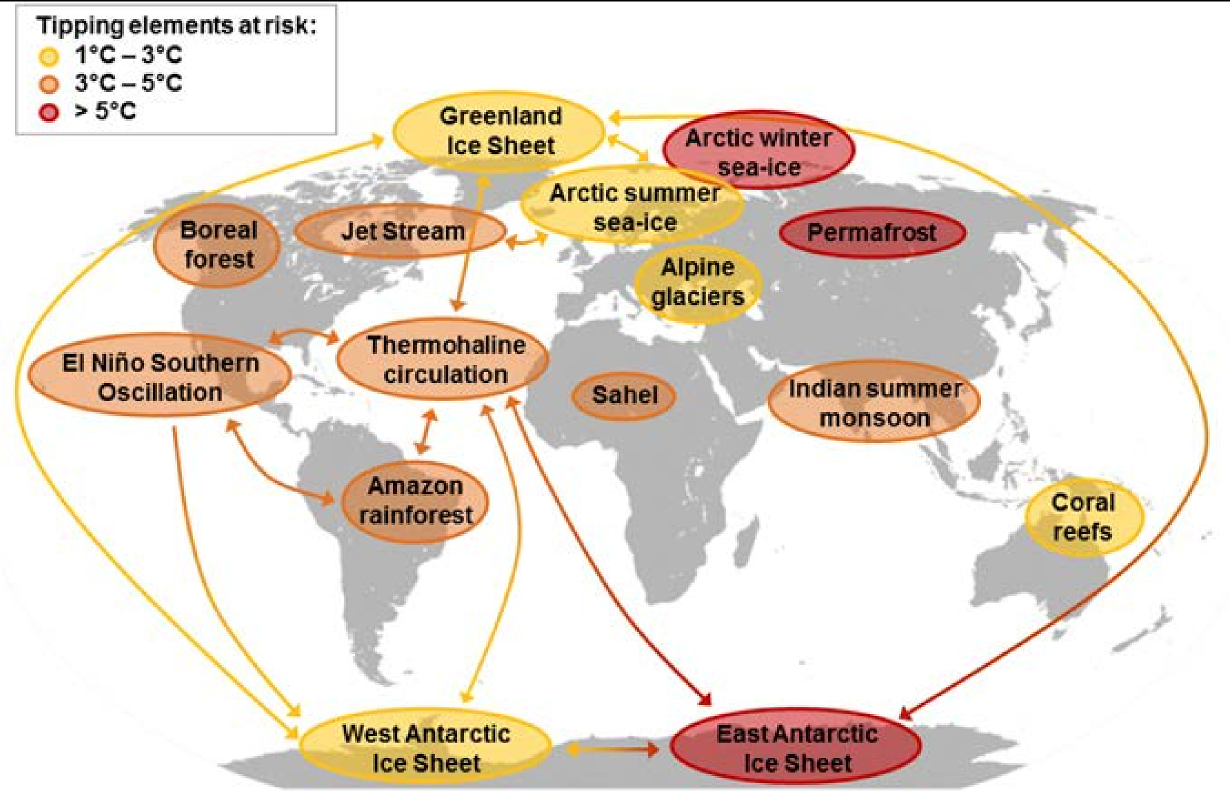
With regard to physical risks (see Annex 1), some of the main sources of modelling uncertainty relate to the following features:

– 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.

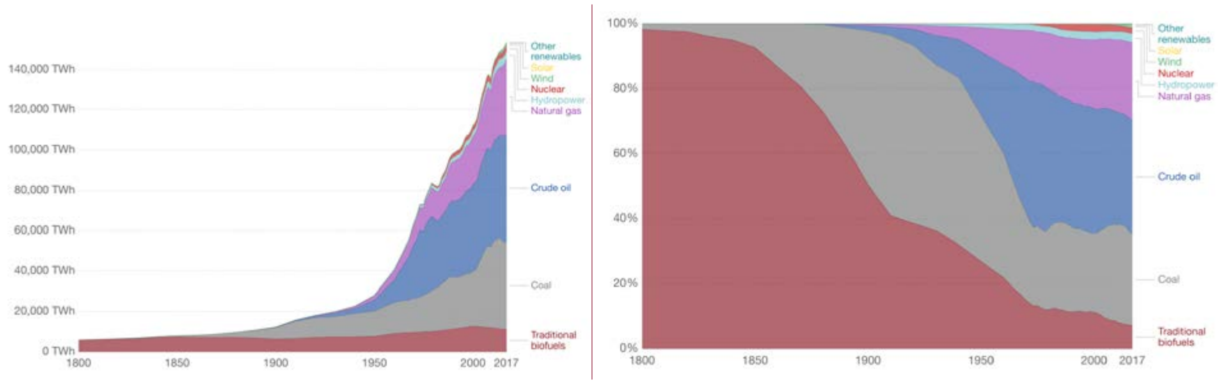
Source: Adapted from Steffen et al (2018).

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.

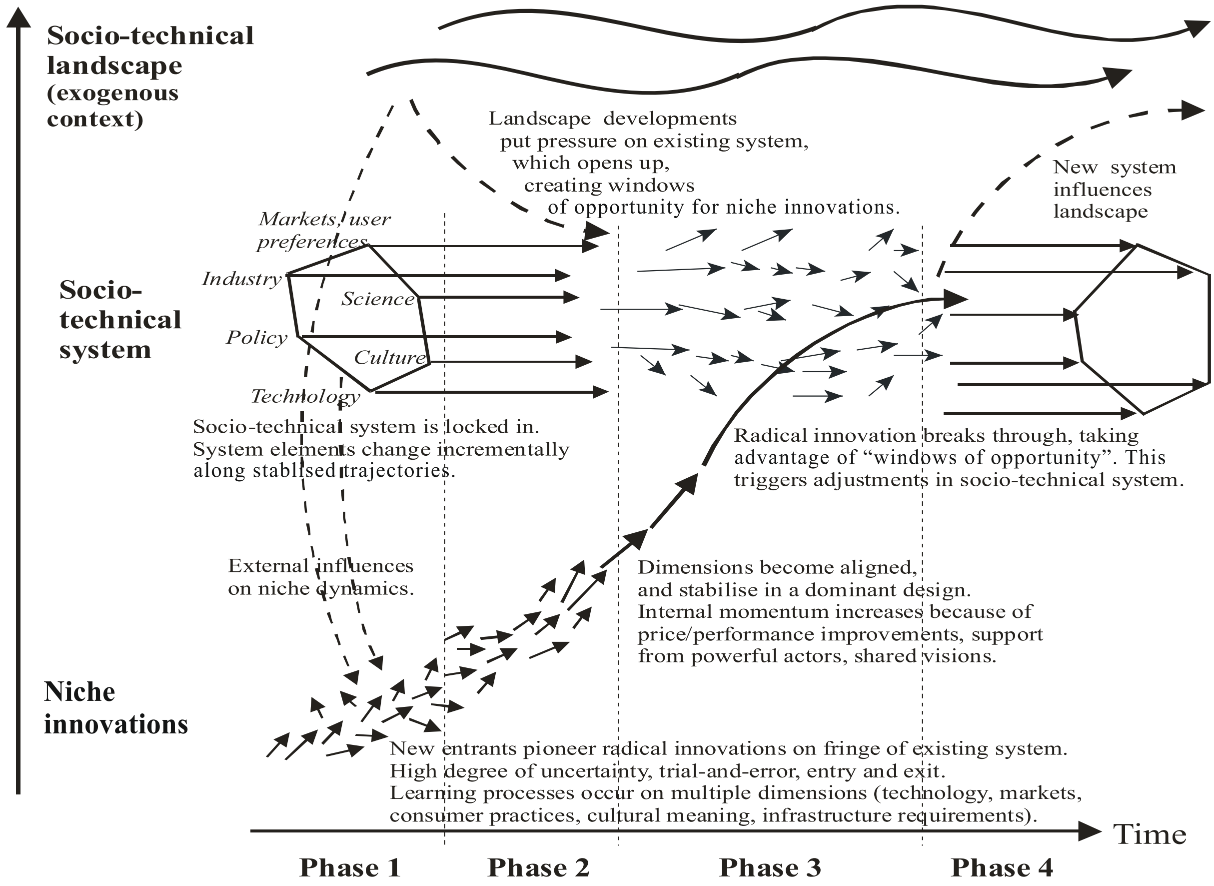
Source: Smil (2017b) and BP (2019). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy.

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).

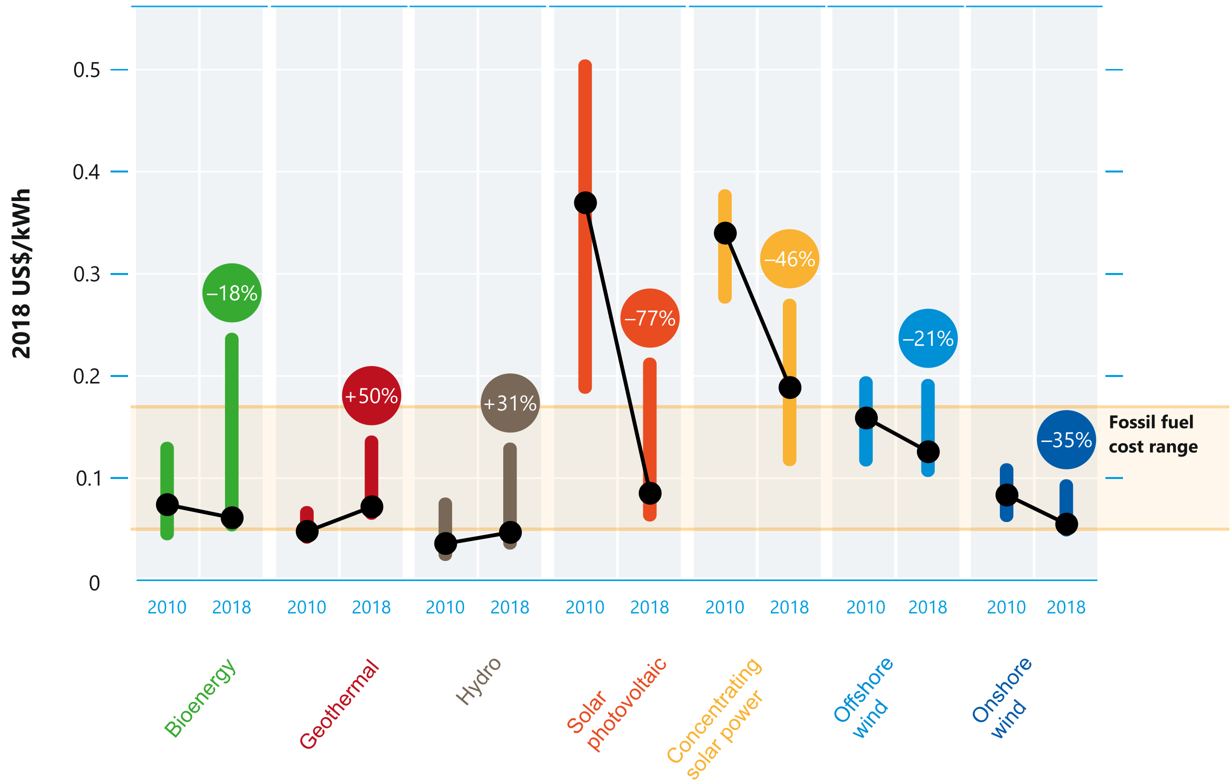
Box 3: A multi-layered perspective on socio-technical transition

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

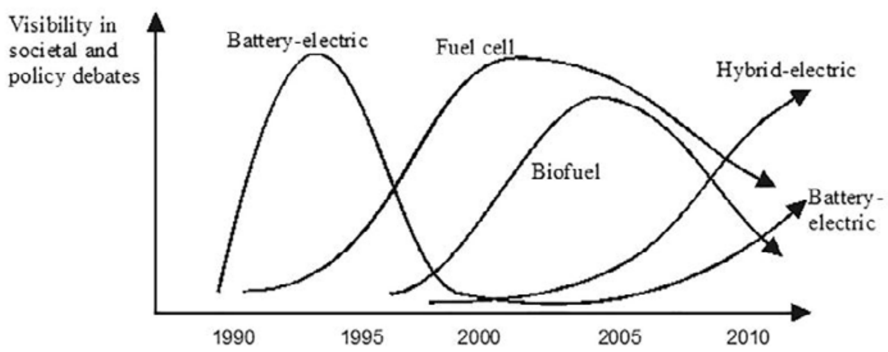
Graph 3.A



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

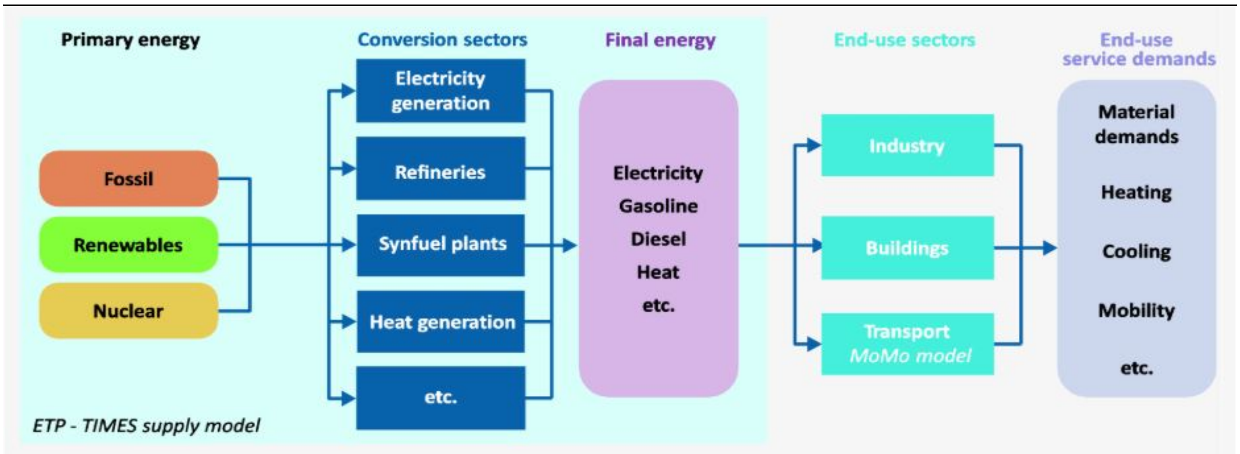
[27] In energy economics, rebound effects occur when initial energy efficiency gains are cancelled out by behavioural or systemic responses, for instance if a consumer uses the financial gains from increased housing energy efficiency to set higher temperatures or to increase energy use elsewhere. As 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)).

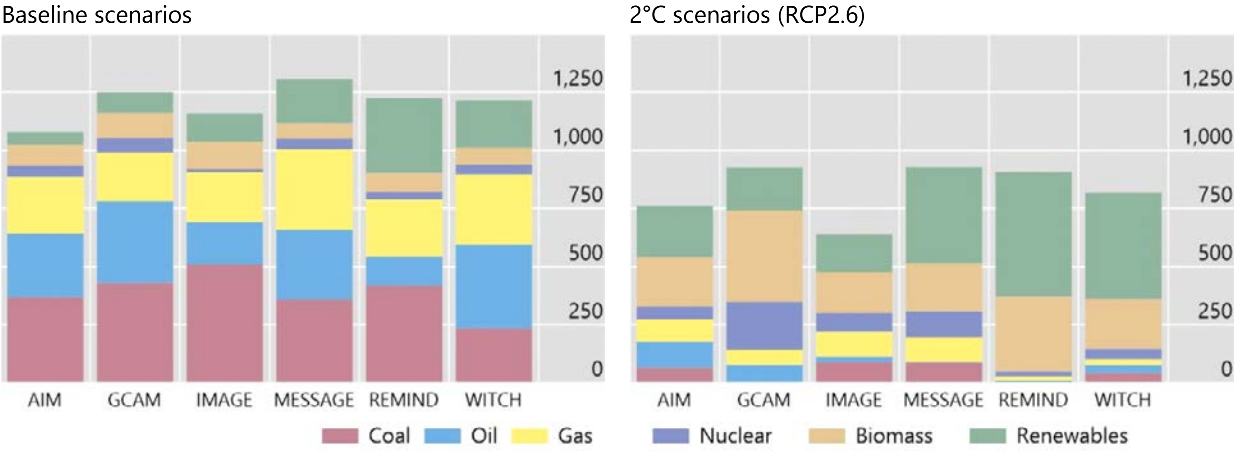
As a result, a scenario with a large role for negative emissions and CCS will naturally reduce the amount of assets that are stranded (eg the GCAM model in the graph below, for a 2°C scenario), whereas a scenario with less room for negative emissions will require a more massive development of renewables (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.

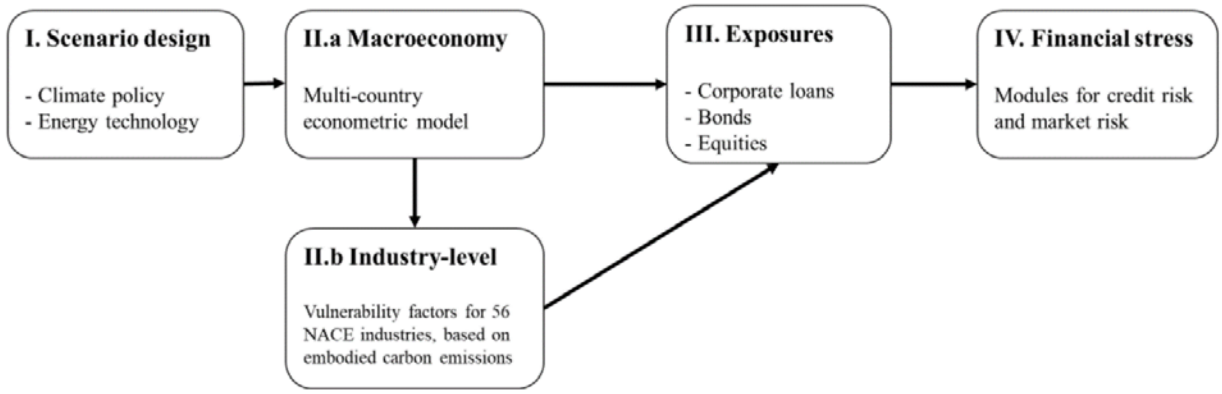
Box 4: The Netherlands Bank's climate stress test

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.

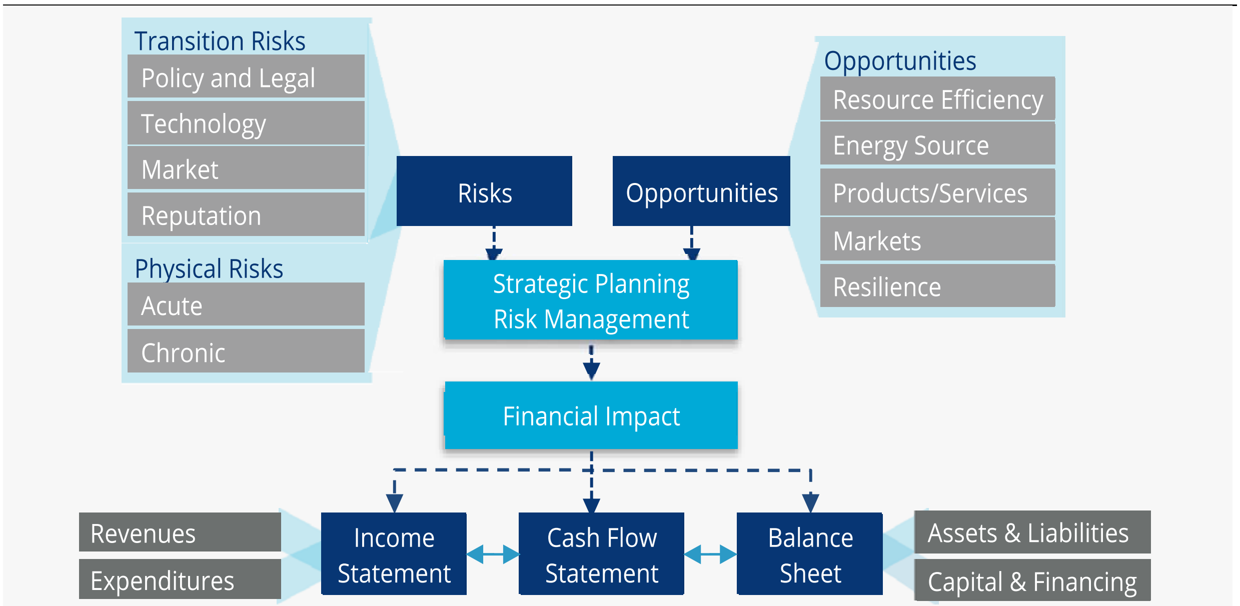
Overview of the stress test framework Graph 4.A



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/.

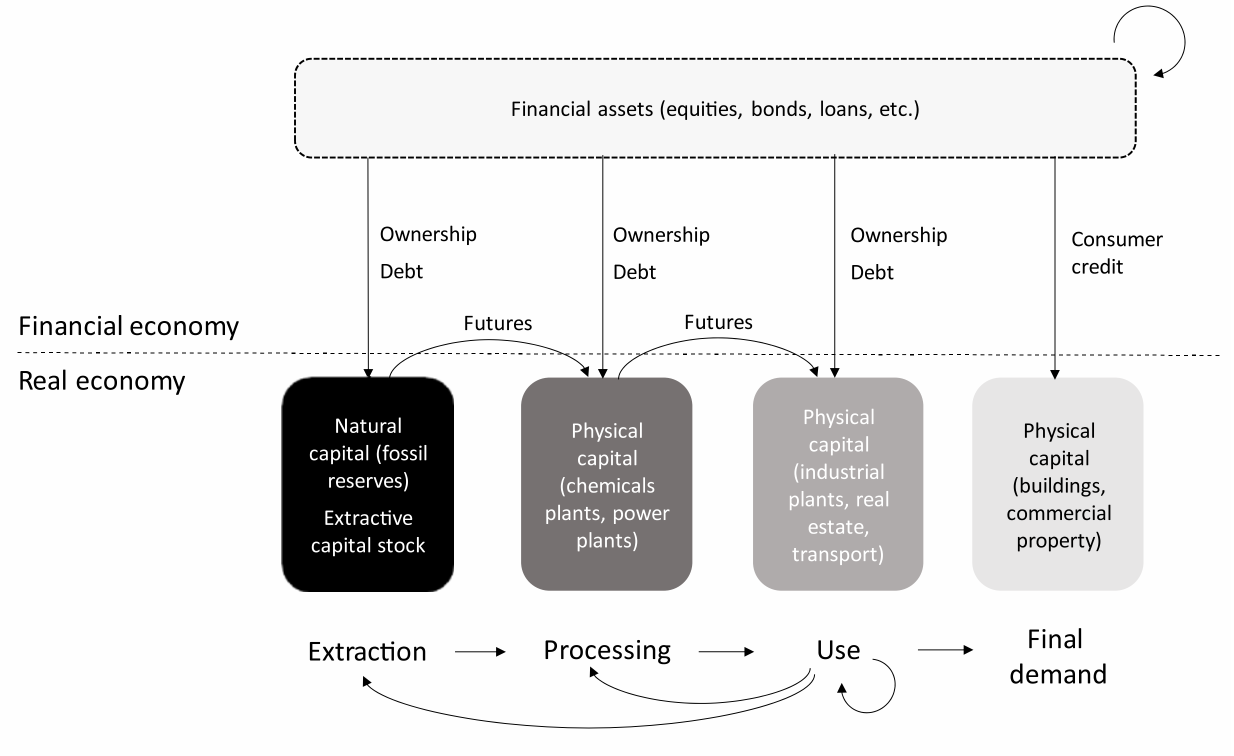
Other approaches have also emerged to better account for the indirect exposures to climate-related risks, without necessarily relying on scopes 1, 2 and 3. For instance, Battiston et al (2017) classify economic activities into six sectors (fossil-fuel, utility, energy intensive, transportation, housing, 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:

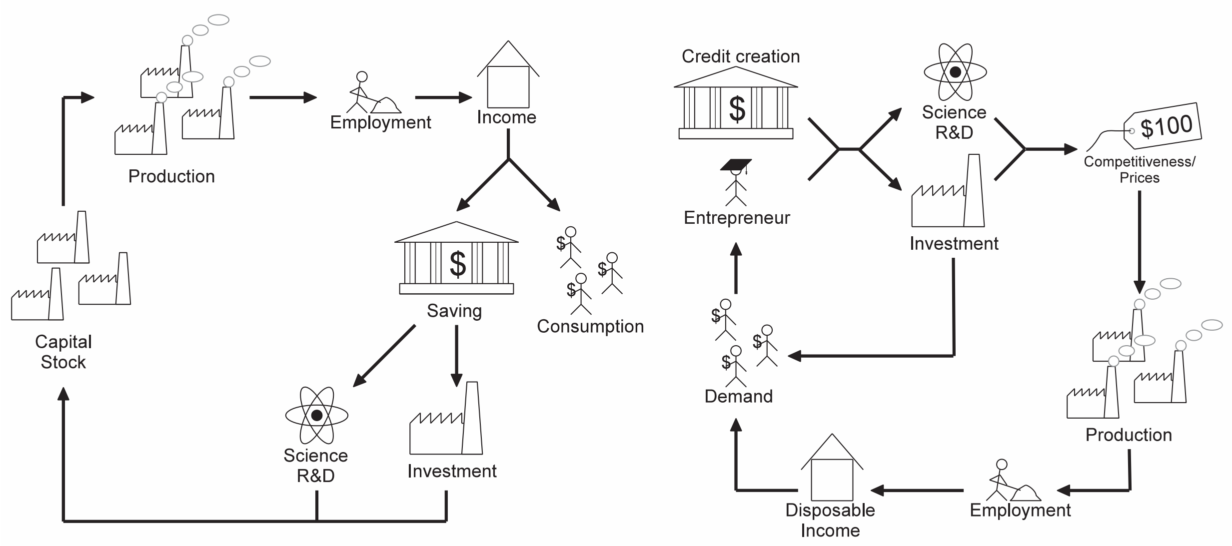
1. Path dependency: in non-equilibrium models, the state of the economy depends on its state in previous time steps. This approach seems particularly aligned with the purpose of scenario analysis, consisting as it does in describing the economy under different possible and diverging circumstances that 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 A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario 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

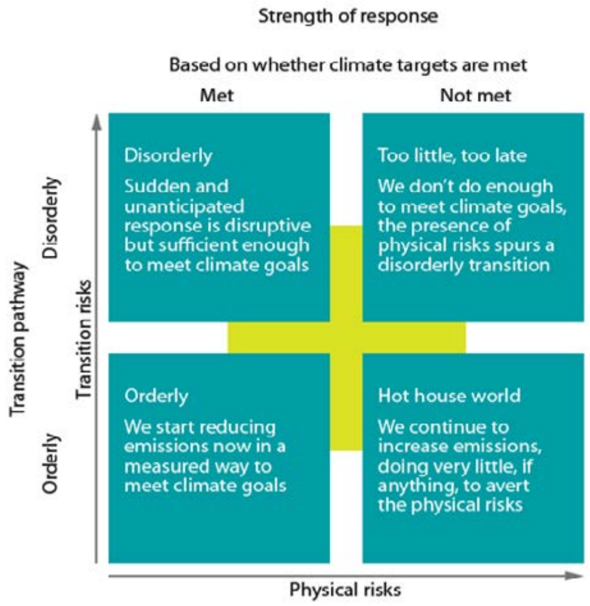
While acknowledging the methodological challenges associated with measuring climate-related risks and the need for alternative approaches (Chapter 3.5), central banks and supervisors should keep pushing for climate-related risks to be integrated into both financial stability monitoring and micro-supervision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

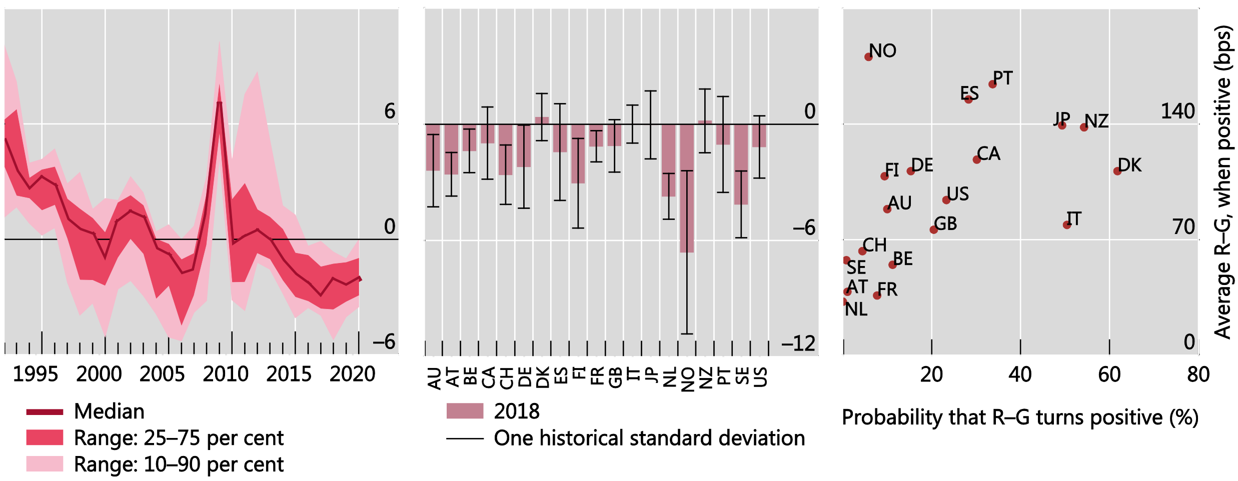
From a very different perspective, and without sharing the conceptual premises of MMT, several economists have recently argued that financing the low-carbon transition with public debt is both politically more feasible than through carbon taxation and economically more sustainable in the current low 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

Cross-country distribution of *R*–*G* | *R*–*G* by country | Likelihood and severity of an adverse scenario



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.

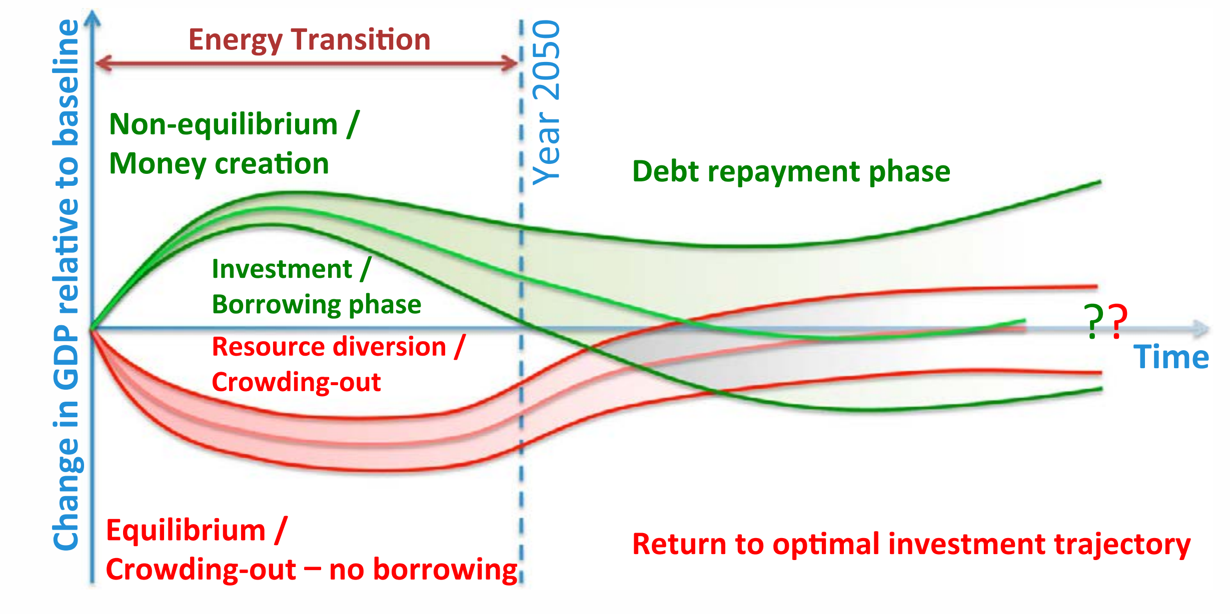
All this should not lead us to consider that there is a "silver bullet" and that the transition to a low-carbon economy can – under current financial circumstances – be easily funded through fiscal policy, as if we had a "free lunch". There could be a risk of a yield snapback. But there are other issues 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).

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/.

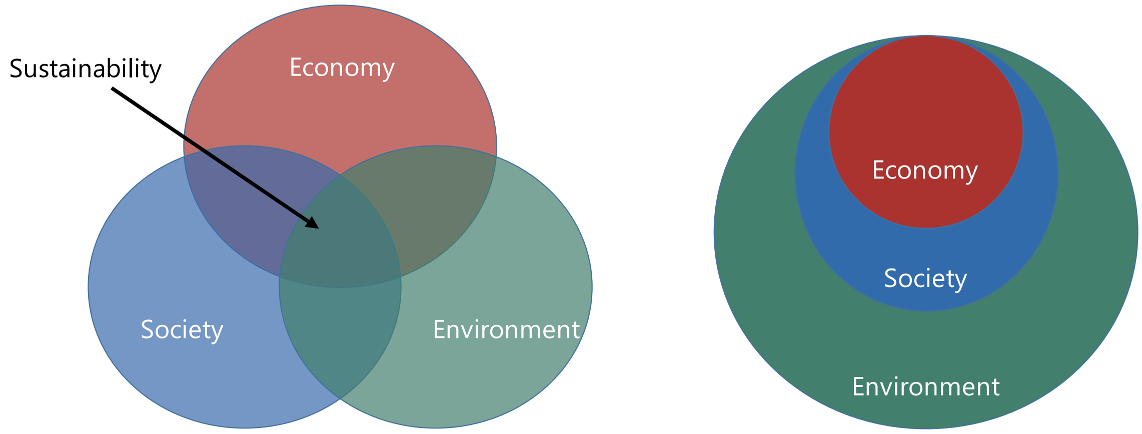
[52] See www.wavespartnership.org/.

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

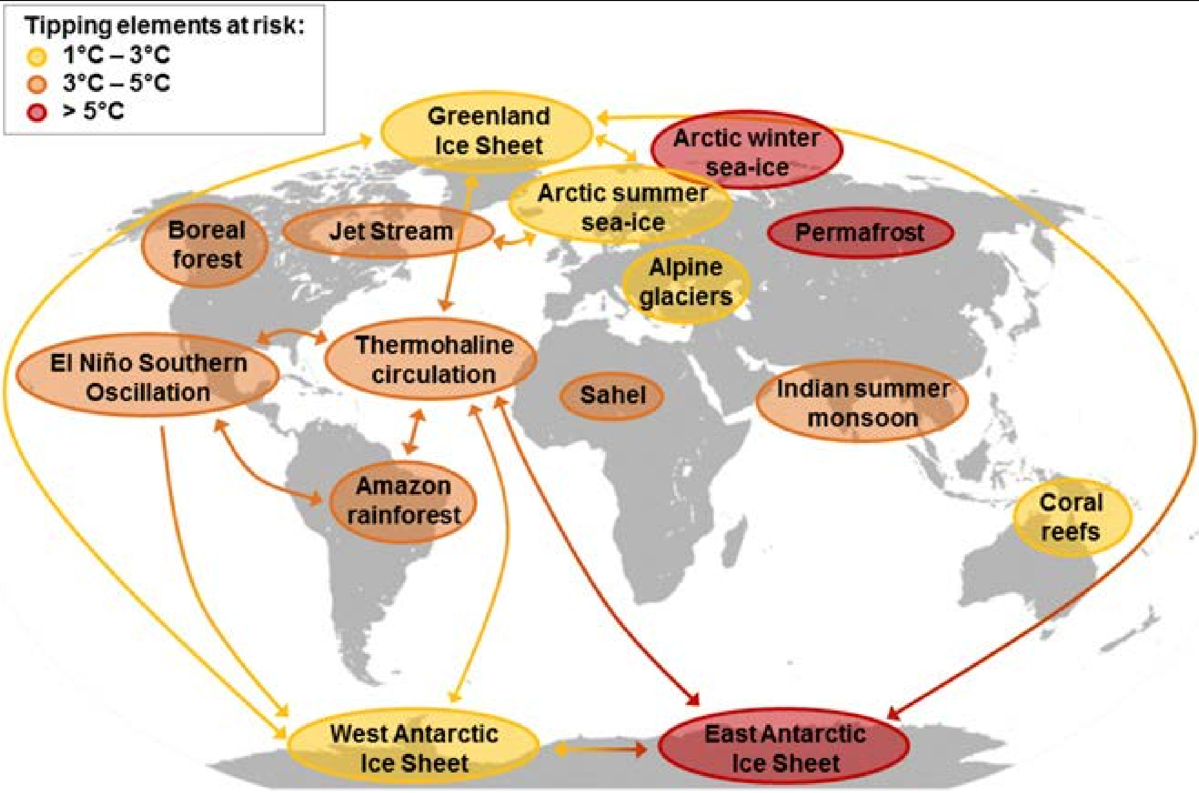
The Earth's climate system is a complex system, with multiple interacting subsystems that can give rise to so-called emerging properties, which refer to new endogenous collective responses. A fundamental (for the purpose of this book) source of emerging properties tied to climate change is irreversibility, 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.

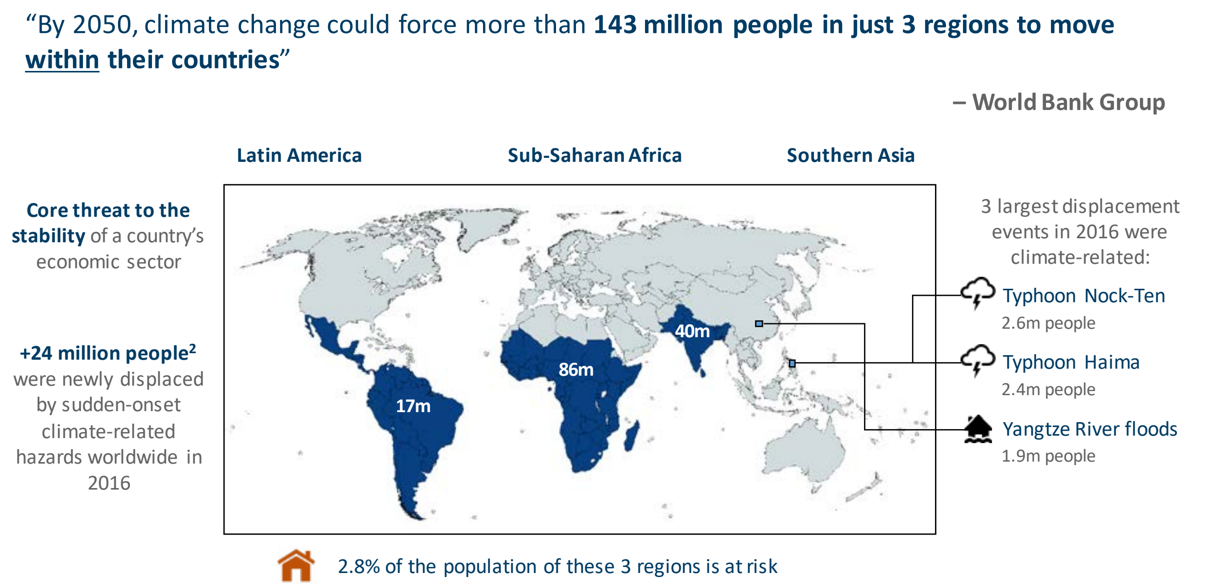
In the light of these challenges, the case has often been made that the damage functions used by IAMs are unable to capture the full uncertainty and complexity of the effects of climate change. In particular, they do not incorporate the high probabilities of extreme risks (or fat-tailed distribution 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.

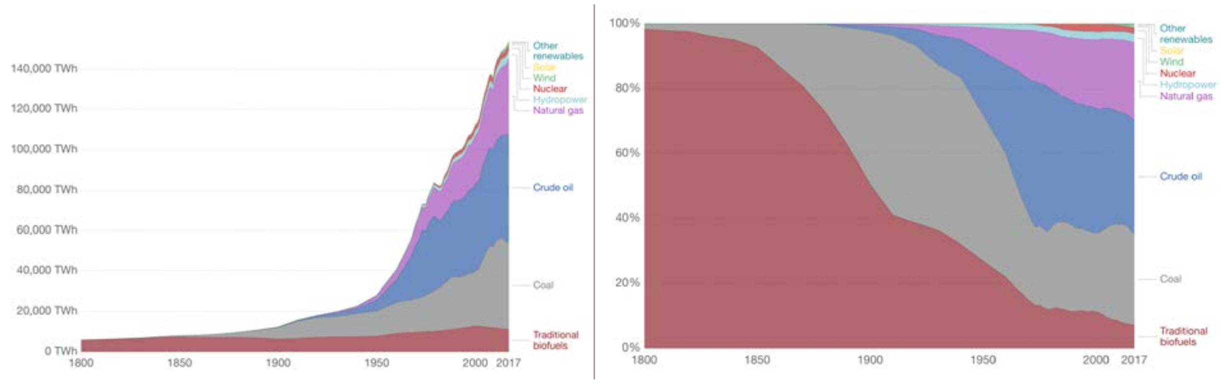
ANNEX 2 – Uncertainties related to transition risks: towards comprehensive approaches to socio-technical transitions

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).

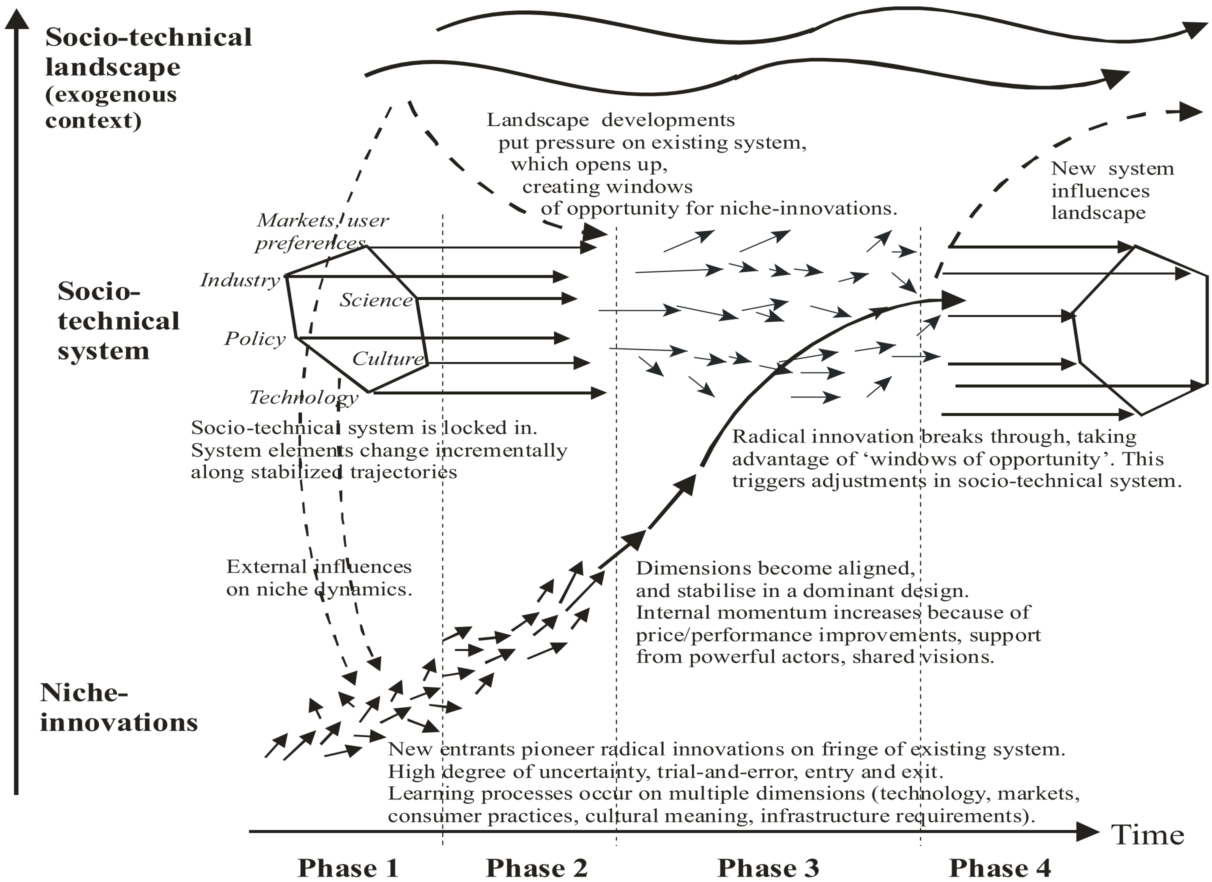
Note: "other renewables" are renewable technologies not including solar, wind, hydropower and traditional biofuels.

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

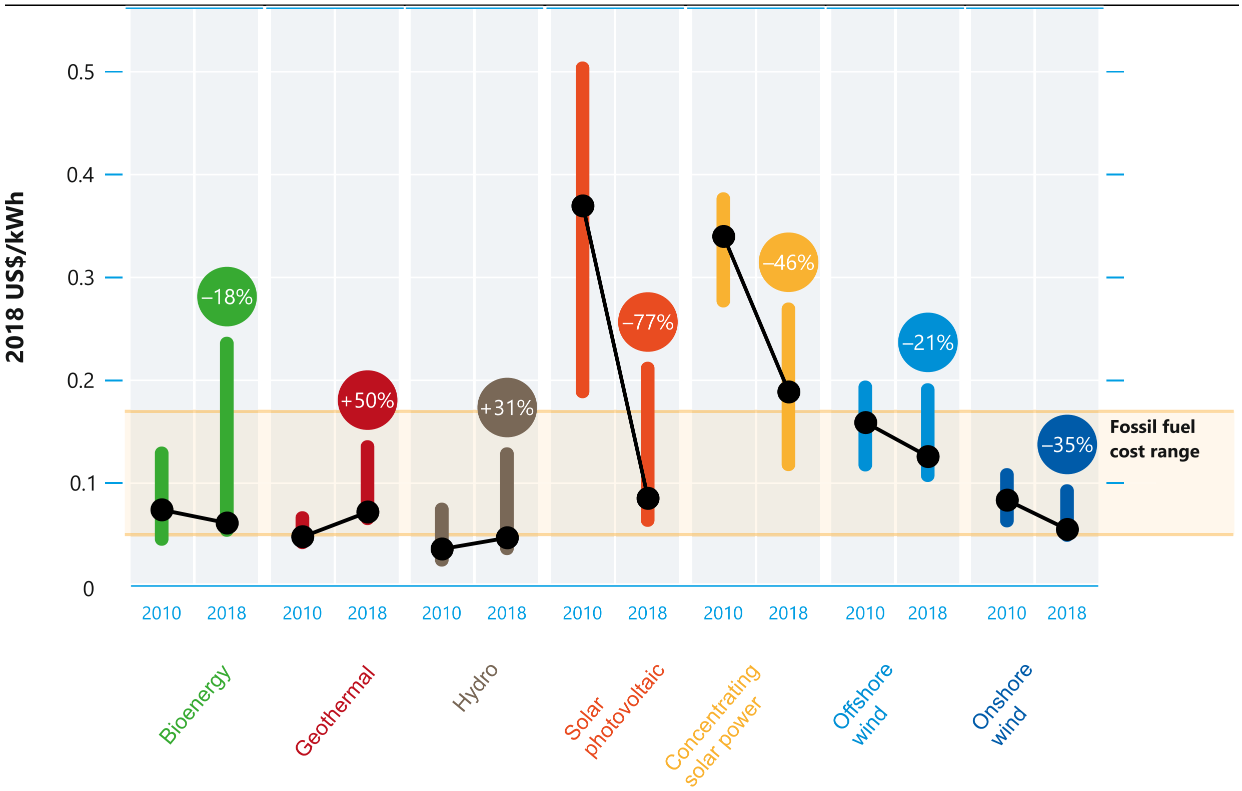


Source: adapted from Geels et al (2017).

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

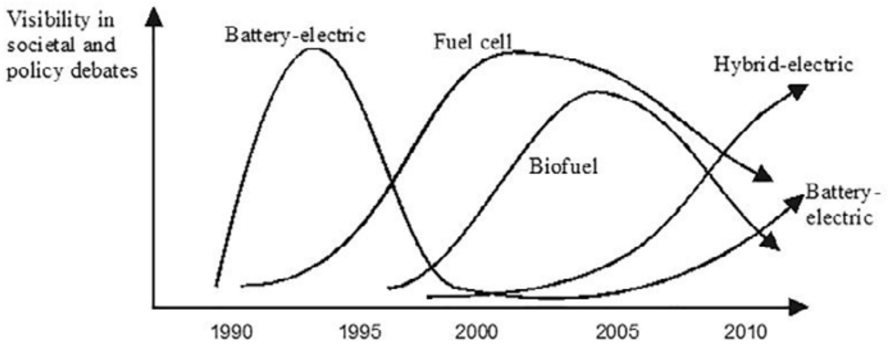


Source: UNEP (2019).

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



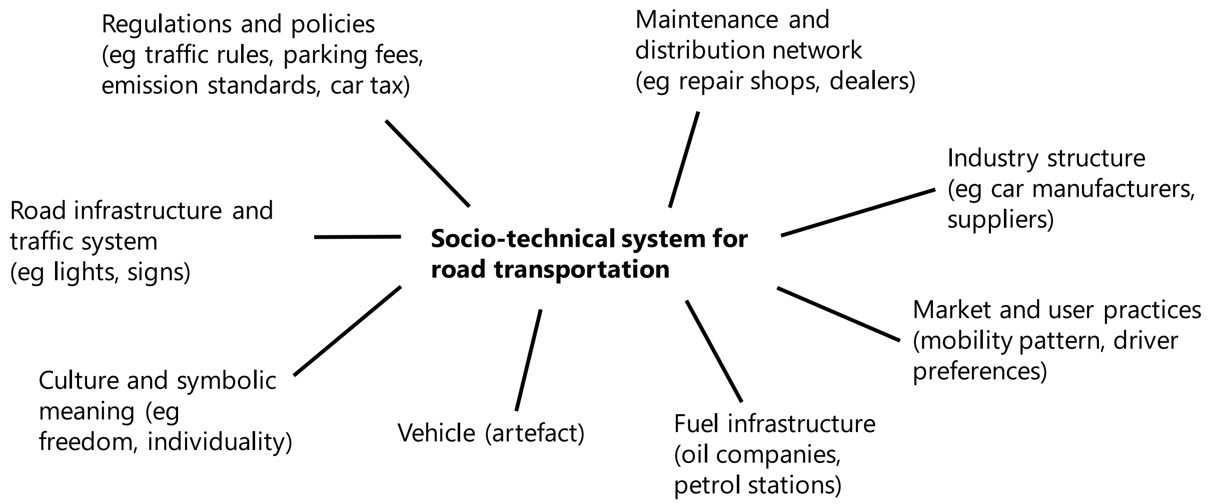
Source: Geels et al (2017).

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).

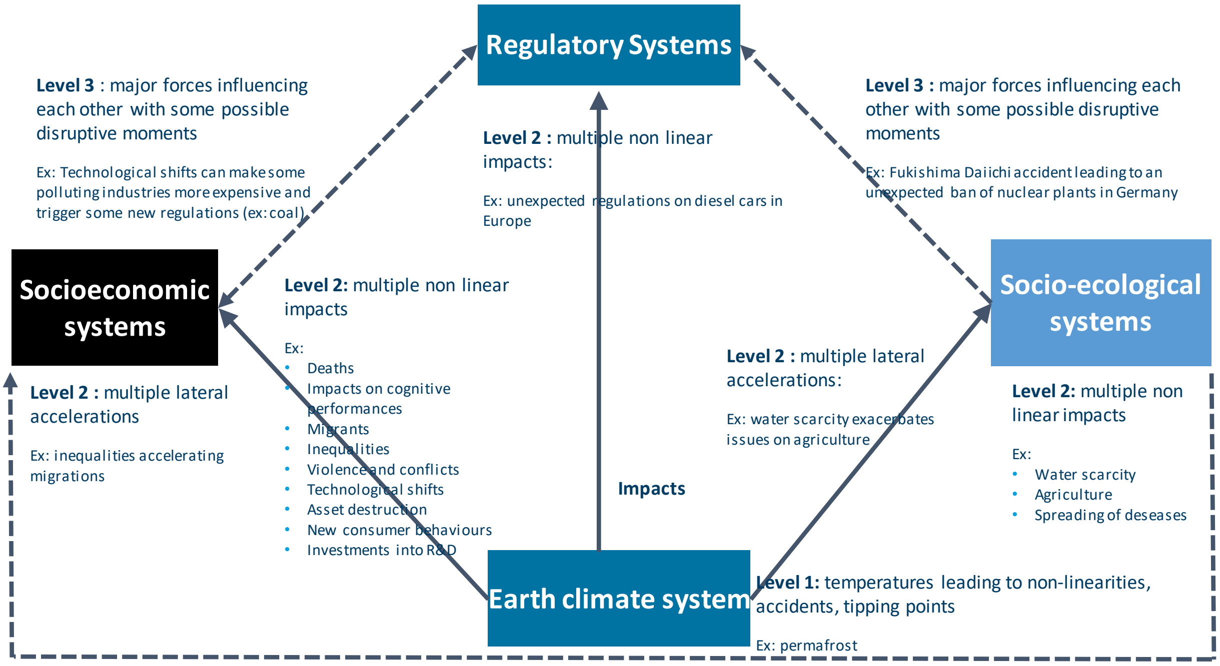
Third, with regard to regulatory and legal systems: climate change has already led to multiple but limited regulatory responses and laws. These can generate positive cascade effects, but they can also put some countries at risk if their economy is mainly based on fossil fuel reserves (McGlade and Ekins (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).

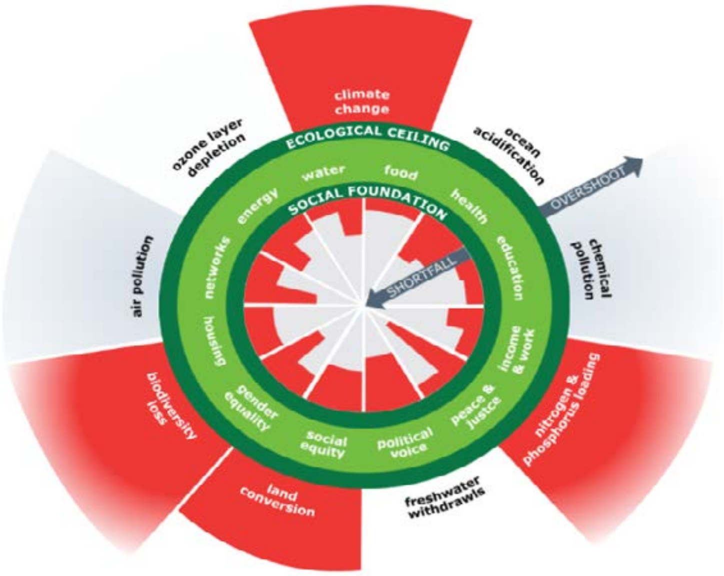
Rockström et al (2009) have identified and quantified nine planetary boundaries, which define the "safe operating space for humanity" associated with the planet's biophysical subsystems or processes. These subsystems are "particularly sensitive around threshold levels of certain key variables. If these 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)).

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The climate commons dilemma: how can humanity solve the commons dilemma for the global climate commons?

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Abstract

In the era when human activities can fundamentally alter the planetary climate system, a stable climate is a global commons. However, the need to develop the economy to sustain the growing human population poses the Climate Commons Dilemma. Although citizens may need to support policies that forgo their country's economic growth, they may instead be motivated to grow their economy while freeriding on others' efforts to mitigate the ongoing climate change. To examine how to resolve the climate commons dilemma, we constructed a Climate Commons Game (CCG), an experimental analogue of the climate commons dilemma that embeds a simple model of the effects of economic activities on global temperature rise and its eventual adverse effects on the economy. The game includes multiple economic units, and each participant is tasked to manage one economic unit while keeping global temperature rise to a sustainable level. In two experiments, we show that people can manage the climate system and their economies better when they regarded the goal of environmentally sustainable economic growth as a singular global goal that all economic units collectively pursue rather than a goal to be achieved by each unit individually. In addition, beliefs that everyone shares the knowledge about the climate system help the group coordinate their economic activities better to mitigate global warming in the CCG. However, we also found that the resolution of the climate commons dilemma came at the cost of exacerbating inequality among the economic units in the current constrains of the CCG.

Keywords Climate change mitigation · Commons dilemma · Common knowledge · Sustainable development

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1 Introduction

Humanity now lives in the epoch that some call the Anthropocene, when human activities can fundamentally alter the workings of the Earth's biosphere (Crutzen 2002). In this context, a stable climate is a global public good (Kaul et al. 1999; Nordhaus 1994), and its sustenance requires a resolution of a commons dilemma (e.g., Dawes 1980; Hardin 1968). We call this the *climate commons dilemma* (CCD). Every country and every individual can enjoy a stable climate if it is sustained. However, as with any commons dilemma, there is a risk of freeriding—enjoying this public good without paying the cost for its provision. The catch is if all countries and citizens choose not to pay the cost, climate change is likely to continue unabated (Milinski et al. 2006; Milinski et al. 2008), and the long-term consequence is dire (IPCC 2014, 2018).

What complicates successful resolution of the CCD is the contemporary global circumstance for humanity. Climate change is ongoing, dangerously altering the planetary system (Rockström et al. 2009), while there is continuing global poverty—783 million people are living below the international poverty line of US$1.90 a day according to the United Nations (http://www.un-documents.net/our-common-future.pdf)—against the background of a growing human population (The United Nations 2019). The twin goals of sustaining the climate commons while eradicating poverty are highly resonant with the ideal of sustainable development (i.e., to maintain economic development while ensuring the environmental sustainability) (Brundtland 1987) and the UN's sustainable development goals. Indeed, climate-sustainable economic growth is fast becoming an imperative. This is because climate change has long-term economic costs (e.g., IPCC 2014; Nordhaus 2014; Stern 2007; Tol 2018), which are more likely borne by less wealthy segments of humanity, and this eventuality further exacerbates global inequality in wealth distribution (e.g., Hallegatte and Rozenberg 2017; IPCC 2014; Rao et al. 2017). Provided that inequality can undermine the collective effort to act on climate (Tavoni et al. 2011), rising global inequality can jeopardise sustainable development.

Therefore, countries and their citizens need to balance potential short-term costs of climate change policies and action against the long-term benefits of sustaining the planetary environment *and* human economic wellbeing (Nordhaus 1994, 2014) by containing global warming to 1.5–2 °C above the pre-industrial average (TheUnited Nations 2015a). Not only climate science but also social science approaches are necessary to address this pressing concern (IPCC 2014, 2018). The main objective of the present research is to investigate under what circumstances ordinary citizens can resolve the CCD by using a newly developed experimental paradigm, the *Climate Commons Game*, where economic growth is explicitly tied to changes in climate.

1.1 The behavioural science of the climate commons dilemma

Within a rapidly growing literature on the behavioural science of climate change (e.g. Clayton et al. 2015; Clayton et al. 2016), experimental approaches are often used to investigate people's ability to resolve the CCD via behavioural- or preference-based proxies for climate change action (Jacquet et al. 2013; Milinski et al. 2006; Milinski et al. 2008). In their groundbreaking work, Milinski et al. (2006) asked German university students how much they would contribute (€0, €1 or €2) to publish a newspaper advertisement about the importance of climate change mitigation. On average, a staggering 94.4% made a contribution when they were not anonymous and especially after reading an expert opinion about the significance of climate change, suggesting a general willingness to bear a personal cost to contribute to climate change action. Milinski et al. (2008) constructed another experimental paradigm, in which climate change mitigation was characterised as giving resources for a mitigation action to prevent the public "bad" of climate change. If the mitigation action is more likely to enable the participants to avoid the adverse effects of climate change, they are likely to contribute to mitigate climate change (for a review of studies using these paradigms, see Jacquet 2015).

The insights gained from these experiments have provided a valuable perspective on understanding ordinary citizens' climate change action outside the lab (e.g., Aitken et al. 2011; Tam and Chan 2018), underscoring the utility of lab-based experimental approaches to understanding commons dilemmas (Falk and Heckman 2009; van Lange et al. 2013). However, existing experimental paradigms have two characteristics, which may limit insights about climate change action. First, the existing experimental paradigms concentrate on the CCD's incentive structure, while largely bracketing out climate knowledge that is required to solve the CCD (Newell et al. 2014; Newell and Pitman 2010). Participants only need to understand that there is an action that, if taken, would successfully mitigate climate change. Details regarding what the action is or how that action would work to address climate change need not be considered. It follows that existing experimental tasks neglect the need for individuals (and societies) to address the cognitively complex task of balancing greenhouse gas (GHG) emissions and global warming against the costs and benefits of taking action on climate change (Burke et al. 2018; Burke et al. 2015; Nordhaus 2014).

Successfully stabilizing global climate requires taking action in a way that accounts for delayed feedback loops relating economic activities to global temperature increase, which in turn may adversely affect the economy itself (Nordhaus 2014; see Fig. 1). Although economic activities drive immediate changes in GHG emissions, their full effects on global warming take time to emerge, because of atmospheric GHG accumulation dynamics. Understanding such a human-climate system is evidently difficult. Even well-educated individuals have difficulty determining the level of emissions necessary to stabilise GHG concentration in the atmosphere (Moxnes and Saysel 2008; Sterman and Sweeney 2007) without additional cognitive support (Guy et al. 2013).

Sewell et al. (2017) constructed an experimental paradigm, which embeds a simplified human-climate system. Although its system dynamics are highly simplified, the task reflects the causal opacity of the nonlinear system dynamics with delayed effects (Fig. 1), which makes decision-making difficult. They found that it takes both an accurate mental model of the

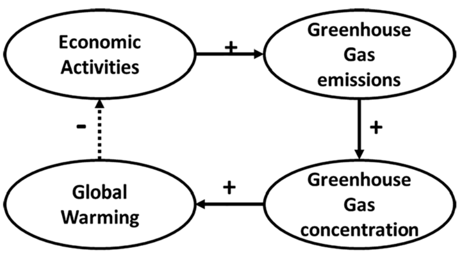

Fig. 1 A schematic causal structure of the economy and global warming. Economic activities produce green gas emissions, which accumulate in the atmosphere. Over time, the accumulated greenhouse gases produce global warming. Warming, in turn, has negative consequences for economic growth (e.g. by provoking changes in the viability of certain industries or creating instability). Because climate change mitigation entails reducing GHG emissions, within this framework, effective mitigation requires limiting economic activity

climate system and opportunity to learn about the feedback loop relating economic activities and global warming (i.e. the negative long-term effect of global warming on the economy) to sustainably manage economic activities.

Second, although existing paradigms highlight the importance of the CCD's incentive structure, they simplify its decision structure (i.e. how a decision to cooperate or freeride is *framed* within the game). In the existing paradigms (Milinski et al. 2006, 2008), participants are required to decide *how much to give* for climate change mitigation, which is called a give-some game, as opposed to a take-some game (Dawes 1980). However, when climate change is framed within the context of policymaking and policy preferences, climate action is often framed as *forgoing* the short-term benefit of economic growth and employment for the global public good. It is not giving but more akin to restraining oneself from taking more from the common resource pool. Given that decision framing of give-some vs. take-some often affects decision-making (e.g. Brewer and Kramer 1986; Rutte et al. 1987; van Dijk and Wilke 2000; van Dijk et al. 2003), insights from the existing CCD games may not generalise when the CCD is framed differently as characterised in Fig. 1.

1.2 Climate Commons Game

We extend Sewell et al. (2017) to construct our Climate Commons Game, an interactive task that emulates causal relationships between human economic activities, GHG emissions, and climate in a simplified way.

Participants play the role of the policy director of one of multiple economic units (analogous to a country's economy) in a dynamic environment in which economic activities are non-linearly linked to the climate, which in turn affect economic productivity. Their job is to set an economic growth target for each year to stimulate or restrict economic activities, so as to pursue a *sustainable development goal* (The United Nations 2015b; i.e., achieving long-term economic growth while keeping global warming at bay). For each economic unit, its economic performance is indicated by a numerical value, and the state of the global economy is indicated by the sum of all units' economic performances. The state of the climate system is indicated by the global temperature and the level of CO_2 concentration. In every round of the game, each economic director receives updated information about the global economy, the climate system and their own economic unit. Each director sets their own yearly economic target, chosen from a fixed range of positive and negative values (i.e. to accelerate or restrict economic growth). Each director's decision determines their unit's economic activities and GHG emissions, and all units' aggregated emissions determine the GHG concentration, global temperature (including delayed effects) and climate-affected economic outcomes (Fig. 1). This process continues for a set number of rounds.

The commons dilemma is inherent in this game. Each local economy can make a greater short-term gain by setting a higher growth target and rapidly growing their economy; however, in so doing, the aggregate GHG emissions increase, which in turn raises the atmospheric CO_2 concentration and therefore the global temperature. Higher temperatures adversely affect every country's economic productivity and therefore hamper its economic outlook in the long term. The decision structure for each economic director (i.e. participant) is homologous to that of a grazier that keeps adding cattle to the commons in Hardin's (1968) parable of the tragedy of the commons.

It may be argued that the director of an entire economic unit is an unrealistic arrangement for a participant. To be sure, an ordinary citizen, or for that matter, even the leader of a country, does not have this power. Nonetheless, in democratic processes, an ordinary citizen is ideally meant to consider the merits and drawbacks of policies if they are implemented and vote for those who advocate the policy that he or she decides is most suitable given the current circumstance. The game is designed to measure an individual's policy preference in this sense. By asking participants to make an economic decision as if they were the directors of the economic units, we can measure their preference for a level of economic growth that they believe would be most suitable given the economic and climate condition. Our question is therefore the following. When there is an incentive to grow the economy, but there is a great deal of causal opacity about the effects of their economic decisions on the climate system with delayed effects on their own economy, what circumstances would shape ordinary citizens' economic policy preferences if multiple economic units need to cooperate to keep the global temperature at a sustainable level? How can the climate change issue be communicated to support their policy preferences to resolve the CCD?

As noted by Pruitt and Kimmel (1977), to achieve cooperation, the multiple parties involved in a commons dilemma need to have a goal to achieve mutual cooperation and a mutual expectation that others will cooperate. What makes a commons dilemma difficult to solve is the requirement of mutuality. That is, only one party holding both the goal and expectation of mutual cooperation is insufficient; a majority, if not every party, needs to have both. In the CCG, the requirement of a mutually shared goal and expectation of cooperation is all the more difficult to meet because of the complex mental models required to balance economic and climate sustainability. In the present research, we investigate under what circumstances ordinary citizens have policy preferences that can resolve the CCD by manipulating the extent to which the goal of mutual cooperation is emphasised among the multiple economic units (experiments 1 and 2) and also the extent to which the expectation of mutual cooperation among the economic units is likely to be held (experiment 2). We discuss these factors in turn.

1.2.1 Goal of mutual cooperation

Although there are a number of factors that can create a goal of mutual cooperation among multiple parties (e.g., Pruitt 1967; van Lange et al. 1997), goal-framing is the most obvious. That is, if the parties involved in a commons dilemma all adopt a goal whose attainment requires or implies mutual cooperation, each party is likely to hold the subgoal of mutual cooperation. Indeed, it has been postulated and shown that when multiple groups share a superordinate goal whose achievement requires mutual cooperation among the groups, mutual cooperation is enhanced between groups while intergroup conflict is reduced (e.g., Gaertner et al. 2000; Sherif et al. 1961); more generally, cooperation goals tend to enhance group achievement and productivity (e.g., Johnson et al. 1981).

The Climate Commons Game has two overarching goals—growing the economy and keeping global temperature at bay. We factorially manipulated these goals in experiment 1. In the climate goal condition, the global temperature goal was explicitly set in line with the UN Paris Agreement, to keep the temperature rise within 2 °C above the pre-industrial average. In the no climate goal condition, this goal was not explicitly stated. We hypothesised the climate goal condition will help people manage the CCD.

H1. There should be greater cooperation in the Climate Commons Game (i.e. lower CO_2 concentration, and lower global temperature) in the climate goal condition than in the no climate goal condition.

The goal of economic growth can emphasise mutual cooperation or competition depending on how it is framed. On the one hand, economic growth is typically understood to be an individual economic unit's job. Each country is to grow its economy to ensure its citizens' wellbeing—well clad, well fed and well sheltered—and ensuring that they do not live in poverty. However, economic growth need not be construed as a purely local goal and can be viewed as a collective goal—to ensure that all humanity's needs are met as the human population increases. This is indeed reflected in the United Nation's Sustainable Development Goal (The United Nations 2015b). The Brundtland Report (Brundtland 1987) arguably frames the economic growth goal as a shared goal for all countries. We hypothesise that even if the same level of economic growth is set as a goal, the shared goal framing, relative to the individual goal framing, will help resolve the CCD.

H2. There should be greater cooperation in the Climate Commons Game in the shared goal framing than in the individual goal framing.

1.2.2 Expectation of mutual cooperation

The expectation of mutual cooperation is also important for cooperation, because most people are conditional co-operators (i.e., 'I will cooperate if you cooperate'; e.g., Fischbacher et al. 2001). Likewise in the CCD, expectations of others' cooperation are likely to be important. That accurate information about how the human-climate system works is *common knowledge* (Lewis 1969) or in *common ground* (Clark 1996; Clark and Brennan 1991) should facilitate people to coordinate their decisions. Having this information in common ground facilitates agreement on how to achieve sustainable development.

To make a case, we first need to clarify what common knowledge or common ground is. Lewis's (1969) definition of common knowledge is a strict logical requirement, and it can be paraphrased as follows. Information is common knowledge if everyone knows the information and also that everyone knows that everyone knows the information (and so on ad infinitum). (Clark 1996; Clark and Brennan 1991) made this requirement more psychologically plausible and suggested that information is in the common ground if everyone has a ground to believe that the information is true and also that everyone has a ground to believe that everyone believes that the information is true, and so on, to a reasonable cognitive limit.

In the CCD, that the human-climate system information is in common ground is particularly important. This is because one of the significant barriers to climate action may be a false belief that many people in their society are climate change sceptics (i.e. many people believe that climate change is not happening, or that even if it may be happening, it is not human caused). Leviston et al. (2012) found that citizens wildly overestimate the prevalence of climate change scepticism, and that those who (falsely) overestimate the prevalence of climate change scepticism tended to hold an entrenched climate change scepticism themselves. Given that climate change sceptics are less motivated to engage in climate change mitigation (e.g., O'Brien et al. 2018), false beliefs about the prevalence of climate change scepticism are likely to undermine people's beliefs about climate change mitigation, and are likely to undermine the belief that the human-climate system information is in common ground. We suggest that if participants do not believe that the human-climate system information is in common ground, they are unlikely to expect that others would be able to coordinate their economic activities with them.

A literature on commons dilemmas suggests the importance of common ground in achieving mutual trust and cooperation (van Dijk et al. 2009). Foddy et al. (2009) showed that people trusted others in their in-group only if their shared group membership (i.e. that they and those others all belonged to the same group) was in their common ground. Similarly, Thomas et al. (2014) found that sharing information about a commons dilemma situation in their common ground facilitated coordination. Facilitative effects of common ground were also detected in games where information about the game was passed on from one generation of players to the next generation (Chaudhuri et al. 2006; Chaudhuri et al. 2009). Field studies have also found that common pool resources can be cooperatively sustained if their users have a shared culture in their common ground (e.g. Ostrom 2015). Therefore, we hypothesise:

H3. There should be greater cooperation in the Climate Commons Game when the information about the human-climate system is in common ground than when it is not.

1.3 Present research

We investigate how goal-framing and common ground affect cooperation in the Climate Commons Game, the interactive decision-making task developed by Sewell et al. (2017), which emulates a dynamic human-climate system. The parameters governing the relationships between GHG emissions, atmospheric CO_2 concentration and temperature are based on the MAGICC intermediate earth complexity model (Meinshausen et al. 2011), providing an accurate depiction of the relevant dynamics. See Sewell et al. (2017) and Appendix C in the Electronic Supplementary for full details of the dynamics. The task simplifies the human-climate system but retains the essential features of the CCD and the causal opacity of the nonlinear system dynamics. Most importantly, it enables us to study the causal effects of goal framing and common ground on citizens' economic policy preference.

In experiment 1, we factorially manipulate the climate goal of keeping the temperature rise below 2 °C above the pre-industrial average (present vs. absent) and the framing of the goal of doubling the economy (collective vs. individual) in a four-person Climate Commons Game. In experiment 2, we set the goal of keeping the temperature rise below 2 °C for everyone but manipulate the framing of the economic goal (collective vs. individual) in a ten-person Climate Commons Game. We also examine the effect of expectation for mutual cooperation by manipulating whether the human-climate system information is in common ground.

2 Experiment 1

2.1 Materials and methods

2.1.1 Participants and procedure

A total of 600 US residents (150 groups of four, 55% male) were recruited from Amazon Mechanical Turk. Numbers of participants and groups in each condition are reported in Table 1. Those who agreed to participate were redirected to the online platform and read the plain language statement and consent form. Participants then completed the task and were debriefed and paid for their participation (US$3).

Table 1 Number of participants and groups in each condition in experiment 1 and experiment 2

Experiment 1				
	Individual economic goal		Shared economic goal	
	Climate goal absent	Climate goal present	Climate goal absent	Climate goal present
Number of participants	128	160	152	160
Number of groups	32	40	38	40
Experiment 2				
	Individual economic goal		Shared economic goal	
	Common ground	No common ground	Common Ground	No common ground
Number of participants	185	177	179	200
Number of groups	20	20	20	23

In experiment 2, the sessions started when there were no less than 7 people in the waiting room who had finished the instruction, with a maximum waiting time of 5 min. In this case, dummy responses were computed by the system which equal to the average response of the round from the participants in the group

2.1.2 Climate Commons Game

In the Climate Commons Game, participants were grouped to play the role of policy directors of different economies in a dynamic environment that is sensitive to the climate. The policy director's job was to set an economic growth target for each year to stimulate or restrain the economy, so as to achieve a long-term economic growth target while keeping global warming at bay. Following classic commons dilemma experiments (e.g., Fehr and Gächter 2000; Hasson et al. 2010), group size was set to 4.

The human-climate relationship (Fig. 1) was verbally described as follows: "Economic productivity affects CO_2 concentration, which in turn affects temperature. Temperature increases make it increasingly difficult to achieve economic growth. Due to time lags in the climate system, the effects of CO_2 on economic growth will only be felt after a considerable delay, after which they will be difficult to reverse. Hence, it is advisable to keep CO_2 concentration from escalating too high". The setup was identical to Sewell et al. (2017; Appendix C).

Once participants read the instructions and correctly answered comprehension questions, they were assigned to a 4-person group and started the game. At the start of each round, each participant received numerical values representing the state of the game: Own Economic Index, the Global Economic Index (sum of all the Own Economic Index values), CO_2 concentration and the global average temperature. Everyone started with their individual economic index of 25, and the initial Global Economic Index of 100 (i.e., 25 × 4). The initial CO_2 concentration was 108 ppm, and the average global temperature of 0.6 °C above pre-industrial levels. Participants did not know the other participants' individual economic indices.

Each director was to set their own yearly economic target using a slider bar that varied between − 1 and + 1. A round ended when all participants made their decisions. The economic indices (each participant and global total), CO_2 concentration and average global temperature were updated, and then a new round began. The game lasted for 70 rounds, which was explicitly mentioned in the instructions. However, because the current round count was not presented on screen, we assume that it would be hard to keep track of the round count. As a result, the end-game effect (Andreoni 1988), where people become more likely to defect toward the end of the game session, is not a large concern in our experiment. At the end of the experiment, participants answered questions about their demographic information. The entire experiment took around 1–1.5 h to complete. See Appendix E for instructions, game interface and a flow-chart illustrating game flow.

2.1.3 Design

In a two-way factorial design, groups were instructed to achieve a different combination of climate and economic goals. One factor was the climate goal of limiting global warming to 2 °C. Half of the groups were given the climate goal, whereas the other half were not. The other factor concerned the framing of the economic goal. In the shared goal condition, groups were told to double the Global Economic Index (i.e. to increase the Global Economic Index to 200 and sustain it); in the individual goal condition, groups were instructed to double their Own Economic Index (i.e. to increase the Own Economic Index to 50 and sustain it). Note that the individual goal condition was economically equivalent to the shared goal condition (i.e. doubling the total economy) if every economy achieved its own goal. This constituted a 2 (shared vs. individual economic goal) by 2 (climate goal present vs. absent) between-sample design.

2.2 Results and discussion

We examined the effects of the climate goal and the framing of economic goal using repeated-measures general linear mixed models (GLMMs), where group was treated as a random effect and an R-side auto-regressive correlation structure was considered. Figure 2 describes trajectories of average individual participant responses (Fig. 2a), Global Economic Index (Fig. 2b), excess CO_2 concentration (Fig. 2c) and global warming (Fig. 2d). Table 2 shows the details of GLMM analysis. Further details are in the Electronic Supplementary (Tables A.1–A.8).

Participants initially increased their economic growth targets, but eventually lowered them as shown by the positive linear and negative quadratic components, presumably to boost their economic indices early while attempting to offset the temperature rise later. Corroborating this observation, the Global Economic Index, CO_2 concentration and the global temperature all show the same pattern of initial rapid increase followed by lower rates of increase. Of interest is the pattern of the Global Economic Index—it peaked around the 30th round, and declined thereafter, in almost all conditions (Fig. 2b)—suggesting that the economic declines due to increasing temperature, restricting economic growth.

Consistent with our H1 and H2, there are significant negative round × climate goal and round × economic goal interactions, showing that the framing of economic goal and climate goal dampen economic growth, thus lowering CO_2 concentration and curtailing global warming. There was no significant three-way interaction, suggesting that the effects of the climate goal and group goal framing were additive.

An interaction effect of the quadratic component of Round and Economic Goal (round^2 × economic goal) was consistently found for all dependent variables. This suggests that the pattern of initial increase and eventual decrease was stronger in the individual goal condition than in the shared goal condition. Those pursuing the individual goal presumably realised the negative environmental impact of their high economic investment at the early stages and tried to reduce their negative impact by rapidly reducing economic growth. However, by the end of their 70 rounds, although the economic index was brought back to a similar level across all conditions, negative climate impacts remained in the individual goal condition. An analogous pattern was found for the climate goal manipulation although the trend was weaker.

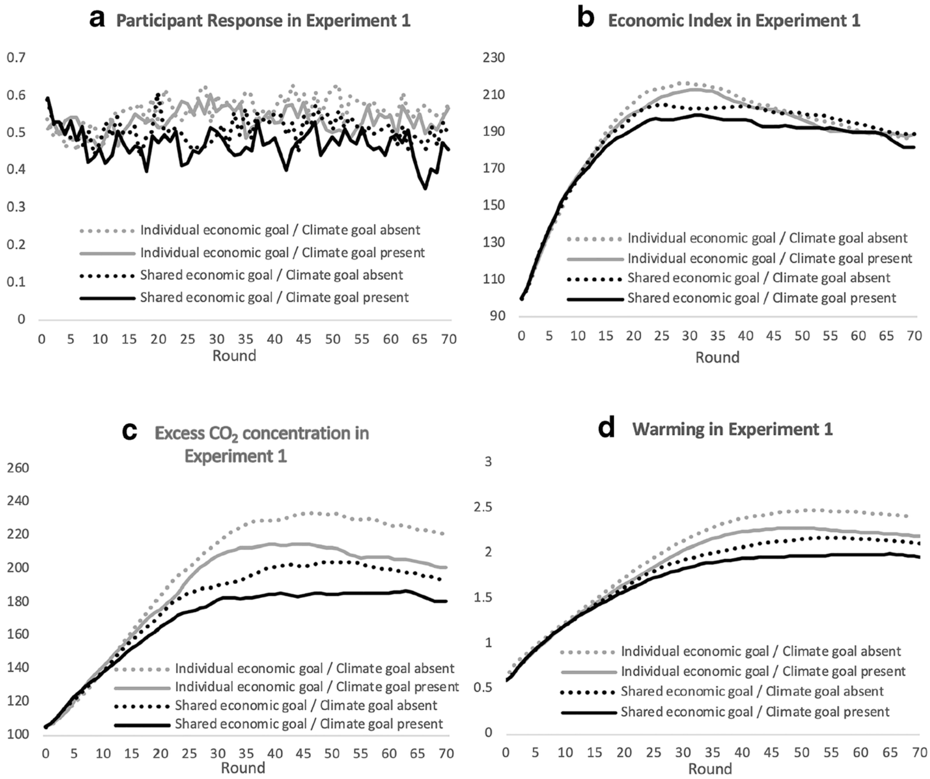

Fig. 2 Average **a** participant response, **b** Global Economic Index, **c** excess CO_2 concentration and **d** warming in experiment 1

Table 2 GLMMs of global economy, excess CO_2 concentration, temperature and participant responses in Experiment 1

	Participant response	Global economy	CO_2	Temperature
	B	B	B	B
Intercept	1.942***	123.910***	93.079***	0.573***
Round	0.019***	4.560***	5.652***	0.069***
Round^2	−0.0002***	−0.056***	−0.056***	−0.0006***
Economic goal	0.044	3.150	11.166	0.110
Climate goal	0.064	2.025	5.779	0.043
Economic goal × climate goal	−0.081	−0.065	−0.457	0.009
Round × economic goal	−0.015**	−0.647***	−1.574***	−0.013***
Round × climate goal	−0.010†	−0.332**	−0.687***	−0.004**
Round × economic goal × climate goal	0.003	−0.109	−0.145	−0.002
Round^2 × economic goal	0.0002*	0.010***	0.015***	9.9E−05***
Round^2 × climate goal	9.8E−05	0.005**	0.004†	4.78E−07
Round^2 × economic goal × climate goal	−4E−05	0.0005	0.004	4.8E−05
Group intercept (covariance)	0.381	588.17	1927.83	0.179

Economic goal: shared = 1, individual = 0. Climate goal: present = 1, absent = 0

***$p < .001$; **$p < .01$; *$p < .05$; †$p < .1$

3 Experiment 2

3.1 Materials and methods

Experiment 1 showed that the goal of mutual cooperation can be facilitated by setting a climate goal and framing the economic growth goal as a collective global target as in the UN Sustainable Development Goals. In experiment 2, we kept the climate goal for all but examined the effect of a shared vs. individual economic goal (H2) as well as that of expectation of mutual cooperation by manipulating whether information about the human-climate system is in a group's common ground (H3). The Climate Commons Game was again used as an experimental paradigm. However, the group size was increased to 10 to see whether these effects generalise to somewhat larger groups, because cooperation in social dilemmas may also be affected by group size (e.g., Shank et al. 2015). We surmised that larger groups may exacerbate the feeling of powerlessness often reported in social dilemmas (e.g., Kerr 1989) and are particularly acute in the climate action (e.g. I am just one among many, and my response will not make any difference; Aitken et al. 2011).

We also explored how the participants managed the twin goals of a stable climate and economic growth because they can be achieved in two different ways. One is for every individual to curtail their own economic growth equally, the other is for some individuals to curtail their own economic growth more than others who grew their economies more than they optimally should have. In the former case, there should not be much economic inequality among the economic units. However, if some players curtail more than others to compensate for those that grow their economy, economic inequality may increase. We explored levels of inequality among participants using the GINI coefficient (Gini 1921)—a well-accepted index of inequality among multiple agents. Its values vary between 0 and 1; the greater, the more unequal. For details, see Appendix D in the Electronic Supplementary and Farris (2010).

3.1.1 Participants and procedure

A total of 741 participants (83 groups, 57.08% male, 21 did not report gender, mean age was 35.52) were recruited from Amazon Mechanical Turk. Numbers of participants and groups in each condition are reported in Table 1.

Participants were asked to play the role of a policy director of one of the 10 economic units. All participants started with their Own Economic Index of 10, which set the Global Economic Index at 100. Each director set their own yearly economic target between −0.5 and +0.5.

As in experiment 1, all participants were told about the human-climate relationship. However, expectation of mutual cooperation was manipulated. In the common ground condition, participants were told that this information was identical for all participants; in the no common ground condition, they were told that the other players in the game 'may or may not receive the same instruction', and 'you may know some of the things that others don't know, but similarly, you may not know some of the things that others know'. Thus, in the common ground condition, all participants knew the nature of the task, but also knew that everyone had this knowledge, whereas in the no common ground condition, participants were left uncertain about the others' knowledge about the nature of the task; as a result, they would have difficulty in predicting the others' decisions, thus reducing the expectation that the others may cooperate to pursue the global climate goal.

Goal framing was also manipulated. In all conditions, participants were told to achieve the climate goal of limiting global warming to 2 °C. In the shared goal condition, they were told to double the Global Economy, whereas in the individual goal condition, they were told to double their Own Economy. A bonus payment of $1 was promised if participants achieved both the climate and the economic goals. In addition, a bonus payment of 10¢ was promised for each point of individual economic growth they achieved.

Once participants read the instructions and correctly answered all comprehension questions, they were assigned into a 10-person group and started the game. The game lasted for 70 rounds. At the end of the experiment, participants answered questions about the experiment and demographics. Each participant received the sum of three parts of payments: a base payment of $3.5, a bonus of $1 if the goals were achieved and an extra payment for the economic growth they achieved.

3.2 Results and discussion

3.2.1 Economic growth, CO_2 concentration and global warming

We evaluated the effects of goal framing and common ground using repeated GLMMs (Table 3). As in experiment 1, the pattern of economic growth and climate degradation showed a non-linear increase—initial rapid increase followed by a slowdown in the rate of increase—as indicated by the significant positive linear and negative quadratic effects of Round. Again, rapid economic growth was achieved at the cost of environmental damages (Table 3; also see Fig. B.1 in the Electronic Supplementary). For further details, see supplementary materials (Tables B.1–B.14).

Nonetheless, the effect of goal framing was similar to experiment 1: the shared economic goal slowed down economic growth, but also climate degradation—both CO_2 concentration and temperature increased more slowly in the shared goal condition than in the individual goal condition. In other words, more sustainable development was achieved when the economic goal was framed as shared, rather than individuals'.

However, common ground moderated the effect of goal framing and showed somewhat different moderation effects across the economic and climate indices. For the Global Economic Index, a round × goal × common ground interaction was positive and significant, suggesting that the effect of common ground on the growth of the Global Economy differed between the shared and individual goal conditions. A follow-up GLMM analysis for each goal condition showed that sharing common ground facilitates the global economic growth more when the goal was framed as shared, rather than individually pursued (Table 4). In other words, when the goal of growing the global economy was framed as shared by all, sharing common ground helped the global economy grow faster. On the other hand, common ground exacerbated the increase of CO_2 concentration and global temperature in the individual goal condition, but not as much in the shared goal condition. Further analyses showed that common ground exacerbated global warming only in the Individual goal condition (Table 4).

These findings imply an ironic effect of having the information about the human-climate system in common ground. Common ground helps groups sustainably develop when they share the goal of global economic growth, presumably because they can coordinate their economic activities better. However, when each economic unit is pursuing its own growth individually, common ground in fact *worsens* climate change without yielding much economic gain, presumably exacerbating competition among the economies.

Table 3 GLMM of group economy, excess CO_2 concentration, temperature, within-group GINI coefficient in experiment 2

	Participant response B	Global economy B	CO_2 B	Temperature B	GINI B
Intercept	0.226***	99.125***	105.56***	0.739***	0.004
Round	0.002***	1.985***	2.8648***	0.043***	0.006***
Round²	−1E−05**	−0.011***	−0.017***	0.000***	0.000***
Common ground	0.010	0.387	−0.528	−0.044	0.006
Goal	−0.047**	1.633	−2.554	0.057	−0.006
Common ground × economic goal	−0.025	−2.806	−5.018	0.004	−0.002
Round × common ground	0.0001	0.071***	0.637***	0.007***	−0.001***
Round × economic goal	−0.001	−0.624***	−1.580***	−0.019***	0.001***
Round × common ground × economic goal	0.002**	0.080***	−0.432**	−0.007***	0.001***
Round² × common ground	−4.32E−07	−0.001***	−0.004**	−4E−05***	2E−05***
Round² × economic goal	1E−05†	0.006***	0.015***	0.0002***	3.41E−06**
Round² × common ground × economic goal	−2E−05*	0.001*	0.005**	7E−05***	−2E−05***
Individual intercept (covariance)	0.023	48.863	904.95	0.078	0.001

Economic goal: shared = 1, individual = 0. Common ground: present = 1, absent = 0

***$p < .001$; **$p < .01$; *$p < .05$; †$p < .1$

3.2.2 Inequality

We computed the GINI coefficient to index the level of inequality within each group. First, the GINI levels increased over time, suggesting that some players grew their economies faster than others did. Further, a significant round × economic goal interaction (Table 3) suggests the rate of increase was greater in the shared than in the individual goal condition. This implies that the sustainable development achieved when the goal was shared was attained at the expense of increasing inequality. This occurred because some players curtailed their economic growth more than others did, suggesting a degree of self-sacrifice and altruism by these players. Finally, common ground blunted the increase in inequality in general, but even more so in the shared goal condition than in the individual goal condition. We speculate that this was achieved because the players adjusted their economic growths to coordinate their own economic activities with the overall global economic activities. Note that the players had access to the Global Economic Index as well as their Own Economic Index. Adjusting one's economic growth to make it proportionate to that of the Global Economic Index would be relatively straightforward.

4 General discussion

Successful resolution of the global climate commons dilemma involves a complex balancing act. Not only do we need to balance a stable climate against the need for economic growth, but we also need to ensure that such balance does not come at the cost of widening economic

Table 4 GLMMs of group economy, excess CO_2 concentration, temperature, within-group GINI coefficient by goal condition in experiment 2

	Group economy		Excess CO_2 concentration		Temperature		GINI coefficient	
	Shared goal B	Indiv_goal B	Shared goal B	Indiv_goal B	Shared goal B	Indiv_goal B	Shared goal B	Indiv_goal B
Intercept	100.660***	99.365***	103.250***	105.950***	.796***	.746***	−.002	.004
Round	1.370***	1.961***	1.305***	2.835***	0.025***	0.043***	0.007***	0.006***
Round^2	−0.005***	−0.011***	−0.003***	−0.017***	−0.0001***	−0.0003***	−4E−05***	−5E−05***
Common ground	−2.302	0.248	−5.900	−1.127	−0.041	−.053	.004	.006
Round × common ground	−0.138***	0.102***	0.180***	0.672***	0.0002	.008***	−.001***	−.001***
Round^2 × common ground	0.0002	−0.002***	0.001†	−0.005**	3E−05***	−5E−05**	−2.49E−07***	1.4E−05***
Group intercept (covariance)	51.771	45.716	346.05	1500.86	0.032	0.127	0.001	0.001

Economic goal: shared = 1, individual = 0. Common ground: present = 1, absent = 0

***$p < .001$; **$p < .01$; *$p < .05$; † < .1

inequality. Achieving all these goals presents a challenge, at least within the confines of the Climate Commons Game. Experiments 1 and 2 both showed that, as participants attempt to grow the economy, the CO_2 concentration goes up, and the earth warms up as well. Furthermore, inequality among economic units tends to increase over time (Experiment 2). Although this latter finding needs to be replicated, it suggests that simultaneous maximisation of environmental sustainability, economic prosperity, and economic equality may be a difficult goal to achieve.

Nonetheless, climate change mitigation is not a lost cause. There are some conditions in which the climate-economy balance is sustained to a degree, and the participants' decisions suggest that they are willing to support weaker economic growth for their economy to contain global warming. First, having a clear and shared climate goal appears to militate against pursuing unmitigated economic growth. In experiment 1, consistent with H1, the presence of a climate goal reduced economic growth. Here, the information about the human-climate system was in the group's common ground.

Second, having a shared global economic goal helps people attain more sustainable development, achieving reasonable economic growth while refraining from over-exploitation of the environment. H2 was supported in both experiments. However, sustainable development was achieved in experiment 2 at the cost of increased inequality through voluntary self-sacrifice of individual economies. In the shared goal condition, where the economic goal was framed as a collective and global effort, the relatively lower levels of economic growth were accompanied by increased levels of inequality across players.

Third, the effect of common ground is not straightforward. When a group has a shared economic goal, common ground helps to achieve sustainable development by gaining a greater economic benefit at a relatively smaller cost to the climate, and it reduces inequality within the group. The reduction of inequality, however, is not so large as to make the levels of inequality in the shared economic goal condition comparable with those in the individual goal condition. In contrast, when economic growth is individually pursued, common ground appears to increase the levels of competition among the players without producing much economic gain. It exacerbates CO_2 concentration and global temperature rise, without helping the global economy grow appreciably, although it tends to blunt the rise of inequality to some extent.

In total, a combination of the climate goal, the shared collective goal of global economic growth, and common grounding of the information about the human-climate system may provide the best chance for garnering the public support for sustainable development while containing inequality to a reasonable level. Some may be sceptical about the possibility that all countries, or even a majority of the countries, share a global economic goal; however, this scenario may not be entirely unrealistic. As globalisation deepens, the global interdependence in economic activities across national borders has become obvious as in the case of the Global Financial Crisis of 2007–2009, and the current COVID-19 induced global economic downturn attests. As the reality of economic interdependence becomes clear to everyone, a shared global economic goal may also become a geopolitical reality. There may then be a window of opportunity through which we can achieve satisfactory levels of economic prosperity and equality while containing the global climate within the safe and just operating space (Raworth 2012).

Nonetheless, even in this best-case scenario, rising inequality can present a serious problem for the global community. In the present experiment, some players appear to have voluntarily refrained from growing their economy, and this seems to have increased economic inequality. However, in the contemporary world, there are pre-existing inequalities between countries, and some economies cannot grow as much or as fast, while others may enjoy high economic growth. Such pre-existing inequalities arise out of historical circumstances of unequal distribution of wealth around the world. Rich countries may be able to grow their economies, but poorer economies may not be able to do so, thereby shouldering a more than fair share of the economic burden to manage the global climate commons. Inequalities among countries can undermine the willingness to cooperate in the Climate Commons Game (Tavoni et al. 2011) especially in these circumstances. Addressing such inequality is therefore vital for marshalling global efforts to combat climate change. There are, however, difficult challenges to overcome. At the individual country level, pre-existing inequality, GDP and carbon intensity interact in a complex way to affect CO_2 emissions (Agusdinata et al. 2020). At the global level, there are complex feedback effects of pre-existing inequality on CO_2 emission control and future economic inequality. Institutional arrangements to manage inequality may be critically important at both national and international levels.

The present research has several limitations. Although the Climate Commons Game does capture some of its key components, the real human-climate system is far more complex. First, the scenarios used in the experiments may be further explored. For example, each participant played the role of a sole economic director who can control their entire economy's growth target over many decades. This was done to provide us with a behavioural measure of people's willingness to support different economic policies within their country. Nonetheless, this needs to be further investigated with other methods and potentially different experimental paradigms. We have set a relatively easy climate target, in particular, to contain the temperature rise to 2 °C, rather than 1.5 °C, with the benchmark of the preindustrial level for study 1, but the initial state of the game for study 2. The initial individual economic status was set to be equal across participants so as to best capture the effects of experimental manipulations on people's choices. For practical reasons, we were limited to groups of 10 agents in the game. However, the real-world climate dilemma involves many more agents whose status is not necessarily equal. The effect of inequality should be further examined in future studies. The current game includes only nation-states as main actors, but other non-state actors such as multinational corporations can play a major role in climate politics. The role of non-state actors may also be incorporated into an experimental paradigm.

Second, some aspects of the human-climate model can be improved. For example, economic target and global temperature have a nonlinear but deterministic relationship with the growth of the economy; CO_2 emissions have a nonlinear deterministic relationship with the global temperature rise. Also, our model assumed global climate change hampers economic growth equally across economies, whereas real-world economic impacts of climate change will vary across nations and will depend on factors specific to those nations and their key industries (e.g. Lemoine and Kapnick 2016). A more realistic model of the human-climate system would incorporate uncertainty into these relationships, albeit at the cost of considerable complexity.

Another significant limitation is that the experimental task has only one single track of economy, accelerating or decelerating the economic growth. However, it is possible to pursue policies of ecological modernisation (e.g. Mol 1996; Spaargaren and Mol 1992), where both traditional and ecologically sustainable economic activities (e.g., renewable energy sources) are supported. Regarding economic inequality, our task did not include an institutional mechanism that can allow participants to reduce inequality by redistributing the economic outcomes in some form.

Despite these limitations, the Climate Commons Game has provided some useful insights into the collective dynamics surrounding the global attempt to manage the global climate commons. Of particular importance is the role of common ground in sustainable development and a potential downside to economic inequality associated with the collective management of the global climate commons. Future research should address the critical questions of how institutional and decisional structures can help us manage the climate commons dilemma and inequality.

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Code availability Not applicable.

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Compliance with ethical standards

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Global Warming: A Tragedy of the Commons

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Global Warming: A Tragedy of the Commons

Abstract: This paper scrutinises two of the leading models for dealing with so-called 'tragedy of the commons' issues as to their suitability to tackle the problem of global warming; the polycentric model favoured by Ostrom, and the Leviathan approach as advocated by Ophuls. The paper then sets out a hybrid approach which it argues is the only viable solution to the current crisis of global warming. It proposes that, while agreement setting out goals for reductions in GHG emissions must be reached on the international arena, such an agreement should confer on each individual nation the choice of the manner of implementation, and that each nation, and also each region or locality, should devise their own strategy for achieving their required reduction. Such decentralised implementation would not only reduce the costs of both formulation and enforcement of solutions, but also permit more broad-based input by the local community, thereby resulting in an enhanced solution. Furthermore, local solutions would enable the development of a more responsive framework of rules and also facilitate regulatory competition.

While legal rules will necessarily constitute a large proportion of the governmental response, this paper also addresses the role that non-legal rules such as social norms may play. Such norms can be altered through the use of taxation, which can effect "carefully biased options," as well as education as to the consequences of certain everyday actions. As Charny noted, systems of non-legal sanctions for the violation of the rules of conduct specified by the norm system help to explain, "in terms of 'rationality'" why individuals often act in ways that ostensibly depart from rational self-interest. Such departure from rational self-interest is exactly what is required to counteract the rational actions which result in 'the tragedy of the commons.' That efficient norms may evolve among members of a close-knit community is yet another argument in favour of decentralisation of the implementation of centrally agreed goals.

Keywords: Tragedy of the Commons, Climate Change, Regulation, Decentralisation, Social Norms.

JEL Classification: K00, K20, K32, Q20, Q54.

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Global Warming: A Tragedy of the Commons

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I. INTRODUCTION TO 'THE TRAGEDY'

The 'tragedy of the commons' refers to the situation when individuals, acting rationally in their own self-interest, nonetheless act irrationally as a collective group by irreparably depleting a resource that is owned in common. The current climate change crisis is an example of 'the tragedy' on a global scale. In the same way that a fishing bay or an open pasture is a common resource that is used by the local fishing or farming community, the atmosphere is a common resource that is enjoyed by the population of the world. 'The tragedy' arises because the incentive for each user to make sacrifices for the benefit of the common resource is significantly less than it is when a resource is privately owned. This is because efforts that are made to preserve the common resource benefit all users in equal measure, whether or not they have made the necessary sacrifices. In the same way, depletion or destruction negatively impacts each user in equal measure, whether or not they have made the necessary sacrifices. The dilemma therefore arises due to the difficulty in privatising the benefits gained through an individual's sacrifices to preserve the commons. These gains are necessarily shared equally by all users, leading to the 'free rider' obstacle. Further, as one user's sacrifices benefit their neighbours as much as themselves, the 'sucker' problem, as Ostrom calls it, arises.[1] As Hardin explains it, those users feel "secretly condemned" as simpletons for making sacrifices while other users continue to exploit the commons.[2] This results in users being further disinclined from making these sacrifices. These 'free rider' and 'sucker' obstacles are two sides of the one coin. Thus the rational approach of each user is to 'free ride' on the other users' sacrifices, with the result that few users make the necessary sacrifices and the resource is eventually depleted or destroyed beyond repair. "Ruin is the destination toward which all men rush, each pursuing his own best interest."[3] 'The tragedy' is therefore a puzzle to many observers, in particular rational choice economists, as, what appear to be rational actions are in fact irrational when viewed in the long term.

While such situations can be extremely difficult to resolve, even when they occur on a small scale, the dilemma is infinitely more complex on a global level. The example used by Hardin is a common pasture. Consider that the pasture is used by 20 farmers. Each farmer who

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[1] E. Ostrom, "A Polycentric Approach for Coping with Climate Change" (2009) http://www-wds.worldbank.org/external/default/WDSContentServer/IW3P/IB/2009/10/26/000158349_20091026142624/Rendered/PDF/WPS5095.pdf, page 33, accessed 06/05/10.

[2] G. Hardin, "The Tragedy of the Commons" (1968) 162 Science, 1243, 1246.

[3] G. Hardin (n 2), 1244.

sacrifices by limiting the number of sheep that he or she allows to graze on the pasture will receive only one-twentieth, or five percent, of the resulting benefit. In a world with over 6 billion people, the percentage benefit received by each individual who makes a sacrifice is miniscule. Further, each individual considers that any contribution they make towards reducing the problem is negligible and therefore few are inclined to make the effort. The 'free rider'/'sucker' obstacles, as outlined above, pertain here on a vast scale. The question therefore arises as to how we can overcome these obstacles, thereby causing people acting individually, within communities or within firms to work towards reducing the number of greenhouse gases they cause to be emitted into the atmosphere.[4] This paper will scrutinise two of the three leading models for dealing with so-called 'tragedy of the commons' issues as to their suitability to tackle the problem of global warming; the polycentric model favoured by Ostrom,[5] and the Leviathan approach as advocated by Ophuls.[6] The third leading model for tackling such issues involves privatisation of the resource.[7] While this approach has operated effectively to resolve 'the tragedy' in many instances, privatisation of the atmosphere is clearly not a viable alternative and consequently that model will be ignored for the purposes of this paper.

II. THE LEVIATHAN AND POLYCENTRIC MODELS

The mainstream approach to tackling 'tragedy of the commons' issues relies upon control and coercion by a centralised institution. This Leviathan model is favoured by scholars, such as Ophuls, who believe that the participants are incapable of solving the problem themselves. This however is disputed by Ostrom who argues that that approach assumes accuracy of information while ignoring the costs of its administration.[8] Ostrom's polycentric approach advocates enabling the users of the resource to establish amongst themselves a system for its management. She argues that this approach results in both reduced informational and enforcement costs.[9] Ostrom's polycentric model also advocates that 'commons' dilemmas are best solved at a local level.

The current approach of world leaders to the phenomenon of global warming has been intergovernmental in nature, rather than creating a global supranational institution to tackle the issue. This paper assesses whether the current approach most closely resembles the polycentric or the Leviathan approach. Such analysis is necessary as we must know exactly what type of system it is that we are advising on before we can provide profitable advice as to feasible and worthwhile improvements. The current approach resembles Ostrom's model

[4] It is considered that the main cause of global warming, and the resulting climate change, is the release of GHGs (greenhouse gases) into the atmosphere, mainly through the burning of fossil fuels including coal, oil and gas.

[5] E. Ostrom, *Governing The Commons: The evolution of institutions for collective action* (CUP, Cambridge 1990), 14.

[6] E. Ostrom (n 5), 9.

[7] E. Ostrom (n 5), 12.

[8] E. Ostrom (n 5), 10.

[9] E. Ostrom (n 5), 14.

in that it aims to secure agreement among all users of the resource (as represented by the governments of the nations of the world), although it clearly does not embody resolution of the dilemma at a local level. While one could argue that the global nature of the crisis obviates this 'local' requirement, Ostrom herself, in recent interviews[10] and, in particular, in her recent paper to the World Bank,[11] has nonetheless focused primarily on solutions at a local level. The current approach of governments to global warming also resembles elements of the Leviathan model which is typically characterised by action at governmental level, which is then imposed on its citizens. This paper will then assess which model is best suited to tackling climate change and whether improvements could be made to the current approach. Such analysis is particularly necessary following the failure of the current approach to deliver a satisfactory result, as evidenced by the non-binding and aspirational declaration by world leaders following the Copenhagen Summit in December of 2009.

III. Hardin's Solution Applied to Global Warming

Hardin's thesis, in his groundbreaking article in 1968, was that "freedom in a commons brings ruin to all,"[12] which he amended in 1985 to state that "*under conditions of overpopulation*, freedom in an *unmanaged* commons brings ruin to all."[13] Prior to overpopulation, the resource appears in no danger of exhaustion and therefore the costs of management outweigh the benefits. However, as scarcity of the resource increases through growth in the number of users, management becomes necessary. In a similar manner, it is the rate of economic growth of developing countries such as China, India and Brazil that is placing increased urgency on the development of a solution in the case of global warming.

Hardin's solution for air pollution involves the curtailing of freedom through control and coercion.[14] Due to his focus on control and coercion, he is often assumed as falling within the category of those who favour solutions devised by a centralised governing institution, and which are then forced on the users of the common resource. This, however, is not the case. Hardin expressly states that, while many interpret coercion as implying "arbitrary decisions of distant and irresponsible bureaucrats", this is not necessarily the case. Hardin's approach could arguably be classified as a hybrid of the Leviathan and polycentric models, and is therefore particularly pertinent to our current discussion. What Hardin, in fact, advocates is "mutual coercion, mutually agreed upon by the majority of the people

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[10] C. Seidler and C. Schwagerl, "Nobel Laureate Elinor Ostrom: Climate Rules Set from the Top Are Not Enough" (2009) http://www.spiegel.de/international/world/0,1518,667495,00.html, accessed 06/05/10; The Solutions Journal, "Nobel Laureate Elinor Ostrom on Why Climate Change Solutions Work Best When They're Local" (2010) http://thesolutionsjournal.com/node/583, accessed 06/05/10.

[11] E. Ostrom (n 1).

[12] G. Hardin (n 2), 1244.

[13] G. Hardin, "An Ecolate View of the Human Predicament" (1985) http://www.garretthardinsociety.org/articles/art_ecolate_view_human_predicament.html, accessed 03/05/10.

[14] G. Hardin (n 2), 1245.

affected."[15] While the focus is on coercion, it is nonetheless predicated upon the prior agreement of the parties.

This paper proposes that such a hybrid approach is the only viable solution to the current crisis of global warming. Before real change 'on the ground' can occur, agreement on a global level by the governments of the majority of nation-states is required. Such agreement must take the form of an acceptance of the general goal; a reduction in GHG emissions, followed by agreement as to a division of the responsibilities of each nation-state. Such a mutually agreed upon solution must then be mutually enforced. This approach takes from the polycentric model in that it relies upon agreement by the parties, accompanied by enforcement by the parties. However, while it may involve application at a local level, the ultimate decision is made at the international level and subsequently enforced on the public.

In assessing why this approach has failed thus far it is helpful to consider Hardin's example of taxes.[16] He notes that citizens accept taxes because they recognise the need for a system of taxation. This implies that it is only when users of a common resource recognise the necessity of action that they will then accept the resulting restrictions on their freedom. However, one could argue that the science of climate change being caused by human activities is beyond doubt. Why then has agreement not yet been reached? This paper argues that such agreement is dependent on two battles being waged and won. The first is knowledge; the second is trust. Such knowledge, while extensive in the developed world, is far from widespread in the developing world. Without such knowledge citizens cannot be expected to accept the costs of the necessary restrictions on their freedom. This is an epistemological challenge and it is difficult to imagine that there can be successful resolution of the dilemma until this obstacle is overcome. Secondly, trust is required. Even when people have accepted the need for action, they are slow to incur the cost of complying with the requirements if they do not trust that others will carry out their respective responsibilities. In order to facilitate this trust, effective monitoring and enforcement mechanisms must be established. Further, countries must trust that other countries are bearing their fair share of the cost. If they feel that they are disproportionately shouldering the burden they will be quick to look for ways to cheat the system in order to return themselves to what they see to be a more equitable distribution of the cost. Such an attitude is similarly evident in the way that there is significantly less tax evasion when people feel, firstly, that the division of taxes is fair and, secondly, that others are not getting away with cheating the system. Thus, a successful solution is reliant on education as to the need for restrictions and also on a fair system being devised and enforced by the relevant parties.

Finally, Hardin notes that while prohibition is easy to legislate, legislating for temperance is significantly more complex.[17] Nonetheless he does proffer certain options. If usage is not to be prohibited but instead limited, then rights for usage can be allocated. Such allocation could occur on the basis of wealth, merit, by lottery or on a first-come first-served basis.[18]

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[15] G. Hardin (n 2), 1247.

[16] G. Hardin (n 2), 1247.

[17] G. Hardin (n 2), 1245.

[18] G. Hardin (n 2), 1245.

IV. A Regulatory Framework: Implementation and Enforcement

While some peoples and nations will respond to appeals to conscience, as discussed further below, this is not enough to effect the necessary level of change required by the current crisis of global warming. Clearly agreement must therefore be reached and enforced at a global level. How detailed such an agreement should be is open to debate. While agreement must be reached on the international arena as to the specific level of reduction in GHG emissions required by each nation, it is not necessary that such agreement should specify how such reductions should be brought about. This paper proposes that such an agreement should leave the manner of implementation of the required reduction to each individual nation, and further that each nation should set goals for each region or locality, but allow each such locality to devise their own strategy for achieving their required reduction. Thus, while the specific goal could be laid down by a centralised institution, the implementation of such a goal should be decentralised. Such local solutions are advocated by Ostrom and are exemplified in her polycentric model, although in her model all decision making is at a local level. One of the reasons as to why such local solutions can be more effective than centralised decision-making processes was set out by Hayek, widely acknowledged as the grandfather of the Chicago School of Economics, which was further developed by Milton Friedman in the 1960s, and subsequently implemented in the Reaganism of the 1980s. Hayek's argument is based on knowledge capabilities and the fact that it is neither efficient nor cost-effective for a centralised institution to retrieve and process all local information before then formulating and enforcing such a centralised solution.[19] Further, a system that may be effective and efficient in one locality, can rarely be expected to be as efficient and effective in all localities due to the many variances and peculiarities among different localities. Thus local knowledge is necessary in order to devise the most effective system for any given locality. An example of local knowledge in the current context may include knowledge of the local possibilities for the production of wind or water generated energy. Additionally, local knowledge, such as the likelihood of a river drying up, may prevent a costly mistake. Thus, decentralised implementation enables more broad-based input by the local community, thereby enhancing the resulting solution.

This ties in with Ostrom's rejection of the centralised approach to resolving commons dilemmas. Not only does she argue that such an approach ignores the costs of collating and assessing local information, but it also ignores the risk that such information will be either incorrect or incomplete.[20] One example which Ostrom provides of this polycentric model in practice is the system for managing certain fishing bays in Nova Scotia's Port Lameron Harbour.[21] In contrast to the years which it may take and millions which it may cost to survey fish movements in the bay and to then devise quotas and an equitable system of division of rights among those using the bay, such local knowledge will often already be known to the local fishermen and women. Therefore, if such local users can be enabled to devise a system allocating user rights within the bay, the likelihood is that such a system will not only cost significantly less to formulate and implement but will also be more likely to operate

[19] F. Hayek, "The Use of Knowledge in Society" (1945) 35(4) American Economic Review, 519.

[20] E. Ostrom (n 5), 10.

[21] E. Ostrom (n 5), 174.

effectively. Further, as the parties themselves have created the system, they are more likely to abide by it and also to enforce it among themselves.

Vital to any such system is the manner of its enforcement. Ostrom advocates that a locally devised solution is also more easily enforced by the local community. In this respect she gives the example of a forest which local residents have determined is being damaged through overuse and have consequently decided that no-one should be allowed entry to at weekends.[22] If such a solution was formulated and enforced by a centralised institution, a member of the community who noticed someone in the forest may take no action. However, if the solution has been devised by the local community, then if one of them sees someone in the forest, they are much more likely to take action. Hardin accepts that there are times when formal enforcement of rules is not required. Shame, for example, can operate as an enforcement mechanism, although he notes that this fails to work after the members of a community exceed 150 in number.[23] In the context of global warming, formal methods of enforcement will be necessary, although certain informal enforcement mechanisms, discussed below, may also be effective regarding individuals. Formal enforcement however will be important because, firstly, as noted above, the percentage benefit to each individual who makes a sacrifice is miniscule, and, secondly, because of the need to ensure that each country implements its obligations, thereby enhancing trust in the system, the importance of which was also highlighted above.

Yet another benefit to local formulation and implementation of solutions is the fact that different solutions will inevitably develop in different localities, thus enabling regulatory competition and the resulting benefits, as identified by Tiebout in his article which demonstrated this conflict between regulatory competition and harmonisation.[24] Such competition enables more effective surveying of the success rate of varying systems, thereby enhancing the overall result as failing systems can learn from more successful solutions. Ostrom considers this to be a further advantage to her polycentric model, stating that; "in experimenting with rule combinations within the smaller-scale units of a polycentric system, citizens and officials have access to local knowledge, obtain rapid feedback from their own policy changes, and can learn from the experience of other parallel units."[25]

Not only does such decentralised implementation of a centrally formulated goal or guiding framework have the above enumerated advantages, but it also allows for a more responsive framework of rules.[26] If a flaw becomes apparent in a locally devised system, a local authority can much more simply and swiftly alter the system and, further, they can much more easily make amendments to the system as the need arises. The key for such a

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[22] C. Seidler and C. Schwagerl, "Nobel Laureate Elinor Ostrom: Climate Rules Set from the Top Are Not Enough" (2009) http://www.spiegel.de/international/world/0,1518,667495,00.html, accessed 06/05/10.

[23] G. Hardin, "Ecolate View" (n 13).

[24] C. Tiebout, "A Pure Theory of Local Expenditures" (1956) 64(5) Journal of Political Economy, 416.

[25] P. Aligica, "Rethinking Institutional Analysis: Interviews with Vincent and Elinor Ostrom" (2003) http://mercatus.org/sites/default/files/publication/Rethinking_Institutional_Analysis_-_Interviews_with_Vincent_and_Elinor_Ostrom.pdf, accessed 08/05/10.

[26] P. Aligica (n 25).

decentralised system, however, is to prevent the local enforcer from being 'captured' by any powerful interests in the locality. The eternal question of "Quis custodiet ipsos custodies?", translated as "Who shall watch the watchers?", again arises and consequently a type of appeals system should therefore be put in place to counter the danger, as John Adams saw it, of a government of men and not laws.[27] While an appeals system may be necessary to ensure the integrity of the local regulators, it will also be necessary to ensure compliance by the regulatees. Therefore, while the rules applied at a local level may be legal or non-legal, there should remain, at the very least, a "residual role for law at the apex" of the enforcement pyramid.[28]

In which situations such rules should be legal and non-legal is also an important question. This paper proposes that the line should be drawn between individuals and firms, with firms subject to legally binding rules, while individuals could be subject to a combination. Ostrom gives some very interesting examples of methods through which individuals' behaviour can be altered through non-binding practices. One example she gives is of a private utility company in Sacramento, California, that began sending out 'smiley faces' on utility bills that were below the average use for a similar size house. Surprisingly, those houses that received personalised bills responded by decreasing their usage by two percent more than those who received standard bills.[29] Further, Ostrom gives the example of students who set up competitions among different dorms to lower electricity usage and that this competition resulted in reduced electricity usage.[30] These two examples demonstrate that people do respond to non-binding practices and therefore further research into behavioural economics may lead to much progress in this sphere. However, this paper proposes that firms, on the contrary, will not respond to such measures. This is because firms are structured, not to mention, in most cases, legally required, to respond to different incentives than individuals, with their primary focus being profit-maximising. Therefore legally binding rules or the market structure of an emissions trading system is preferable. Due to a firm's differing incentive structure, such a trading system can operate either locally, nationally or even internationally.

V. EMISSIONS TRADING: A MARKET-BASED APPROACH

There are a number of available models for such emissions trading including the 'economic efficiency' model, the 'private property rights' model and the 'command-and-control' model. The 'economic efficiency' model aims to resolve the problem of externalities by internalising such externalities through their transformation into transferable rights which can then be

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[27] G. Hardin (n 2), 1245.

[28] C. Scott, "Regulation in the Age of Governance: The Rise of the Post-Regulatory State", in Jacint Jordana & David Levi-Faur eds., *The Politics of Regulation. Institutions and Regulatory Reforms for the Age of Governance* (Edward Elgar, Cheltenham 2005) 145, 157.

[29] E. Ostrom (n 1), 38.

[30] The Solutions Journal, "Nobel Laureate Elinor Ostrom on Why Climate Change Solutions Work Best When They're Local" (2010) http://thesolutionsjournal.com/node/583, accessed 06/05/10.

cost-effectively allocated through a market structure to the highest bidder.[31] Such a system is based on Coase's theory concerning externalities.[32] The aim of the 'private property rights' model is to substitute government control of the commons with private control, while the focus of the 'command-and-control' model is to "re-regulate" by substituting previously ineffective regulation with a more flexible regulatory strategy.[33] Ostrom has remarked on the weaknesses in such market-based mechanisms, arguing that they can be "gamed" and will not result in the necessary emissions reductions.[34] In response to this argument, Bartlett and Hickman maintain that "we cannot afford to allow the perfect to be the enemy of the good."[35] This ties in with Hardin's argument for implementing a solution if it is preferable to the status quo, rather than waiting indefinitely for the perfect solution.[36] Further, market systems have their advantages due to the possibility that outcomes generated by the political process may be, as Yandle points out, "conditioned by special interest struggles best explained by rent-seeking and bureaucratic behaviour."[37] Whether or not market solutions are preferable in the context of climate change is open to debate. However, Gunningham points out that the consequences of the recent financial crisis may have implications for the development of such a system, noting that there are signs of a move towards "a new era of 'social capitalism' involving substantial government intervention and regulation to replace the freshly discovered evils of neo-liberalism and free-market fundamentalism."[38]

VI. Legally Binding Rules v Social Norms

Hardin noted that certain problems have no 'technical' solution,[39] and it is arguable that climate change requires more than just a change in techniques, but that it also requires a change in the outlook and values of the global community. While technical solutions, such as inventions regarding 'green' technologies, will certainly go no small way towards reducing the problem, it must be accepted that people, in the developed world at least, will also have to change their attitudes. Such an alteration may involve a change in their attitude towards wastage of food or electricity, or whether it is viewed as acceptable to drive to a shop located just a five minute walk away, or even whether it is viewed as acceptable to eat meat. Thus social norms will also need to change. Although clearly not all such changes can be

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[31] S. Bogojevic, "Ending the Honeymoon: Deconstructing Emissions Trading Discourses" (2009) 21(3) J.Env.L. 443, 452.

[32] R. Coase, "The Problem of Social Cost" (1960) 3 J.L.& Econ. 1.

[33] S. Bogojevic (n 31), 456, 460.

[34] T. Vededl, "Thoughts from Cop 15" (2009) http://blog.nibrinternational.no/#category4.0, accessed 08/05/10.

[35] S. Bartlett and J. Hickman, "Copenhagen as a Monumental Tragedy of the Commons" (2009) http://www.onlineopinion.com.au/view.asp?article=9844&page=2, accessed 08/05/10.

[36] G. Hardin (n 2), 1247.

[37] B. Yandle, 'Public Choice at the Intersection of Environmental Law and Economics' (1999) 8(1) E.J.L.& Econ. 5, 23.

[38] N. Gunningham, 'Environment Law, Regulation and Governance: Shifting Architectures' (2009) 21(2) J.Env.L. 179, 211.

[39] G. Hardin (n 2), 1243.

implemented by a set of legally binding rules, changes in such social norms can, in certain instances, be induced through the passing of legislation. Just as failure to send children to primary school a century ago, or drink-driving just a few decades ago, was not necessarily frowned upon, the introduction of legislation altered attitudes dramatically and now significantly fewer people would drink-drive even if the legislation was repealed, and even fewer would dream of not sending their children to primary school. Alternative efforts to alter such social norms can include taxation, which can effect "carefully biased options,"[40] as well as education as to the consequences of certain everyday actions. If social norms can be modified in such a manner, shame can act as an effective enforcement mechanism for communities of much larger membership than merely 150 people. Charny notes that such a system of non-legal sanctions for the violation of the rules of conduct specified by the norm system explains "in terms of 'rationality' why individuals often acted in ways that seemingly departed from rational self-interest."[41] Such departure from rational self-interest is exactly what is required to counteract the rational actions which result in 'the tragedy of the commons.' The difficulty is that such norms take longer to develop and therefore are more of a long term solution to an urgent crisis. Nonetheless, such informal institutions, despite being more difficult to spontaneously establish than the setting down of legally binding rules, can also be more effective once they become embedded in a community's psyche. Teubner chillingly illustrated the power of social norms in his article concerning an 'honour' killing, in which the social norms of the local Columbian community triumphed over the local law, despite the fact that such norms were not considered 'good' or 'better' than the local law, even by the local community.[42] Charny further notes that transactional settings are the preferable environment for the creation of spontaneous norms because the repeated transactions allow for both refinement and effective enforcement of such norms. He highlights the fact that common-pool systems generally lack such transactional opportunities, although he quotes Ellickson who emphasises that efficient norms may still evolve among members of a "close-knit community."[43] This is yet again another argument for decentralisation of the implementation of centrally agreed goals. However, when such norms develop they may then be organised and transplanted to other regions or sectors of an economy. This highlights the cyclical quality of such norms, which may be induced through legislation and then allowed to be informally enforced, or which may develop spontaneously only to be subsequently codified and centrally implemented. Further, as Charny notes, this political impulse towards organisation may be crucial as decentralised spontaneous generation and enforcement of norms will likely be too haphazard to achieve effectiveness across large, complex, geographically dispersed systems.[44] Prior to such organisation however, an assessment should be made as to the effectiveness of such norms. Charny is not convinced, as he maintains Llewellyn was, of the "Hayekian belief in the wisdom and durability of embedded social norms, which the law would adopt if enlightened and would oppose at its peril." In contrast to their position, Charny describes Bernstein's

[40] G. Hardin (n 2), 1246.

[41] D. Charny, "Illusions of a Spontaneous Order: 'Norms' in Contractual Relationships" (1996) 144 University of Pennsylvania Law Review, 1841, 1845.

[42] G. Teubner, "Regulatory Law: Chronicle of a Death Foretold" (1992) 1 Social and Legal Studies, 451.

[43] D. Charny (n 41), 1846.

[44] D. Charny (n 41), 1847, 1248.

work as "exemplary."[45] While it must be noted in this respect that Charny and Bernstein are discussing commercial norms, their conclusion is also of relevance to the current context of global warming.

VII. Hardin's 'Conscience' Argument

It is worth considering Hardin's argument that relying only on a person's conscience could lead to the eventual extinction of those with a conscience.[46] The question arises as to whether this applies by analogy to regulation on a country by country basis, or even to Ostrom's preference for action on a local level. The question is thus; will regulation by only western countries merely serve to substantially weaken their economies, either by causing their products to become uncompetitive or by forcing their enterprises to relocate to unregulated countries. It is up for debate as to whether it is preferable for European countries to lead by example or to maintain their position of power as a bargaining tool in order to eventually encourage other countries to regulate along with us. Either conclusion would invariably depend on whether or not European countries considered that the industrialised developing nations were close to accepting the need for action and therefore likely to follow our lead.

VIII. Transaction Costs and Rational Choice Theory

Since reaching a binding agreement at international level has proven extremely difficult, it is worth considering some of the possible reasons for this failure. In this regard it is interesting to consider Coase's theory that one of the chief obstacles to the conclusion of agreements is high transaction costs.[47] Given the complexity of the issue, high transaction costs are clearly an obstacle to international agreement. Such complexity is evident in the debate as to how best to distribute responsibility given the developed countries' historical responsibility for the crisis, and the disagreement as to whether larger nations with forests should be allowed to discount these carbon sinks against their obligations to reduce emissions. According to Coase's hypothesis, if such transaction costs could be reduced, the probability of successful agreement would increase. Further, rational choice theory states that parties behave rationally, in this context by not reaching agreement. The question thus arises as to whether it is possible in the circumstances to make reaching agreement the rational choice for the participants.

IX. Conclusion

The 'tragedy of the commons' is not a modern occurrence. As Aristotle noted, "that which is common to the greatest number gets the least amount of care."[48] However, its current

[45] D. Charny (n 41), 1854.

[46] G. Hardin (n 2), 1246.

[47] A. Aviram, "A Note on Economic Theories of the Firm" (2006) http://ssrn.com/abstract=880435, page 6, accessed 14/09/09.

[48] Aristotle, Politics, Book II, Chapter 3.

manifestation in the form of global warming constitutes the playing out of ‘the tragedy’ on possibly its grandest scale yet. Neither a local solution nor a global solution alone will be sufficient. As such it requires a new approach, a fusion of the models developed thus far, in order to enable the tackling of the crisis on all fronts. Such a hybrid solution therefore should entail international agreement on a framework goal for emissions reductions, followed by decentralised local implementation, at least regarding individuals. Further, such local implementation, in the case of firms, may be sectorally local as well as geographically local, and in this regard the increased research being undertaken into networks theory may be immensely beneficial.

It can be expected that, within the next ten if not five years, agreement will have been reached on the international stage, providing for concrete and binding goals regarding emissions reduction. Such a prediction is based on the fact that awareness of the crisis and its consequences is steadily increasing. However, the fear is that, due to the global nature of the problem, and the necessity for international agreement as to the guiding framework, that the possibility for locally devised solutions to a global problem will be overlooked. Professor Ostrom, following her Nobel Prize in Economic Sciences, recently gave a presentation to the World Bank, in which she focused on the importance and benefits of such local solutions. My hope is that she maintains her presence in this arena so that her proposals can, whenever solid and binding international agreement is finally reached, form part of the implementation framework. However, while Ostrom has much to teach us, Garrett Hardin’s article, written over forty years ago, and constituting only five pages, also contains a vast array of advice which is immensely pertinent for the current generation faced with tackling this global crisis. Finally, Hickman and Bartlett have noted that crises “often compel new thinking about political institutions, and the necessity to respond to the shared threat of global warming may be the reason that we devise something more workable than the nation-state.”[49] Such a statement is true and it is possible that a more effective international structure will result from the current crisis. While nations have experimented with many forms of governance, from monarchy to dictatorship to democracy, our experimentations with global governance are in their infancy. The United Nations has certainly not been an unqualified success and, while the European Union has had significant success, it appears to be now facing its own crisis. Global warming may well be the catalyst for a new approach.

[49] J. Hickman and S. Bartlett, “Global Tragedy of the Commons at COP 6” (2001) http://www.greens.org/s-r/24/24-26.html, accessed 08/05/10.

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Property in Land and Other Resources

Edited by Daniel H. Cole
and Elinor Ostrom

Foreword by Douglass C. North

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Climate Change

The Ultimate Tragedy of the Commons?

JOUNI PAAVOLA

The dominant view among scholars and policy makers has been that climate change governance should be based on international agreements that involve most nations (Hare et al. 2010). The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (KP) are cornerstones of this approach. These kinds of governance strategies face two key hurdles. First, wide participation has to be secured for any agreement to come into force. Second, all agreements need to be implemented through national policies. But top-down solutions relying on the central role of the state have been a false panacea in the governance of many resources (E. Ostrom, Janssen, and Anderies 2007). It is no surprise, then, that progress in governing climate change has been slow and that only modest results have been obtained in curtailing greenhouse gas (GHG) emission reductions.

More recently, the debates on climate change governance have centered on the comprehensiveness of feasible agreements (Kuik et al. 2008). The proponents of comprehensive international agreements remain at one end of the continuum (Hare et al. 2010). At the other end are those who would not rely on international action (Rayner 2010). In between are those who consider that progress is best made through regional, sectoral, and other less comprehensive governance strategies (Barrett and Toman 2010; Falkner, Stephan, and Vogler 2010; Schmidt et al. 2008; Sugiyama and Sinton 2005). Within each strand, the relative merits of different policy instruments are still debated, although carbon markets have already gained a prominent position (Bernstein et al. 2010; Kuik et al. 2008; but see Spash 2010). Another strand of literature has examined voluntary governance solutions that do not centrally rely on the role of the state (Bäckstrand 2008; Bulkeley and Betsill 2003; Kern and Bulkeley 2009; Newell 2000). Much of the existing literature believes that a feasible strategy for climate change governance does exist, but opinions differ on what it is.

This chapter investigates the potential of institutional diversity and polycentric governance in the area of climate change. The new institutional literature (Dolšak and Ostrom 2003; E. Ostrom 1990; 2005; E. Ostrom et al. 2002; Young 2002) and governance literature in general (Rhodes 1996; Rosenau 1995) consider the absence of coercive state power as the hallmark of governance. But governance is what governments do. The apparent juxtaposition of “governance” and “government” hinges on the conception of government. But rather than being a monolithic external actor, the government can be understood as a set of arenas and instruments of collective action. This viewpoint helps construe governance as a continuum between state-based solutions and solutions that do not involve the state, with hybrid forms in between (Lemos and Agrawal 2006; Paavola 2007). That is, environmental governance can be understood broadly as the establishment, reaffirmation, or change of diverse institutions in order to manage the use of environmental resources.

New institutionalism has informed a significant body of research on local common-property arrangements and on international environmental conventions, but its potential is far from exhausted. Understanding the challenges of and solutions for governing large and complex environmental resources such as atmospheric sinks have been identified as key future tasks (Berkes 2008; Dietz, Ostrom, and Stern 2003; E. Ostrom et al. 1999). However, much of the literature still examines relatively simple single-level governance solutions, although the governance of large environmental resources is typically based on diverse solutions operating at multiple levels and across levels simultaneously. Thus, there is a need to develop analytic ways to address institutional diversity (E. Ostrom 2005; E. Ostrom et al. 1999).

In the related body of literature on polycentricity (E. Ostrom 2009; 2010a; 2010b; V. Ostrom 1972; V. Ostrom, Tiebout, and Warren 1961), polycentric order has been defined as "one where many elements are capable of making mutual adjustments for ordering their relationships with one another within a general system of rules where each element acts with independence of other elements" (V. Ostrom 1999, 57). Polycentric order is likely to emerge in a bottom-up way when diverse actors in a phenomenon like climate change seek to realize diverse benefits (or to avoid diverse costs) that accrue on different scales (E. Ostrom 2009). As Elinor Ostrom (2009) remarks, mitigation actions not only generate global benefits by reducing greenhouse gas emissions and the rate of climate change, but also create cobenefits such as better air quality, reduced reliance on fossil fuels, reduced exposure to their price fluctuations, and improved energy security. These benefits can be a sufficient motivation for mitigation actions, although perhaps not on a comprehensive scale.

Myriad voluntary climate change initiatives already exist. For example, the Cities for Climate Protection (CCP) program and the Cement Sustainability Initiative (CSI) attempt to address substantial GHG emissions, comparable to those of major emitting states. These initiatives have been successful in reducing GHG emissions or slowing their growth in comparison with business as usual. However, tentative evidence suggests that voluntary initiatives may do best at, or be limited to, realizing cost-saving emission reductions. Therefore, state-based and hybrid governance solutions may be needed to complement voluntary ones in order to stabilize the atmospheric concentrations of GHGs at a safe level. That is, institutional diversity is likely to characterize climate change governance, and it will emerge through both bottom-up and top-down processes.

Climate Change as a Problem

The Stern review considers climate change "the market failure on the greatest scale the world has seen" (Stern 2007, 27). The language of market failure and externalities is indeed widely applied to climate change. However, this chapter examines climate change as a problem in the sustainable use of atmospheric sinks for GHGs by drawing from the literature on the management of common-pool resources (Berkes 2008; E. Ostrom 1990; 2005; E. Ostrom et al. 2002; Poteete, Janssen, and Ostrom 2010).

Atmospheric sinks for GHGs can be understood as a common-pool resource (CPR) just like an aquifer or a fishery (Paavola 2008a). Sinks are stock resources that provide a flow of sink services. Aquifers and fisheries have a relatively well-understood capacity to generate a flow of resource units. Watercourses, air basins, and global atmospheric sinks have a comparable capacity to absorb pollutants that is replenished by natural processes. Atmospheric GHG sinks fulfill the first condition of being a CPR because the use of units of sink services is rival or subtractable: a unit used by one user is not available to others (E. Ostrom 1990). A key challenge in governing atmospheric sinks for GHGs is the same as with all other CPRs: to constrain their use so as to prevent their destruction. A derivative task is to distribute the sustainable capacity to provide sink services among the competing users.

Atmospheric GHG sinks also fulfill the second condition of being a CPR because it is difficult to exclude unauthorized users from using them (Paavola 2008a). The users of GHG sinks range from large coal-powered electricity-generation plants to families driving a car or keeping cattle. The size of the sink, the range of activities that make use of it, and the large number of users make it difficult to monitor the use of the sink and to exclude users. The perfect mixing of emissions of GHGs in the atmosphere and absence of clear borderlines contribute to the difficulty of exclusion (E. Ostrom 1990).

Because of these resource attributes, atmospheric sinks may experience the ultimate "tragedy of the commons" (Hardin 1968). Users have incentives to use sink service units before other users make them unavailable, and it is difficult to prevent them from doing so. When everybody acts in self-interest rather than exercising restraint to conserve global GHG sinks, the tragedy is nigh. Although Hardin (1998) later became optimistic about the emergence of restraint in the use of global atmospheric sinks, progress to date has been modest.

When exclusion costs are low, challenges of rival consumption are typically resolved by establishing private ownership and deciding who is entitled to what. Markets can then allocate resources to their most valuable uses. But private ownership is not feasible when exclusion costs are high, as is the case with global atmospheric sinks and other CPRs. Alternatives for governing global atmospheric sinks are the same as for other CPRs and include collective ownership and management (which may involve the use of markets), voluntary agreements to constrain the use of atmospheric sinks for GHGs, and widely shared values with associated individual behavior change to reduce GHG emissions. These alternatives may coexist as parts of a wider polycentric governance strategy for climate change.

The challenges of governing atmospheric GHG sinks are also shaped by the attributes of their users, which determine the starting point for collective action aimed at establishing or modifying governance institutions, affect the costs of acting collectively, and influence what governance solutions can be agreed on. Political-economic factors and current patterns in the use of atmospheric sinks for GHGs affect the prospects of collective action. One of the most important aspects of the global political-economic order is the role of states in representing users of global atmospheric sinks within their territories. The law on international relations treats states as equal, sovereign actors in international affairs. This formal equality contrasts with their unequal capacities and developmental attainments. Most developed countries have high levels of per capita income and strong, capable states. In the developing world, many states are weak and some are dysfunctional, and they have been unable to promote income growth and well-being among their citizens. Many developing-country states also have weaker capacity to advance their (and their citizens') interests in international negotiations.

States' economies exhibit different degrees of complexity, which affects their vulnerability to climate change impacts. Most developed countries have complex economies that offer many sources of income and are more resilient during periods of stress. The economies of many developing countries depend on primary production and are exposed to substantial climatic and economic risks. Because of underdeveloped financial and insurance sectors in those countries, people cannot insure their assets and stand to lose them when disasters occur (Paavola 2008b; Paavola and Adger 2006). In developed countries, income is not sensitive to extreme weather events such as the European heat wave of 2003, although it caused substantial asset losses. In contrast, extreme weather events such as hurricanes can tax more than 10 percent of the gross domestic product (GDP) of a low-income country (Linnerooth-Bayer, Mechler, and Pflug 2005). The differences in vulnerability are even more significant with regard to loss of life. For example, Hurricane Andrew killed 23 people in Florida in 1992, but a comparable typhoon killed more than 100,000 people in Bangladesh a year earlier (Adger et al. 2005). Brooks, Adger, and Kelly (2005) suggest that educational attainment, health status, and quality of governance explain much of the difference in mortality due to natural disasters among countries.

Heterogeneities in the global community such as the ones just discussed make it difficult to agree on how to govern the use of atmospheric sinks for GHGs. Developed countries have invested in energy-intensive lifestyles, technologies, and infrastructure, which make GHG reductions time consuming and expensive. But developed countries also have the capability to avoid adverse consequences of climate change, as well as to recover from them. Furthermore, they form a relatively homogeneous and powerful negotiation bloc that has experience from collective action in other contexts. Developing countries, particularly the least developed countries, have contributed little to climate change because of their limited energy use and reliance on renewable sources of energy, but their economic development requires increasing energy use and GHG emissions. They are also highly vulnerable to adverse climate change impacts. Finally, developing countries form a large and heterogeneous negotiation bloc whose members range from oil-producing countries to small island states that are threatened with inundation by rising sea levels.

There are, of course, more coalitions in climate change negotiations than just developed and developing countries, and the contours among and within the groupings are far more complex than the preceding discussion suggests. But even this narrow account highlights that in the light of the literature on common-pool resources, there are significant obstacles to collective action to govern atmospheric sinks. The following account of progress to date in international climate change negotiations underscores this.

The Conventional View of Climate Change Governance and Its Record

Several lines of reasoning lead to the view that climate change governance has to be negotiated by states, codified as multilateral environmental agreements, and implemented through national legislation. First, research in environmental science has sought to understand phenomena such as climate change and the loss of biodiversity through lenses of global environmental change and earth systems science (Steffen et al. 2004; Vitousek et al. 1997). This kind of analytic globalization of environmental change easily leads to the view that feasible responses to global problems also must be global in nature.

Second, scholarship in international relations, particularly the realist tradition, provides a justification for "statism." Realism extends rational-choice reasoning to the "society of states." Other actors do not matter, and their involvement would be dubious anyway because it could violate the sovereignty of states. Self-interested states will agree to take collective action on an issue like climate change only if all parties to the agreement benefit either directly or via side payments or benefits made available by those who do directly benefit from an agreement (Barrett and Toman 2010; Sprinz and Vaahtoranta 1994). But all such international agreements lack mandatory power and need to be implemented through top-down processes that involve enactment and enforcement of national legislation.

Third, public finance reasoning supports "maximal multilateralism." From this viewpoint, internalization of an externality or the provision of a public good should take place at a scale encompassing all affected parties (Musgrave and Musgrave 1976; Tiebout 1956). In the case of climate change, the affected parties would be all who have to share the burden of mitigation, who benefit from mitigation actions, and who bear the burden of having to adapt to residual climate change impacts. That is, most, if not all, states should be involved in negotiations on climate change governance. There are, of course, counterarguments, which will be discussed later in this chapter.

Substantial mitigation of GHG emissions is possible. Technological solutions that are already known can deliver the GHG emission reductions needed to stabilize their atmospheric concentrations at 450 to 550 parts per million (ppm) (Pacala and Socolow 2004). These reductions can also be achieved at a reasonable cost. Stern (2007) argues that stabilizing the GHG concentrations at 500 to 550 ppm by 2050 would cost 1 percent of global GDP. In contrast, he estimates that "the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more" (Stern 2007, iv). About a third of the emission reductions needed to stabilize atmospheric concentration of GHGs at 450 to 550 ppm by 2030 would save rather than cost money (Enkvist, Nauclér, and Rosander 2007). But it has been difficult to reach an international agreement on GHG emission reductions.

The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992 as the key international response to climate change. The Kyoto Protocol (KP), adopted in 1997, established emission-reduction commitments for carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride emissions for 37 industrialized countries and the European Community, or the so-called Annex 1 countries. Parties to the KP committed themselves to an overall 5 percent GHG emission reduction from 1990 levels during 2008–2012.

The GHG emissions of Germany, the United Kingdom, and Sweden were already 10 to 20 percent below those of the Kyoto base year in 2008 (EEA 2010). In the same year, GHG emissions of many countries of the former Soviet Union and of countries with economies in transition were 25 to 60 percent below their 1990 levels because of the collapse of their economies and manufacturing (EEA 2010). But GHG emissions were 32.2 and 42.3 percent higher in Portugal and Spain, respectively, in 2008 than they had been in 1990 (EEA 2010). Emissions also grew in Australia, Japan, and the United States by 15 to 25 percent from 1990 to 2004 (UNDP 2007). For comparison, carbon dioxide emissions of Brazil, India, and China, which were not parties to the KP, increased by 60 to 110 percent from 1990 to 2004 (UNDP 2007).

The "safe" level of below two degrees of global warming would require the stabilization of atmospheric GHG concentrations at 400 to 500 ppm (Mastrandrea and Schneider 2004), which would in turn require a reduction of 50 to 85 percent in GHG emissions by 2050 from 2000 levels (IPCC 2007). The KP cannot deliver this because too few countries participate in emissions reduction, because the targets of the countries that do participate are too lax (and are not complied with), and because too many sources of GHGs remain outside its scope. There have been calls to involve major developing economies in emissions reduction because of their substantial total emissions. But some major developing economies, such as China, Iran, and South Africa, also already have higher per capita GHG emissions than the globally available per capita emissions consistent with the stabilization of atmospheric GHG concentrations at a safe level (UNDP 2007). Land use and land use change, deforestation, aviation and marine bunker fuels, and carbon leakage associated with the consumption of imports from non–Annex 1 countries to Annex 1 countries are examples of issues that remain wholly or largely unaddressed by the current climate change regime.

Thus, the inclusive UNFCCC process has to date failed to generate solutions for tackling climate change. Barrett and Toman (2010), referring to research by Velders et al. (2007), suggest that the Montreal Protocol, which was adopted in 1987 to reverse the depletion of the ozone layer, has achieved GHG emission reductions four times greater than those of the KP. The Montreal Protocol was easier to negotiate because the depletion of the ozone layer involved fewer parties, mitigation costs were lower, and the same substances that deplete ozone layer are also greenhouse gases (Cole 2009).

Polycentric Climate Change Governance

Although climate change can usefully be understood as a problem of using a CPR, global atmospheric sinks for GHGs, the problem of the governance solution as a whole is distinct from decisions on the quality of CPRs. A stable climate is a public good (just like water or air quality, where pertinent sinks are also CPRs) because its use is not rival, and because it is difficult to exclude users from it once it is provided. Samuelson (1954) suggested that markets do not make available an optimal amount of public goods, and that they should be publicly provided. But public provision of a stable climate is not trivial; it should happen on a spatial scale that encompasses all affected parties (Musgrave and Musgrave 1976). That is, the provision of a stable climate should happen globally.

However, there is no world government, so the provision of a stable climate requires collective action. Olson (1971) argued that collective action is more likely to be unsuccessful in large groups where actors deem that their impact on collective-action outcomes is small and as a consequence have a stronger incentive to free ride. This argument applies to climate change if it is considered as a problem for humanity as a whole. When a large proportion of actors assess their situation in the way described here, collective action will be undermined.

One way to overcome the problem is to mobilize collective action on a smaller scale. This helps reduce the incentive to ride free because the impact of each individual on collective-action outcomes increases. At the same time, smaller groups may increase the homogeneity of involved actors, which should also facilitate collective action. Coordination among groups can be achieved by establishing larger-scale solutions in which the groups are represented. Representation treats collective-action groups as individuals and reduces the original large-numbers situation to one of small numbers. That is, multilevel governance solutions are likely to emerge as instruments for facilitating collective action in large groups.

The system of states representing their populations is one possible solution of this kind. However, it is not the only one, and state-based solutions are not necessarily one-size-fits-all. Ronald Coase's (1937) work on the nature of the firm suggests that the scope of any governance solution (in his case, the firm) is determined by the relative transaction costs of carrying out transactions internally and externally. Transaction costs do not favor comprehensiveness to the extreme. Subsequent work in transaction-cost economics highlights that different governance solutions create different incentives and have differential abilities to govern different kinds of transactions (Williamson 1999; 2000; 2005). The implications of this finding for climate change governance are that different rationales may exist for different governance solutions and that they may have different, albeit potentially coexisting, scopes. That is, multiple noncomprehensive solutions are a more likely outcome than one, all-encompassing governance solution.

Theoretical explanations of the emergence of multilevel governance also suggest that diverse institutional designs should exist for the provision of public goods such as a stable climate (Paavola 2008a). Different governance functions, such as provisioning, monitoring, and enforcement (Paavola 2007), may have different economies of scale or different optimal scales of operation (V. Ostrom, Tiebout, and Warren 1961). Collective environmental decisions may be best made at a higher level, while provision of the resource may best be undertaken at a lower level, for instance. This is the rationale for many comanagement arrangements. Important here is that the governance cost approach points to different kinds of multilevel solutions than the collective-action approach. The latter suggests nested governance solutions that are identical except for their different scale. The governance cost approach suggests that levels of governance may be functionally differentiated and complementary for a reason.

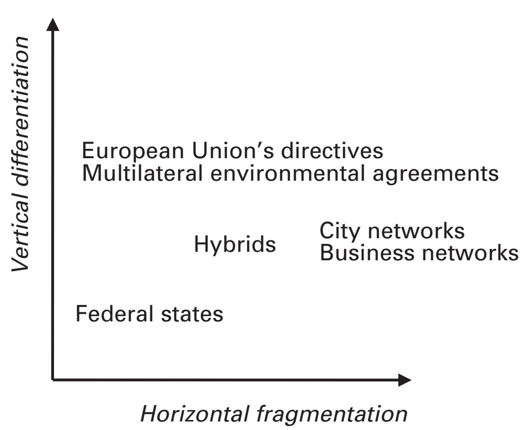
The literature on polycentricity offers additional insights for understanding institutional diversity in climate change governance. Vincent Ostrom and his colleagues originally proposed the notion of polycentricity to characterize complex metropolitan governance structures that had emerged after World War II for public service delivery in the United States (V. Ostrom 1972; V. Ostrom, Tiebout, and Warren 1961). These new complex structures did not have the single core that characterized conventional monocentric governmental arrangements. The scholarship on polycentricity sought to establish the rationale of such structures.

Until and even after Vincent Ostrom's seminal contributions and those of Buchanan (1965), Coase (1960; 1974), and Tiebout (1956), the government was considered the default provider of public goods and services. Market-failure reasoning provided the intellectual justification of this view. Against this background, the key interest of Vincent Ostrom was the horizontal dispersion of authority to govern. At that time, this was a novel phenomenon that the established notions of government and governance were not well equipped to account for. But vertical structuring of governance is also involved in the examples Ostrom and his colleagues discuss (V. Ostrom 1972; V. Ostrom, Tiebout, and Warren 1961).

The degree of horizontal dispersion of authority varies from monolithic governmental solutions to fragmentation of authority (figure 14.1). Hybrid solutions lie somewhere in between (Lemos and Agrawal 2006). Governance solutions range from those characterized by vertical symmetry to those that are vertically completely differentiated. Although individual governance solutions characterized by fragmentation of authority can be considered examples of polycentric governance, institutional diversity—the multitude of diverse governance solutions prevailing simultaneously—necessarily leads to polycentricity in a wider sense.

FIGURE 14.1

Horizontal Fragmentation and Vertical Differentiation as Dimensions of Polycentricity



Another important attribute of governance solutions is the way in which they emerge: from the bottom up as a result of voluntary collective action or bargaining, or as a result of top-down, mandated processes. As previously noted, polycentric order may emerge in a bottom-up way when actors seek to realize benefits or to avoid costs that accrue on different scales (E. Ostrom 2009). Top-down processes create other governance solutions, which increases institutional diversity.

There is thus more to climate change governance than international negotiations and state-based climate change policies. Solutions based on or involving non-state actors also exist and are likely to be networks, rather than hierarchies or markets, and to exhibit the dispersion of authority and vertical differentiation simultaneously. Hooghe and Marks (2003) suggest that these governance solutions are likely to be voluntary (negotiated) and temporary rather than permanent and to have overlapping rather than exclusive membership. Hybrid governance solutions can involve states and partly rely on their mandatory powers, but they can also grant important roles to other actors and voluntary action. They play a role in the portfolio of governance solutions alongside state-based and voluntary solutions.

Voluntary Initiatives and Climate Change Governance

Polycentric climate change governance can involve a variety of actors, such as local governments and communities, nongovernmental and church-based organizations, businesses, and governmental organizations in different combinations and roles. Some solutions are limited to one area of activity, such as local governmental activities or an industry, while others can be more general in nature. Many of these solutions are voluntarily adopted and have voluntary membership, although the act of joining can create responsibilities. The Cities for Climate Protection (CCP) program and the Cement Sustainability Initiative (CSI) are examples.

Cities for Climate Protection

Local governments have actively developed and implemented governance solutions for reducing the emissions of greenhouse gases from their jurisdictions. The pioneer in this area has been the International Council for Local Environmental Initiatives (ICLEI) with its Cities for Climate Protection (CCP) program. Others include Climate Alliance, C40, and the U.S. Mayors' Climate Protection Agreement (Gore 2010; Kern and Bulkeley 2009; Linstroth and Bell 2007; Román 2010).

The ICLEI launched its CCP program in 1993. It aimed to enlist one hundred municipalities worldwide with joint emissions of one billion metric tons of CO_2 (ICLEI 1993). The program also sought to strengthen local commitments to GHG emission reduction, to develop and disseminate planning and management tools, to research and develop best practices, and to enhance national and international ties among municipalities.

The CCP program expects members to develop a local action plan to reduce GHG emissions, to undertake measures to reduce emissions from municipal building stock and vehicle fleets, to institute public awareness campaigns on climate change, and to join procurement initiatives that seek to create demand for climate-friendly products and services. Members are also expected to link with local governments in developing and emerging-economy countries to foster technological and financial transfers (ICLEI 1993).

The CCP progress report published in 2006 (ICLEI Local Governments for Sustainability 2006) highlighted that 550 local governments had joined the program since 1993. Their combined population was a quarter of a billion, or more than 4 percent of the global total. The combined GHG emissions from participating local governments were 1.85 billion tons of eCO_2 (carbon dioxide equivalent), or more than 6 percent of the global total (excluding emissions from land use and land use change). That is, GHG emissions of CCP members are comparable to those of large Annex 1 countries, such as Germany, Japan, and Russia. The participants reduced their joint emissions by 3 percent or 60 million tons of CO_2 between 1990 and 2006. These emission reductions brought substantial savings to participating cities that amounted to about $35 per reduced ton of CO_2 emissions (ICLEI Local Governments for Sustainability 2006).

Cement Sustainability Initiative

Another example of climate change governance is the Cement Sustainability Initiative (CSI), a program of the World Business Council for Sustainable Development (CSI 2002) that has been considered a model for the sectoral approach to climate change mitigation (Meckling and Chung 2009; Schmidt et al. 2008). The cement industry is a significant GHG emitter. Its worldwide CO_2 emissions are about 5 percent of the global total, comparable to those of Germany, Japan, and Russia in 2004 (CSI 2002; UNDP 2007).

The CSI was formed by 10 large cement manufacturers in 2002. Today, its members represent nearly two-thirds of the global cement-manufacturing capacity outside China (CSI 2009). The CSI aims to increase the cement industry's contribution to sustainable development and public understanding of that contribution. The agenda for action adopted in 2002 contained six key areas of work: (1) climate protection; (2) fuels and raw materials; (3) employee health and safety; (4) emissions reduction; (5) local impacts; and (6) international business processes (CSI 2002). The agenda invited other cement producers to join and committed to reporting on progress in three years' time.

GHG emissions of the cement industry originate from the chemical reactions of the key raw material, limestone (50 percent of the total), fuel used in the manufacturing processes (40 percent of the total), and electricity consumption, transport, and other sources (10 percent of the total). Thus, the industry's climate protection encompasses raw-material considerations, fuel mix (the use of renewable sources of energy or energy derived from waste), process technology and its efficiency, product quality (which influences the use of cement per output unit), logistics, and other factors (Damtoft et al. 2008).

The CSI developed a CO_2 protocol for use in defining and publicizing baseline emissions of involved companies. It facilitated the setting of targets by involved companies against their baseline emissions, as well as annual reporting of CO_2 emissions (CSI 2002). The data suggest that CO_2 emissions per produced ton of clinker decreased

6 percent between 1990 and 2006. Thermal energy efficiency improved by 14 percent over the same period. But the emissions of CSI members increased by 35 percent because their output grew by 50 percent in the same period.

The CSI data suggest that operational optimization has limited scope to influence CO_2 emissions because it is tied to the technological design of plants. Industry performance improves mainly through the addition of new, efficient plants and the decommissioning of old, inefficient plants. Alternative fossil fuels, waste, and biomass contribute to the fuel mix in different ways in different regions (CSI 2009). Raw-material mix, fuel mix, and product choices have substantial potential to reduce CO_2 emissions by the industry over the long run.

Key Observations

Climate change governance initiatives such as the CCP and the CSI can cover GHG emissions comparable to those of major Annex 1 countries. The CCP has also achieved GHG emission reductions comparable to those of major Annex 1 countries, and it has done so by providing cost savings to participants. The CSI has improved performance compared with business as usual in a period when the cement industry's output grew by 50 percent (CSI 2009). But voluntary initiatives such as the CCP and the CSI are most likely to be able to realize only those emission reductions that will yield cost savings. These are not insignificant—as Enkvist, Nauclér, and Rosander (2007) suggest, nearly a third of emission reductions needed by 2030 would actually provide a net benefit.

New forms of climate change governance may also have other, less tangible implications. The CCP and the CSI have established processes for assessing current performance and for setting targets and planning for their attainment. These processes make performance transparent and can create stakeholder pressure for further improvement. The CCP and the CSI have also identified and disseminated best practices and have pursued the creation of a market for new climate-friendly products and services. Over time, they may help bring down the marginal abatement costs of carbon and thus create new cost-effective measures for reduction of GHG emissions.

But because two-thirds of the GHG emission reductions needed by 2030 entail economic sacrifices, there clearly remains a role for conventional state-based solutions as part of a wider polycentric governance strategy. This raises the question: what should the division of labor among state-based, hybrid, and voluntary governance solutions be, and how do they interact? Voluntary industry initiatives such as the CSI are likely to benefit from the existence of political commitments because those commitments provide a basis for longer-term planning and investment. State-based governance solutions can also foster and facilitate the functioning of hybrid and voluntary climate change governance initiatives. For example, markets need backing by states, such as legal recognition and enforceability of contracts in courts, to be credible and to function.

From another viewpoint, hybrid and voluntary forms of climate change governance may play an important role in legitimizing and mainstreaming climate change to actors participating in them and to external political and economic decision makers. That is, they may lower the threshold of participating in mitigation activities and increase pressure to make progress in conventional state-based forms of climate change governance. At the same time, voluntary and hybrid forms of climate governance as part of a wider polycentric governance strategy offer a decentralized, flexible, and incentivized way to learn, innovate, and experiment with promising ways of reducing GHG emissions and targeting research and development investments.

In light of the foregoing conceptual and empirical discussion, what could a wider polycentric governance strategy for climate change look like? As already suggested, bottom-up and top-down processes are likely to generate a mosaic of institutional diversity that includes state-based, hybrid, and voluntary measures that operate at levels from local to international and across levels (table 14.1). The international cornerstones of climate change governance will continue to play a role and will gradually cover more GHG sources, include more ambitious emission-reduction targets, and address adaptation and its financing. However, this is likely to happen in a piecemeal and incremental way rather than comprehensively. National policies on climate change and related issues will also develop, both to implement international agreements and to pursue domestic goals. In light of the multiple-benefits origins of polycentric governance, voluntary initiatives focused on adaptation to climate change are likely to emerge when the adaptation agenda gains force. Insurance and risk-sharing arrangements for adaptation are likely to demand public-private cooperation and to be based on hybrid solutions. Public-private cooperation and hybrid solutions are also likely to underpin mitigation-focused activities, particularly those related to carbon markets and experimental technologies such as carbon capture and storage. Regional and local governments will also increasingly

TABLE 14.1
Institutional Diversity in Polycentric Climate Change Governance

Type and Level	Conventional	Hybrid	Voluntary
Global	Kyoto Protocol; post-Kyoto targets; adaptation funding	Carbon markets; REDD	Business sector initiatives
Regional	European Union's emissions trading scheme (EU-ETS)	Regional carbon markets; insurance provision and underwriting	Adaptation clearinghouses
National	Climate change; energy; and other legislation	Carbon markets; public-private partnerships in CCS; insurance provision and underwriting	Adaptation networks of local governments
Local	Climate-proofed zoning; property tax regimes; joint mitigation and adaptation	Public-private partnerships	Carbon-neutral communities

be involved in the delivery of mitigation and adaptation through planning, regulation, and public service provision.

Although the discussion here has focused on the potential and promises of hybrid and voluntary forms of climate change governance, they can also have problematic implications. Collaborative industry initiatives may not in reality be open to all and may result in restraints of competition. Voluntary initiatives in general are not representative, and their accountability remains unclear. These issues are increasingly drawing attention in research (Bäckstrand 2008; Unerman and O'Dwyer 2006).

Fostering Polycentric Climate Governance

The governance framework for climate change is still largely in the making, but both new institutional arguments about polycentricity and the emerging empirical evidence suggest that institutional diversity will characterize it. The governance framework will partly be based on the UNFCCC and the protocols and decisions of parties made under it. However, national policies and regulations, subnational and local policies and plans, and a variety of hybrid and voluntary initiatives will also play a role in climate change governance. Together, these institutional responses will create a wider polycentric governance strategy for climate change that will disperse authority and responsibility.

Although the dynamics of different kinds of institutional solutions as part of a wider polycentric governance strategy largely remain to be studied, something can be said about them. Voluntary and hybrid governance initiatives can clearly be comparable to major Annex 1 countries in terms of GHG emissions and emission-reduction achievements. These initiatives will be at their best in realizing emission reductions that save money, but they can also help create markets for carbon-friendly products and abatement technologies and bring down the marginal abatement cost of carbon over time. However, climate stabilization will also require emission reductions that will entail economic sacrifices. This means that state-based governance solutions will remain a part of the wider polycentric governance strategy.

The question is: how different governance solutions within the wider polycentric strategy will interact? Voluntary solutions may benefit from political commitment which can provide a basis for longer-term planning and investment. State-based governance solutions can also foster hybrid solutions involving markets. Voluntary initiatives may in turn play a role in mainstreaming and legitimizing climate change to actors participating in them and to external political and economic decision makers. They can lower the threshold of participating in voluntary climate change measures and create pressure for making progress in state-based forms of climate change governance. Voluntary and hybrid forms of climate change governance also offer a decentralized, flexible and incentivized way of learning about low-cost and promising ways of reducing greenhouse gas emissions and targeting R&D investments effectively.

There clearly is an urgent need to improve the evidence base on the performance of nonconventional forms of climate change governance and the interaction of different types of governance solutions that form parts of a wider polycentric governance strategy. The scholarship on common-pool resources and polycentricity is well placed to make a contribution in this area because it can draw on both a conceptual apparatus and comparable empirical evidence.

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Collective Responsibility in the Cooperative Governance of Climate Change

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Abstract: This paper sets out a proposal for framing collective responsibility as a central element within the cooperative governance of climate change. It begins by reconstructing the analysis of climate change as a Tragedy of the Commons in the economic literature and as a Problem of Many Hands in the ethical literature. Both formalizations are shown to represent dilemmatic situations where an individual has no rational incentive to prevent the climate crisis and no moral requirement to be held responsible for contributing to it. Traditionally both dilemmas have been thought to be solvable only through a vertical structure of decision-making. Where contemporary research in political economy has undergone a "governance revolution", showing how horizontal networks of public, private, and civil society actors can play an important role in the management of the climate crisis, little research has been carried out in the ethical field on how to secure accountability and responsibility within such a cooperative structure of social agency. Therefore, this paper contributes by individuating some conditions for designing responsible and accountable governance processes in the management of climate change. It concludes by claiming that climate change is addressable only insofar as we transition from a morality based on individual responsibility to a new conception of morality based on our co-responsibility for preventing the climate crisis.

Keywords: cooperative governance; governance networks; social ontology; shared agency; collective responsibility; problem of many hands; tragedy of the commons

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1. Introduction

To a large degree, the mitigation of the effects of climate change represents the greatest ethical and political challenge that our society faces today. The urgency of taking tempestive and effective climate action has been recognized by the United Nations as one of the key goals for sustainable development [1]. As the Intergovernmental Panel on Climate Change (IPCC) has claimed, "each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850" and according to the most up to date climate data analyzed by the World Meteorological Organization, the "average temperatures for the five-year, 2015-to-2019, and 10-year, 2010-to-2019, periods are almost certain to be the highest on record" [2]. Anthropogenic emissions of greenhouse gases are the main drivers of such an increase in global temperatures and they derive from increased energy consumption, industrial development, growing demographic numbers, land-use change, and consumption habits. To maintain the commitments of the Paris Agreement of limiting the increase in global average temperatures to 1.5 °C with respect to preindustrial levels, governments have to accelerate the transition toward sustainable development. However, the management of such transition pathways to "deep decarbonization" requires the coordination of complex socio–technical–ecological systems, which are characterized by the intertwinement of natural ecosystems, institutional regulations, private markets, infrastructures, technological innovations, and user practices [3,4]. As Oran Young has recognized, "sustainable development is a broad objective that calls for a melding of economic, social, and environmental factors, both to enhance the well-being of individual humans and to produce resilient socio-ecological systems from the local to the global level" [5]. The management of such complex adaptive systems [6], which involves the expertise necessary for organizing the layered composition of technical, economic, environmental, and social challenges, is no longer within the reach of central administrations within nation states. To a large extent, traditional command-and-control practices are proving to be only a partial solution to the challenge of governing the complexity of the sustainable transition [7]. Within the academic literature, a variety of new approaches for the management of social–ecological systems has emerged: from *polycentric governance*, which is centered around the multiple and nested centers of decision-making involved in devising context-specific solutions to environmental problems [8,9], to *adaptive governance*, which is based on the dynamic capacity of social networks to self-organize, share knowledge, and respond adaptively to emergent social–ecological phenomena [10,11], to *collaborative governance*, which is grounded in the ability of multiple stakeholders, both public and private, to effectively share information and mutually learn from best practices in the achievement of common societal goals [12,13]. All of these approaches have emerged as an answer to the shortcomings of centralized regulation and downstream implementation in managing social–ecological systems, and they have contributed to a shift in the academic discourse toward cooperative and participatory models of governance. The advantages of these governance networks are the increased ability to adapt quickly to emergent phenomena, to provide fine-grained information on local impacts, to deploy articulated expertise in technological innovations, and to allow for effective multi-level coordination across government scales. In fact, as the scale and complexity of policy problems has increased exponentially, public policy has undertaken a "governance revolution" [14], where a vertical and centralized conception of public administration, focused on the *structure* of government, has been gradually supplanted by a horizontal and decentralized model of governance, centered instead on the *process* of governing, opening the management of policy problems to governance networks of societal actors from public, private, and civil society sectors [15]. This shift to the cooperative management of social–ecological systems has nonetheless brought about new challenges: a less structured decision-making process, a multiplicity of actors with diverging perspectives and interests, and the necessity of a continuous reciprocal adaptation of plans and policies. Therefore, the moral question of a sustainable future is centered around the successful management of the increasingly complex nature of the Earth system's governance [16]. The responsibility toward present and future generations for a sustainable transition forces all societal actors to address the question of how to achieve responsible collective agency. Hence, this article will concentrate on how governance can today answer to the planetary crisis that is climate change; at its center, this paper outlines two main challenges that a theory of governance has to meet when managing the effects of anthropogenic global warming: the fragmentation of agency between a collection of self-interested societal actors [17] and the resulting risk of failing to achieve any meaningful form of responsibility. A promising solution lies in creating a full theory of responsible cooperative governance within the management of social–ecological systems.

2. Methodology

This paper develops by modeling climate change as an instance of the Tragedy of the Commons in the economic literature [18] and as a Problem of Many Hands in the ethical literature [19,20]. Within the economic literature, much work has been carried out on the formalization of climate change as a commons dilemma [21–24]. Here, I will first offer a reconstruction of Garrett Hardin's original argument, and I will proceed to adopt Elinor Ostrom's account of commons dilemmas, which in many ways reformulates the initial set of assumptions present in Garrett Hardin's original work. In particular, I will show that Ostrom's theoretical and empirical work has contributed to questioning two main assumptions, framed within rational choice theory, which inform Hardin's reading of commons dilemmas: the absence of communication between players and the exclusively self-interested and utilitarian character of individual rationality. For what concerns the formalization of climate change as a Problem of Many Hands, I will follow the work of van de Poel in his *The Problem of Many Hands: Climate Change as an Example* [25].

As the paper aimed at establishing a parallel between the rational dilemma that is the Tragedy of the Commons and the moral dilemma that is the Problem of Many Hands, its structure will alternate, in an ABAB scheme, between paragraphs devoted to the economic analysis of climate change and paragraphs devoted to its ethical discussion.

3. Materials

3.1. An Economic Formalization of Climate Change: The Tragedy of the Commons

It is first important to sketch in further detail how climate change has been formalized, inside economic theory, as a problem of "common resources" management in Garret Hardin's 1968 article *The Tragedy of the Commons* [18]. That paper, framed within a Malthusian logic [26], addresses one main challenge for our civilization: Earth is becoming too densely populated, which puts an unprecedented burden on our shared resources, namely, the commons. The core of Hardin's argument is to be found in the theoretical impasse reached in managing common-pool resources within a model of individual rationality. The argument develops by drawing a now renowned scenario: a group of herders lets their herds graze in a common pasture. Each herder will try to rationally maximize his utility by steadily growing his herd; at a certain moment, though, a certain threshold will be reached and an additional increment of one animal to the field will incur in the overgrazing of the pasture. At this point, so Hardin's argument goes, the addition of one animal will represent, for each herder, both a positive and a negative component of utility [18]:

> *The positive component is a function of the increment of one animal. Since the herdsman receives all the proceeds from the sale of one additional animal, the positive utility is nearly +1.*
>
> *The negative component is a function of the additional overgrazing created by one more animal. Since, however, the effects of overgrazing are shared by all the herdsmen, the negative utility for any particular decision-making herdsman is only a fraction of −1.*

As the scenario shows, the depletion of a common-pool resource occurs when the resource stock is consumed by the appropriators faster than its regeneration rate [27]. Nonetheless, irrespective of the consequences, in economic terms for each herdsman, the marginal benefits of adding cattle to the graze are larger than the marginal costs. Therefore, the rational conclusion to be drawn by any herdsman, faced with a decision between cooperating or defecting in the collective action, will be to "free-ride" and unilaterally choose what is in his best interest; the result will be the gradual addition of cattle to the pasture, with the further consequence of eventually depleting the commons. For Hardin, this shows how a model of individual rationality, applied to the management of a common resource, results in its eventual depletion: this fact constitutes the conceptual core of the Tragedy of the Commons. As Hardin commented, in commons dilemmas, we face a tragic situation where we lack a solution that has a "technical" character [18]:

> *A technical solution may be defined as one that requires a change only in the techniques of the natural sciences, demanding little or nothing in the way of change in human values or ideas of morality.*

It is possible to describe this technical failure in a game-theoretic language by framing the common pasture as an interactive decision-making game, where the optimal choice at the individual level paradoxically constitutes a suboptimal choice at the collective level [27]. As a result, in a Tragedy of the Commons, each herdsman, who is in the dark with respect to the other herdsmen's decisions, has an incentive to unilaterally defect, or "free-ride", rather than cooperating; this failure of coordination in a collective action ultimately results in an outcome that is not an equilibrium, and thus represents a cooperation problem [28]. As Hardin saw, this failure to cooperate would eventually place unsustainable pressure on common resources. Nowadays, an infinite number of tragedies of the commons, caused by unilateral and self-interested decision-making, feeds the daily reports on the ongoing catastrophe that is climate change: oceans are undergoing progressive acidification, human and non-human life is threatened by the erosion of natural habitats, the atmosphere is becoming increasingly polluted, and global temperatures are rising. At every level, from nation states to city administrations, private companies, and consumer habits, human conduct is proving to be dramatically inadequate to prevent the depletion of our commons, bringing about an environmental and social disaster of unprecedented dimension. What Hardin provides is a game-theoretic analysis of such a disaster, showing how an insular model of *homo economicus*, moved by the maximization of individual utility, is bound to meet his anthropological limits when faced with the problem of managing a common resource.

3.2. An Ethical Formalization of Climate Change: The Problem of Many Hands

Coming to the ethical analysis of the Tragedy of the Commons, this section tackles the problem of climate change in terms of our moral responsibility to prevent it. The aim will be to argue how commons dilemmas constitute not only a rational impasse but also a moral one, as climate change can be modeled as a case of "collective responsibility without individual responsibility". This responsibility gap constitutes what, in the literature, has been called the Problem of Many Hands. Here, the meaning of responsibility will be taken as close to its etymological sense, as answering for one's actions; specifically, agents will be regarded as responsible for an action φ, when they are causally linked with a harm that they cannot reasonably justify, making their action blameworthy in an objective-reasons implying sense [29,30]. Where responsibility is usually framed within the context of past actions, in terms of remedial responsibility, here responsibility will be analyzed not in its backward-looking sense, but rather its forward-looking sense, as a form of prospective responsibility: we bear such a responsibility when we should prevent some event to bring about a bad outcome. To the degree that climate change poses an unprecedented threat to both present and future life on Earth, it can be maintained that preventing its devastating impacts represents a clear case of prospective responsibility [31]. Within metaethical theory, Ibo van de Poel has suggested that we hold a prospective responsibility (PR) when the following conditions apply [20,32]:

1. *Capacity condition*: the agent is capable of moral agency;
2. *Causal efficacy condition*: the agent is causally efficacious in producing the outcome;
3. *Normative condition*: bringing about the outcome is morally wrong.

Let us now examine how these three conditions apply to the actions of individuals in the case of climate change as an instance of a Tragedy of the Commons. Starting from the *capacity condition*, the attribution of moral capacity is regarded as a fundamental attribute of every person capable of intentional action. To the degree that an agent is capable of intentional agency, it can be claimed that such a person satisfies the capacity condition. As for the *causal efficacy condition*, it is possible to ask: can individuals prevent the depletion of the shared resource in a Tragedy of the Commons? Baylor Johnson, in *Ethical Obligations in a Tragedy of the Commons*, has convincingly argued that it seems difficult [33]. Looking closely at Johnson's argument, it is possible to see that the main point centers around the impossibility of being causally efficacious in non-coordinated agency:

> *[. . .] voluntary, unilateral reductions of use have no reasonable expectation of success when the situation faced strongly resembles a Tragedy of the Commons in other respects. It is very unlikely that most commons users will adopt such widespread restraint without organized assurances that others will mirror one's own restraint. The reasons are those given above: the incentives users have in such cases; each user's knowledge that her restraint is likely only to reward less scrupulous users; each user's awareness that every other user sees the same discouraging prospect; the need for nearly universal restraint in order to effectively protect the commons or reassure users that their sacrifice is not in vain.*

As it appears clear from the excerpt, what determines the absence of causal efficacy is not just the limited agency of the person but also the structure of the coordination game that every actor faces. Indeed, many philosophers have held that no individual person can be reasonably regarded as causally efficacious in preventing climate change [20,34–36]. Coming to the third, and final, *normative condition* for prospective responsibility, it can be asked whether any individual actor is engaging in some form of wrong-doing. Within the field of climate ethics, Walter Sinnott-Armstrong has argued, in his *It's Not My Fault: Global Warming and Individual Obligations*, that no individual actor can be held responsible for a form of wrong-doing in the case of climate change [34]. Here, the author claims, no plausible moral principle can determine a wrong-doing in failing to limit our carbon footprint, since individuals are neither sufficient nor necessary for determining global warming as a harm, individuals act under no intention of harming, and individual harms cannot be simply aggregated since global warming is an emergent, threshold phenomenon. A similar point is made by Johnson by arguing how an individual does not engage in wrong-doing in a commons dilemma because unilateral restrictions cannot be effective in preventing the depletion of the resource, the moral duty to unilaterally restrict the consumption of the resource might be overridden by the sacrifice and competitive disadvantage it entails, and finally, no one person's use of the commons is large enough to cause its depletion [33]. Therefore, it seems that from a moral perspective, no forward-looking responsibility can be attributed to individuals for preventing the depletion of our planetary resources. I submit that this fact constitutes a form of Moral Tragedy of the Commons. Conversely, from the point of view of the collective, these three conditions seem to be met: regarding the *capacity condition*, as long as humanity achieves some form of coordinated agency, it can be regarded as capable of intentional and moral agency; regarding the *causal efficacy condition*, as a collective, humanity can be causally efficacious in preventing climate change; finally, regarding the *normative condition*, as a whole, humanity can be considered morally blameworthy for bringing about the devastating intergenerational crisis that is climate change. As it appears from the reconstruction proposed, it can be advanced that there is symmetry in a Tragedy of the Commons between the dilemmatic disconnect between individual and collective rationality in its economic formalization and between individual and collective responsibility in its ethical formalization: just as there are collective reasons, but not individual ones, to prevent the depletion of common resources, there are collective moral reasons, but not individual ones, for preventing the disastrous effects that climate change will bring about. This dilemmatic situation, in which we have a fundamental gap between individual and collective responsibility, was first introduced by Dennis Thompson in *Moral Responsibility and Public Officials* as the Problem of Many Hands [19]. According to Ibo van de Poel, the Problem of Many Hands can be defined as follows [20]:

> *The Problem of Many Hands (PMH) occurs if a collective is morally responsible for φ whereas none of the individuals making up the collective is morally responsible for φ.*

Therefore, it can be argued that the Problem of Many Hands provides a useful ethical formalization of commons dilemmas, as in the case of climate change. As it appears from the reconstruction that has been proposed, we can advance the thesis that whenever a rational failure, such as a Tragedy of the Commons occurs, a parallel moral failure occurs as a Problem of Many Hands, since "free-riding" the commons is not irrational or irresponsible at the individual level, while it constitutes a rational and moral failure at the collective level.

3.3. Conventional Solutions to the Tragedy of the Commons: Governments and Markets

Within the field of economics, to face the structural shortcomings of collective action in commons dilemmas, two proposals have traditionally been advanced, both of which are grounded on the establishment of institutions: on the one hand, the appeal to the institution of the state, by turning the commons into a public good; on the other hand, the appeal to the institution of private property, by turning the commons into a private good. Where, in the first case, the structure of the coordination game gets changed through the power of the state by introducing sanctions that modify the structure of individual incentives for defecting in the mutual effort and deviating from the equilibrium; in the second case, the coordination problem is solved by eliminating the very necessity of a collective action, as the commons get partitioned between the different actors, and the role of coordination is thereafter provided by the market. As Elinor Ostrom pointed out, the debate revolved for the better part of the 1970s and 1980s around a fundamental opposition between defenders of the "market" formula and supporters of the "Leviathan" solution [21]. On both views, the failure of individual rationality in a commons dilemma requires the creation of an external institution to enforce rules on the actors to prevent their eventual depletion. Hardin pointed out how the pollution of our environment represents such a case: while it is rational for an individual to indefinitely profit from activities that produce the pollution of the environment as byproducts, it is not rational for the collective as a whole to engage in such activities beyond a point where their aggregated effects produce a net disadvantage in the balance of benefits and costs [18].

On the one hand, many economists saw a solution to the problem of negative externalities, such as a polluting factory, in the workings of the invisible hand of the market. Basing their arguments on Coasian bargaining [37], economists argued that when an economic activity produces some externality, a market on the externalities, allowing for a bargain between the parties involved, will reach a Pareto efficient outcome. Nonetheless, as Hardin correctly assumed, for many cases of pollution of natural resources—such as our rivers, seas, and atmosphere—defining and enforcing clear property rights would seem difficult, if not impossible. Furthermore, as Coase himself pointed out, in most cases of polluting externalities, the spread of the impacts among a large number of individuals would make the organization of a bargain extremely costly, making transaction costs extremely high. Elinor Ostrom systematized these observations, pointing out the limits of privatization in solving commons dilemmas when: (1) resources are nonstationary, (2) resources are global or have a large geographical extension, (3) it is difficult to place boundaries and protect the private property, and (4) resource flow is unevenly distributed in both space and time [27]. Many common resources, such as oceans, water basins, coral reefs, animal habitats, the atmosphere, and many of Earth's ecosystems, are difficult, and indeed at times impossible, to privatize. As a result, the problem of negative externalities in many commons dilemmas seemed to be simply unsolvable via the simple mechanism of the market.

On the other hand, Hardin eventually became a supporter of the public management of commons, arguing that "if ruin is to be avoided in a crowded world, people must be responsive to a coercive force outside their individual psyches, a 'Leviathan' to use Hobbes' term" [18]. In this picture, the authority, as a Leviathan, must act in the collective interest by modifying the structure of incentives producing the externalities and restore optimal coordination in the management of the commons. For economists advocating a bigger role of the state in solving externalities, the action of government has to take the form of Pigovian taxation, designing incentives or establishing sanctions to change the structure of payoffs in the game and restore coordination between the actors involved, so as to internalize the externalities and prevent a less-than-efficient outcome from being realized. In this way, the actors can carry on their activities based on the exploitation of the common resource without depleting it. However, Ostrom claimed that turning commons into public goods was bound to face some shortcomings when (1) creating new institutions may turn out to be slow or difficult, (2) creating new institutions has high costs, and (3) institutions may demonstrate inefficient in managing the commons [27]. Interestingly, within environmental governance, the "market" solution, of Coasian inspiration, is at the base of contemporary cap-and-trade systems [37,38]. These markets work by setting a maximum threshold of emissions within a country and allowing companies to trade in emission permits according to their productive necessities. In contrast, the "Leviathan" solution, of Pigovian inspiration, grounds contemporary forms of carbon taxation [39]. In this case, the negative externalities are internalized through a different form of carbon pricing: a Pareto efficient outcome is secured by setting a tax on emissions equal to the social costs generated through the polluting activities.

3.4. Conventional Solutions to the Problem of Many Hands: Organization and Authority

As we saw, within the field of applied ethics, van de Poel defines the Problem of Many Hands as a dilemmatic disconnect between individual and collective responsibility. Within his philosophical framework, the Problem of Many Hands is framed as resulting from a failure to effectively distribute responsibility in a group [20]. The argument develops by pointing out that whenever a collection of agents lacks a proper organizational structure, no single actor has a formally defined role with a respective array of task-responsibilities. This is a consequence of the impossibility of properly discharging the collective responsibility among an uncoordinated collection of agents, since the group lacks an organizational structure for effectively distributing responsibility at the individual level. The main proposal of van de Poel is then to suggest that, to prevent the occurrence of the Problem of Many Hands, a collective needs a better organizational structure for efficiently distributing responsibilities among the various actors. Accordingly, van de Poel seems to follow the work of Grossi, Royakkers, and Dignum in *Organizational Structure and Responsibility* by claiming that increased organization is to be achieved through the establishment of clearer *authority*, defining a hierarchical structure of responsibility delegation from a decisional center; better *coordination*, granting an increased flow of relevant information and knowledge between the actors involved; and increased *control*, securing a stricter supervisory activity [40,41]. According to van de Poel, we can sketch a taxonomy of three different types of groups to which the Problem of Many Hands applies in cases of prospective responsibility [20]:

> *1. Organized groups (also sometimes called 'corporate agents') that can formulate and adopt collective aims by a collective (decision) procedure;*
>
> *2. Collectives involved in a joint action. The joint action is characterized by a collective aim that is in some sense [. . .] shared by the members of the collective;*
>
> *3. Occasional collections of individuals that lack a collective aim but that nevertheless can be reasonably expected to form a collective in one of the two above senses to avoid harm or to do good.*

Van de Poel suggests that, as one moves from organizations down to collectives and collections, the progressive fragmentation of agency and the resulting impossibility to distribute responsibilities back at the individual level creates the conditions for the emergence of responsibility gaps like the Problem of Many Hands. Therefore, preventing responsibility gaps from occurring requires organizing a group in a hierarchical structure that is centered around authority, coordination, and control.

While these conditions constitute the basis for the design of a clearer organization within hierarchical entities, like corporations or public administrations, it should nonetheless be noticed how such conditions are ill-suited to provide a proper ground for the coordination of governance networks in the management of the environment. In fact, a centralized conception of vertical organization best applies to traditional public administration where hierarchical trees and command and control practices define the structure of task-delegation within a group of public officials [15]. However, crucially, governing social–ecological systems confronts administrations with complex problems that are difficult to solve by a unique decision-making center [7,10]. The analysis and the management of complex feedbacks between social and ecological systems require the aggregation of a multiplicity of actors from public, private, and civil society sectors that provide a diverse range of expertise in articulated knowledge domains. Accordingly, the complexity of social–ecological systems is increasingly mirrored by the complexity of governance networks. This creates a new set of challenges at the substantive, strategic, and institutional levels: different actors hold different perceptions of policy problems, they follow different interests involving different and sometimes contrasting strategies, and finally, decision-making spans across different institutional settings, often with the superimposition of many accountability mechanisms [15]. Such interdependent structures clash against a vertical organization of decision-making. As Kljin and Koppenjan argue "mutual dependencies make it impossible for each of the involved actors to act in isolation, or as principals and agents" [15]. This structural interdependency renders it difficult to organize governance networks along hierarchical lines. Accordingly, the governance of social–ecological systems has taken an increasingly polycentric character, where multiple and diverse decision-making centers interact through a hybrid matrix of competitive and cooperative ties.

4. Results and Discussion

4.1. The Role of Cooperative Governance in Managing the Climate Commons

One of the biggest merits of Elinor Ostrom has been the redefinition of our understanding of commons situations. During her career, she helped to establish a third theoretical solution, between market and state proposals, to the Tragedy of the Commons.

4.1.1. Polycentricity in Commons Situations

Where the conventional theory of collective action predicted that, when faced with a commons dilemma, the actors would inevitably run into the destruction of the shared resource if not regulated by an external institution, the work of Elinor Ostrom, starting with her essay *Governing the Commons*, focused on providing empirical and theoretical insights to show that this was not an inevitable outcome [21]. Indeed, on many occasions, actors faced with a commons were able to reach an agreement among themselves and mutually enforce a contract that efficiently allocated the resource among the participants. What Ostrom discovered was that the set of assumptions made by neoclassical economists, which framed the commons situation as a game played by self-interested actors striving to maximize immediate utility and not engaging in communication, did not apply in many real-world situations. Ostrom and her team showed that agents, within a repeated game and allowed to have face-to-face communication, were shown to be "extremely successful in increasing joint returns" [42]. By repeating the game, the communication between actors allowed for the *emergence of collective forms of learning and normativity*: the emergence of the reputation of players, the emergence of trust in other players, and the emergence of mutual monitoring and sanctioning behaviors. In this way, the actors were able to devise and enforce a cooperative strategy, allowing them to reach Pareto efficient allocation of resources [21]. This theoretical insight allowed Elinor Ostrom to elaborate with Vincent Ostrom, her husband and colleague at Indiana University, a theory of polycentric governance, where decentralized, multilevel, and cooperative decision-making grounded a new understanding of institutional networks [8,42,43]. The Ostroms framed polycentric systems as being "characterized by multiple governing authorities at differing scales rather than a monocentric unit" where each governance unit "exercises considerable independence to make norms and rules within a specific domain" [42]. Polycentric systems were originally conceived by Vincent Ostrom as redundant governance systems where the compresence of competition and cooperation among decision-making centers was able to secure levels of dynamism and coordination at the same time. What Elinor Ostrom contributed was a dynamic understanding of how increased cooperation can emerge in the face of commons dilemmas. As the analysis of commons dilemmas had already brought to the fore, the progressive establishment of cooperative networks within polycentric systems presents the double advantage of allowing mutual learning between actors and fostering the emergence of coordinated action by means of shared normative structures setting common goals and rules. In fact, as Ostrom claimed, polycentric systems constitute a governance architecture that is likely to "enhance innovation, learning, adaptation, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales" [42]. In what is perhaps the most in-depth study of polycentric governance of climate change, Jordan et al. frame polycentricity as a theory built around five propositions [44]: "(1) Governance initiatives are likely to take off at a local level through processes of self-organization; (2) Constituent units are likely to spontaneously develop collaborations with one another, producing more trusting interrelationships; (3) The willingness and capacity to experiment is likely to facilitate governance innovation and learning about what works; (4) Trust is likely to build up more quickly when units can self-organize, thus increasing collective ambitions; (5) Local initiatives are likely to work best when they are bound by a set of overarching rules that enshrine the goals to be achieved and/or allow conflicts to be resolved".

However, where polycentricity has shown great promise at small- and mesoscales, many have voiced caution regarding the possibility of governing a global phenomenon like climate change cooperatively [45,46]. In this regard, Felix Ekardt has argued that cooperative networks work best only when the "cooperation of other participants is to be expected, when the situation is manageable, and norm violations are noticed and sanctioned"; all of these characteristics are problematic to assume in the global governance of climate change [46]. Nonetheless, some considerations might contribute to weakening the concerns around the development of cooperative action in tackling the climate crisis. In fact, despite the predictions of classical game theory, we assisted in recent decades to the creation of a myriad of cooperative initiatives in climate governance, from public–private partnerships to transnational networks of municipalities and regions. The United Nations Environmental Program currently counts 269 international networks of non-state actors in its Climate Initiatives Platform. Accordingly, these numbers contribute to present some evidence that the existence of "conditional cooperators" in the climate commons is far more widespread than assumed by rational choice models. Therefore, faced with the rapidly growing reality of cooperative governance networks, the most pressing question seems to be no longer whether such governance architectures could play a role in the management of climate change, but which role should we assign to them.

4.1.2. Climate Action: The Complementary Role of Cooperative Governance Networks

In addressing the challenge of the environmental governance of climate change, Ostrom has argued that conventional approaches that strive for the creation of global institutions have so far turned out to be too slow for the urgency of climate action, global regulation without local participation is bound to be ineffective, and finally, universal norms are often unresponsive to contextual situations and problems [9]. Within the fight against climate change, creating global institutions for governing the sustainable transition has proved to be extremely difficult so far. Since the 1990s, transnational efforts to converge on a shared and legally binding agreement between world governments have largely failed. Starting from the Rio Conference in 1992, the collective effort to create a global institution that can enforce a shared body of rules in tackling climate change has fallen short. In particular, as the Kyoto Summit in 1997 failed to gather widespread political support around common measures and regulations against global warming, there has been increasing recognition that environmental governance can benefit from a more cooperative and horizontal structure. The limits of the universalist approach of the Kyoto Protocol have been at the base of the different approach toward environmental governance championed within the 2015 Paris Agreement. This new international agreement moved away from the top-down logic of treaties and shifted toward a more flexible and bottom-up model, based on Nationally Determined Contributions, where targets, plans, and mutual monitoring mechanisms have to be set in place in the absence of any higher-order institution. This more flexible mechanism has allowed for a much larger commitment, with 191 countries and the EU among its signatories. As this shift away from rigid governance structures can be traced back to a form of *realpolitik*, it is also the case that Ostrom's work has brought new awareness to the potential of cooperative governance when dealing with the climate crisis [44]. Nonetheless, Ostrom always warned against the tendency to believe in policy panaceas that advocated for a single solution to the management of social–ecological systems [47]. In fact, the theory of polycentric governance was never intended to be the only answer to the challenge of meaningful climate action. In an important sense, Ostrom's main critique of the standard top-down approach that advocated for the creation of a global institution for tackling climate change is that such a theory is too one-sided and it disregards the evolutionary dynamics of cooperation. In this regard, a theory of bottom-up and polycentric governance should be considered a necessary complement to top-down and centralized approaches for three main reasons. First, where top-down theories tend to provide a static answer to the challenge of climate change, usually framed in the form of abstract institutional architectures with a universal reach, Ostrom's approach can bring forth an *evolutionary understanding of institutional emergence* that is based on increasing cooperative ties among a differentiated set of local actors that progressively strengthen their mutual trust, align their goals and values, and only ultimately come to a shared framework of norms and rules. In this sense, the Kyoto Protocol represented an attempt to put the cart before the horse by proposing a universal normative structure, without the previous establishment of a meaningful body of cooperative ties based on mutual trust, shared goals, and aligned values. In this respect, the genealogical development of the Sustainable Development Goals and the bottom-up structure of the Paris Agreement marked a step forward in the comprehension of the evolutionary character of institutional emergence. Ostrom's theory of institutional development can therefore provide a better understanding of the *process* through which we arrive at the creation of shared institutions [22]. Second, cooperative governance networks are essential for providing a *bottom-up structure of local participation*, which is essential to complement the top-down imposition of a set of global regulations. As Ostrom pointed out, the institutional costs of regulatory enforcement are bound to be unsustainable without the creation of collaborative networks for climate action at every governance scale [9]. Local participation, from neighborhood initiatives to transnational municipal networks, is key for complementing top-down regulations with bottom-up cooperative action. In this regard, the emergence of cooperative networks of climate action at every scale has contributed to disprove the classic assumption of rational choice theory, which predicts that no actor faced with a commons dilemma will change his behavior unless an external authority enforces rules from above [9]. Governance networks, such as the Global Covenant of Mayors or the C40 Cities Climate Leadership Group, have proven effective at gathering widespread political support around climate initiatives. Furthermore, sub-state actors have often proven themselves capable of leading the way in setting ambitious targets of emissions reductions that far exceed those of national governments [44,48]. Even if we currently lack clear data for measuring the effectiveness of such initiatives, the progressive construction of shared commitments, data sets, research and innovation programs, and financing platforms represents an encouraging first step in the elaboration of cooperative strategies for flexible climate adaptation and effective climate mitigation [49–51]. Third, where centralized institutions can create stable, predictable, and durable governance architectures, polycentric networks can supplement the relative rigidity of top-down organizations with *increased levels of institutional flexibility* [5,52]. The advantages of adopting such a polycentric structure rely on the increased adaptiveness, institutional flexibility, and resilience of governance networks. In this respect, polycentric networks present a larger potential for establishing a social–ecological fit between institutional architectures and ecological interlinkages within the Earth's system. The polycentric, redundant, and flexible nature of cooperative governance networks is better suited to responding more swiftly and adaptively to evolutionary changes in complex social–ecological systems [13]. As Oran Young has argued, "as we move deeper into a world of complex systems characterized by non-linear change, bifurcations and emergent properties, there is a growing premium on creating governance systems that are agile or nimble in responding to changes in the issue areas they address" [52]. Accordingly, a value-driven and goal-based model of climate change governance could grant political accountability in setting climate targets while allowing for a level of policy flexibility that can better address the local differentiation of social and ecological conditions in the Earth system. To be sure, polycentric governance, with its emphasis on diversity and multiplicity in governance theory, can lead to institutional disorder and uncertainty when left unchecked [53]. Accordingly, as Young emphasizes, the design of climate governance architectures must rely on the pragmatic balance between the dynamic benefits of policy fragmentation and the stabilizing effects of policy hierarchization [54]. In this respect, policy systematization, prioritization, and integration are essential tools within the process of institutional emergence [55]. However, institutional simplicity by means of excessive hierarchization risks reducing the institutional fitness to govern the complex nature of social–ecological interlinkages within the Earth system. Accordingly, we should strive to maintain a balance between "the perils of institutional reductionism and institutional overload" [54]. It can be argued that two great pragmatist lessons lie at the heart of Elinor and Vincent Ostrom's theory of governance: the refusal of untenable dualisms balkanizing the theoretical space in supporters of states or markets, centralization or decentralization, and the proposal of a theory of governance based on a dynamic understanding of collective agency as a process of institutional emergence.

4.2. Framing Responsibility in the Cooperative Governance of Climate Change

As argued, a large scholarly literature has been accumulating on how cooperative governance offers a promising approach in the management of social–ecological systems in the face of climate change. Come to this point, some problems can be raised: if cooperative governance networks are not organized along hierarchical lines, how can collective responsibility be distributed back to individual actors in the absence of a central authority? Can governance networks properly discharge the collective responsibility for preventing climate change? How do these networks have to be designed in order to allow for the coordinated agency necessary to distribute responsibilities across a collective? This section will then take charge of laying the building blocks of such a theory of collective responsibility in governance networks by grounding it on the social ontology of shared agency [56]. Once this is accomplished, the ultimate goal will be to propose a theory of cooperative governance that can avoid the emergence of responsibility gaps like the Problem of Many Hands.

4.2.1. The Shortcomings of the Hierarchical Model

Let us, first, recapitulate the terms of the problem: humanity is the leading cause of climate change; this fact constitutes a prospective responsibility, i.e., a responsibility toward the future, to prevent this environmental crisis from occurring. As previously argued, prospective responsibility obtains when a societal actor is capable of moral agency, is causally efficacious in preventing the outcome to occur, and bringing about the outcome is normatively wrong. Van de Poel argues that only a form of organization based on *authority*, *coordination*, and *control* can properly discharge its prospective responsibility by creating effective mechanisms for distributing responsibilities at the individual level. Once this conclusion has been established, most authors within environmental ethics have focused on the role of national institutions in mitigating climate change. In fact, within this *hierarchical* approach, only national governments are regarded as bearing the collective responsibility for preventing the climate crisis due to their ability to properly discharge this responsibility through an organized and effective structure of decision-making, and therefore, be causally efficacious in solving it [17,20,34,36]. Accordingly, individual persons—but also other societal actors, which can be said to have an organized agency like firms, municipalities, regional institutions, etc.—are believed to lack a full responsibility to address the climate crisis, as they cannot be regarded as effective at mitigating the effects of global warming. Therefore, the argument continues, national governments bear the full responsibility to establish a set of global measures to grant a sustainable transition. Unfortunately, this solution is not fully satisfactory. What these authors seem to underestimate is the fact that the problem of responsibility is just moved to a higher level, but its structure remains the same since up until this point governments were not able to converge on the creation of a global institution. If we follow this hierarchical model, the absence of a global institution that can distribute collective responsibility implies the implosion of the individual responsibility of national governments to prevent climate change. Hence, it seems that governments are facing a paradigmatic case of the Tragedy of the Commons and, consequently, a paradigmatic case of the Problem of Many Hands. In fact, even if nation states could be, but ultimately are failing to be, causally efficacious in governing a sustainable transition (second condition for PR), it still seems problematic to regard such a failure as a form of wrong-doing (third condition for PR) because unilaterally restricting the consumption of the commons can be seen as both ineffective and unfairly competitively disadvantageous, and continuing to consume it as neither sufficient nor necessary to cause climate change. Accordingly, the international governance of climate change can be seen as another instance of collective responsibility without individual responsibility, and therefore, as an instance of the Problem of Many Hands. Reached this point, we encounter a dead-end: only national institutions can be causally efficacious in the transition and only to the degree that they converge on a global institution that distributes the collective responsibility for climate action among them; such an institution is missing, making the single countries ultimately not responsible. Which options remain available in this scenario? At this point, it is important to notice that a hierarchical approach rests on two basic assumptions:

- *Pragmatic assumption*: only national or international institutions are causally efficacious in tackling climate change;
- *Theoretical assumption*: only a hierarchical structure organized around a decision-making center can effectively distribute responsibility.

At the pragmatic level, it can be pointed out how between the first 100 global economic revenue collectors, only 29 are states, while 71 are corporations [57]. Even setting aside the mere question of economic power and resources, a study by the Climate Accountability Institute showed that just 20 companies have contributed to 35% of the global greenhouse gas emissions since 1965 [58]. Additionally, one can also consider sub-state institutions as a promising vector for effective change in sustainable governance; for instance, as Jordan argues, "more than 100 regional governments have committed themselves to reducing emissions by at least 80 per cent by 2050, a target exceeding that of most sovereign states" [44]. In fact, we assisted in recent decades to a flourishing of climate networks between actors as diverse as regions, such as the Governors' Climate and Forests Task Force; municipalities, such as the C40 Cities Climate Leadership Group, the Global Covenant of Mayors, and the International Council for Local Environmental Initiatives; and more broadly, a vast array of public–private partnerships. Once this is taken into consideration, it seems clear that a much larger range of social entities, from corporations to subnational actors such as regions and municipalities, can be causally efficacious in tackling climate change. Furthermore, at the theoretical level, the idea that only an organization structured along hierarchical lines can discharge our collective responsibility for climate mitigation is also questionable. Therefore, the main challenge of the next pages will be how to achieve an effective distribution of responsibility in cooperative governance networks. Our strategy will be to take the philosophy of shared agency developed by Michael Bratman in his Shared Agency: A Planning Theory of Acting Together [56] and argue that it can provide a theoretical grounding for the design of an organized distribution of moral labor in governance networks, so as to allow for the creation of responsible governance.

4.2.2. A Theory of Shared Agency: Five Design Principles for Cooperative Governance

Michael Bratman has spent his career working on a grand project aimed at the articulation of a full theory of human agency. Since his seminal work *Intention, Plans, and Practical Reason*, Bratman has focused on the crucial role of intentions in defining what constitutes the essential nature of our agency [59]. According to Bratman, an intention is essentially a plan to achieve a goal. Accordingly, what sets intentions apart from desires is their peculiar role in practical rationality to settle our conduct through time: intentional action does not derive from responding to the momentary whims of the will, but from following those ends that we decide to treat as the reasonable guides of our action through life. In the vocabulary of Bratman, intentions are characteristic psychological planning states that constitute higher-order, conduct-controlling pro-attitudes that settle upon deliberation our cross-temporal agency on certain goals [59–61]. For Bratman, every time we act intentionally, we respond to a cognitive structure of norms of intentional rationality, such as norms of (1) *plan–belief consistency*, as plans should be consistently grounded on our beliefs; (2) *means–end coherence*, as plans should be coherently supported by subplans that devise the right means to our ends; (3) *plan agglomeration*, as plans should consistently add together in a coordinated structure of agency over time; and finally, (4) *cross-temporal stability*, as plans should be stable in order to organize agency through time.

After sketching this general picture of intentional action, it is then possible to proceed to frame cooperative agency as a form of shared intentionality. As a matter of fact, Bratman has made a major contribution to the field of social ontology by creating a theory of shared agency that is grounded on the role of intentions in coordinating cooperation between agents [56]. According to Bratman, collective action can be analyzed under the lens of *shared intentions*; sharing a goal with others, in this perspective, constitutes the basic glue of sociality. In its most simple description, when a group of agents takes on a collective action based on a shared aim, we can formalize the intention of each of the members as expressing "I intend that we J" (where J is the shared activity): this structure of practical rationality is what allows the embedding of individual actions in a collective endeavor, and thus, to have *intermeshing intentions*. Bratman's thesis is that, as the normative structure of individual intentions is rich enough to grant intrapersonal coordination of individual agency across time, the very same normative structure can allow interpersonal coordination of individual agency across the social space. This mirrors the Nagelian recognition that we are, as rational agents, under the necessity of coordinating ourselves both intra-personally across time and inter-personally across social interactions [62]. Therefore, the same norms of practical rationality described above can supply the normative structure of our cooperative agency [56]. In this way, for Bratman, the four norms of individual practical rationality give rise to four associated norms of social plan–belief consistency, social means–end coherence, social plan–agglomeration, and social cross-temporal stability (or *social consistency*, *social coherence*, *social agglomeration*, and *social stability*). Therefore, we come to a crucial question for the development of a theory of cooperation: which are the essential rational conditions for achieving a consistent, coherent, and stable shared agency? Bratman's answer is that our shared agency meets the criteria for social consistency, coherence, and stability when these five conditions apply: (1) *intention condition*: each intends that we J and the intentions of each are interlocking (each intends to J by way of the intention of each that we J) and reflexive (each intends that we J by way of their own intention that we J); (2) *belief condition*: each believes that if the intentions of each in favor of J are persistent and interdependent, we will be effective at J-ing; (3) *interdependence condition*: each continues to intend that we J only if each continues so to intend such that there is interdependence in persistence; (4) *common knowledge condition*: it is common knowledge that 1–3 is occurring; (5) *mutual responsiveness condition*: each adapts their relevant subplans and actions by way of public mutual responsiveness to each other's sub-plans and actions in a way that keeps track of the shared intention to J by means of our intermeshing plans. When a collective agency is organized around these five conditions, we reach a form of cooperative agency. Hence, it can be suggested that Bratman's theory of shared agency can provide a rational structure for sketching some *design principles for cooperative governance*. Indeed, within Bratman's theory of shared agency, cooperation is bound to lose its gluing power as the number of decision-making centers scales up, but this does not imply that cooperation is less effective as we scale up the dimension of the governance units over which decision-making centers preside. It can then be advanced that governance networks are cooperative structures insofar as:

1. actors share a goal and elaborate interlocking and reflexive policies;
2. actors believe that if the policies are persistent and interdependent, the network will be effective in reaching the goal;
3. such policies are interdependent in persistence;

4. the network grants common knowledge to all actors by way of relevant information flow;
5. actors achieve mutual responsiveness in elaborating subplans, so as to achieve intermeshing of plans.

These conditions represent a set of practical rationality norms for the coordination of agency within cooperative networks and, it can be argued, they provide a set of design principles for cooperative governance networks. To the extent that polycentric networks are structured in such a way, they can be said to act cooperatively. Once these conditions apply within a governance network, the group can engage in a shared deliberation about the distribution of responsibilities among its members. Such a shared deliberation is a form of shared agency, first, because it is embedded within the shared intentional activity, second, because such deliberation is itself a form of shared intentional activity, and finally, because the proposals made within a shared deliberation are raised from within a structure of shared commitments to a common goal [56]. Therefore, when a collective is faced with a prospective responsibility within a cooperative agency structure, Bratman's theory provides the actors with the rational instruments for engaging in a shared deliberation that provides an agreed-upon policy that distributes responsibilities among the participants [56]. The five design principles for cooperative governance networks represent functional criteria for avoiding the fragmentation of agency and, hence, they constitute essential requirements for preventing responsibility gaps like the Problems of Many Hands. We then take Bratman's theory to provide the rational foundation for a theory of cooperation in governance networks. The capacity to effectively discharge the collective responsibility for preventing climate change is thus met without reference to an authority that delegates tasks, but by a shared deliberation based on common goals; interlocking, persistent, and interdependent policies; common knowledge; mutual responsiveness; and therefore, intermeshing plans.

4.2.3. Responsibilization: A Processual Account of Moral Change

One important consequence of developing this analysis of responsibility within cooperative governance is that our prospective responsibility for climate action can no longer be considered dependent upon a higher institution that takes charge to distribute it. Hence, the theoretical assumption of centralized approaches, according to which only a vertical institution can effectively discharge responsibility, has ultimately been demonstrated to be unwarranted. The moral consequence is that, at this point, responsibility falls back into the hands of the many actors that can be causally efficacious in preventing climate change by cooperating. As it was previously claimed, there is no reason for holding corporations and subnational actors like regions and municipalities as not causally efficacious in tackling climate change. This recognition amounts to a redistribution of moral labor from governments alone to a much larger array of societal actors, which share with these the prospective responsibility to coordinate and cooperate in order to mitigate the effects of climate change. In this regard, cooperative networks will vary in their degree of normative alignment: from relatively fragmented and voluntary forms of loose cooperation based on shared goals to increasingly organic and binding forms of tight cooperation, involving the emergence of shared normative practices of value setting, value prioritization, and finally, value operationalization by means of the systematic organization of an institutional body of norms. In a pragmatist spirit, we should see collective responsibility not only as an abstract requirement of practical reason but also as a concrete instance of moral evolution, as an emergent and continuous process of responsibilization in the face of a new societal challenge. Just as Ostrom provides us with an economic theory of institutional emergence in the face of social dilemmas, pragmatism can be regarded as complementary to Ostrom's analysis in proposing an ethical theory of moral emergence in the face of new practical problems. For this reason, we should avoid framing responsibility exclusively as the act of responding to abstract and universal reasons of morality; instead, we should complement it with an understanding of responsibility as a societal process of responsibilization in the face of the emergent threat of climate change. The concern for the top-down establishment of a series of moral and legal norms should therefore be accompanied by the articulation of a bottom-up process of decision-making that is characterized by participatory, transparent, and flexible procedures that allow for the development of shared goals, values, and norms.

To conclude, we should redistribute the moral responsibility for swift climate action from national governments to a much larger array of actors encompassing firms, municipalities, and subnational regions. This responsibility is based on their potential to be causally efficacious in preventing climate change and in their ability to create a spectrum of cooperative structures that can properly discharge the collective responsibility for climate action through shared policies. Therefore, states, regions, cities, and firms are not discharged of their individual responsibility to act until the establishment of a global institution. Accordingly, this implies a great reduction in the severeness of the moral dilemma that is the Problem of Many Hands regarding climate change. Where interests, goals, or values are aligned, the creation of cooperative networks should be regarded as a promising way to organize a process of responsibilization within the global governance of climate change. Waiting for a global agreement to discharge our responsibility to act might be a strategical failure and indeed a morally unwarranted conclusion. Therefore, the prospect of meaningful climate action at the global level is considerably expanded, even if it can still be difficult to attribute such a prospective responsibility to individual persons. Nonetheless, as many authors have emphasized, individuals still retain a prospective responsibility as citizens to mobilize in order to pressure states, regions, and cities to take serious measures to tackle the moral and ecological crisis that is climate change [20,25,63]. Furthermore, even if individual persons cannot be said to bear the full responsibility for climate action, it might as well be a question of moral integrity to be consequential with our political responsibilities and apply the sustainable behavior we ask of our governments to our individual lives [64,65]. Furthermore, it is possible to argue that individuals have a prospective responsibility as consumers to boycott, when possible, those corporations that are among the main contributors to climate change. These recognitions amount to a further weakening of the Problem of Many Hands regarding climate change, as the gap between collective and individual responsibility for single citizens is, ultimately, a matter of degree and not of sharp opposition. Furthermore, the fact that we might not be fully responsible for meaningful climate action at the individual level does not exclude the fact that we might find alternative ways of living sustainably that are still preferable and more meaningful. Indeed, the appreciation for nature, simplicity, and the ecological character of human life, while not part of what is morally required, acquires perhaps even more meaning in its gratuitousness.

5. Conclusions

In this article, I aimed to reconstruct how climate change has been formalized as a Tragedy of the Commons in economic theory and as a Problem of Many Hands in ethical theory. I then proposed a conceptual connection between these two dilemmas and claimed that whenever a rational failure like the Tragedy of the Commons occurs, a parallel moral failure occurs, namely, the Problem of Many Hands, since "free-riding" the commons is not irrational or irresponsible at the individual level, while it constitutes a rational and moral failure at the collective level. I then proceeded to analyze how classical solutions to both dilemmas, which are usually framed in terms of the establishment of vertical structures of decision-making, are not the only possible answer to the challenge of the responsible governance of climate commons. I take Elinor Ostrom's theory of polycentric governance as a promising candidate to complement this classical top-down model with a bottom-up approach based on horizontal structures of governing with increasing levels of cooperation. At this point, three questions have emerged: how can collective responsibility be distributed back to individual actors in the absence of a central authority? Can governance networks properly discharge the collective responsibility for preventing climate change? How must these networks be designed in order to allow for the coordinated agency necessary to distribute responsibilities across a collective? The theory of shared agency of Michael Bratman has provided, in this regard, the theoretical basis for sketching five design principles for cooperative governance networks. I argued that such networks can properly discharge responsibilities by engaging in a shared deliberation when cooperative networks are built around a shared goal; interlocking, persistent, and interdependent policies; common knowledge; mutual responsiveness; and thus, intermeshing of plans. I further claimed that we should frame collective responsibility not only as an abstract requirement of practical reason but also as a concrete evolutionary process of responsibilization. In the face of climate change, cooperative networks will certainly evolve in their degree of normative alignment: from fragmented and voluntary forms of loose cooperation based on shared goals to increasingly organic and binding forms of tight cooperation that involve the emergence of shared normative practices of value setting, value prioritization, and finally, value operationalization by means of the systematic organization of an institutional body of shared norms. The article has then contributed to show how institutional emergence and moral emergence can be analyzed as two aspects of a process of collective responsibilization.

Faced with the limits of the "technical resources" offered by economic rationality in a Tragedy of the Commons, Hardin wrote that the world "requires a fundamental extension of our morality" [18]. For Hardin, this was to be found in the coercive power of a Leviathan; I hope to have shown a way in which our morality can be fundamentally extended within a cooperative structure of collective agency.

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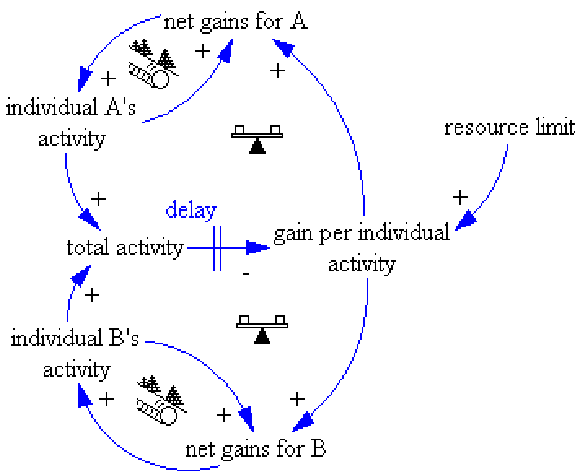
Climate change and the "tragedy of the commons"

by **WALTER ROBINSON**

"The tragedy of the commons" is familiar to anyone who has taken a course in environmental studies. We imagine a "commons", say a shared green where villagers pasture their cows. The quality of the resource inevitably declines as villagers put more and more cows out to pasture on the green, leading to overgrazing. They do this because each villager obtains *all* the gain from having one more cow to milk, whereas the cost of the degradation of the pasture is shared among all the villagers, so the cost to each villager is the total loss divided by the (presumably large) number of villagers.



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The "tragedy of the commons" (subsequently TTOTC) is also often applied to explain the overexploitation and subsequent collapse of commercial fisheries.

Recently TTOTC has been deployed to explain global warming. Superficially, at least, this makes sense. Earth's climate is, indeed, a global commons. Nearly everyone suffers if the climate is degraded. And the benefits one derives from actions that contribute to such degradation accrue to individuals. If I drive my car to the store I, and I alone, benefit, from the convenience of getting my groceries home quickly and easily, while the carbon dioxide my car emits contributes to the degradation of the climate that is shared by everyone.

Yet there is a critical way in which TTOTC does *not* apply to climate change, at least not the usual metaphors of a village green or a fishery. Consider, first, the village green. If I choose *not* to pasture another cow on the green, the grass will be a little better, and this will encourage others to pasture more cows. Similarly, in a fishery, if I keep my boat in port, others will have a slightly better catch, and they will keep there boats at sea longer to avail themselves of it. In both cases, my restraint in choosing not to overexploit a resource has no beneficial effect, since others quickly snap up whatever resource I leave "on the table."

But this is *not* what happens in global warming. In no way do my efforts to reduce emissions of heat trapping gases encourage or incentivize others to emit more. Simply put, when I reduce my emissions, the atmospheric burden of heat trapping is reduced, however slightly, leading to reduced (again, if slightly) climate change, resulting in reduced damage to the planet and reduced human misery. In short, *any* reduction I make in my emissions is an unalloyed good.

This is a striking and important way that climate change differs from the standard examples of TTOTC, yet it does not seem to be widely appreciated. On the contrary, whenever there is discussion of a national policy (in the US) to reduce emissions, someone is sure to say "but what about the Chinese?" As if, somehow, reduced emissions of heat trapping gases by the US will incentivize the Chinese to pollute more. In fact, the opposite is likely the case. As we emit less, this leads to technological developments, such as in clean energy, that enable reduced emissions everywhere. And US leadership in reducing emissions can produce social and geopolitical pressures that encourage others to pollute less. But even without such "knock-on" benefits, there is the simple fact that a ton of CO2 we do not emit – be it from our town, our university, our state or our nation – is a ton of CO2 that is not in the atmosphere wreaking current and future climate mayhem.

This is a hugely optimistic understanding, It tells us that efforts to reduce emissions on any level – personal, campus, community, state – are intrinsically beneficial and worthwhile, and we should go forward with them, whether or not there is effective climate leadership at the national and global levels. An example is what is happening right now in my State of

North Carolina, where, under the aegis of Governor Roy Cooper's Executive Order 80.we are in the midst of the bottoms-up, stakeholder (who, on Earth, is *not* a stakeholder in the climate?) driven development of a clean energy plan for North Carolina. As a participant in this process, I am encouraged by the commitment of participants, from many sectors, including the energy sector, to set North Carolina on the path to greatly reduced emissions of heat trapping gases.

One can imagine this process is being repeated by thousands or tens of thousands of entities, each one exerting its agency to reduce the damage global warming is wreaking on our planet. While it remains to be seen if this will work, or at least work well enough to avert a global climate catastrophe, it is only because the contributions made by each entity to reduce emissions are truly additive that it stands any chance of working. Unlike in a village green or a fishery TTOTC does not apply, and there is no inexorable dynamic that drives our climate to a tragic end.

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