Assessing the Macro-Critical Impacts of Climate Change: Key Considerations for a Research Agenda[1]

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Abstract: The assessment of climate-related economic impacts and the formulation of effective policies present significant analytical challenges. This paper explores these challenges by examining the socio-economic system's key characteristics, such as uncertainty, nonlinear shock transmission, and socio-economic tipping points, which are essential for evaluating climate impacts and devising decarbonization strategies. The study identifies the most pertinent avenues for improving diagnostic and analytical tools used in the macroeconomic evaluation of the physical impacts of climate change, as well as the risks and opportunities associated with low-carbon transition policies. Furthermore, it advocates for a collaborative approach to integrate these insights into global development strategies. These findings aim to support policymakers in addressing climate challenges and promoting sustainable development.

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1. Introduction

Climate change is increasingly causing more frequent and intense *acute* extreme weather events such as droughts, floods, tropical cyclones, and wildfires (IPCC 2021, 2023). The World Meteorological Organization reported that 2024 set new climate records, signaling an escalating crisis (WMO 2024). However, the extent of climate change impacts is anticipated to intensify based on the specific emission trajectories and temperature pathways that the world ultimately follows. Yet, climate impacts are unlikely to occur in isolation. Instead, they may compound with various socioeconomic crises—such as the enduring effects of the COVID-19 pandemic, geopolitical tensions like the Russian war in Ukraine, and the 2023 El Niño phenomenon—potentially amplifying the overall impact of climate change (World Economic Forum 2023; NGFS 2023, Dunz et al. 2023).

A low-carbon transition to stop growing climate change, in turn, will require climate policies to guide structural economic changes, creating winners ('sunrise industries') and losers ('sunset industries') in the transition phase. Entire sectors could be driven out of business, which could expose countries to fiscal, socioeconomic and financial losses (Espagne et al. 2021; von Dulong et al. 2023) and lead to abrupt financial asset revaluation and stranded high-carbon assets (Battiston et al. 2017; Caldecott 2018; Mercure et al. 2018; van der Ploeg and Rezai 2020; Semieniuk et al. 2022). At the same time low-carbon transition has the potential to generate opportunities by boosting technology and innovation (Grubb et al. 2021), reduced energy costs and cross-border dependency (Mercure et al. 2021), more efficient resource allocation, and co-benefits such as lower air pollution (Andersen 2017; Markandya et al. 2018).[1]

Despite advancements over the last years (e.g., Varga et al. 2022; Dunz et al. 2023; Hallegatte et al. 2024; Schoder and Tercioglu 2024), many macroeconomic models still struggle to grasp and model critical characteristics of climate impacts and the low-carbon transition. There is a stark disjoint between macroeconomic analyses of physical impacts and climate policy informed by physical science (IPCC 2021, 2022a, b, 2023; Woillez et al. 2020). For example, the most well-known climate economics model, DICE (Nordhaus 1993), projects only minor economic damages by 2100 (Nordhaus 2018).[2] Yet, damage estimates are recurringly revised upwards with every update of the model (Barrage and Nordhaus 2023). Empirical cross-country evidence, using historical climate patterns also do not attest to large economic damages (Kahn et al. 2021).

The prevailing uncertainty surrounding climate change, coupled with our still developing understanding of its impacts, can lead to inaccuracies in modeling climate-related effects. These inaccuracies are problematic as they may result in underestimating both the severity of climate shocks (Stern et al. 2021) and the benefits of climate mitigation and adaptation policies (Koeberle et al. 2021; Anand et al. 2023).[3] This could discourage and delay action as it undermines the consensus building needed to incorporate climate considerations into the core macroeconomic policy of ministries and central banks (IMF 2022; IMF 2023; Kuik et al. 2023). Because of estimated small impacts, policy dilemmas arise where a global concerted effort to reduce climate change becomes a strategic game where only some participate, and others continue the status quo (Pindyck 2012). In contrast, a more accurate and nuanced assessment of climate impacts and opportunities could better indicate trade-offs, policy and financial needs for addressing and coping with climate change. Hence, these issues need to be addressed. Otherwise, climate mainstreaming efforts could remain fragile.

However, current research on climate change faces significant challenges in adequately capturing the full scope of climate-related impacts on global development and economic stability.

Specifically, the literature reveals gaps in understanding how uncertainty, non-linear transmission channels, and socio-economic tipping points may amplify climate impacts and change the nature of optimal climate policy, respectively. These gaps hinder the development of robust strategies for adapting and mitigating to climate change, particularly in terms of evaluating expected climate damages, assessing financial risks like stranded assets, and designing optimal climate action.

To address these critical challenges, this paper reviews the literature to identify key issues and gaps in climate impact and policy analysis while suggesting future research directions alongside three core themes: uncertainty, non-linear transmission channels, and socio-economic tipping points.

Better understanding the implications of uncertainty associated with climate change is important as uncertainty influences investment decisions, a key driver of economic growth (Bloom et al. 2018; Auffhammer 2018; Pindyck 2021). The paper explores the current literature and prevailing gaps on the role of policy credibility in shaping investor sentiments and the risks posed by sudden policy changes, particularly in assets like coal, which could lead to significant financial instability (NGFS 2019; van der Ploeg and Rezai 2020).

Another important feature for better understanding climate change is how climate-related impacts propagate through socio-economic systems, potentially leading to non-linear amplification impacts. For physical impacts, the paper highlight key mechanisms such as cascading impacts (Baqaee and Farhi 2019), compounding effects (Zscheischler et al. 2018) and protracted effects (Lukasiewicz and O'Donnell 2022). For transition impacts, it explores how policy interactions (Acemoglu et al. 2016) can intensify climate shocks across the economy. The section focuses on understanding non-linear effects from multiple climate and policy shocks, crucial for effective mitigation strategies, and emphasizes the importance of policy complementarity and the complex dynamics of investment irreversibility (Landeri 2018).

Finally, the paper discusses how climate change can trigger significant, often irreversible shifts in socio-economic systems. These tipping points represent a specific form of non-linearity, where small changes can lead to large, transformative impacts (van Ginkel et al. 2020). The section discusses the challenges of modeling these tipping points, the importance of defining stable states, and understanding transitions between them. Identifying and anticipating these tipping points is essential for developing effective transformative policies and harnessing opportunities for positive change (van der Ploeg and Venables 2022).

These insights offer significant potential to mainstream climate change considerations into macroeconomic diagnostics, such as those used in comprehensive country assessments, financial stability analyses, and debt sustainability evaluations, which ultimately inform policy advice and decision-making processes. Those insights can also be instrumental in designing mitigation and adaptation policies. Enhancing this capacity will directly benefit governments and policymakers by providing a better understanding of the critical drivers of climate impact amplification. This, in turn, can improve the allocation of limited public financial resources and lead to the design of policies that incentivize private sector action.

The remainder of the paper is organized as follows. Section 2 examines fundamental typologies of uncertainty and explores the role of policy credibility in shaping investor sentiments. Section 3 explores how climate-related impacts propagate through socio-economic systems focusing on cascading impacts, compounding effects, protracted effects, and policy interaction effects. Section 4 examines the relevance of socio-economic tipping points. Section 5 concludes with implications for improving policy-making by addressing key challenges like uncertainty, non-linear transmission channels, and socio-economic tipping points in climate change and the low-carbon transition.

2. Dealing with uncertainty and the role of policy credibility

2.1. Physical risks

The vast range of potential climate damages and remaining multiple sources of uncertainty present significant challenges in accurately capturing the costs of future climate impacts and the associated risks, relevant for climate policy design. Traditionally, the literature has approached this challenge by reporting damage projections through GDP loss and other macroeconomic variables as either point forecasts or probability distributions over climate shocks for different climate scenarios but then often reverting to the mean for the projections, thereby neglecting potential tail risk. However, while this is consistent with much of the climate macroeconomic literature and forecasting traditions, the focus on point forecasts tends to give limited attention to tail risks and uncertainties, particularly in a situation where assigning probabilities is challenging. To more effectively capture the risks posed by climate impacts, it's crucial to better represent uncertainty (please see Appendix I for a high-level typology of uncertainty), offering a broader range of severe yet plausible outcomes that align with policymakers' concerns. Improving how standard tools simulate climate impacts is critical, as multiple sources of uncertainty significantly expand the range of potential climate damages.[4]

Uncertainty shocks affect how economic agents form expectations about the future which in turn shapes their economic behavior. For instance, consider the effect of global warming on agricultural output: It is well understood that a higher mean temperature (first moment) may reduce agricultural output on average. However, also a mean-neutral increase in the variance of the temperature distribution (second moment) may reduce the incentives to invest in agriculture because droughts (extreme realizations of the temperature distribution) become more frequent. The second moment measures the spread of a distribution, which is a measure of risk. It is critical to understand that even the mere expectation of such shifts in the temperature distribution may impact economic decision making and thereby create economic costs. Macroeconomic models with rational expectations are typically solved by linear approximation around the steady state. This, however, only allows to study the first moment (mean) of climate impacts because the assumption of certainty equivalence renders shifts in the second moment irrelevant for economic behavior.

A substantial body of research, both theoretical and empirical, has explored how increases in mean-neutral variance within the distribution of climate shocks, influence economic behavior and macroeconomic outcomes. The finance literature has long highlighted the importance of higher-order moments in economic behavior, particularly the relationship between climate risk and financial markets. This research focuses on integrating climate risk uncertainty into financial models and evaluating its impact across different asset classes. Key questions include how climate risk, through its effects on asset prices and risk perceptions, might alter risk premia in financial markets and impact financial stability (Giglio et al. 2020; Battiston et al. 2021; Venturini 2022; Barnett 2023). Moreover, uncertainty shocks have also gained increasing interest within macroeconomics (Bloom 2009; Christiano et al. 2014; Bloom et al. 2018; Fernández-Villaverdea and Guerrón-Quintana 2020; Fernando et al. 2021). Methods have been developed to address these shocks by solving non-linear rational expectation models without relying on linear approximations.

Theoretical and empirical exploration of how increased variance in climate shocks affects economic behavior can deepen our understanding of climate-related economic impacts, as it incorporates economic agents' expectations and responses under uncertainty. This is relevant as risk and uncertainty and respective behavior provide another layer of shaping climate physical impacts on top of the actual physical events.

The literature further underscores the importance of exploring shifts in uncertainty and expectations on the theoretical front within the realm of climate policy modeling. This exploration is essential for understanding how changes in the variance of uncertain events and associated expectations can affect outcomes. Models that adhere to a full-probability approach, incorporating both equations and stochastic elements like shock variances, are crucial for assessing the frequency and impact of extreme weather events. Key methodologies for modeling and estimating uncertainty shocks, including insights from Fernández-Villaverde and Guerrón-Quintana (2020), provide foundational methods for modeling and estimating uncertainty shocks. Additionally, this discussion points to the limitations of the rational expectation solution, suggesting that integrating actual expectations through a weighted average between adaptive and rational expectations.[6]

On the purely empirical front, regression methods could be used to explore the relationship between macro variables and proxies for uncertainty. Measuring uncertainty and its causal impacts on economic outcomes presents significant challenges in empirical research. Various methods have been proposed, including the volatility of macroeconomic variables (Jurado et al. 2015) and financial market indicators, such as the VIX index (Whaley 2000), dispersion in firm-level cross-sections (Christiano et al. 2014), dispersion in analysts' forecasts (Bachmann et al. 2013), and the frequency of uncertainty-related keywords in news (Baker et al. 2016; Xu et al. 2019). Among these methods, the well-known measurement estimation of Bloom (2009) and Baker Bloom, and Davis (2016) can be applied to relate peaks and drops in a *climate news index* (see Engle et al. 2020) with changes in economic activity, for instance, with a simple VAR or local projection and to obtain an estimate of the effects of this news on output, inflation, and other variables of interest.

To synthesize the effect of increased uncertainty, particularly related to the second moment, in a more aggregate setting, a reduced form of the impact of uncertainty on TFP could be developed for broader operationalization. An environment of increasing uncertainty could alter the expected process of technology diffusion and generate new inefficiencies in the optimal use of factors of production, thus reducing the potential output of an economy. For instance, total factor productivity would be an important channel of capturing the implications of increased uncertainty due to climate change in the economy, altering productivity of capital and labor and thus spreading through the economic system.

2.2. Transition impacts: policy credibility and financial risks

The relevance of climate policy credibility

Policy credibility is crucial in the transition to a low-carbon economy. Its significance lies in shaping forward-looking and model-consistent expectations, which are essential for accurately capturing the implications of future transition impacts. Modeling forward-looking and model-consistent expectations helps understand the immediate effects of policy under varying levels of credibility, as well as future climate damages. While bounded rationality and market rigidities limit the influence of rational expectations in decision-making, this approach significantly impacts the range of policy options. The importance of forward-looking expectations and policy credibility underscores the need to explore institutional arrangements that align policymakers' interests with the low-carbon transition (Nordhaus 2015; Pahle et al. 2022). On the adaptation side, such models

Figure 1. The role of expectations for the low-carbon transition.

might be able to capture structural economic changes if firms avoid investing in future disaster-prone areas.

Expectations play a key role in determining the trajectory of the low-carbon transition (Fried et al. 2021). Economic agents make investment decisions under uncertainty, heavily relying on stable policies and market conditions. These expectations are influenced by the perceived strength and timing of climate mitigation efforts, such as carbon pricing (World Bank 2022). For instance, recent research indicates that firms' and investors' expectations about future climate policies could make a difference for a smooth low-carbon transition (Battiston et al. 2021; Dunz et al. 2021; Gourdel et al. 2022; Bauer et al. 2018). Climate transition risks, stemming from sudden and uncoordinated climate policies, technological disruptions, and shifts in consumption patterns, have the potential to render entire sectors obsolete. This can lead to sudden revaluation of financial assets and result in stranded high-carbon assets (Battiston et al. 2017; NGFS 2019), negatively affecting both the real economy and government finances (Dunz et al. 2021).

Credible climate policy commitments can lead the private sector to front-load low-carbon investment (Fuchs et al. 2024), reducing the risk of stranded carbon assets (Atanasova and Schwartz 2019). Macro-financial linkages through balance sheet dynamics in the banking sector are sensitive to shocks to expectations and volatility. The divergence in expectations about the low-carbon transition's credibility is illustrated by the Russian invasion of Ukraine's impact on stock prices. After the invasion, U.S. stocks exposed to transition risks surged, while European stocks remained stable or declined (see Figure 1). This suggests that investors expected differing impacts on climate policy, with Europe accelerating its clean energy transition and the U.S. slowing it down (Deng et al. 2022).

Despite its significance, there is limited research on how investors and firms respond to climate change (Hass et al. 2023).[7] Although still a developing field, studies by Corugedo, Gonzalez, and Guerson (2023) utilized a DSGE model with regime-switching rational expectations to assess the macroeconomic benefits of investing in resilience against natural disasters. Moreover, while much of the existing literature treats policy uncertainty as an external factor, von Dulong et al. (2023) argue that optimal policy should consider capital stocks, which are influenced by policy expectations. While some studies integrate capital stranding with heterogeneous expectations

(Cahen-Fourot et al. 2023; Campiglio et al. 2023), most other assume homogeneity (Baldwin et al. 2020; Campiglio et al. 2022; Rozenberg et al. 2020). Some research also shows that the most ambitious commitments can also be the most credible, highlighting the importance of strong political institutions in supporting these efforts (Campiglio et al. 2023; Victor et al. 2022). Nonetheless, studies that connect expectations to the problem of policymakers' time inconsistency, as well as the uncertainty related to policy that firms and investors confront during investment decision-making, are still limited.

Challenges for making credible climate policy commitments

The UN Climate Change Conference (COP28) (UN 2023) and the Climate Summit (IP1 2023) emphasize the need for utmost ambition in climate policies. The IPCC (2018) highlights the urgency of cutting greenhouse gas emissions by half from 2019 levels by 2030 to limit global warming to 1.5°C, yet current NDCs are more aligned with 2.7°C. This gap underscores the need for stronger policies, particularly in the energy sector (Black et al. 2023). Despite commitments, the credibility and actual implementation of climate policies remain inconsistent, as evidenced by fluctuating support for clean energy in Europe and the U.S., and reversals in Australia's carbon pricing (Sendstad et al. 2022; Bakhtiari 2018). Market failures and financial constraints also hinder investments in low-carbon development.

The primary challenge lies in aligning long-term environmental objectives with immediate economic and political pressures. Transitioning to a greener economy involves short-term costs, but delays can lead to substantially higher future expenses (IMF 2022; Kuik et al. 2023; Caldecott et al. 2021). Carbon pricing is considered as a key element to the low-carbon transition, but political factors make removing subsidies or raising carbon taxes difficult. Instead of delaying reforms, forward guidance and expectations management can be effective in promoting the transition. While governments may avoid immediate tax hikes or subsidy cuts during high energy prices, they can commit to increasing carbon price trajectories. The key question is what institutional arrangements can ensure these commitments are seen as credible by the private sector.

The interaction between fiscal constraints and climate policy presents a trilemma for policymakers, balancing climate objectives, debt sustainability, and political feasibility (IMF 2023; Dunz et al. 2021; Ferdinandusse et al. 2024). Fiscal considerations and political factors such as lobbying may further exacerbate issues of time inconsistency (Kalkuhl et al. 2020). Especially in countries with limited fiscal resources, pursuing environmental objectives can significantly increase public debt and pose financial challenges. Current strategies to achieve net-zero emissions heavily depend on subsidies and public spending, which are expected to raise public debt by 40-50 percentage points relative to GDP in both developed and emerging economies by 2050 (IMF 2023). This is particularly problematic for countries with restricted fiscal room, low tax capacity, and limited access to market financing, all of which compound adaptation costs. Fiscal policy constraints, like the impracticalities of using non-distortionary taxes and issues such as welfare considerations and information asymmetries, add further complexity to the situation (Fischer 1980).

The complexity of climate policies arises from the interactions between various tools, making it essential to recognize these interactions for effective implementation. Balancing credibility in monetary and fiscal policies, aligning short-term and long-term goals, and coordinating domestic and international efforts are critical (Carney 2015; Diluiso et al. 2021; Campiglio and Ploeg 2022; Nemet et al. 2017). Drawing on Kydland and Prescott's work on time-consistent policy-making, these strategies are crucial in climate policy to avoid short-term pressures that may lead to backtracking on carbon commitments (Brulle 2018; IMF 2022).

The time-inconsistency of policy presents a significant challenge for policymakers, particularly in maintaining credibility. Net zero goals set fixed timelines and emission levels, but new economic or political developments could necessitate adjustments (Campiglio et al. 2023; Dolphin et al. 2023). Political pressures, such as elections, can lead to short-term decisions that conflict with long-term commitments (Kalk and Soger 2023; Harstad 2020), and economic agents doubt the credibility of commitments unless substantial costs are linked to deviations. Political-economic barriers, such as opposition from industries invested in polluting technologies, also challenge climate policy implementation and can lead to conflicts over stranded assets (Jenkins 2014; Bertram et al. 2015; Vogt-Schilb and Hallegatte 2017; Rozenberg et al. 2020; von Dulong et al. 2023). The influence of oil and gas lobbyists at COP28 (Meredith 2023) and the Yellow Vests protests in France highlight public resistance to policy changes, requiring a balance between public sentiment and policy enforcement (Kalk and Sorger 2023).

Striking the balance: credibility and flexibility in climate policy design

Achieving net-zero targets requires a multi-faceted approach. Realistic policy recommendations must consider political feasibility (Acemoglu and Robinson 2013) and social challenges (Caldecott et al. 2021). While economists favor carbon pricing for its economic efficiency, actual implementation often needs additional measures to address distributional issues and political resistance. To ensure that these ambitious targets are durable and enforceable, incorporating net-zero goals into domestic law and developing specific emission reduction policies are essential steps (Hilson 2020; Carver 2021). Countries like Sweden, the United Kingdom, Australia, Japan, Korea, Canada, New Zealand, and Nigeria, and the European Union, have enshrined net-zero targets in law (Carver 2021), but legal mandates alone are not sufficient. Policy design must remain adaptable to evolving climate challenges, integrating new information and adjusting to changing conditions while maintaining credibility for long-term success (Nemet et al. 2017).

Reducing uncertainty by strengthening policy credibility is essential for stabilizing expectations and fostering confidence in the low-carbon transition. Institutional solutions are key to anchoring private sector expectations. For instance, institutional solutions, such as sovereign sustainability-linked bonds (SLBs) pioneered by Chile (Ministry of Finance of Chile 2024) and Uruguay (Ministry of Economy and Finance of Uruguay 2024), and the Climate Asset and Liability Mechanism (CALM) proposed by Warwick McKibbin, can anchor private sector expectations and incentivize governments to meet their decarbonization targets (Academy of Social Sciences in Australia 2020). This approach prices carbon annually out to 2050 through a hybrid approach of combining trading of long-term carbon certificates in fixed supply with a fixed short-term certificate price achieved by a climate bank intervening in the carbon market. This measure would create a constituency with a financial interest in the low-carbon transition.

Future studies should explore the macroeconomic effects of different climate policy designs and their implementation, comparing the impacts of a sudden, unexpected policy announcement (i.e., a disorderly transition) versus a gradual and orderly policy shift. It is anticipated that investor responses and corresponding asset valuations will drive macroeconomic outcomes in these models. Advancements in financial sector modeling and the incorporation of financial frictions could greatly enhance understanding in this area. Developing a richer financial-macroeconomic nexus would illuminate more nuanced and potentially overlooked transmission channels, highlighting possible amplification effects.

3. Non-linear transmission channels

Another important feature of better understanding potential macro-critical implications of climate change is to better understand how these risks propagate through the socio-economic system, potentially leading non-linear amplification effects. We identify key transmission channels characterizing how climate impacts and policy shocks propagate through the socio-economic system on a micro, sectoral, and macro level. The focus lies on non-linear effects arising from the cascading of micro-economic climate shocks to macro-economic outcomes (Baqaee and Farhi 2019), the interaction and amplification of multiple climate shocks with interacting effects (Dunz et al. 2021; Zscheischler et al. 2018), the combined effects of multiple policy instruments with interaction effects which motivates policy complementarity and a smart policy mix (Acemoglu et al. 2016), as well as the irreversibility of capital investment (Landeri 2018) which has critical repercussions for the risk of stranded assets.

It is important to note that a variety of transmission mechanisms frequently interact to disseminate a single climate-related impact, with the perception of risk serving as a critical factor in its amplification and distribution (Challinor et al. 2018). These include both direct effects of climatically generated complex risk transmission and indirect effects stemming from behavior - driven risk transmission, such as those influenced by expectations, policy credibility, and interactions (Figure 2).

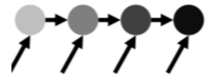
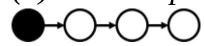
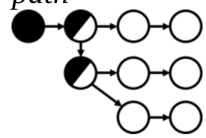
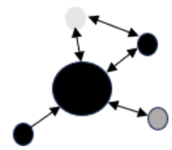
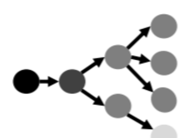
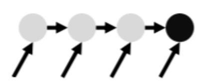
3.1. Cascading, compound, and protracted Impacts

Climate-related impacts could transmit through the economy in multiple fashions (see Table 1 for an overview) with different macroeconomic implications. Physical impacts could induce *cascading effects*, if impacts exceed the ability of different components of the system (e.g., firms along a supply chain) to absorb the shock (i.e. a domino effect). Hence, initially small shocks could have macroeconomic impacts. *Compounding impacts*, such as from COVID-19 and extreme weather events (Dunz et al. 2021; Ringsmuth et al. 2022), could further lower the resilience threshold of economic agents. The combination of climate shocks with existing macro-financial vulnerabilities can exacerbate social and financial risks, resulting in disproportionately large economic damage (Ranger et al. 2021).

To effectively manage and mitigate climate-related risks, it is essential to understand better the pathways through which these impacts propagate within the climatically generated complex risk transmission and economic behavior-generated risk transmission (Monasterolo et al. 2021; Challinor et al. 2018). However, gaps in the current literature, including ambiguous terminology and limited exploration of interactions between protracted, compound, and cascading risks, complicate the quantification of these risks and limit the precision needed for accurate assessments (Pescaroli et al. 2018; Cradock-Henry et al. 2020). These issues complicate our understanding of risk transmission within these specific channels, as highlighted in Figure 2.

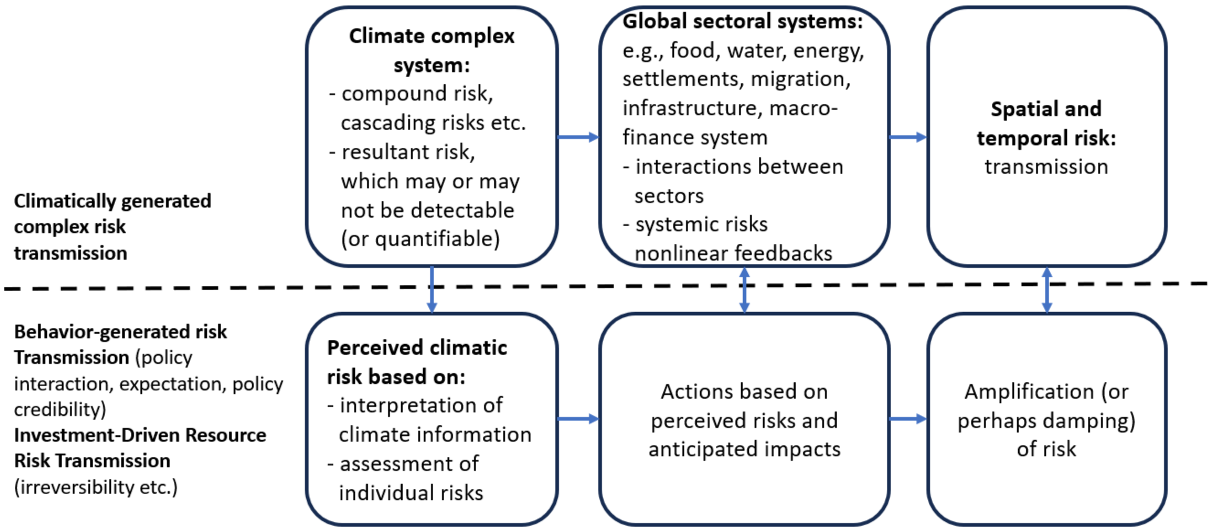
The IPCC has made efforts to define certain terms like "compound risk." However, issues arise with risk quantification because the IPCC categorizes compound events into discrete categories (Leonard et al. 2014). This approach may not adequately capture the complexities of risk dynamics (Pescaroli et al. 2018). While definitions for compound risks evolve (Table 1), the precision in their boundaries and quantification remains a challenge (Zscheischler et al. 2020; NFGS 2023; Simpson et al. 2023; Lukasiewicz and O'Donnell 2022). Moreover, IPCC lacks clear definitions for other complex risks such as "cascading risks" and "protracted risks which can lead to conceptual confusion and difficulties in policy interpretation (see Simpson et al. 2021 for a list of with and

Table 1. Complexity of climate change processes and interactions

Effects	**Illustration**[8]
Cumulative effect: Incremental impacts (e.g., fossil fuel generation) could cumulate over time, leading to "tipping points".	
Cascading effect: Cascading impacts from extreme weather/climate events occur when an extreme hazard triggers a chain of secondary events across natural and human systems. These secondary events lead to disruptions that are physical, natural, social, or economic in nature. Cascading effects can follow either a linear or nonlinear path, determined by whether the sequence involves amplifying factors and subsidiary disasters (IPCC 2022c; Pescaroli and Alexander 2015; Pescaroli and Alexander 2018; Simpson et al. 2023).	*(a) Linear path*  *(b) no-linear path* 
Compound effect: Compound risk refers to the risk arising from a combination of multiple drivers and/or hazards, impacting society and/or the environment. Physical climate-related compound shocks involve at least one climate-related event compounded with another shock, which may or may not be climate-related. These shocks are categorized based on their interrelations—preconditioned, multivariate, temporally compounding, or spatially compounding—and their origin systems as either physical climate, transition climate, other environmental, or non-environmental (Zscheischler et al. 2018, 2020; Bevacqua et al. 2021; Simpson et al. 2021; NGFS 2023).	
Protracted effects: It refers to the long-lasting impacts of a disaster or crisis that persist over time without clear beginnings or endings. These effects evolve slowly, lacking distinct phases, making them difficult to manage. Examples include the prolonged impacts of climate change, like extended droughts or rising sea levels, which continuously affect communities, economies, and ecosystems (Hsu 2017; Cutter 2020; de Brito 2021; Lukasiewicz and O'Donnell 2022; Staupe-Delgado 2019).	
Ripple effect: Climate change could have a ripple effect on other crises (e.g., nature/biodiversity loss). For example, CO_2 can lead to ocean acidification, which could warm oceans and impact coral ecosystems. This could in turn lead to migration of coastal populations.	
Tipping points: Socioeconomic tipping points could emerge with potentially irreversible impacts. Technology is a case in point. Once the adoption rate of low-carbon technologies has passed a critical threshold, network effects and economies of scale could lead to a new equilibrium.	
Feedback loops: Feedback loops could either worsen or strengthen the initial driver over time. They consist of chains of cause and effect where an initial effect is fed back into the system to influence subsequent actions. This cycle can either reinforce the initial action (positive feedback) or counteract it (negative feedback).	

Source: Adapted from IAA Climate Risk Task Force (2021) and Simpson (2021)

Figure 2. Pathways of behavior and investment driven resource generated risk transmission, and climatically generated risk transmission.



Source: Authors' adaptation based on Challinor et al. (2018).

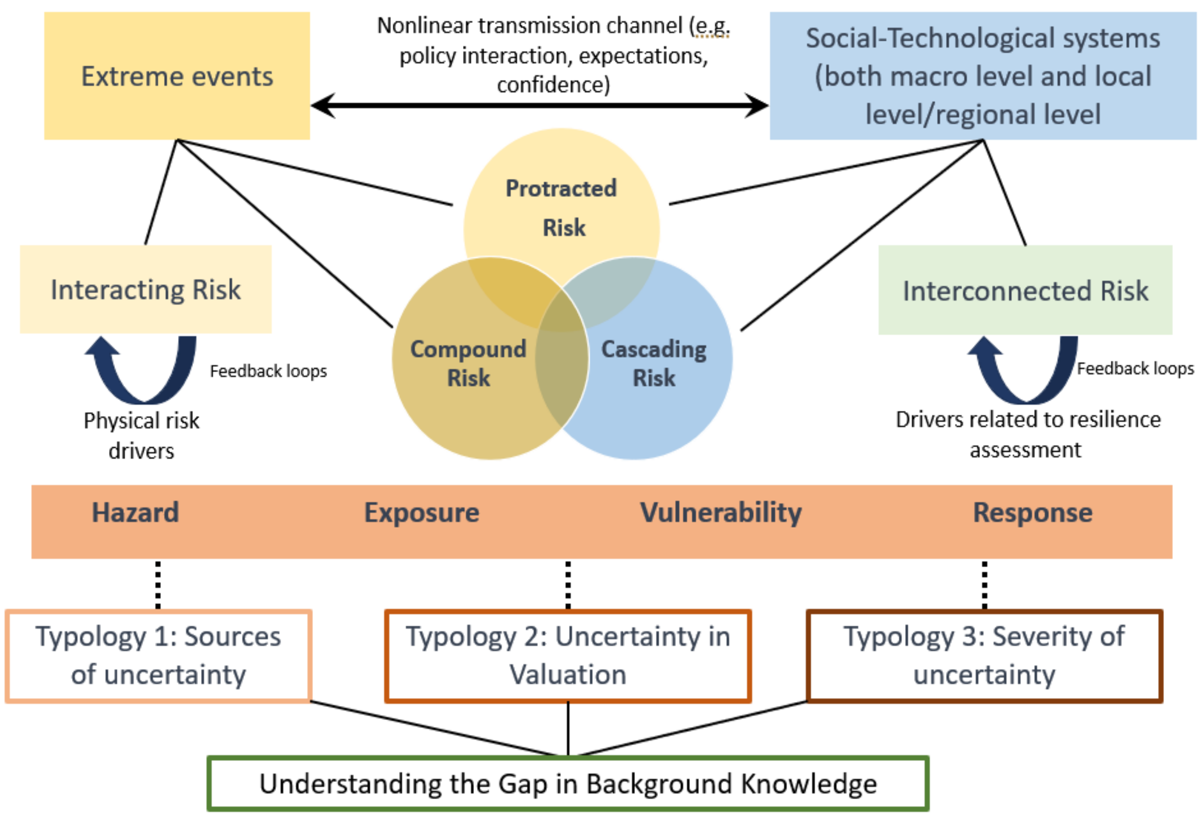
without an IPCC definition).

Additionally, the interaction between protracted, compound, and cascading effects is underexplored, despite its critical importance. Climate change impacts require a broader understanding that includes both sudden extreme events and the more subtle, ongoing changes that are frequently neglected in contemporary research (Lawrence et al. 2020; Lukasiewicz and O'Donnell 2022). Protracted effects—those with unclear beginnings and endings that persist over long durations—intersect with other risks, creating complex, evolving challenges (Figure 3). Although some studies have begun to investigate these interactions, much remains to be explored (Leonard et al. 2014; Kruczkiewicz et al. 2021; Lukasiewicz and O'Donnell 2022; Hsu 2017; Cutter 2020; de Brito 2021; Staupe-Delgado 2019).

Most current research on non-linear climate impacts relies heavily on qualitative methods, such as narratives and expert insights. While these approaches provide valuable perspectives, they lack the capability to model complex interactions quantitatively (Simpson et al. 2023; Lawrence et al. 2020; Zscheischler et al. 2020). This creates a significant gap in evaluating interconnected impacts, necessitating advanced analytical tools to better capture and predict the dynamics of climate variables (de Brito 2021). This is especially true for the interaction within and across production networks (Baqaee and Farhi 2019; Fernandes and Ferreira 2023). While similar dynamics have been studied in disaster risk and networked infrastructures (AghaKouchak et al. 2018; Alexander 2018), empirical studies in climate change are sparse, leading to significant underestimations of risks and (Cradock-Henry et al. 2020; Lawrence et al. 2020).

Network models offer a promising approach to assessing these challenges. These models are valuable for assessing how network disturbances can exacerbate initial shocks, emphasizing the importance of node locations within economic and financial systems (NGFS 2023). For instance, a promising approach is provided by Baqaee (2018) and Baqaee and Farhi (2019), who develop a

Figure 3. A Holistic Framework for Complex Effects



Source: Adapted from Pescaroli and Alexander (2018)

framework of network linkages through which microeconomic shocks can have macroeconomic impacts (see Appendix IV). Despite the potential of these models, there remain knowledge gaps in how these interactions can be appropriately captured within macroeconomic frameworks to assess their long-term impacts.

Addressing these gaps is vital for understanding how economic components interact and transmit during crises, particularly in EMDEs, where infrastructure and resources are limited. Building resilience involves either moderating or mitigating initial shocks early on or ensuring quick recovery from cascading impacts, such as through rapid access to finance for rebuilding, thereby helping to avoid the amplification of risks (Colon et al. 2020).

3.2. Non-linear policy shock transmission: policy interaction and irreversibility of capital investment

Policy interaction

The interaction between different policy instruments is receiving increasing attention. In a second-best world situation as we are in, multiple climate policy interventions could be welfare enhancing compared to a singular carbon price (Lipsey and Lancaster 1956; Stiglitz 2019). Multiple market failures exist, ranging from carbon emission externalities (Pigou 1932), over technological (Popp 2010; Acemoglu et al. 2012) and network (Springel 2021) externalities, to information asymmetries and the tragedy of the horizon (Carney 2015). This deems the use of complementary climate policy instruments beneficial. For instance, a carbon tax is more effective in reducing emissions when firms can easily switch to renewable energy. Public investment in renewable infrastructure enhances the effectiveness of carbon pricing. However, most models currently struggle to capture the non-linearities that emerge from these policy interactions.

The impact of combining different policies is not simply the sum of their individual effects; synergies between policy tools can lead to more significant outcomes. For example, the carbon price required to overcome the current fossil fuel technology lock-in can be much lower when combined with other policies (Mercure et al. 2014; Lam and Mercure 2021; Knobloch et al. 2019). However, these interactions are not always straightforward. One notable example is the "waterbed effect," where emission reductions in one sector under a fixed emissions cap can lead to increased emissions in another, potentially nullifying the overall impact (Perino et al. 2019; Energy Resources Aotearoa 2021).

Moreover, different policy instruments target specific problems, making it unlikely that a single instrument will be transformative. For instance, a carbon tax is effective for phasing out carbon-intensive activities, while other policies, such as regulations, mandates, and technology-specific subsidies, are better suited for bringing low-carbon solutions to market. Therefore, combining carbon taxes with technology policies creates a complementary approach (Grubb et al. 2021; Lilliestam et al. 2020). Research shows that policy instruments beyond carbon pricing, such as feed-in tariffs and regulation, have been instrumental in bringing green technologies to market (Penasco et al. 2021). While carbon markets help reduce emissions, they are less effective in incentivizing innovation compared to targeted regulations and subsidies.

Future research should evaluate the interactions between climate policies, including fiscal measures like carbon taxes, monetary policy, emission trading systems, financial regulations, trade policies such as Carbon Border Adjustment Mechanism (CBAM), and energy market regulations. The impact of policy commitments and forward guidance should also be explored.

Irreversibility of capital investment

Irreversibility of capital investments affects economic behavior and reinforces the issue of stranded assets. Financial frictions significantly amplify and prolong the effects of macroeconomic uncertainty, as detailed in foundational studies by Bernanke and Gertler (1990) and Kiyotaki and Moore (1997), and more recently by Alfaro, Bloom, and Lin (2022). Many climate-macro models assume that capital stock is owned by the households and rented out to the most profitable enterprise (e.g., Varga et al. 2022). This means that, in the absence of additional adjustment costs, capital stock can be swiftly switched from firms with high to firms with low carbon-intensive technology when facing carbon pricing, for instance. Other models assume firm-specific capital stock, nevertheless, the assumption prevails that positive and negative investment shocks are equivalent.[9] This means they assume that capital can be equally increased by investment, as it can be decreased by disinvestment. Looking at real world considerations, there actually exists an asymmetry between investment and disinvestment, in fact, disinvestment is often not possible (Lanteri 2018). This has strong implications for the degree of climate-related risks and impacts as stranded assets could emerge, when unanticipated ambitious climate policies are introduced (Baldwin et al. 2020).

This potential for stranded assets arises because physical capital often cannot be repurposed for alternative uses, leading to significant financial implications. Post-industrial cities in the North of England are a historical example. Multiple factories and industrial sites have been around for a long time and represented depreciated capital. Similar fates could emerge for the world's oil and coal industry, especially if the transition happens rapidly. As physical capital becomes unprofitable, firms and investors face economic and financial losses, which could pose a financial stability issue if happening at scale and within a limited time span. Models would need to be equipped to be able to represent this aspect, as with reversible capital investment, models tend to underestimate the effects of the transition in the high-carbon sectors/countries. In such a modeling framework, the transition would artificially 'free up' capital to be recycled into the new sectors (e.g., oil rigs becoming wind turbines), whereas reality might look different.

To address this, macroeconomic models need to accurately represent the asymmetry between investment and disinvestment. Ideal models should include firm-specific capital, avoiding assumptions that capital can be freely leased or repurposed. In such models, capital adjustments would primarily occur through investment, with limited options for disinvestment except in cases of external depreciation. Yet, a large enough shock could lead to negative investment (as for instance the fossil fuel energy sector would face substantial overcapacity in the model). In the standard macroeconomic model, the sector would sell its capital stock. A reduced capital stock and higher sector's cash flow are the consequences. Incorporating the irreversibility of capital investment into models assessing climate impacts helps to realistically simulate economic decision-making. This approach provides insights into the risks of asset stranding and the structural changes needed in response to climate policies.

The irreversibility of capital investment has far-reaching policy implications. As models reflect the long-term and fixed nature of real-world capital, researchers and policymakers can more effectively evaluate and plan for structural adjustments and understand the risks associated with capital investments under climate change scenarios. With stranded assets that cannot be reused and limits to divestment, early retirement of fossil assets and high-carbon technologies will become necessary. To manage this transition, however, involves specific financial tools with potentially macro-critical impacts as they tend to be costly. Policy tools include "climate bad banks", as introduced in Poland.[10] Another framework to guide the transition is the Asian Development Bank's Energy Transition Mechanism, which purchases coal-power plants from investors to retire them early thereafter.

The exploration of the impact of environmental policy uncertainty on irreversible investments has evolved to encompass a wide range of models. This research spans from partial equilibrium analyses (Xepapadeas 2001; Kalkuhl et al. 2020), to general equilibrium models (Bretschger and Soretz 2018; Khalil and Strobel 2023; Fried et al. 2022). These models provide insights into the dynamics of investment reversibility and delve into the learning effects associated with policy shifts (Rozenberg et al. 2020; Baldwin et al. 2020). For a detailed discussion, see Appendix II.

Future research should consider delving deeper into the endogeneity of policy and technology development and how these factors influence capital flows and the economic effects of climate policies. Despite studies like those by Kalkuhl, Steckel, and Edenhofer (2020) and Hagen, Jaakkola, and Vogt (2022) beginning to explore how policies evolve under systemic transition risks and how incentives for policymakers are shaped by expectations of asset stranding, there remains a significant gap in the literature (von Dulong et al. 2023). Additionally, discussions on the endogeneity of technological innovation are also lacking, with existing research primarily focused on capital shifts within established technological frameworks from fossil fuels to clean energy, neglecting how new technological innovations could influence capital reallocation.

4. Socio-economic tipping points

Socio-economic tipping points differ significantly from biophysical tipping points, such as those in climate and ecological systems. The literature generally categorizes socio-economic tipping points into two areas: the direct impacts of climate change and the transformational responses it triggers, including adaptive and mitigatory actions. While adaptation tipping points are well-covered in the literature, there is a notable lack of focus on mitigation tipping points (van Ginkel et al. 2020).

The possibility of climate-related impacts triggering the crossing of socio-economic tipping points is a core aspect of why climate-related impacts could become macro-critical. Tipping points are a specific form of non-linearity with the critical feature that systems change permanently once a temporary disturbance has shifted the system beyond this point (van Ginkel et al. 2020). At the same time, they are characterized by small changes that could induce amplifying feedback mechanisms and limited reversibility, hence shifting the socioeconomic system to a new state (Winkelmann et al. 2022; Milkoreit 2022). The existence of tipping points has far-reaching consequences for both the assessment of climate-related impacts and the identification of optimal decarbonization policy. This is because temporary climate-related impacts, such as physical climate shocks or decarbonization policies, could induce fundamental and permanent macroeconomic effects.

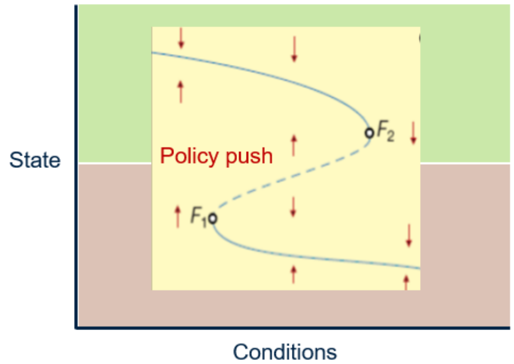
However, despite a clear definition of tipping points in academic literature they present substantial challenges for modeling.[11] Modeling tipping points requires a non-linear system with at least two locally stable steady states (Figure 4). Current literature struggles to define stable states within socio-economic systems, especially under conditions of strong human intervention. Once a temporary shock pushes the system beyond the tipping point, the steady state and the system

dynamics change. A steady state is locally stable when the system always returns to it after a temporary, sufficiently small shock (Dijkstra 2013). A common feature of tipping point dynamics is external effects such as network effects. Note that tipping points are more than just the existence of multiple equilibria or trending variables. The existence of non-linearities and peer effects does not necessarily imply a tipping point. To assess if macro-models should be extended to include tipping point dynamics (at the expense of simplicity), we need to first understand the order of magnitude by how much system dynamics change compared to their linear approximation.

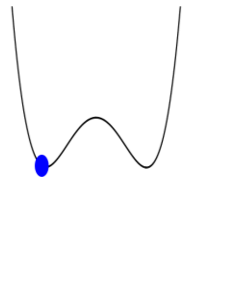
The process of gradual change from one steady state to the other and the speed of the transition are of critical importance (Figure 4). Mercure (2018) outlined a dynamic theory of tipping based on a discrete choice (logit) model where agents' decisions are influenced by the behavior of others around them—essentially, agents tend to imitate each other. For technology, the driving force are agent interaction *and* the irreversibility of induced innovation (learning-by-doing). The solution are two limiting steady states. For technology or most practical problems, it takes many years to reach the steady state, so the transition is what is interesting.

Moreover, it is crucial to clearly differentiate between "sectoral" and "full-system" tipping points to ensure that identified transformations adhere to the criteria for significant, structural changes (Tàbara et al. 2021; Milkoreit 2022). This need arises because many studies on social tipping points lack clear system boundaries and analytical scales, which complicates defining and assessing changes pre- and post-tipping events. Such studies often overlook the interaction of different scales within the system, a key factor for accurately predicting and observing social changes. For example, research can focus on a segment or the entire social structure. Many studies overlook how individual behaviors, community interactions, and policies at various levels interact

Figure 4. Stylized representation of a tipping point scenario



(a) Static



(b) Dynamic

Note: Figure 4 (a), adapted from Scheffer et al. (2001), and Figure 4 (b), a "Tipping Point Animation" from Carbon Brief (2022) by Chris Boulton, visualize the concept of tipping points. The left-hand box of Figure 4 (b) depicts a system with two states: a ball represents the current state, and the depth of each basin its stability. A tipping point occurs when forces push the system from one stable state into another, a change often irreversible. The right-hand box shows a time series tracking the movement of the ball between states.

within this system, creating complex dynamics. Additionally, the analysis of socioeconomic tipping points typically emphasizes a transition process, like the gradual acceptance of renewable energy from initial skepticism to broad adoption, rather than identifying a precise, stable endpoint. This method underscores a more qualitative and ongoing change, offering a contrast to the static states usually outlined by complex dynamic systems theory.

4.1. Transformative impacts

Climate change has the potential to trigger major social transformations. Extreme weather events like cyclones may lead to food insecurity, riots, and mass migration. But this is not a proportional relationship. Sometimes, even small events can generate major social transformations, while at other times major events can have only limited social impact. This is due to the built-in resiliency of socio-economic systems. Socio-economic tipping points are reached when a community shifts from a state of stability to instability: from peace to violence, from a democracy to an authoritarian regime, or from a sedentary lifestyle to emergency migration, among others. They are defined as points within a socio and ecological system at which the social components, driven by self-reinforcing feedback loops, inevitably and often irreversibly lead to a qualitatively different state. Although adaptation and mitigation efforts can delay socio-economic tipping points, limitations in physical, economic, and social capacities mean they cannot always prevent them. These tipping points are especially prevalent in developing countries, where socio-economic resilience is generally lower (van Ginkel et al. 2020).

An example of how socio-economic tipping points can manifest is found in labor supply dynamics, particularly migration. When the decision to migrate depends on the proportion of the local community that has already migrated, a tipping point may be reached. Initially, a small share of migrants may not lead to vast consequences. However, as this share increases, the same climate impact could trigger a mass exodus. With agent heterogeneity and gradual global warming (increasing the frequency and intensity of extreme weather events), a single event may push the system beyond the tipping point with most of the community emigrating (Missirian and Schlencker 2017; McLeman 2018).

4.2. Transformative policy

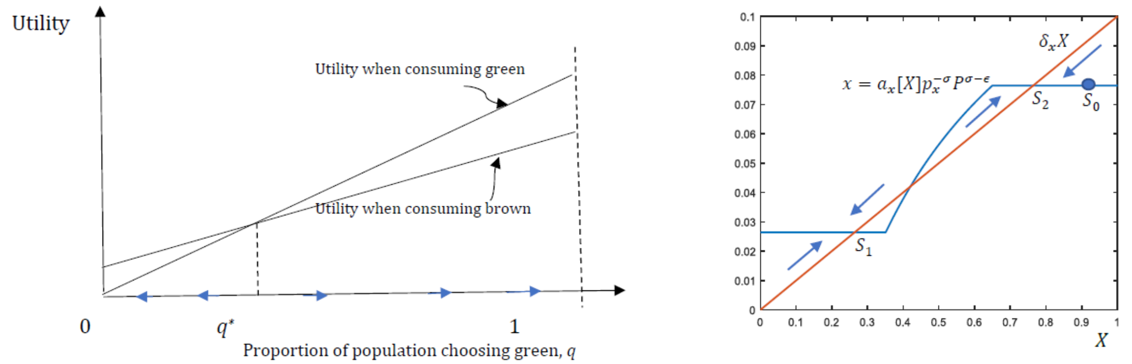
Given the potential for transformative impacts, climate policies must account for tipping points. Traditionally, most models motivate marginal policy change because the non-linearities and peer effects necessary for tipping point dynamics are difficult to model and to identify empirically. Without tipping point dynamics (or similar non-linearities or unit-root processes), model-based policy analysis ends up at the same conclusion: To induce permanent change, permanent policy change is required. This is the case for stationery, linear models. For instance, models predict that carbon taxes will have to keep increasing to reduce emissions over time. If the policy was removed, emission would return to baseline. This is quite a strong model implication and may overstate the importance of sustained policy change as well as the long-term effects (such as GDP loss).

Recognizing the existence of socio-economic tipping points could fundamentally change the way we think about policy (Franzke et al. 2022). These tipping points challenge the idea that policy needs to be permanent. With tipping points, the nature of policy may be different as argued by van der Ploeg and Venables (2022): Radical climate policies and big temporary pushes may be able to exploit the existence of multiple steady states and move the economy to the new low-carbon position which does not require much further policy (also see Mercure et al. 2014). A strong climate policy push may trigger a technological transformation which moves the economy to a new low-carbon steady state at which the economy remains even after the policy measure is removed (Way et al. 2022; Nelson and Winter 2009). Similarly, initial de-risking measures in the financial sector could support the financial sector to establish a risk profile for low-carbon activities, hence, allowing the measures to be eventually phased out. Hence, knowing the intervention points that could trigger such positive policy-induced tipping points could allow more targeted and more efficient climate policy design (Farmer et al. 2019; Otto et al. 2020; Lenton et al. 2022).

However, tipping points are more than just a rationale for permanent decarbonization effects of temporary policy. Permanent effects of temporary policy can also be modelled as unit root processes or non-stationary systems. For instance, in (linear) CGE, or macro-structural or DSGE models, temporary carbon taxes may alter relative prices permanently giving rise to a different steady state.[12] Yet, this modelling approach misses the critical feature of tipping points: external or network effects and interaction effects, which are also crucial for informing policy design. Because it matters what other agents in the market are doing, small policy shocks are counteracted by strong forces pushing the system back to the old equilibrium. Yet, when the policy shock is strong enough it will push the system over the edge towards a new equilibrium. This is the critical difference between sudden tipping point dynamics and a more gradual unit-root type of path dependence.

Identifying socio-economic tipping points is therefore key to developing effective environmental strategies, but two main challenges hinder this process. Firstly, research has predominantly focused on data-rich sectors like financial markets and power grids, leaving a significant potential for broader studies in socio-economic areas (Milkoreit 2022; van Ginkel et al. 2020). Secondly, policymakers often view tipping points only as large-scale impacts, overlooking their occurrence in small-scale, complex systems (Figure 4). This misperception leads to neglected system-scale dynamics crucial for nuanced policy-making (Scheffer et al 2012). To address this issue, a paradigm shift in policy framing is necessary to fully appreciate the intricate nature of

Figure 5. How to model tipping points?



(a) Peer Influence and Technology Adoption *(b) S-shaped Dynamics and Equilibria*

Note: Figure 5 (a) and Figure 5 (b) are adapted from van der Ploeg and Venables 2022

socio-economic tipping points.

The theoretical analysis of social tipping points also faces challenges in integrating existing social theories. Established theories on collective behavior, norm cascades, innovation diffusion and Schelling's micro-behaviors, among others, can potentially explicate these dynamics more robustly (Milkoreit 2022). For instance, tipping points can arise through technology adoption. To the extent that the technology used by a firm's stakeholders affects the firm's choice of technology, tipping points may exist in the dynamics characterizing low-carbon technical change (e.g., Loorbach and Rotmans 2006).

Empirically evaluating the relevance of policy tipping points is a complex task, as it is a novel but rapidly evolving field. Literature has been developing increasingly sophisticated methodological approaches to study tipping dynamics. Some of the more sophisticated modeling studies have attempted to include empirical data, for example, using survey data to inform model parameters (Milkoreit 2022; Wiedermann et al. 2020), but to a large extent this work remains detached from the observation and measurement of actual social systems. A critical gap has been identified in the current research on transformation tipping points, which predominantly relies on qualitative and descriptive methods (van Ginkel et al. 2020).

To address these issues, a structured strategy for empirical evaluation is outlined. A first starting point could be to implement tipping point dynamics, as described in Figure 5 (a) , within a small but empirically robust macroeconomic framework. Showing that tipping point dynamics can be simulated in a calibrated macro-framework is already a task in itself. There is a vast literature on modelling multiple equilibria with tipping points dynamics. At the core of socio-economic tipping points is the assumption individual behavior (preferences, technology choice, etc.) depends on the behavior of the herd or network. A seminal paper by Nobel Laureate Thomas Schelling (1971) forms the core of much of today's understanding of tipping points, where he explored tipping point dynamics to explain racial segregation.

The tipping point mechanism has been applied to many questions including the shift from high to low-carbon equilibria. Van der Ploeg and Venables (2022) emphasize the importance of peer effects in this process. On the household level, the adoption of green technologies tends to increase as more households make the switch, which in turn can intensify the impact of carbon pricing on reducing emissions. On the production side, the presence of externalities, such as economies of scale, plays a significant role. As the production volume of green products increases, their costs tend to decrease, following a pattern similar to Swanson's law, where each doubling of the cumulative production of technologies like windmills, solar panels, or batteries leads to a 20% to 40% reduction in unit costs.

In modeling tipping points, a dynamic model in its simplest form might exhibit a unique but unstable steady state. For instance, this could be an unstable Nash equilibrium in the choice of (low-carbon or high-carbon) technology or consumption good with the choice affecting the choice of peers. The system will converge to a corner solution with only a low-carbon or high-carbon technology available (see left figure below taken from van der Ploeg and Venables 2022).

The model with the typical S-shaped non-linearity will be fit to the data. The challenge will be to find data on the variables that are subject to the tipping point dynamics for the slope and curvature parameters to be identified. Non-linear filtering techniques such as the particle filter can be employed to estimate non-linear likelihood functions (for details see Sarkka 2013). The final step is to evaluate if the estimated tipping points are also economically relevant. This can be achieved by comparing simulations of the tipping point model with those of a model version that is linearized around the steady state in which the economy is located.

In a more advanced setup, additional forces pushing the trajectory away from the corners can be introduced. These could be motivated, for instance, by large marginal returns to a technology or large marginal utility of low/high-carbon goods when the technology/good is used to a sufficiently small extent. It gives rise to an S-shaped non-linearity that cuts the linear system three times giving rise to two stable equilibria and one unstable one which demarcates the tipping point (see Figure 5 (b)).

Future research should prioritize the clear definition of system states and the identification of mechanisms that stabilize or shift these states, as understanding these dynamics is crucial for predicting when and how tipping points might occur. Special attention should be given to the abrupt and nonlinear nature of these changes, as they are often the most disruptive and impactful within socio-economic systems. Moreover, it is essential to explore how the speed of change, rather than just its magnitude, can trigger socio-economic tipping points, including how localized shifts can lead to broader impacts. This understanding is critical for managing significant changes arising from climate change and the transition to a low-carbon economy. Improving methodologies and data collection is vital, as better data and advanced analytical tools will enable more precise modeling of these complex dynamics. Researchers should also investigate the prevalence of social tipping points across various systems, such as energy, finance, and food, to assess their potential to drive significant sustainability transformations. (Milkoreit 2022). This knowledge is essential for developing effective policies and resilience strategies that align with sustainable development goals.

5. Conclusion

The paper highlights significant knowledge gaps and corresponding modeling challenges that climate change and the low-carbon transition pose for assessing their macro-criticality. Three main areas are identified: uncertainty, non-linear transmission channels, and socio-economic tipping points. To address these challenges, the paper advocates collaborative efforts to enhance and expand the portfolio of analytical tools for policy-making, which will help integrate climate considerations more effectively into development strategies. Through a structured three-step approach—conducting a literature review, identifying key challenges and knowledge gaps, and suggesting future research directions—this paper provides foundational insights and practical recommendations aimed at improving the assessment of societal impacts of climate change. This work is intended to guide research programs on these assessments, informing adaptation and mitigation policies crucial for fostering sustainable development in the face of evolving climate challenges.

Notes

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1. In the aftermath of the Paris agreement from 2015 renewable energy costs have already decreased tremendously at an unexpected pace. In 2014 the IEA projected that average solar prices would reach \$0.05/kWh by 2050, saying it would take *36 years*. However, it took only *6 years* to reach this price, while solar and wind are already the cheapest form of electricity generation in countries representing 70 percent of global GDP and it is expected to be so everywhere by the late 2020s (SystemIQ 2020).

2. The Nordhaus (2018) damage function is calibrated to cause roughly 10 percent of GDP damage under a 6°C global average temperature increase compared to a scenario with no global warming.

3. The notion of climate-related impacts in the rest of this paper will entail both, climate physical and transition impacts. If one is meant in particular it will be stated in the text.

4. For instance, Hsiang et al. (2017) provide a decomposition of uncertainty sources for climate damage assessments in the USA in their appendix section.

5. Scholars frequently develop customized taxonomies of uncertainty sources based on their specific analyses. For additional classifications, see works such as Hallegatte et al. 2012; Pindyck 2017; Brock and Hansen 2018; Heal and Millner 2013; Pindyck 2021; Knutti and Sedláček 2013; Lemoine 2021; Giglio et al. 2020; Prahl et al. 2016, which explore various dimensions of uncertainty.

6. It would also be intriguing to examine the impact of alternative mechanisms for forming expectations, such as incorporating a learning-based approach. This approach, which diverges from the conventional mix of rational and backward-looking expectations, has been shown to significantly influence outcomes in the G-Cubed model, as detailed by McKibbin and Tan (2009).

7. While both public and private capital are important, our focus here is on the critical role of private investment in the transition to a low-carbon economy.

8. In the referenced figure, black dots represent causes, white spaces indicate effects, and areas featuring both black and white signify entities that can be both causes and effects. It's important to note that, unlike other figures in the same context, here the colors do not denote intensity. For a more detailed explanation, see the work by Pescaroli and Alexander (2015).

9. In the G-Cubed model, the physical capital specific to each sector changes only through investment and divestment decisions, causing GDP to fall due to its inflexibility during significant global economic restructuring (NGFS 2022).

10. Climate bad banks manage high transition risk assets, cleansing balance sheets and enabling financial institutions to focus on low-carbon investments. While this strategy aims to reduce financial risks from asset devaluation, it is still in early stages (Daumas and Salin 2021).

11. They are particularly well established in the ecological and natural science literature. See for instance Dijkstra (2013) for a mathematical introduction and Lenton (2011) for an overview of climate tipping points.

12. See Appendix III for core differences between recursive macroeconomic models (e.g., DSGE) and macro-structural/CGE models.

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Appendix I: Typologies of Uncertainty

To address these challenges, we can categorize the different types of uncertainty that influence climate assessments. By organizing these uncertainties into clear typologies, we can systematically examine their effects on the analysis and develop strategies to mitigate their impact.

Typology 1: sources of uncertainty. Uncertainty manifests at every stage of the causal chain, from hazard modeling to damage estimation on both micro and macro levels (Prahl et al. 2016). These sources of uncertainty can be broadly categorized into scientific and socio-economic uncertainties (Heal and Millner 2013).[5]

It is worth acknowledging that most scientific uncertainties have already been extensively discussed in the literature (e.g., trajectory uncertainty, shock uncertainty, and model uncertainty) (Oberpriller et al. 2021). However, the focus of research and debates increasingly lies in socio-economic uncertainty, which arises from human and societal responses to climate change.

Among socio-economic uncertainties, our focus lies on policy development uncertainty, which remains a critical gap in the literature. *Policy development uncertainty* includes policy instrument choice and timing, commitment, policy paths (Hass et al. 2023). For example, delays or incomplete implementation of policies may lead to an inadequate response to climate change, increasing the risk of extreme weather events and other impacts of climate change (IMF 2022).

Our contribution addresses this gap by highlighting the importance of more effectively integrating policy development uncertainty into climate models. For further discussion, refer to Section 2.2, Transition impacts: policy credibility, and Section 3.3, Non-linear policy shock transmission: policy interaction.

Typology 2: Uncertainty in valuation: linking climate change to market, non-market, and socially contingent impacts. The literature on the "value of uncertainty" extensively covers its effects on GDP; however, nonmarket damages and the interconnections between market and nonmarket effects remain poorly understood (Chan and Casey 2022; Newell et al. 2021; OECD 2015). Climate change impacts are multifaceted, extending beyond GDP and temperature fluctuations to include both market and non-market effects, as well as social and contingent aspects. This broader view captures essential aspects often overlooked, like human health and security, social economic tipping points (e.g., migration and war). Since Downing and Watkiss's work in 2003, there has been progress in understanding non-market damages and the interplay between market and non-market effects. However, the sociopolitical ramifications and the modeling of critical phenomena are still not well understood (Figure 1).

Typology 3: Severity of uncertainty. The severity of uncertainty in climate change, particularly through tipping points ("known unknowns") and deep uncertainty ("unknown unknowns"), is not adequately represented or understood. This inadequacy directly affects our ability to assess the true severity of these uncertainties. To better capture and address this severity, it is essential to explore new factors such as social and political risks, including the credibility of government policies and stakeholder expectations, and to examine nonlinear dynamics like path dependency and feedback loops, as detailed in sections on nonlinear transmission and socio-economic tipping points. However, the quantitative assessment of tipping points and deep uncertainties remains challenging and is currently excluded from the core modeling framework of most models. For further discussion, refer to Section 4, Socio-economic tipping points.

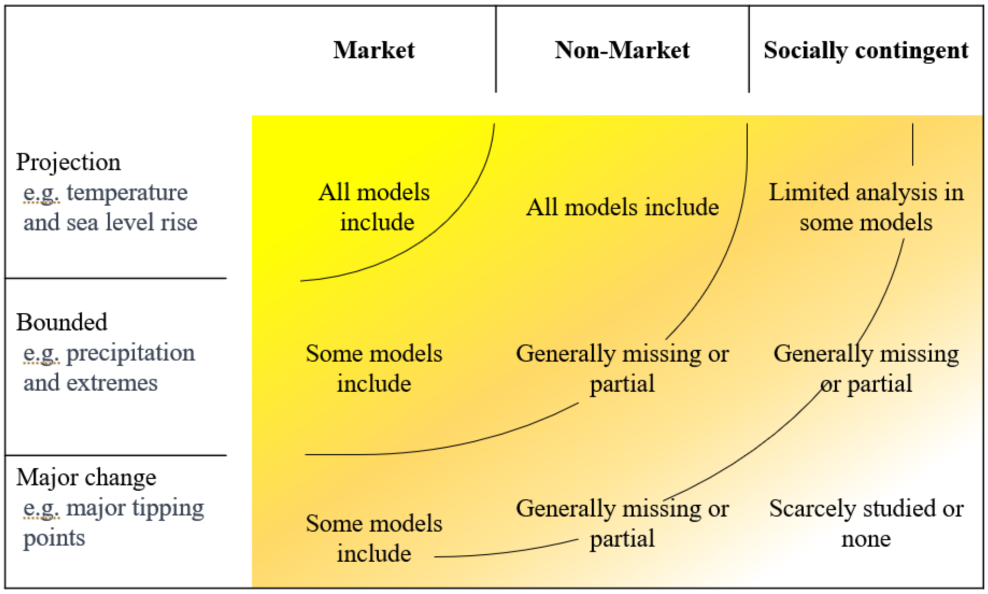
For improving the assessment of climate impacts, addressing key challenges is essential. A comprehensive approach that incorporates fat-tail risks, risk aversion, and welfare considerations is required. The *first challenge* is improving the accuracy of future climate damage probability distributions, accounting for all sources of uncertainty and allowing for skewed distributions with fat tails. The *second challenge* is considering the welfare implications of climate damage beyond GDP, integrating factors like air pollution, biodiversity, and natural services.

The *third challenge* comprises the accuracy of possible damage outcomes and how they could be mapped into a welfare measure. Damage models require functions to convert the physical impacts of climate change into monetary terms. There are three main types of these functions: (1) general aggregate models, (2) specific sector-focused models, and (3) models based on macroeconomic estimates. Ideally, these functions should encompass all sectors impacted by climate change, considering regional variations and indirect effects. However, achieving this comprehensiveness is challenging for all three types. The scarcity of data on high temperature increases and long-term effects makes it difficult to make reliable future predictions. Therefore, much of the development and adjustment of these functions remains ad hoc (Oberpriller et al. 2021).

The *fourth challenge* consists of finding ways to capture climate uncertainty in conventional scenario analysis to achieve more accurate probability distributions for potential damage outcomes This can be done by refining shock uncertainty with non-standard fat tail distributions (Weitzman 2011; Rasmussen et al. 2016) and addressing parameter uncertainty through Monte Carlo simulations informed by Bayesian methods. The *fifth challenge* is with multiple uncertainty sources, models must be robust to large or compounded shocks, though it's challenging to assess how different uncertainties contribute to total risk (NGFS 2023; Kim et al. 2019). The *final challenge* relates to the valuation of expected damages and how they depend on measures of risk aversion and how policy makers should respond to uncertain climate outcomes. Currently, studies tend to report the mean of the distribution (i.e., the point forecast) of GDP loss and other macroeconomic variables and the corresponding confidence bands. Yet, this neglects the importance of risk aversion especially towards catastrophic outcomes. Estimates for risk aversion are provided by l'Haridon and Vieider (2019).

Navigating policy-making under uncertainty remains a pivotal aspect of addressing climate change. Studying climate policy as a control problem assumes that a planner knows enough to make optimization feasible, but physical and economic uncertainties prevail. For instance, different models provide different projections. The recent literature addresses the issue from various angles: One primary approach to deal with model uncertainty is multi-model ensemble analysis of inter-model structural choices (Sanderson 2018). At its core is Bayesian model averaging which assigns probability weights to competing models. One constraint is the availability of models of catastrophic outcomes. Kemp et al. (2022) argue that models capturing the costs of worst-case scenarios such as societal collapse are underexplored. An alternative approach is suggested by Manski, Sanstad, and DeCanio (2021), who advocate for using the minimax-regret decision criterion (minimize the maximum regret) over the various model forecasts to account for deep uncertainty in climate modeling. DeCanio, Manski, and Sanstad (2022) study choice of climate policy that minimizes maximum regret with deep uncertainty regarding both the correct climate model and the appropriate time discount rate to use in intergenerational assessment of policy consequences. The analysis specifies a range of discount

Figure 1. Coverage of categories in damage models.



Note: This figure updates the original mapping by Watkiss et al.(2005) and Watkiss (2011) with the incorporation of recent literature. A detailed mapping matrix can be found in Watkiss et al. (2005). As Watkiss noted in their 2011 revision, mapping various models across the risk matrix is inevitably somewhat arbitrary. The 2011 update by Watkiss considered the main areas covered by three major economic Integrated Assessment Models (IAMs) – DICE, FUND, and PAGE2009 – along with their foundational literature. Our update expands on this by incorporating a broader range of the WBG macroeconomic models for climate policy analysis such as MFMOD, ENVISAGE, MANAGE, CPAT, and GIDD (World Bank Group 2022), Additionally, it includes insights from Nikas, Doukas, and Papandreou (2018), which covers more than 60 individual IAMs, including DICE, FUND, and PAGE2009, and features a literature review by Auffhammer (2018), and Savona and Ciarli (2019). Recent economic studies have addressed major catastrophic events, such as sea level rise and tipping points, as cited in van Ginkel et al. (2020), McKay et al. (2022), and Ditlevsen and Ditlevsen (2023). These studies also explore the complex, socially contingent impacts of climate change on conflict, migration, and more. However, the knowledge within the entire matrix remains fragmented and highly uncertain.

rates to express both empirical and normative uncertainty about the appropriate rate. The minimax regrets analysis points to use of a relatively low discount rate of 0.02 for climate policy, allowing to stay within 2 °C average global temperature increase.

Appendix II: Theoretical Literature on Climate Policy Uncertainty and Irreversible Investment Impacts

The theoretical literature exploring the impacts of climate policy uncertainty on irreversible investment has delved into various aspects, including:

Partial vs. General Equilibrium Impacts

The literature distinguishes between the impacts on partial equilibrium, as studied by Xepapadeas (2001) and Kalkuhl, Steckel, and Edenhofer (2020), and general equilibrium impacts, as examined by Bretschger and Soretz (2018), Khalil and Strobel (2023), and Fried et al. (2022). Xepapadeas (2001) investigates the abatement investment and location decisions under environmental policies, focusing on their irreversibility. Kalkuhl, Steckel, and Edenhofer (2020) employ a sector-specific partial equilibrium model for the energy sector, examining stranded assets in climate policy and the effects of irreversible investments and regulatory time inconsistency.

On the other hand, the research conducted by Bretschger and Soretz (2018), Khalil and Strobel (2023), and Fried et al. (2022) delves into the general equilibrium effects of climate policy uncertainty, investment, and irreversibility. Their studies can be broadly categorized based on several key differentiators: single-sector versus multi-sector applications, single-policy versus multi-policy frameworks, varying transmission channels (such as the presence or absence of financial transmission), and the distinction between one-off and permanent policies.

Bretschger and Soretz (2018) focus on a one-sector model to analyze the theoretical impacts of stochastic taxes and subsidies on production factors in both dirty and green sectors. They discover that the uncertainty in taxing dirty capital drives investors to divest from these sectors. Khalil and Strobel (2023), in contrast, broaden this approach to a two-sector model encompassing both green and dirty sectors, distinguished by their energy intensity and carbon emissions. Their study is notable for incorporating an analysis of the financial sector's role in the dissemination of climate policy uncertainty shocks, and it includes an empirical examination of investment and market valuation in U.S. listed companies, elements not addressed in the Bretschger and Soretz study.

Regarding the impacts of one-time versus continuous uncertainties in climate policy, Bretschger and Soretz (2018) and Fried et al. (2022) diverge in their approaches. Bretschger and Soretz (2018) examine the scenario of persistent uncertainty, as exemplified by the stochastic fluctuations in carbon tax policies, similar to ongoing total factor productivity shocks. Fried et al. (2022), however, investigate the immediate economic consequences of sudden, one-off policy shifts in a dynamic general equilibrium model, like the abrupt implementation of a carbon tax. Their model demonstrates that a shift in climate policy alters the capital composition and reduces output, highlighting two primary effects: the diminishing returns on fossil capital relative to clean capital and the reduction in output due to climate policy risks shifting capital composition away from the allocation entrepreneurs would ideally choose in the absence of climate policy risk.

Degree of Reversibility

Research varies in focus from fully reversible investments to irreversible investments (Gerling et al. 2022). Between these two extremes lie partially reversible investments (Baldwin 1982; Abel and Eberly 1996; Abel et al.1995). Lanteri (2018) and Fried et al. (2022) delve into the intricacies of partial irreversibility. In contrast, Gerling et al. (2022) focus on the balance between irreversible and partially reversible investments in climate change scenarios. Davis and Cairns (2017) analyze lumpy investments across the entire spectrum of reversibility. Meanwhile, Rozenberg, Vogt-Schilb, and Hallegatte (2020), along with Eisenack and Paschen (2022), explore the consequences of completely irreversible investments in climate change. Eisenack and Paschen (2022) explore an irreversible design decision when the investment starts, combined with an irreversible option to abandon. Rozenberg, Vogt-Schilb, and Hallegatte (2020) use a Ramsey model to calculate the transition costs to cleaner capital amid irreversible polluting investments, pointing out that policies aimed at avoiding stranded assets might lead to decreased efficiency in emission reduction and higher transition costs. They also note that their analysis does not fully encompass strategies such as capital retrofitting or learning-by-doing, which could improve the efficiency of clean capital. Additionally, their analysis does not consider the perspectives of short-sighted agents or those with limited commitment capacity.

Learning-by-Doing Effect

In exploring the "learn by doing" effect, Rozenberg, Vogt-Schilb, and Hallegatte (2020) and Baldwin, Cai, and Kuralbayeva (2020) offer contrasting approaches within their respective studies on climate mitigation policies. Rozenberg, Vogt-Schilb, and Hallegatte (2020) utilize a Ramsey model to assess the impacts of various policies like mandates and carbon pricing, focusing on the trade-off between efficiency and political feasibility in the context of stranded assets. Their model, akin to Baldwin, Cai, and Kuralbayeva (2020) approach on irreversible investments, does not, however, explore the learning-by-doing effect. Contrastingly, Baldwin, Cai, and Kuralbayeva (2020) emphasize this learning effect, noting its significance in accelerating renewable energy investments. They investigate how the irreversibility of 'dirty' and 'clean' capital affects optimal carbon pricing and environmental subsidies, highlighting an "irreversibility effect" where 'dirty' capital yields higher short-term returns post-investment cessation. Unlike Rozenberg, Vogt-Schilb, and Hallegatte (2020) who suggest a temporary halt in investments upon policy implementation, Baldwin, Cai, and Kuralbayeva's (2020) findings indicate continued investments in the short term even under strict policies, based on real-world data. This distinction highlights differing perspectives on the dynamics of investment in response to climate policies.

Endogeneity of policy

Very few studies examine how policies develop in tandem with expectations of asset stranding (von Dulong et al. 2023). However, notable exceptions include the studies by Kalkuhl, Steckel, and Edenhofer (2020), as well as Hagen, Jaakkola, and Vogt (2022). The former endogenizes policy choices, considering public finance and political economy, and finds multiple equilibria with stranded assets. The latter identifies multiple equilibria in climate policy-making under systemic transition risks, where systemic shocks are influenced by policies. Policymaker incentives regarding asset stranding are shaped by market outcomes, which depend on expectations of their actions.

Endogeneity of Technology

The prevailing literature primarily examines capital shifts within existing technological frameworks under anticipated stricter climate policies, focusing on moving capital from fossil fuels to current clean energy technologies without considering endogenous innovation (Fried et al. 2022; Basaglia et al. 2022). However, this approach overlooks how new technological innovations might influence capital reallocation. In contrast, some studies suggest that incorporating endogenous innovation into models could not only facilitate a shift to existing clean technologies but also stimulate new clean technology innovations, accelerating the transition. As Fried (2018) noted, limiting the discussion to climate policy transition risk may underestimate the broader macroeconomic impact, especially when considering the potential of future carbon taxes to enhance returns on clean technology innovations compared to fossil fuels.

Empirically, only a few studies have investigated how climate policy uncertainty, coupled with investment irreversibility, influences investment decisions. Gulen and Ion (2016) used the policy uncertainty index developed by Baker et al. (2013) to assess its impact on firm-level capital investment. They discovered a substantial negative correlation between investment and policy uncertainty, notably more pronounced in firms with high investment irreversibility and dependence on government spending. This finding implies that policy uncertainty can cause delays in investment due to the irreversible nature of these decisions. Dibiasi et al. (2021) further emphasized the significance of irreversibility in shaping firms' responses to uncertainty shocks. Their study, centered on the effects of uncertainty shocks on firm beliefs and adjustment costs, revealed that both labor and capital play crucial roles in this dynamic. Basaglia et al. (2022) observed that the news-based climate policy uncertainty index is linked to increased stock price volatility and significant reductions in investment, particularly in sectors that are both pollution-intensive and capital-intensive. Khalil and Strobel (2023) adopted a news-based methodology to identify climate policy uncertainty shocks and their impact on investment and market valuation in U.S. firms. Their results corroborate theoretical predictions, indicating that climate policy uncertainty devalues the "dirty" sector relative to the "green" sector, reducing investment and capital stock in the former while increasing it in the latter. In practice, they noted substantial financial market downturns for carbon-intensive firms and a marked reallocation of investment from manufacturing to services following these shocks.

Appendix III: Recursive macroeconomic models and macro-structural/CGE models.

The core difference between the recursive macroeconomic models (e.g., DSGE models[5]) in the tradition of Ljungqvist and Sargent (2012) and macro-structural is that the former meticulously derives behavioral relations as the first order conditions of inter-temporal optimization under constraints and rigidities and the assumption of rational expectations. The latter macro-structural models amend micro-founded behavioral equations characterizing the long-run equilibrium path of the economy with econometric terms accounting for the short-term deviations from these long-run paths. While these econometric terms describing short-run dynamics have no straight-forward economic interpretation (they cannot be traced back uniquely to the structural parameters of an economic model) they improve the empirical fit of the model considerably (see Burns et al. 2019). Modelling these out-of-steady-state adjustments consistent with microeconomic theory and allowing for an integration of short-term adjustment and long-term outcome is the primary value added of recursive macroeconomic models. Because recursive macroeconomic models with rational expectations start from first principles (all model parameters are deep parameters and expectations are consistently carried through the analysis) they are immune to the Lucas (1976) critique or Goodhart's (1975) law.

Another advantage is the consistent treatment of not only stocks and flows but also expectations and asset prices which is critical for questions regarding wealth effects, financial risks, endogenous financial constraints, and expectation management. For instance, an announced coal phaseout will immediately affect capital asset prices as well as stock prices and, hence, financial wealth. This will affect both investment and consumption. Financial fragility may reinforce adverse effects. Exchange rates and imports and exports will respond. Recursive macro-models can consistently track and predict these interrelations between expectations, asset prices, and quantities.

The main disadvantage of recursive macroeconomic models lies in the lower flexibility in adjusting and expanding the framework as additional behavioral features need to be integrated into the optimization problems of the agents. Agent heterogeneity is an important assumption for many features such as market power and mark-up pricing. Hence, the consistent aggregation of heterogenous micro-behavior to a relationship between macro-variables is a challenging task. Moreover, the strict requirement that both short and long-term dynamics are entirely derived from economic theory allows the model to tell a complete economic story but comes at the cost of an empirical fit that is often not as great as that of macro-structural models. Recursive macroeconomic and macro-structural models are thus complementary as the former are particularly strong in explaining economic transitions, while the latter have their strength in assessing transitions empirically (i.e. 'letting the data speak freely to a certain extent.').

The empirical valuation and parameter estimation also differ often between recursive macro-models and macro-structural models (even though this is not a feature of the models themselves). While most recursive macro-models are estimated using a full-probability approach (which perceives the economic model as the econometric model) and Bayesian inference, macro-structural models are often estimated using system or single-equation approaches. Different estimation

[5] CGE/DSGE modelling are well discussed in the research-literature (e.g., Ackerman 2002; Stiglitz 2018; Haldane and Turrell 2018; Christiano et al. 2018; Söderholm 2012; Vagliasindi 2023). In the latest IPCC-report includes thirty out of thirty-one models are GCE or DSGE models (IPCC 2014; Hafner et al. 2020)

procedures offer opportunities for synergies. For instance, parameter distributions that cannot be inferred in the Bayesian approach due to a flat likelihood could be identified through a prior that is informed by the macro-structural estimation. On the other hand, parameters that cannot be estimated by the macro-structural model due to lack of data could be calibrated using the posteriors of the Bayesian estimation. In any case, given the sensitivity of model results with respect to parameterization, having available a second set of estimation results as a robustness check would be a major value added.

The structure and characteristics of the proposed model are deemed well-suited for forward-looking climate policy analysis and capturing macro-financial linkages. Facilitated by increasing computational resources, forward-looking expectations models have become a new work-horse model for climate-related macroeconomic analytics. A prominent example is the G-Cubed model as summarized by McKibbin and Wilcoxen (2013). The contribution of the proposed model is the Bayesian estimation which allows for clean accounting of shock and parameter uncertainty which translate into posterior uncertainty of the results.

The policy measures, model features, adjustment mechanisms or transmission channels captured by the model are well anchored in the empirical literature. The model will also benefit in this regard from other activities within this paper. The model incorporates the most relevant of them in an internally consistent way and allows the data to weigh them relative to each other. Hence, the model results are highly flexible and not predetermined by modeling choices. They are mainly driven by the model parameterization which relies on empirical evidence and estimation. The model is designed for data-driven policy analysis under a well-thought and flexible theoretical framework.

Appendix IV: Production networks a la Baquaee and Farhi

In a series of publications, Baquaee (2018), Baquaee and Farhi (2019), and Baquaee and Farhi (2020) develop a general theory of aggregation in inefficient economies. Their modeling framework incorporates input-output connections, imperfect competition, microeconomic elasticities of substitution, and external economies of scale. Those features are usually not included in first-order approximations but allow their model to capture non-linear macroeconomic impacts that originate from microeconomic productivity shocks. The framework puts a particular emphasis on the systemic importance of industries as supplier and consumer of inputs and the underlying market structure.

The model framework is able to distinguish effect channels of intensive margins, which result from changing relative prices, and extensive margin effects that are triggered by intensive margin productivity shocks and cause entry and exist across industries which affect changes in output.

In a series of historical shock applications, the authors find that their model can capture non-linear macroeconomic impacts that are caused to shocks in critical sectors such as the 1970s oil shocks. Baquaee and Farhi (2021) assessed the conditions for production networks to matter in the context of COVID-19 impact assessments. An adapted version of the framework has recently been applied by Bachmann et al. (2022) to assess the impacts of a Russian energy import embargo on the German economy.