Irene Monasterolo

Embedding Finance in the Macroeconomics of Climate Change: Research Challenges and Opportunities Ahead

ABSTRACT

The role of finance in the low-carbon transition, as well as the deep uncertainty and endogeneity of climate finance risk, are currently neglected by climate economic models. This leads to a false sense of control in terms of risks and opportunities associated with the low-carbon transition. Further, it prevents people from understanding under which conditions climate policies and finance could be a driver or a barrier. Recent research has started to shed light on how climate economic and financial risk modeling could embrace this complexity.

The importance of "making finance flows consistent with a pathway toward low greenhouse gas emissions and climate-resilient development" (Art 2 (1)(c)) has been highlighted by the Paris Agreement (PA) signed by most UN countries in 2015 (UNFCCC 2015). The potentially enabling role of finance in supporting the low-carbon transition has also been recognized by the European Action Plan on Sustainable Finance and by the European Green Deal.[1]

However, more recently, financial supervisors have been focusing on the financial risks associated with climate change and with a disorderly transition to a low-carbon economy. In 2015, the former Governor of the Bank of England, Mark Carney, warned the financial industry about the impact of climate change on the economy and finance (Carney 2015). Carney highlighted that the temporal mismatch between climate impacts (mid to long term) and the short-termism of time horizons in financial decision making, could lead investors to overlook the economic and financial risks of climate change.

Since then, more than 70 central banks, financial regulators and development finance institutions have joined the Network for Greening the Financial System (NGFS) to mainstream climate financial risk assessment and climate stress testing in financial portfolios (NGFS 2019). The NGFS concerns about climate-related financial risks are aligned with a stream of research in climate finance that has developed around the seminal work of the climate stress test (Battiston et al. 2017).

The contribution of financial supervisors, practitioners, and policy-relevant research has been pivotal in advancing the analysis of climate-related financial risks and opportunities. In this regard, understanding under which conditions climate policy and finance could be a driver or a barrier to the low-carbon transition requires one to (i) analyze the risk transmission channels from climate change (either physical and transition risks) within the economy and in the finance sector, (ii) price forward-looking climate risks in investor portfolios and (iii) introduce climate change considerations in risk management strategies including through climate stress testing.

Addressing these issues requires models able to consider the nature of climate change risks for finance, i.e. its deep uncertainty, non-linearity and endogeneity. Climate economic models have so far downplayed the complexity of risk across possible climate change scenarios by limiting the impact of uncertainty to averaged shocks on economic output. Further, by focusing on identifying optimal policies (e.g., carbon pricing) and the social cost of carbon, such models neglected the role of agents' adaptive expectations in the realization of climate risk. Importantly, they have overlooked the role of finance and its complexity in amplifying risks.

These are major limitations that could lead to misunderstand the channels through which finance interacts with investment and policy decisions in the low-carbon transition, and thus to underestimate risks and opportunities of climate action.

Overcoming these limitations is crucial for the implementation of effective climate policies and regulations, when investors fail to fully anticipate the impact of the policy introduction, thus affecting volatility of asset prices. In this paper, we address three main questions that are rel-

Irene Monasterolo

is an Assistant Professor of Climate Economics and Finance at the Vienna University of Economics and Business.

[1] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.

evant to advance research in climate economics and finance:

1. What is the nature of climate risks relevant for investment decisions?
2. How well can the models used so far embed such risks?
3. What are the knowledge gaps and what can we do to fill them?

In particular, we discuss why climate risks challenge traditional approaches in climate economics, focusing on the role of time horizons, incentives and externalities. Next, we discuss the solutions offered by recent macroeconomic and financial risk research rooted in evolutionary economics and complex networks (Monasterolo et al. 2019).

The article is organized as follows. Section 2 discusses the conditions for finance to function as a driver or a barrier to the low-carbon transition. Section 3 explores the nature of climate change risks for the economy and finance, while section 4 elaborates on the challenges for climate economics models to address them. Section 5 presents advancements in climate finance research and section 6 discusses climate stress tests for internalizing climate financial risks in decision making. Section 7 concludes.

THE ROLE OF FINANCE IN THE LOW-CARBON TRANSITION: DRIVER OR BARRIER?

Analyzing under which condition finance could be a driver or a barrier for climate mitigation and adaptation represents a crucial research challenge. Latest IPCC reports (2014, 2018) highlighted the **enabling role that finance could play** in achieving the climate targets by mobilizing capital for low-carbon investments. New financial instruments, including Environmental Social Governance (ESG) products and green bonds, are increasingly considered a tool for scaling up sustainable finance. For instance, in the first quarter of 2020, i.e. when the COVID-19 crisis started, ESG-related funds outperformed the markets.[2]

Nevertheless, climate finance is not increasing at the pace and amount needed to align economies with the PA and with the Sustainable Development Goals (SDGs). Challenges include the uncertainties that characterize climate change and climate policy impacts; the lack of a standardized, operative taxonomy of sustainable investments (Monasterolo and Volz 2020); the low degree of transparency of sustainable financial instruments (Karpf and Mandel 2018, Berg et al. 2019, Busch et al. 2020); the lack of mainstreaming of consolidated tools for climate financial risk assessment (Battiston and Monasterolo 2020).

Another related reason can be found in the consequences of a "disorderly" low-carbon transition for the economy and finance, i.e., when investors fail to fully anticipate the impact of the policy introduction on their business, thus affecting the volatility of asset prices (Monasterolo and Battiston 2020). Firms whose business either depends on fossil fuel production and utilization for revenues, or that are located in areas exposed to climate-related hazards, will be affected by losses, experiencing carbon-stranded assets (Leaton et al. 2012). These losses could negatively affect the value of the firms' financial contracts and securities, and cascade to financial portfolios invested in those firms (Stolbova et al. 2018). The high degree of interconnectedness of financial actors can further amplify losses for individual financial actors and for the financial sector, as occurred in the last financial crisis (Battiston et al. 2016a).

In this context, **finance could turn out to be a barrier to the low-carbon transition.** By not revising its investment decisions (i.e., assigning higher risk to high-carbon firms and a lower risk for low-carbon investments) and not adapting its investment strategies to the new climate and climate policy context, the financial sector could introduce new risks for economic and financial stability. Indeed, central bankers have developed the notions of the climate "Minsky Moment," i.e., a sudden drop in carbon assets prices and of "Green Swan," i.e., global financial distress triggered by climate change (Bolton et al. 2020).

Research has shown that central banks have good reason to worry because investors and countries are highly exposed to economic activities that can become stranded assets (Dietz et al. 2016, Battiston et al. 2017, Volz et al. 2020, Battiston and Monasterolo 2019).

THE NATURE OF CLIMATE CHANGE RISK IN THE ECONOMY AND FINANCE

Understanding the characteristics of climate change risk is crucial for assessing its impacts in the economy and finance, to identify the most suited policies to address them, and the conditions for implementing them. These characteristics include (see Monasterolo 2020 for a review):

- **Deep uncertainty**. Forecasts of climate change and its impact on humans and ecosystems contain irreducible uncertainties because of the nature of the earth system, including the presence of tail events (Weitzman 2009) and tipping points that could lead to the possibility of crossing the planetary boundaries (Steffen et al. 2018) and of triggering domino effects (Lenton et al. 2019).
- **Non-linearity.** Recent analyses show that the distribution of extreme climate-related events (heat/cold waves) is highly non-linear (Ackerman 2017). Fourteen of the fifteen hottest years on record have occurred since 2000, while 2015–2019 were the five hottest years on record

[2] https://www.morningstar.com/articles/976361/sustainable-funds-weather-the-first-quarter-better-than-conventional-funds

(WMO 2019[3]). If this trend continues, historical data could be a poor predictor of future events and their magnitude, and thus of future losses induced by climate change.
- **Forward-looking** nature of risk. The impacts of climate change and climate mitigation actions (e.g., net zero transition) are on the time scale of two decades or longer, whereas the time horizon of investors and financial markets, and policy makers, is much shorter (a few months, and three to five years, respectively).
- **Endogeneity of risk.** Climate financial risks are endogenous, depending on the perceptions of future climate risks of policy makers and investors. These affect their expectations and policy/ investment decisions, and thus have an impact on the realization of climate risks themselves (Battiston 2019).

Hot Spots for Research Challenges in Climate Finance

Traditional climate economic models based on optimal policy have brought the attention to climate policy design and to the narrative of carbon-stranded assets. However, in the analysis of climate finance, these approaches face several challenges and limitations:

- **Treatment of climate shocks.** Climate shocks are usually considered as exogenous, and their averaged impacts assessed on aggregate GDP. Importantly, the intertemporal impact of climate shocks depends on assumptions made regarding future discounting, in a cost-benefit framework (see e.g., Nordhaus 1993, 2017). In reality, climate change is being endogenously generated by the production and consumption decisions of economic agents, by the decisions of governments to introduce (or delay) climate policies, as well as by the investment decisions of financial actors. Further, given the non-linearity of climate change and its impacts, extreme shocks scenarios should be considered to avoid underestimating risks.
- **Deep uncertainty over climate impacts and climate policy** leads agents to make decisions under conditions involving imperfect information about the future. It also implies potential mispricing of climate risks (and opportunities) in financial contracts (see e.g., Ramelli et al. 2018, Morana and Sbrana 2019, Monasterolo and de Angelis 2020), meaning that agents can be subject to information asymmetries (e.g., on risks and returns of different investments, or on the exposure of investors to climate risks). In this context, assumptions regarding perfect foresight on the part of agents involving the future and the actions of all other market participants, of market clearing prices, and of perfect substitutability of production factors (that allow a fast return to equilibrium) do not allow these dynamics to be captured.
- **Endogeneity of risk**. Perceptions of future climate risks held by today's policy makers and investors could lead to multiple possible pathways (or equilibria, in the sense of strategic interaction of economic agents) that are very different based on the future prevalence of dominant climate policies and energy technology shocks (Battiston 2019), or forward-looking investors' expectations (i.e., their "climate sentiments", Dunz et al. 2020a). If governments delay policy introduction, climate risks could affect countries and investor financial stability in the near future. But if governments introduce early climate policies and financial actors do not trust them, they will not revise their investment strategies and the low-carbon economy will not develop. This, in turn, would make it costlier for policy makers to further implement climate policies, and could eventually lead to a policy impasse.
- **Risk transmission channels and drivers of risk.** In today's interconnected economies, climate change and policy impacts can be transmitted to economic and financial agents via chains of investment exposures, influencing their reactions. This, in turn, can give rise to endogenously generated macroeconomic dynamics. Identifying climate risks transmission channels and the reinforcing feedback is crucial in assessing the overall magnitude of impacts and their distributive effects (Dunz et al. 2020b). However, most climate economic models consider uncertainty of climate impacts only as an aggregate shock on GDP growth. In addition, model behaviors are constrained by assumptions on market clear pricing, presence of representative agents with perfect foresight, and perfect substitutions of production factors, and by the lack of the role of finance and complexity. These assumptions critically constrain and limit the understanding of risk-transmissions channels and distributive impacts.
- **The role of finance and its complexity**. Finance plays a main role in the economy and is recognized as a powerful driver of risk amplification via portfolio interconnectedness (Battiston et al. 2012, Billio et al. 2012, Adrian and Brunnermeier 2016, Battiston et al. 2016b). Climate economic models either do not include a financial sector or only consider a stylized financial actor that acts as a conduit of savings for investments, subject to economic efficiency criteria in asset pricing. This is at odds with the functioning of the financial sector, where access to finance is costly and often not available, in particular in times of crisis, or for new sectors that do not have a clear track record (e.g., some low-carbon investments). Neglecting finance and its complexity could lead to a false sense of control over policy decisions and their

[3] https://public.wmo.int/en/media/news/july-matched-and-maybe-broke-record-hottest-month-analysis-began.

impacts and to underestimating the risks (and opportunities) from the low-carbon transition.

- **Beyond monetary value to assess externalities.** Climate economic models carry out the valuation of costs and benefits of climate policy action (or inaction) solely in monetary terms. Nevertheless, several elements that are crucial for mitigating and adapting to climate change, e.g., biodiversity and oceans, do not have a monetary value. Thus, the negative externalities associated with the impact of human activities, including finance and policy, on these dimensions, and their impact on the well-being of current and future generations, do not enter calculations in cost-benefit analyses. This leads one to underestimate the costs of climate inaction and to overestimate the costs of policy action in the short term.
- **Time horizon and incentives.** The time horizon of climate change and its largest impacts are expected to occur in the longer term (2050–2100 and beyond). This is also the time dimension considered in most climate economic models. However, policy makers and investors' decisions are taken on a much shorter time horizon (usually an electoral term and a semester, respectively). This mismatch between time horizons creates negative incentives for policy makers and investors to act early on the climate.
- **Beyond optimal policy: second best solutions.** Deep uncertainty, non-linearity and endogeneity of risk represent the primary obstacles to implementing optimal climate policies and could result in a general inability to come up with optimal carbon pricing. It has been highlighted that introducing a first-best solution in optimal policy context (e.g., a carbon tax) is complex in actual practice, and that it may not suffice alone (Stiglitz 2019). In this context, central banks and financial regulators (e.g. those of the NGFS) are now considering the introduction of climate risk considerations in their monetary and macroprudential policies.

ADVANCES IN MACROECONOMIC AND FINANCIAL ASSESSMENT OF CLIMATE CHANGE

Assessing the impact of climate policies and investment decisions in the low-carbon transition require standardized and actionable definitions of sustainable economic activities and of carbon-stranded assets, both of which are lacking to date.

Standardized classification of sustainable activities

The lack of a common and consolidated definition of green finance makes it challenging to identify and track green financing initiatives, instruments, and eventually projects and sectors. In addition, it introduces an additional source of uncertainty (i) for investors, who want to assess and manage climate risks and opportunities in their portfolios, (ii) for financial supervisors with a financial stability mandate that have to assess the drivers of individual and systemic climate-related financial risks, and (iii) for policy makers, in the analysis of the winners and losers of the policies for the low-carbon transition.

To fill this gap, the European Commission (EC) has introduced the EU taxonomy of sustainable investments (the 'Taxonomy'). The final regulation approved in June 2020 (PE/20/2020/INIT) refers to 'sustainable economic activities' based on the contribution to at least one of six environmental goals, including climate mitigation and adaptation. Furthermore, investments in such activities should do no harm with regard to the six environmental goals. Every activity (defined according to the NACE sector level, thus excluding certain firms) that passes the threshold can be considered sustainable according to the taxonomy criteria. Thus, in order to be taxonomy eligible, economic activities need to be not only in the list of eligible NACE codes, but also to pass activity-specific thresholds and Do-No-Significant-Harm (DNSH) criteria.

While the EU Taxonomy builds on the NACE code classification (NACE Rev2), in several cases a more granular classification by energy technology is required in order to identify economic activities that can be considered sustainable. Indeed, several firms have business lines characterized both by high and low-carbon technologies (e.g. ENEL, ENI). In addition, the EU Taxonomy does not provide a proxy of climate risk for the financial investments. Finally, it does not directly provide a standardized classification of sectors or economic activities that can are exposed to carbon-stranded assets. These challenges may contribute to delay implementation of the EU Taxonomy in the financial market.

The limits of carbon-stranded assets

The concept of carbon-stranded assets has provided a powerful metaphor to conceptualize the risks that climate change and a disorderly low-carbon transition could represent for the economy and finance. Van der Ploeg and Rezai (2020) identified four sources of carbon-stranded assets, i.e., abandoned carbon, abandoned capital, anticipated stranded asset, and realized-stranded asset. Cahen-Fourot et al. (2019) studied the most carbon-exposed sectors along the value chain using input-output matrices and analyzed the share of capital stock at risk of being stranded by country, especially in the electricity and industrial sectors.

However, when it comes to assessing climate-related financial risks, three challenges emerge with the current analyzes of carbon-stranded assets. First, the lack of a standardized definition means that the application and results of models are not comparable. Then, a convergence in the definitions of carbon-stranded assets is needed also with regard to identifying the economic activities at a level of disaggregation that is relevant for financial and policy analysis (e.g., NACE 4-digit level). Third, the narrative of stranded assets alone shadows the opportunities for returns for investors who embrace a smooth low-carbon transition and thus the role of co-benefits of climate policies.

Toward a standardized assessment of economic activities' exposure to climate risks

To address these limitations and provide a standardized and actionable classification of economic activities that are exposed to climate transition risk, Battiston et al. (2017) developed the Climate Policy Relevant Sectors (CPRS) classification. This framework considers economic activities that could be affected positively or negatively (becoming stranded assets) in a disorderly low-carbon transition. CPRS are identified by considering (i) their direct and indirect contribution to GHG emissions; (ii) their relevance for climate policy implementation (i.e., their costs sensitivity to climate policy change, e.g., the EU carbon leakage directive 2003/87/EC); (iii) their role in the energy value chain.

Starting with the NACE classification (4 digit), these criteria yield six sectors (fossil fuel, utility, energy-intensive, housing, transportation, agriculture) that can be further disaggregated considering different technologies that are relevant for the energy transition (e.g., fossil fuel/coal, fossil fuel/oil, fossil fuel/gas). For example, some activities that pertain to the value chain of the transportation sector are classified in terms of NACE codes under C-Manufacturing. Regrouping them by CPRS allows their energy technology to be considered and to analyze the contribution and relevance of the investment more directly in relation to climate mitigation or adaptation. As such, CPRS overcomes the limits of classification of exposures based on GHG emissions; it adds information on the climate risk exposure to the NACE 4-digit sector classification, which by itself does not provide any proxy of climate risk ; it provides information on the energy technology mix of the economic activity and its relevance for climate policy implementation.

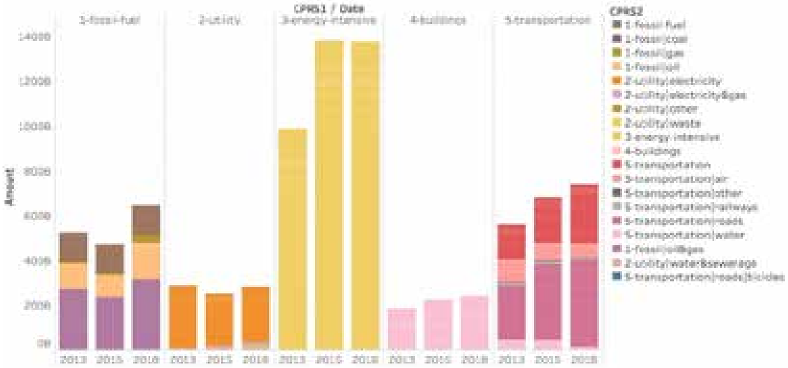
The CPRS classification is used by several financial institutions, including the European Central Bank (ECB 2019), the European Insurance and Occupational Pension Authority (EIOPA, Battiston et al. 2019), the Austrian National Bank and Banca d'Italia. The European Commission's Joint Research Center (Alessi et al. 2019) used the CPRS to analyze the climate transition risk exposure of the EU Taxonomy financial coverage (total financial value of equities and bonds), at the level of the NACE codes (4-digit). It used the CPRS classification in its aggregate (CPRS1) and disaggregate (CPRS2) form (Figure 1) over time.

INTERNALIZATION OF CLIMATE FINANCIAL RISKS AND OPPORTUNITIES IN DECISION MAKING

Recently, climate stress-tests have been developed to assess the financial risk implications of climate change and climate transition scenarios in investors' portfolios. In 2017, Battiston et al. developed the first climate stress test that embeds forward-looking climate transition scenarios in financial risk assessment of individual portfolios and of the financial system. The climate stress test methodology is based on four modules (Figure 2):

Figure 1

Breakdown of Market Capitalization by CPRS over Time



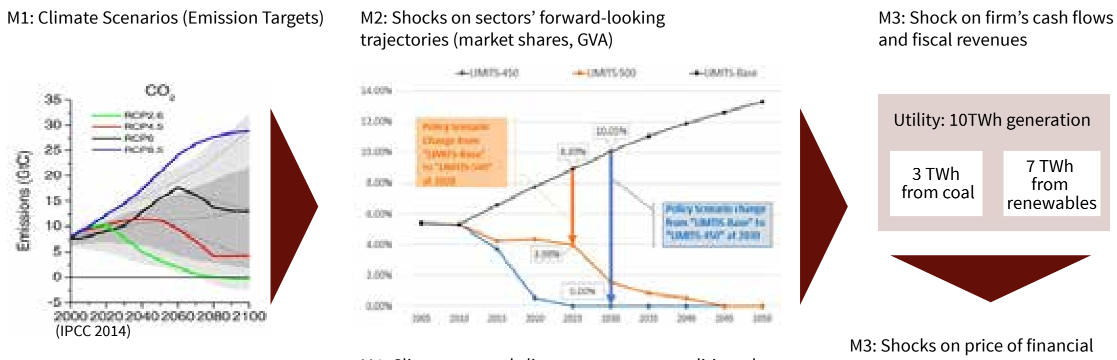
Source: Alessi et al. 2019.

1. **Forward-looking climate shocks** on outputs of low-carbon and high-carbon economic activities conditioned to climate scenarios are calculated based on trajectories of energy technologies provided by the Integrated Assessment Models (IAM, Kriegler et al. 2013, McCollum et al. 2018) conditioned to climate policy introduction, through time. From these trajectories, we calculate shocks on the market shares of sectors (NACE 4 digit), based on their energy technology (fossil fuel, renewable). The shock affects the economic activities' output and contribution to the Gross Value Added (GVA) and can be intended as a jump from one equilibrium state of the economy (i.e., the Business as Usual) to another equilibrium state of the economy characterized by the climate policy shock.
2. **Climate financial risk pricing of assets** carries out a valuation adjustment and a risk adjustment of individual financial contracts and securities (e.g., loans, bonds, equity), i.e. in their Probability of Default (PD) conditioned to the shock scenarios of 1.
3. **Climate financial risk assessment** calculates the adjustment on key financial risk analytica at the level of investor portfolios, i.e., the Climate Value at Risk (Climate VaR), Expected Shortfall, and Climate Spread (for bonds), conditional to the climate shock scenarios.
4. **The Climate stress test** assesses the largest losses for individual portfolios conditioned to the climate scenarios, considering risk amplification and reverberation driven by financial interconnectedness, and the implications on systemic financial risks.

The climate stress test development and application to investor portfolios has highlighted the following

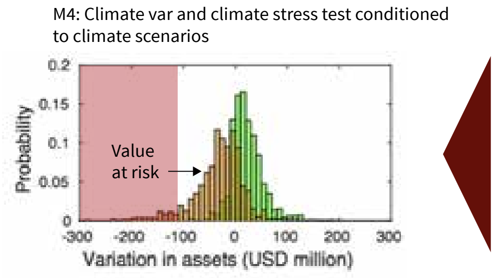
Figure 2

The Four Modules of the CLIMAFIN Tool for Climate Financial Risk Assessment in Investment Decisions



M3: Shocks on price of financial contracts

Country	Witch: bond shock (%)	Witch: yield shock (%)
Austria	1.3	–0.16
Australia	**–17.36**	**2.45**
Canada	–5.21	0.67
Norway	**–14.82**	**2.05**
Poland	**–12.85**	**1.75**



Source: Monasterolo and Battiston 2020.

challenges: (i) the choice and use of climate scenarios, (ii) the macroeconomic assessment of the risk transmission channels.

Choice and use of climate scenarios for climate stress testing

The scenarios and trajectories of energy technologies composition of sectors are provided by climate economic models. The IPCC uses trajectories and scenarios provided by the last generation of IAMs that offer a granular representation of the energy technology mix of aggregate sectors that would allow us to achieve the 1.5 degrees C or 2 degrees C world that comprise the economy. One main challenge in assessing the attainability of the climate trajectories is the fact that climate mitigation scenarios do not account for the role of finance and its complexity in achieving the same scenarios (Battiston et al. 2020). Climate-aligned investments are assumed to be available without frictions (no credit constraints) and the trajectories do not reflect the impact of mitigation scenarios on investment decisions of financial institutions. A set of these scenarios is recommended by the NGFS for climate stress testing exercises. In particular, the NGFS has identified a single transition scenario that it considers disorderly, based on a late introduction of climate policies (NGFS 2020). This definition and selection of disorderly transition scenario could lead one to largely underestimate the PD of individual investors and induce investor moral hazard (Battiston and Monasterolo, 2019). In contrast, climate scenarios used in climate stress testing should be broad enough to consider the associated uncertainty (e.g., the type, timing and magnitude of climate policy and its impact). In addition, the term disorderly should include not only the timing of policy but, most important, the lack of investors' anticipation of the policy impact.

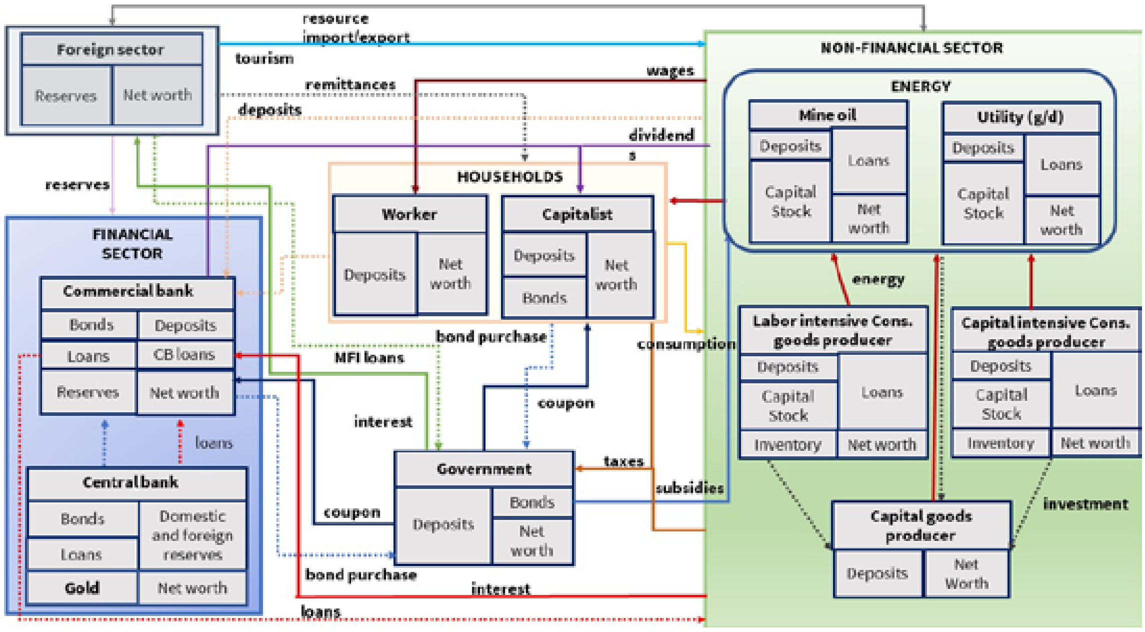
Risk transmission channels from the economy to finance

Assessing the risk transmission channels from climate change and policy to the economy and finance is crucial for climate stress testing. In this regard, macroeconomic models should:

– Be flexible enough to consider different and even extreme climate scenarios (probability of occurrence and magnitude of shocks) and the time delay of impacts on investors' and policy makers' decisions;
– Represent heterogeneity in agent preferences, allow agents to depart from perfect foresight and endow them with adaptive expectations in order to allow them to consider the impact of radical uncertainty in decision making;
– Be able to assess the drivers of reinforcing feedback loops and out-of-equilibrium dynamics in the economy, conditioned to climate change and climate policy scenarios. In this regard, it is crucial that shocks transmissions are traceable, and the causal relations statistically assessed to allow transparency of outcomes and increase the policy relevance of results
– Allow a realistic representation of the economic and financial investment, and government and central bank policy decisions in the low-carbon transition, thus departing from a world of first-best solutions.

Recent macroeconomic models based on Stock-Flow Consistency and complexity science contributed to

Figure 3
EIRIN Model Framework



Note: The figure represents the main agents and sectors of the EIRIN economy, and main capital and current account flows.
Source: Dunz et al. 2020b.

analyze the climate risk transmission in the economy and finance (see e.g. Bovari et al. 2018, Monasterolo and Raberto 2018, 2019; Dafermos et al. 2017; Naqvi and Stockhammer 2018; Yilmaz and Godin 2020). As a main feature, these models can assess shock transmission channels among agents and sectors, and the drivers of reinforcing feedback loops that give rise to non-linearity.

Heterogeneous sectors and agents are represented by their balance sheets entries that are connected in a network of relations (see Figure 3). Similarly to Agent Based Models (Dosi et al. 2010, Caiani et al. 2016, Lamperti et al. 2019), agents are endowed with adaptive expectations about the future and their decisions can depart from perfect foresight and optimization in contexts of deep uncertainty. These features allow the interplay between shock transmission and agent response to be represented as endogenously generated effects on macroeconomic variables, and government and central bank policy responses.

CONCLUSION

In this paper, we provide an overview of the challenges and opportunities for introducing finance and its complexity in the macroeconomic assessment of climate change and of the low-carbon transition.

We presented the characteristics of climate change risks, i.e., deep uncertainty, non-linearity and endogeneity, and the challenges for embedding them in climate economic models. In particular, we analyzed the implications of selection of mild climate scenarios, the treatment of uncertainty on economic impacts and investment decisions, the use of optimal policy approach and the neglecting the complexity of finance on the climate policy relevance of models' results.

We discussed the limits of taxonomies of investments and of the current conceptualization of carbon-stranded assets for assessing the exposure to climate risk of investor portfolios, going beyond the GHG emissions accounting and carbon budget. Finally, we presented recent approaches in macroeconomic and financial risk modeling that are contributing to address these challenges (e.g. climate stress testing), and that are now applied by central banks, financial regulators and development finance institutions.

Addressing the methodological challenges analysed here can open new avenues of research in climate finance and provide more policy-relevant and actionable results. This, in turn, requires the climate economics community to engage in interdisciplinary research, and to explore the added value of complementary modeling approaches in climate finance. Filling these research gaps is crucial for supporting policy makers and financial institutions in implementing credible, sustainable and effective climate policies, and avoiding trade-offs in financial stability and inequality.

REFERENCES

Ackerman, F. (2017), *Worst-case Economics: Extreme Events in Climate and Finance,* Anthem Press.

Adrian, T. and M. K. Brunnermeier (2016), "CoVaR", *The American Economic Review,* 106(7), p. 1705.

Alessi, L., S. Battiston, A. Melo and A. Roncoroni (2019), "The EU Sustainability Taxonomy: a Financial Impact Assessment", European Commission Joint Research Center ISPRA, available at https://ec.europa.eu/jrc/en/publication/eu-sustainability-taxonomy-financial-impact-assessment.

Battiston, S. (2019), "The Importance of Being Forward-looking: Managing Financial Stability in the Face of Climate Risk", in: Greening the Financial System: The New Frontier, pp. 39–48. Paris: Banque de France.

Battiston, S. and I. Monasterolo (2019), "The Climate Spread of Corporate and Sovereign Bonds", Working paper available at SSRN: https://ssrn.com/abstract=3376218.

Battiston, S., P. Jakubik, I. Monasterolo, K. Riahi and B. van Ruijven (2019), "Climate Risk Assessment of the Sovereign Bond Portfolio of European Insurers", in: European Insurance and Occupational Pension Fund (EIOPA) Financial Stability Report, pp. 69-89, December, 2019.

Battiston, S., A. Mandel, I. Monasterolo, F. Schütze and G. Visentin (2017), "A Climate Stress-test of the Financial System", *Nature Climate Change* 7:283–88.

Battiston, S., J. D. Farmer, A. Flache, D. Garlaschelli,, A.G. Haldane, H. Heesterbeek, C. Hommes, C. Jaeger, R. Mayand and M. Scheffer (2016a), "Complexity Theory and Financial Regulation", *Science*, 351(6275), pp. 818–819.

Battiston, S., G. Caldarelli, R. M. May, T. Roukny and J. E. Stiglitz (2016b), "The Price of Complexity in Financial Networks", *Proceedings of the National Academy of Sciences,* 113(36), pp. 10031–10036.

Berg, F., J. F. Koelbel and R. Rigobon (2020), "Aggregate Confusion: the Divergence of ESG Ratings", available at SSRN 3438533.

Billio, M., M. Getmansky, A. W. Lo and L. Pelizzon (2012), "Econometric Measures of Connectedness and Systemic Risk in the Finance and Insurance Sectors", *Journal of Financial Economics,* 104(3), pp. 535–559.

Bolton, P., M. Despres, L. A. Pereira da Silva, F. Samama, and R. Svartzman (2020), "The Green Swan: Central Banking and Financial Stability in the Age of Climate Change", Basel and Paris: Bank for International Settlements and Banque de France.

Bosetti, V., F. Lamperti, A. Roventini and M. Tavoni (2019), "The public Costs of Climate-induced Financial Instability", *Nature Climate Change* 9, no. 11: 829–833.

Bovari, E., G. Giraudand and F. Mc Isaac (2018), "Coping With Collapse: a Stock-flow Consistent Monetary Macrodynamics of Global Warming", *Ecological Economics,* 147, 383–398.

Busch, T., M. Johnson and T. Pioch (2020), "Corporate Carbon Performance Data: Quo Vadis?", *Journal of Industrial Ecology*.

Cahen-Fourot, L., E. Campiglio, E. Dawkins, A. Godin and E. Kemp-Benedict (2019), "Capital Stranding Cascades: The Impact of Decarbonisation on Productive Asset Utilisation", Working Paper, WU Epub.

Caiani, A., A. Godin, E. Caverzasi, M. Gallegati, S. Kinsella and J. E. Stiglitz (2016), "Agent Based-stock Flow Consistent Macroeconomics: Towards a Benchmark Model", *Journal of Economic Dynamics and Control* 69: 375–408.

Carney, M. (2015), "Breaking the Tragedy of the Horizon—Climate Change and Financial Stability", Speech given at Lloyd's of London by the Governor of the Bank of England, July 29, 2015.

Central Banks and Financial Regulators' Network for Greening the Financial System (NGFS) (2020), "Guide to Climate Scenario Analysis for Central Banks and Supervisors", Paris: Central Banks and Supervisors Network for Greening the Financial System.

Central Banks and Financial Regulators' Network for Greening the Financial System (NGFS) (2019), "A Call for Action: Climate Change as a Source of Financial Risk". First Comprehensive Report, April, NGFS, Paris. https://www.ngfs.net/en/first-comprehensivereport-call-action.

Dafermos, Y., G. Galanis and M. Nikolaidi (2017), "A Stock-flow-fund Ecological Macroeconomic Model", *Ecological Economics,* 131, pp. 191–207.

Dietz, S., A. Bowen., C. Dixon and P. Gradwell (2016), "Climate Value at Risk of Global Financial Assets", *Nature Climate Change*, 6(7), pp. 676–679.

Dosi, G., G. Fagiolo and A. Roventini (2010), "Schumpeter Meeting Keynes: A Policy-friendly Model of Endogenous Growth and Business Cycles", *Journal of Economic Dynamics and Control* 34, no. 9: 1748 1767.

Dunz, N., A. Naqvi and I. Monasterolo (2020a), "Climate Transition Risk, Climate Sentiments, and Financial Stability in a Stock-Flow Consistent Approach," *Forthcoming on Journal of Financial Stability.* SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3520764

Dunz, N., A. Mazzocchetti, I. Monasterolo and M. Raberto (2020b), "The Macroeconomic and Financial Risk Assessment of Compounding COVID-19, Climate Change and Financial Risk", working paper.

European Central Bank (ECB) (2019), "Climate Change and Financial Stability", in: *Financial Stability Review,* May 2019.

European Commission (EC) (2020), "Taxonomy: Final Report of the Technical Expert Group on Sustainable Finance", Brussels: European Commission.

IPCC (Intergov. Panel Clim. Change) (2014), "Climate Change 2014: Synthesis Report", Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed. RK Pachauri, LA Meyer. Geneva: IPCC.

IPCC (Intergov. Panel Clim. Change) (2018), "Summary for Policymakers", in: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, ed. VP Masson-Delmotte, HO Zhai, D Pörtner, J Roberts, PR Skea, et al. Geneva: IPCC.

Karpf, A. and A. Mandel (2018), "The Changing Value of the 'Green' Label on the US Municipal Bond Market", *Nature Climate Change* 8(2):161–65.

Kriegler, E., M. Tavoni, T. Aboumahboub, G. Luderer and K. Calvin et al. (2013), "What Does the 2°C Target Imply for a Global Climate Agreement in 2020? The LIMITS Study on Durban Platform Scenarios", *Climate Change Economics* 4(4):1340008.

Lamperti, F., V. Bosetti, A. Roventini and M. Tavoni (2019), "The Public Costs of Climate-induced Financial Instability", *Nature Climate Change* 9, no. 11: 829-833.

Leaton J. (2012), "Unburnable Carbon: Are the World's Financial Markets Carrying a Carbon Bubble?", Report, CarbonTracker Init., London. https://carbontracker.org/reports/carbon-bubble/.

Lenton, T.M., J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen and H. J. Schellnhuber (2019), "Climate Tipping Points—Too Risky to Bet Against", *Nature*.

Monasterolo, I. (2020), "Climate Change and the Financial System", *Annual Review of Resource Economics*, Volume 12, 1–22.

Monasterolo, I. and S. Battiston (2020), "Assessing Forward-looking Climate Risks in Financial Portfolios: a Science-based Approach for Investors and Supervisors", in: NGFS Handbook of Environmental Risk Assessment for Investors.

Monasterolo, I. and L. de Angelis (2020), "Blind to Carbon Risk? An Analysis of Stock Market's Reaction to the Paris Agreement", *Ecological Economics,* 170, 1–10.

Monasterolo, I. and U. Volz (2020), "Addressing Climate-related Financial Risks and Overcoming Barriers to Scaling up Sustainable Investments", T20 Policy Brief, Rhiad: Think20.

Monasterolo, I. and M. Raberto (2019), "The Impact of Phasing Out Fossil Fuel Subsidies on the Low-Carbon Transition", *Energy Policy*, 124, 355–370.

Monasterolo, I., A. Roventini and T. J. Foxon (2019), "Uncertainty of Climate Policies and Implications for Economics and Finance: An Evolutionary Economics Approach", *Ecological Economics* 163: 177–182.

Monasterolo, I. and M. Raberto (2018), "The EIRIN Flow-of-Funds Behavioural Model of Green Fiscal Policies and Green Sovereign Bonds", *Ecological Economics,* 144, 228–243.

Monasterolo, I., J. I. Zheng and S. Battiston (2018), "Climate Transition Risk and Development Finance: a Carbon Risk Assessment of China's Overseas Energy Portfolios", *China & World Economy,* 26(6), pp. 116–142.

Monasterolo, I., S. Battiston, A. C. Janetos and Z. Zheng (2017), "Vulnerable Yet Relevant: the Two Dimensions of Climate-Related Financial Disclosure", *Climatic Change*, 145(3-4), 495–507.

Morana, C. and G. Sbrana (2019), "Climate Change Implications for the Catastrophe Bonds Market: An Empirical Analysis", *Economic Modelling,* 81, pp. 274–294.

Naqvi, A. and E. Stockhammer (2018), "Directed Technological Change in a Post-Keynesian Ecological Macromodel", *Ecological economics,* 154, pp. 168–188.

Nordhaus, W.D. (1993), "Optimal Greenhouse-gas Reductions and Tax Policy in the" DICE" Model", *The American Economic Review,* 83(2), pp. 313–317.

Nordhaus, W.D. (2017), "Revisiting the Social Cost of Carbon", *Proceedings of the National Academy of Sciences,* 114(7), pp. 1518–1523.

Ramelli, S., A. F. Wagner, R. J. Zeckhauser and A. Ziegler (2018), "Investor Rewards to Climate Responsibility: Evidence from the 2016 Climate Policy Shock", (No. w25310) *National Bureau of Economic Research*.

Steffen, W., J. Rockström, K. Richardson, T. M. Lenton and C. Folke et al. (2018), "Trajectories of the Earth System in the Anthropocene", *Proceedings of the National Academy of Sciences,* 115(33):8252–59.

Stolbova, V., I. Monasterolo and S. Battiston (2018), "A Financial Macronetwork Approach to Climate Policy Evaluation", *Ecological Economics,* 149, 239–253.

Van der Ploeg, F. and A. Rezai (2020), "Stranded Assets in the Transition to a Carbon-free Economy", *Annual Review of Resource Economics,* Vol. 12:281–298.

Weitzman, M. L., (2009), "On Modeling and Interpreting the Economics of Catastrophic Climate Change", *Review of Economics and Statistics,* 91(1):1–19.

UNFCCC, (2015), Report of the Conference of the Parties on its Twenty-first Session, held in Paris from 30 November to 13 December 2015. Part two: Action Taken by the Conference of the Parties at its Twenty-first Session. Rep. FCCC/CP/2015/10/Add.1, UNFCCC, Paris.

Yilmaz, S.D. and A. Godin (2020), "Modelling Small Open Developing Economies in a Financialized World: a Stock-Flow Consistent Prototype Growth Model", AFD Research Papers.