Macrofinancial Risks of the Transition to a Low-Carbon Economy

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Introduction

To achieve net-zero greenhouse gas (GHG) emissions in a way that is compatible with the temperature targets of the 2016 Paris Climate Agreement, the global economy must decarbonize (IPCC 2021). The transition to a carbon-free economy will require an increase in the share of low-carbon activities and technologies and a decrease in the share of high-carbon activities and technologies.[1] These trends have two key macrofinancial implications. First, the expansion of low-carbon activities will require significant physical and financial investments. This means that firms will need to produce and install low-carbon capital, while financial institutions will need to invest in and lend to low-carbon firms. Second, high-carbon sectors will need to be phased out in a controlled manner, with new high-carbon physical and financial investments declining rapidly and eventually ending altogether. In addition, a strategy needs to be developed for dealing with the existing stocks of high-carbon physical and financial assets so that their early decommissioning does not destabilize the economic and financial system (van der Ploeg and Rezai 2020b).

These issues have triggered widespread concern about the macrofinancial impacts of the low-carbon transition among policy makers, corporations, and financial institutions. Such

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[1]Low-carbon activities include productive processes based on clean electricity or hydrogen, production of electricity through renewable energy sources, improvement in the energy efficiency of buildings and industry, electric mobility, and other similar activities. High-carbon activities include fossil extraction and distribution; production of electricity using fossil-fueled plants; carbon-intensive manufacturing processes in the steel, cement, chemical, and other industries; fossil-fueled transportation; and other activities that produce large carbon emissions.

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concerns are not surprising given human societies' lack of experience in managing major technological shifts. Historically, technological transitions were driven mainly by the emergence of more productive technologies, including fossil-based technologies (Fouquet 2010), that market actors "naturally" adopted. However, this does not appear to be occurring (yet) for low-carbon technologies because policies are still needed to incentivize low-carbon investments. Furthermore, there is still a lack of research on the macrofinancial implications of technological transitions, especially concerning "sunset" industries that will need to be phased out or radically transformed (Semieniuk et al. 2021).

This article seeks to increase our understanding of how the transition to a low-carbon economy may affect macrofinancial stability and to identify policy strategies to mitigate macrofinancial transition risks. With this in mind, we identify and discuss four main avenues of research in this area: (i) conceptual frameworks and qualitative analyses of potential transition scenarios, (ii) empirical quantification of the physical and financial exposure to transition risks, (iii) dynamic modeling of macrofinancial transition patterns, and (iv) analyses of policy and institutional strategies aimed at ensuring an orderly transition. The final section discusses current knowledge gaps and suggests priorities for future research.

Conceptualizing Macrofinancial Transition Patterns

The academic and policy literature has recently developed conceptual frameworks for examining the implied risks of possible future low-carbon transition scenarios for macroeconomic and financial stability (Batten 2018; Campiglio et al. 2018; NGFS 2019; Bolton et al. 2020; Semieniuk et al. 2021). This literature focuses in particular on the potential for a "disorderly" transition—that is, a process of technological change that is accompanied by large socioeconomic costs and financial volatility. We can break disorderly transition risks into four key dimensions: (i) the drivers of macrofinancial transition risks, (ii) the impacts on nonfinancial firms, (iii) the impacts on financial institutions, and (iv) the broader macrofinancial impacts. We discuss each of them in turn.

Drivers of Macrofinancial Transition Risks

The literature generally highlights three main categories of transition risk drivers. First, the implementation of climate mitigation policies may not be anticipated by economic agents, which could cause an abrupt reevaluation of the profitability of fossil fuel extraction and other carbon-intensive activities. This in turn may lead to a fall in the price of firms' financial assets. Anticipated but very stringent mitigation policies could also trigger these types of effects. For example, if the policy-driven emission pathway is steeper than the one implied by the "natural" lifetime of existing productive assets, some of these assets will have to remain idle, which could affect the market valuation of the firm.

The second risk driver concerns unanticipated or very rapid improvements in technology. Such changes can have economic and financial implications by making existing capital stocks prematurely obsolete and leading to sudden drops in the share prices of carbon-intensive firms, independent of the climate policies implemented. Similarly, negative emission technologies (e.g., carbon capture and storage, direct removal of CO_2 from the air) may become competitive in the future and contribute to the continued use of fossil-based technologies.

Third, rapid changes in the preferences, beliefs, and expectations of consumers, entrepreneurs, and financial investors could affect businesses' profitability and financial asset prices. Increased environmental awareness and social movements (e.g., the "Fridays for Future" movement, inspired by Greta Thunberg) could be one such driver. Another driver could be a sudden and unanticipated change in public opinion concerning the urgency of decarbonization in response to a particularly dramatic climate-related event.

Impacts on Nonfinancial Firms

There are two main potential impacts of transition risks on nonfinancial companies: (i) a decrease in revenues or an increase in costs, which results in a decline in business profitability (i.e., a "flow" effect), and (ii) a change in the valuation of assets on companies' balance sheets (i.e., a "stock" effect). Two types of physical assets are at risk of becoming "stranded" during a disorderly low-carbon transition: (i) reserves of fossil fuels may remain unextracted, and (ii) long-lived stocks of high-carbon capital (e.g., fossil-fueled electric power plants) may have to be retired before the end of their normal lifetime, used below their standard capacity utilization rate, or repurposed at a cost. These economic impacts can then spread from carbon-intensive activities to other sectors through the interfirm production network.[2]

Impacts on Financial Institutions

These stock and flow economic effects on nonfinancial firms can also have potential implications for financial institutions. First, the proportion of carbon-intensive firms defaulting may increase, thus increasing the probability of loans not being repaid and putting commercial banks at risk. Second, a sudden downward revision of nonfinancial institutions' expected profits would likely trigger a revaluation of their outstanding financial assets (e.g., bonds, stocks), thereby negatively affecting the portfolios of investors that hold them. The effects of a disorderly low-carbon transition on financial institutions depend on various factors, including the degree and distribution of financial institutions' exposure to affected productive sectors, the strength of the ties among financial institutions, and the extent to which transition risks have already been internalized in financial asset prices.

Macrofinancial Impacts

Finally, if strong enough, the combination of economic and financial effects can trigger additional impacts at the broader macroeconomic level. Semieniuk et al. (2021) and others mention several impacts, including increased financing costs for firms; reduced demand for credit; loss of confidence by households, firms, and banks; reduced income and consumption; unemployment; increased public debt and worsening of financing conditions for sovereign borrowing; and inflationary pressures. The scenario in which a combination of these impacts significantly affects macrofinancial stability is often referred to as a "climate Minsky moment" (Carney, Villeroy de Galhau, and Elderson 2019) or a "green swan" event (Bolton et al. 2020). The qualitative literature on sociotechnical transitions might offer additional insights in this regard,

[2]For example, an increase in electricity prices triggered by a carbon price may affect the operations of downstream firms that use electricity.

but with some recent exceptions (e.g., Geddes and Schmidt 2020), it still lacks a well-developed integration of financial dimensions.

Empirical Analysis of Macrofinancial Transition Risks

We next examine the empirical literature on financial transition risks and whether there is supporting evidence for the conceptual framework discussed in the previous section. In particular, what is the likelihood of the transition triggering large-scale macrofinancial volatility? Three strands of the empirical literature attempt to address these issues. The first strand examines the number and type of physical assets (either fossil fuel reserves or productive capital stocks) at risk of becoming stranded. The second strand studies the direct and indirect exposure of financial institutions to high-carbon activities. The third strand, rooted mainly in finance, assesses the degree to which transition risks are included in the price of financial assets (stocks, bonds, loans, and others); this is important because the extent to which investors have already priced in these risks determines the potential magnitude of future volatility. We examine these three strands of the literature in turn.

Physical Stranded Assets

If effective mitigation policies are introduced or if technological progress makes fossil-based technologies obsolete, reserves of oil, gas, and coal will remain at least partly unutilized. While there is substantial uncertainty about the exact size of a 1.5°C or 2°C carbon budget (Meinshausen et al. 2009; Rogelj et al. 2019),[3] it is clear that this budget is lower than the amount of emissions that would occur if all reserves were extracted. For example, Welsby et al. (2021) use a partial equilibrium model to identify the cost-efficient distribution of reserves to leave in the ground and find that to stay within a 1.5°C carbon budget, approximately 60 percent of oil and gas reserves and 90 percent of coal reserves might have to remain unextracted at the global level, with large variations across regions. This reduction in fossil fuel extraction and the associated loss of revenues are likely to have macroeconomic repercussions. For example, Mercure et al. (2018) find that a 2°C temperature target and a transition driven by technological diffusion both lead to significant stranding of fossil reserve assets, which triggers GDP losses for some regions (mainly large fossil exporters, like the United States and Canada) and GDP gains for others (fossil fuel importers, such as China and the European Union).

Productive capital stocks that use fossil fuels, either as an intermediate input or to create heat, are also at risk of stranding. These include electricity plants, blast furnaces, cement kilns, chemical plants, buildings, transport infrastructure, and other long-lived carbon-intensive capital stocks. The amount of emissions "committed" (or implied) by operating these physical assets can be calculated (assuming certain lifetimes and utilization rates) and compared with 1.5°C or 2°C carbon budgets. For example, Tong et al. (2019) calculate the committed CO_2 emissions from existing and proposed global infrastructure in electricity, industry, transport, and other fossil-burning sectors. Their results suggest that these emissions may already be above the 1.5°C carbon budget and around two-thirds of the 2°C budget. Similarly, IEA (2020) finds

[3]The carbon budget is the maximum cumulative emissions that can occur while keeping the temperature below its target level.

that global CO_2 emissions locked in by existing energy-related assets are already close to the emissions produced in its Sustainable Development Scenario, which achieves a 1.65°C rise in global temperature with a 50 percent probability. These results concerning committed emissions and carbon budgets suggest that new investments in high-carbon capital assets should be immediately or rapidly discontinued and that a significant proportion of existing carbon-intensive capital stock is in danger of being stranded.

Integrated assessment models (IAMs) have been used to examine how and to what extent stranding might occur as a result of a technological transition. These studies generally find that cost-effective pathways to 1.5°C or 2°C require a reduction in the lifetime and capacity utilization of high-carbon assets (Cui et al. 2019; Fofrich et al. 2020). Johnson et al. (2015) show that delaying the introduction of stringent policies actually worsens asset stranding, especially in China and India.[4] Smaller-scale analytical models have also been used to study optimal stranding pathways under a carbon budget that requires a proportion of dirty capital stocks to remain unutilized (Coulomb, Lecuyer, and Vogt-Schilb 2019; Baldwin, Cai, and Kuralbayeva 2020; Rozenberg, Vogt-Schilb, and Hallegatte 2020). Neither numerical nor analytical IAMs include an explicit representation of financial systems.

The literature on asset stranding often focuses on specific sectors that have a high risk of stranding, particularly mining or coal- or gas-fueled electricity production. However, transition risks extend beyond these sectors, affecting other productive activities that rely on their products as intermediate inputs and, ultimately, negatively impacting the entire economic system (Hebbink et al. 2018; Devulder and Lisack 2020). Cahen-Fourot et al. (2021) calculate a set of "stranding multipliers" that provide an estimate of the stock of capital at risk of remaining underutilized as a result of a negative shock that occurs in the fossil sector of a particular region. Their results suggest that international exposure to the risk of physical asset stranding is significant and also affects downstream sectors (such as real estate, public administration, and health) via second-round effects that occur within the production network. However, further research is needed to apply the insights from the economics literature on international production networks (Acemoglu et al. 2012; Carvalho and Tahbaz-Salehi 2019) to the analysis of a disorderly transition to a low-carbon economy.

High-Carbon Exposure of Financial Institutions

The issue of financial exposure was first examined by Leaton (2011) and Leaton et al. (2013), who compared the 2°C carbon budget with the potential emissions from the fossil reserves owned by the top 200 fossil fuel companies (as listed on the world's stock exchanges). They find that the emissions that would be created from using these fossil reserves greatly exceed the emissions that are compatible with a 2°C rise in temperature. This indicates that fossil fuel companies may be riding a "carbon bubble"; that is, they may be overvalued compared with their true worth in a 2°C world. Several subsequent studies (often by researchers at central banks) have assessed the exposure of financial institutions to specific sectors. For example, Giuzio et al. (2019) examine the exposure of European banks to climate-sensitive sectors;

[4]Their analytical approach, based on looser or stricter emission targets in the short term (2030) followed by the unanticipated implementation of a long-term 2°C-consistent policy, was subsequently adapted by Bertram et al. (2021).

Faiella and Lavecchia (2020) examine the carbon content of Italian loans, while Delgado (2019) provides a similar analysis for Spanish banks; and EIOPA (2020) maps the exposure of European insurers to a low-carbon transition scenario.

These analyses typically consider only the direct exposure of financial institutions to specific upstream high-carbon sectors (extraction industries, electricity generation, energy-intensive manufacturers). One could expand the analysis by applying a network perspective to financial systems. Given the interconnections among financial firms and that they are all exposed to each other (to some extent) via financial contracts, firms may be vulnerable to transition risks even if they are not directly exposed to fossil-intensive sectors (Battiston et al. 2017; Stolbova and Battiston 2020). For example, Roncoroni et al. (2021) examine the impacts of a climate policy shock on the Mexican financial system, identifying several rounds of effects, including (i) losses suffered by banks and investment funds as a result of direct exposure (bonds and loans) to climate-related risks; (ii) revaluation of claims among financial institutions, driven by the increased risk of banks' default; (iii) "fire sales" (i.e., large-scale sales of assets at a heavily discounted price) of external assets by banks and investment funds, which cause further asset price declines; and (iv) losses that are too large to be absorbed by banks and are instead transmitted to external creditors.

Transition Risks and the Price of Financial Assets

It is important to understand the extent to which financial institutions are aware of their potential exposure to transition risks and are pricing these risks into financial assets. This is because if and when there is a transition shock, there is likely to be more upheaval in the financial system if investors have previously failed to internalize transition risks. This empirical issue is not easy to address, and the current literature provides conflicting evidence.[5]

Some studies suggest that carbon-intensive companies pay a "carbon premium" to investors to convince them to accept the transition risks faced by these firms. For example, Bolton and Kacperczsyk (2021a) combine financial and carbon emissions data for a large sample of US listed companies in 2005–2017 and find that financial markets are already at least partly internalizing transition risks by forcing firms with higher total emissions to offer a higher premium to investors. This carbon premium is also associated with year-by-year changes in emissions, suggesting that companies capable of cutting emissions have easier access to capital. The authors also find that the carbon premium has emerged only in recent years. Performing a similar exercise for firms in 77 countries, Bolton and Kacperczyk (2021b) find empirical evidence of a positive and increasing carbon risk premium in stock market returns. They also find that the premium is higher in countries with more stringent climate mitigation policies and larger fossil-extracting sectors and in countries that are more exposed to physical climate risks such as floods, wildfires, and droughts. On the basis of a sample of 600 North American oil firms over the 1999–2018 period, Atanasova and Schwartz (2020) find that growth in oil reserves negatively affects firm value, especially for firms with higher extraction costs and for undeveloped oil reserves located in countries with strict climate policies.

[5]For a more comprehensive review of this topic, see Daumas (2021) and Campiglio, Monnin, and von Jagow (2022).

Sen and von Schickfus (2020) follow a different empirical approach, estimating the effect of the gradual implementation of a German climate policy aimed at reducing coal-fired electricity production on the market value of energy utilities. Their findings suggest that investors account for the risk of stranding in their valuation but that they also expect the government to compensate them for this risk, and hence that they will not be financially affected. Only the announcement of possible barriers to compensation triggered a reaction in financial markets, leading to financial losses for three major German utilities. This suggests that there needs to be further investigation of the use of litigation for compensation when firms are faced with disorderly climate policy changes.

Other research focuses instead on the provision of syndicated bank loans. Delis et al. (2021) find that an increase in the fossil fuel reserves of a firm increases the interest rates it has to pay to banks. Ehlers, Packer, and de Greiff (2021) reach similar conclusions in a study of firms with high emission intensity.[6] Ilhan, Sautner, and Vilkov (2021) also find empirical support for a carbon premium in the market for options.

However, the issue of carbon premiums remains unresolved because other studies find that low-carbon investment strategies are associated with higher returns, which suggests that the risk associated with carbon emissions is underpriced. For example, In, Park, and Monk (2019) find empirical evidence that a portfolio that is long in shares of low-carbon companies and short in shares of high-carbon companies generates abnormally high and positive returns. This suggests that markets underprice carbon risk to the extent that responsible green investors perform better than nongreen investors. Görgen et al. (2020) do not find evidence of a carbon premium, while Bernardini et al. (2021) find evidence of a low-carbon premium in the European utility sector.

An alternative approach to capturing investors' perceptions of transition risks elicits opinions through surveys. The empirical literature based on this approach suggests that, despite several obstacles, investors increasingly take account of climate-related risks, including transition risks (Harnett 2017; Amel-Zadeh 2019; Krueger, Sautner, and Starks 2020; Stroebel and Wurgler 2021). As we discuss in the final section, one could also attempt to examine agents' transition-related beliefs and expectations through text analysis or experiments.

Modeling Macrofinancial Transition Dynamics

Empirical analysis is crucial to understanding past and present conditions and provides insights on the potential exposure of macrofinancial systems to transition risks. However, we cannot rely solely on past evidence to understand the future dynamics of the low-carbon transition because changing conditions may lead agents and the financial system itself to respond differently to the same shock at different times. Moreover, some of the potential scenarios, such as a green swan, are historically unprecedented, which means that there is a lack of empirical evidence. To assess the macrofinancial dynamics associated with future low-carbon transitions,

[6]More precisely, Delis et al. (2021) find that a 1 standard deviation increase in the fossil fuel reserves of a firm increases the loan spread by 25.3 basis points, and Ehlers, Packer, and de Greiff (2021) find that a 1 standard deviation increase in the intensity of direct emissions (also known as scope 1 emissions) implies a carbon risk premium of around 17 basis points.

we must use forward-looking (i.e., prospective) modeling methodologies that carefully and consistently integrate the economic, financial, and climatic dimensions (Svartzman et al. 2020). In the remainder of this section, we discuss the modeling approaches that are being used to study the macrofinancial implications of a low-carbon transition and identify their current limitations.

Available Modeling Options

We identify three main prospective modeling approaches: (i) IAMs, (ii) neoclassical macroeconomic and financial models, and (iii) complexity models. The first two approaches tend to develop supply-side models based on optimizing forward-looking agents and clearing markets, with the goal of identifying optimal transition paths. In contrast, the third approach is usually demand led, based on macroeconometric relations and adaptive expectations and aimed at studying possible system behaviors.

IAMs

The first approach includes models that explore the interactions between the economy, energy systems, and climate dynamics. We can further distinguish among large-scale numerical models that include a detailed representation of energy technologies and pollutants, driven by welfare maximization or cost minimization (numerical IAMs); multiregional models with a granular representation of international and intersectoral flows (computable general equilibrium models); and small-scale analytical models aimed at identifying optimal rules for policy and private sector behavior (analytical IAMs). While different in many respects, all of these models are consistent with the neoclassical modeling paradigm, which is usually characterized by clearing of markets, homogeneous rational agents, and optimal behavior. Large-scale IAMs tend to have a relatively simple economic module with no financial dimensions. Hence, with some exceptions (e.g., Dietz et al. 2016), numerical IAMs are currently used mainly to provide reference emission, energy, and carbon price pathways that are then incorporated into other models that provide a more sophisticated representation of macrofinancial dynamics (Allen et al. 2020; Bertram et al. 2021). Given their more manageable size relative to numerical models, analytical IAMs might be a more promising option for incorporating stylized macrofinancial dynamics such as inflation, financial valuation, and monetary policies.

Neoclassical models

The second type of modeling approach is based on neoclassical macroeconomic and financial models. Here we can distinguish between dynamic models characterized by representative rational agents that respond to stochastic shocks (real business cycle [RBC] or dynamic stochastic general equilibrium [DSGE] models) and financial models aimed at capturing optimal asset prices along the transition path (e.g., capital asset pricing models). These approaches seek to identify optimal transition paths or optimal reactions to exogenous shocks. Only recently have they started to focus on environmental questions by incorporating climate variables (e.g., a carbon budget, a climate damage function) or transition-related variables (e.g., a distinction between green and dirty sectors). The first studies using an RBC setting compared the macroeconomic and welfare effects of different mitigation policies in the presence of productivity shocks or studied the features of optimal mitigation policies (Fischer and Heutel 2013). These were followed by studies using the new Keynesian DSGE approach, which introduces financial frictions and nominal rigidities (e.g., informational asymmetry, stickiness of prices, capital adjustment costs) to examine how monetary policies and financial regulation can be used to supplement climate policies (Annicchiarico and Di Dio 2015; Benmir and Roman 2020; Comerford and Spiganti 2020; Carattini, Heutel, and Melkadze 2021). DSGE and asset pricing models have also been used to examine optimal asset pricing behavior under uncertainty and the effects of risk premiums for green and carbon-intensive assets along the low-carbon transition (Karydas and Xepapadeas 2019; Hambel, Kraft, and van der Ploeg 2020).

A key finding of these models is that the capital stock may not be reduced to zero in the carbon-intensive sector, especially if damages from global warming are modest and the risk of climate disasters does not rise too much with temperature. The point is that the benefits of mitigating emissions by reducing stocks of high-carbon capital should be balanced against the costs of being less able to hedge against shocks to the different sectors of the economy. It may thus be optimal to keep some of the carbon-intensive sectors open for hedging purposes. Although carbon-intensive assets may display a risk premium, in the sense that investors demand a higher rate of return, this risk premium may be much higher in the presence of policy transition risks (in line with the empirical evidence in Bolton and Kacperczyk [2021a, 2021b]). Thus, the probability of a future government enacting a more stringent climate policy makes carbon-intensive stocks riskier, which leads investors to demand a higher return on these stocks. The consequences of these risks are more substantial if it is more difficult to redeploy and repurpose capital from the carbon-intensive to the green sectors. Technically, this requires that the models allow for irreversibility of investments or, alternatively, intersectoral and intertemporal adjustment costs for investments. Such models can then be used to identify the risk of stranded financial assets.

Complexity models

The third approach is based on complexity theory and the study of dynamic systems. Here we can further distinguish among (i) stock-flow consistent models, which represent the economy using the dynamic balance sheets of institutional sectors (households, firms, banks, government, etc.; Dafermos, Nikolaidi, and Galanis 2018; Dunz, Naqvi, and Monasterolo 2021); (ii) agent-based models, which assume that each sector is populated by a set of agents characterized by heterogeneous preferences, endowments, and decision criteria (Ponta et al. 2018; Rengs, Scholz-Wäckerle, and van den Bergh 2020); and (iii) diffusion models, which propose a more aggregate perspective of technology adoption processes (Mercure 2015). These approaches share methodological features that are rooted in nonneoclassical schools of economic thought, such as post-Keynesian, evolutionary, or ecological economics (Mercure et al. 2019). They model economies as out-of-equilibrium systems driven by demand rather than supply, allowing for multiple frictions (e.g., underutilization of input factors, price and wage distortions). Instead of looking for the optimal path through intertemporal welfare maximization (or cost minimization), these models use macroeconometric estimation to explore possible future scenarios depicting economic behaviors. Expectations of economic agents are usually assumed to be adaptive and backward looking. Given their complexity, these models are typically solved numerically to examine a set of simulation scenarios. However, they are often challenging to estimate and calibrate, and their results may not be easy to interpret. Moreover, because they rely on adaptive expectations, which is due to both methodological preferences and the desire to ease computational complexity, they do not allow the economy to anticipate future changes in technology or climate policy.

How Well Do These Models Capture Transition Risks?

Although the modeling approaches that we have presented here offer valuable insights, they have at least three limitations. First, the endogenous nature of transition risk drivers is still poorly understood. In fact, models typically produce a disorderly transition because they assume an unanticipated and abrupt increase in carbon prices. For example, the Network for Greening the Financial System (NGFS) includes a "disorderly transition" scenario in which a carbon price is unexpectedly introduced in 2030 and subsequently rises at a rapid rate (Bertram et al. 2021).[7] In contrast, under their "orderly transition" scenario, a carbon price is introduced in 2020 and subsequently rises at a more gradual rate. The unanticipated climate policy shock approach draws on what is known as stress testing, a methodological approach that analyzes "severe but plausible" scenarios (Vermeulen et al. 2018; Allen et al. 2020; EIOPA 2020; Carattini, Heutel, and Melkadze 2021). Technological breakthroughs are a less common driver of transition risk in models, and they are usually treated as exogenous (Vermeulen et al. 2018; Allen et al. 2020). The third main driver of transition risk (discussed above)—changes in the beliefs and expectations of individuals and firms—has been studied the least. In this respect, we believe that the literature on the low-carbon transition would benefit from developing closer links to the literature on the role of heterogeneous expectations, social norms, and sentiments in macroeconomic dynamics (e.g., Bordalo, Gennaioli, and Shleifer 2018; Hommes 2021). Finally, several additional drivers and mechanisms that could disrupt the macrofinancial transition to a low-carbon economy (e.g., an overvaluation of green financial assets) have thus far received little or no attention in the modeling literature.

A second limitation of the available modeling approaches, which mostly treat transition risk drivers as unexpected shocks, is that they do not fully account for the role or the related uncertainty of expectations concerning policy implementation. For example, a policy might affect investment behavior and asset prices well before it is implemented or even announced, simply because forward-looking agents might already be considering the possibility of its implementation. Thus far, only a few small-scale general equilibrium models have explicitly examined how uncertainty about the timing of policy or technological breakthroughs might affect macrofinancial and transition dynamics (e.g., Barnett 2019; van der Ploeg and Rezai 2020a; Fried, Novan, and Peterman 2021).

The third limitation is the lack of a full understanding of the rich complexity of technological, economic, financial, and climatic dynamics. Indeed, most of the literature thus far has focused on specific dimensions or has developed stylized models to provide insights

[7] Launched in 2017, the NGFS is a network of more than 100 central banks and financial supervisors aimed at "strengthening the global response required to meet the goals of the Paris agreement and to enhance the role of the financial system to manage risks and to mobilize capital for green and low-carbon investments" (see http://www.ngfs.net).

on key dynamics. However, understanding macrofinancial transition risks will require a systemic perspective comprising a number of distinct dynamic components, something that is very hard to achieve. For instance, production and financial networks are generally excluded from prospective dynamic modeling. In fact, not even a solid link between production and financial networks has been fully developed. The most advanced numerical exercises along these lines include those of Allen et al. (2020), who combine three numerical IAMs to provide pathways for energy mixes, carbon prices, and other similar variables; a new Keynesian macroeconomic model (National Institute Global Econometric Model; see Hantzsche, Lopresto, and Young 2018) that calculates macroeconomic variables (GDP, employment, interest rates) for a set of aggregate regions; a production network model (Devulder and Lisack 2020) that transforms aggregate macroeconomic dynamics into sector-specific results; and a set of Banque de France financial models that estimate the probability of default and the change in the price of financial assets (bonds and stocks). These models indicate that a disorderly and sudden transition scenario has moderate aggregate impacts but significant sectoral impacts. Brandoli et al. (2021) perform a similar multiple-model analysis for the Italian financial sector and also study the exposure of financial institutions to transition risks. However, none of these contributions offer a complete picture of macrofinancial transition dynamics; for example, they lack a feedback mechanism from financial dynamics back to transition pathways.

Policy Strategies for Achieving an Orderly and Rapid Low-Carbon Transition

Thus far, we have highlighted the role of several drivers in triggering transition-related disruptions that could affect macrofinancial stability. What policy strategies could be used to mitigate the risk of such a disorderly transition? This is a difficult question to answer because the policies themselves could trigger socioeconomic disruptions. One policy strategy is the early implementation of a sufficiently high carbon price, followed by a gradual and credible increase in the price in subsequent years, which would provide incentives for firms and households to invest in the “green” transition and avoid carbon-intensive investments. However, ambitious carbon pricing is difficult to implement in practice (World Bank 2021) because it is unpopular and hence has negative impacts on the electability of policy makers. In fact, there is conflicting evidence concerning the impact of carbon prices on carbon-free investment and innovation (Lilliestam, Patt, and Bersalli 2021). Furthermore, additional market failures in financial systems suggest that carbon prices alone may not be sufficient to convince investors to reallocate their portfolios in a way that contributes to an orderly macrofinancial transition (Campiglio 2016). What other policy options are available? And are such policies institutionally feasible? In the remainder of the section, we discuss green financial and monetary policies and their institutional feasibility.

Green Financial and Monetary Policies

We consider three main policy categories: (i) policies aimed at expanding or improving the sustainability-related information available to economic agents, (ii) green financial regulation, and (iii) green monetary policies.

Green informational policies

One set of policy options aimed at achieving a smooth low-carbon transition focuses on gradually nudging investors to become aware of their exposure to financial transition (as well as physical) risks so that they can avoid abrupt market swings later on. Investor awareness can be improved through various strategies. First, the definitions and rules need to be made clear to financial institutions. Efforts in this direction include the development of "sustainability taxonomies" that clarify which activities can be considered sustainable, the introduction of green bond standards, and the definition of climate-related benchmarks (e.g., a "Paris-aligned" benchmark). Second, financial institutions need to be able to assess their exposure to climate-related risks. Several policy and industry initiatives have sought to develop methodologies for assessing climate-related risks for nonfinancial firms, financial firms, and financial systems (e.g., climate stress testing; NGFS 2019). However, it is not easy to assess climate-related risks at the present time because of a lack of sufficiently granular data. Third, once exposure to climate-related risks is assessed, it needs to be disclosed to all market participants in a standardized form (TCFD 2017) so that market discipline can play its intended role of including risks in financial asset prices.

Although these measures are moving in the right direction, they are unlikely to be sufficient to either adequately shift investments toward low-carbon activities or protect financial institutions against climate-related risks (Christophers 2017; Ameli et al. 2020). In addition, most of these policies are voluntary, and because of the methodological complexities discussed above, they may be unable to offer a comprehensive and commonly acceptable risk assessment technique. Because a full assessment of exposure to climate-related risks may be infeasible, economists have called for central banks and financial supervisors to use a precautionary approach when dealing with climate-related risks (i.e., to start acting on the basis of available data and methods, even if they are imperfect; Chenet, Ryan-Collins, and van Lerven 2021).

Green financial regulation

Another strategy is to pursue proactive policies that more directly push financial institutions to invest in low-carbon activities.[8] One such option is to design financial regulation to offer economic incentives to financial institutions that invest in low-carbon firms (D'Orazio and Popoyan 2019), such as having banks' capital requirements depend on the carbon intensity of borrowing firms. Indeed, Carattini, Heutel, and Melkadze (2021) find that targeted financial policies in the form of taxes and subsidies on banks' assets can have positive (although limited, if a carbon tax is absent) effects on the low-carbon transition and associated macro-financial dynamics. However, the literature still needs to address a fundamental asymmetry. That is, although it may be helpful to tighten capital requirements for carbon-intensive firms that face transition risk, it would not be wise to loosen capital requirements for green firms because of the risk of higher macroeconomic volatility, more defaults, and welfare losses.

[8] Of course, governments themselves can participate in financing low-carbon investments, e.g., through the action of national and multilateral banks (Mazzucato and Semieniuk 2018). However, we focus here only on policies directed at private financial actors.

Green monetary policies

Monetary policy and other conventional central banking policy instruments could also be used for transition-related purposes. For instance, requirements to hold reserves at central banks could be eased for banks that lend to green activities such as renewable energy or energy efficiency, as was done by the Lebanese Central Bank (Campiglio 2016). The same approach could be used for the interest rate that is applied to the central bank financing of banks (Böser and Colesanti Senni 2020). Similarly, van 't Klooster and van Tilburg (2020) propose green targeting of longer-term refinancing operations. Alternatively, the central bank collateral framework (the rules governing the eligibility of financial assets that commercial banks deposit as collateral at the central bank) might include climate-related considerations (McConnell, Yanovski, and Lessmann 2020; Oustry et al. 2020). In addition to using market-based incentives, central banks could request that banks allocate their credit according to certain sectoral quotas, as was done by the Reserve Bank of India and the Bangladesh Bank (Dikau and Ryan-Collins 2017).

Finally, central banks could shift "quantitative easing" (QE) programs (i.e., the purchase of sovereign bonds, corporate bonds, and other financial assets by central banks) toward purchases of low-carbon financial assets. For example, Matikainen, Campiglio, and Zenghelis (2017) and Papoutsi, Piazzesi, and Schneider (2021) use microdata on bond holdings, firm characteristics, and emissions to show that the portfolios of the European Central Bank and other central banks are biased toward carbon-intensive sectors. This is a natural result of the market-neutral strategies adopted by central banks; that is, if a significant proportion of the bond market is composed of assets issued by large carbon-intensive firms, then central banks' purchase strategies are likely to reinforce this carbon-intensive bias. However, the extent to which a green QE would be effective in practice is not yet clear; for instance, Ferrari and Nispi Landi (2020) find only a small positive effect of green QE on environmental variables and welfare.

Institutional Coordination and Governance Frameworks

The discussion above suggests that a wide range of policies should be implemented to support the orderly reallocation of physical and financial investments toward low-carbon activities. However, whether these policies will actually be implemented in practice depends on the underlying institutional framework.

Indeed, we find that green financial and monetary policies have been applied heterogeneously across countries. Informational policies such as sustainable taxonomies, green bond standards, and the definition of climate-related benchmarks have been applied in a significant number of jurisdictions, with the aim of mitigating climate-related financial risks through market discipline (BIS 2020). However, more proactive policies aimed at achieving promotional objectives (e.g., expanding green financial investments) have been implemented primarily in emerging economies (D'Orazio 2022).

Baer, Campiglio, and Deyris (2021) argue that this policy heterogeneity can be explained by two main factors. First, countries are characterized by different degrees of public control over the dynamics of private financial markets. In emerging economies such as China, financial dynamics are affected by the pervasive presence of public regulators (e.g., the People's

Bank of China). In contrast, in high-income regions (e.g., in the European Union), public regulators try to avoid interfering in financial markets to help ensure efficient resource allocation. Second, the ways in which central banks and financial supervisors respond to their governments' development strategies vary across jurisdictions. While in many emerging economies the government is able to align the efforts of all public institutions toward the same strategic objectives, high-income countries are generally characterized by independent institutions with limited mandates (e.g., central banks focus primarily on maintaining price stability; Vonessen et al. 2020).

The combination of these two factors has resulted in different policy strategies concerning the low-carbon transition. In many emerging economies, governments are able to steer the policies of central banks and financial regulators toward low-carbon objectives, and these institutions are in turn able to impose binding constraints on private financial markets (Dikau and Ryan-Collins 2017; Campiglio et al. 2018). In contrast, in jurisdictions characterized by independent authorities, financial policies are not allowed to be used to allocate credit to green sectors. In fact, the introduction of financial policies favoring green sectors must be based on clear evidence that high-carbon assets are more financially risky, and such evidence is still not generally available.

However, it appears that the current institutional framework may be evolving. Indeed, there are increasing signs that central banks, even in high-income countries, intend to move beyond market neutrality to explicitly promote investments in low-carbon activities (ECB 2021; Lagarde 2021). In fact, accounting for climate-related risks may be necessary to ensure that central banks' primary objectives and fiduciary responsibilities are attained (Svartzman et al. 2020; Dikau and Volz 2021). At the same time, climate activism by central banks could decrease their credibility (which would affect their ability to achieve their primary objectives) or trigger a public backlash against unelected officials implementing policies without having a democratic mandate to do so.

Alternative options for maintaining solid and credible institutional frameworks while also ensuring effective climate action include (i) expanding the current mandate of central banks to include climate change, as has occurred in the United Kingdom (Sunak 2021), or (ii) delegating the authority to establish a clear and credible schedule for future carbon prices to an independent institution (Helm, Hepburn, and Mash 2003; Delpla and Gollier 2019; G30 2020). In the latter case, emission reduction targets would be defined by the government, but the mandate for maintaining a carbon price compatible with these targets would be assigned to an independent authority (a "carbon central bank" or "carbon council"). Alesina and Tabellini (2007) show that delegating such functions to independent bureaucrats is justified if the tasks are sufficiently technical or there is uncertainty about whether politicians have the ability required to carry out these tasks. This would appear to be the case for the task of keeping cumulative emissions below a certain target, and thus it supports the establishment of an independent carbon central bank.

Directions for Future Research and Policy

This article has examined the academic and policy literature on the macroeconomic and financial implications of a low-carbon transition. While this literature has expanded rapidly in recent years, there are still some crucial gaps in our knowledge. This suggests a need for further research and more sophisticated analysis to help guide policy makers as they seek to achieve the orderly and rapid decarbonization of their economies. We suggest some priorities below.

Address the Need for More Data

The first step is to ensure the availability of sufficiently granular data on physical assets, their emissions, their ownership structure, and the interlinkages among companies, banks, and other financial institutions. These data are often absent, sparse, or not consistent. Spatial databases are being developed (with the help of satellite imagery) to provide asset-level data on productive physical assets,[9] to study financing flows (Manych, Steckel, and Jakob 2021), and to analyze emission patterns (Susmita, Somik, and David 2021).

Focus on Climate- and Transition-Related Expectations and Beliefs

Another important research priority is to study the expectations and beliefs of individuals and corporations regarding their perceived risks of global warming, anticipated changes in climate policy, and the probabilities of breakthroughs in renewable technology. An understanding of what people and corporations think can help us anticipate the decisions they might make, including their choices concerning consumption, physical and financial investments, and laws and policies. While expectations and their impacts on macroeconomic dynamics have been extensively studied in monetary economics (e.g., Assenza et al. 2021), more research is needed in the context of the low-carbon transition. We see four possible approaches to examining expectations and beliefs about the low-carbon transition.

First, financial asset prices and their dynamics can provide insight about the expectations of asset managers and financial investors concerning the low-carbon transition (e.g., Bolton and Kacperczyk 2021a). However, as discussed above, the recent econometric literature presents conflicting results about the presence of a carbon premium. In addition, because financial markets are social phenomena that evolve over time, research on their features will need to be continuously updated. Now that finance researchers have started to examine climate-related topics (e.g., Giglio et al. 2021), we expect to see more abundant and sophisticated research in this area in the near future.

Second, transition-related beliefs can be elicited directly. Although there have been a few surveys of financial investors and other relevant stakeholders (Krueger, Sautner, and Starks 2020; Stroebel and Wurgler 2021), this research needs to be expanded to cover more and different psychological dimensions, time lines, and geographical areas. However, gathering a sufficiently large number of survey respondents will be a challenge; moreover, it remains unclear whether survey responses accurately reflect the decisions people make in the real world.

Third, research can be conducted on people's stated opinions and their communications concerning climate change and the low-carbon transition. For example, text analysis methods can be applied to tweets and social media posts, newspaper articles, speeches by officials, parliamentary acts, and other oral and written communication (e.g., Baylis 2020; Engle et al. 2020). This data-intensive line of research will benefit from the recent methodological

[9] See, e.g., Global Energy Monitor (https://globalenergymonitor.org/) and the GeoAsset Project (https://www.cgfi.ac.uk/spatial-finance-initiative/geoasset-project/).

advances in big data analysis and machine learning techniques (Noailly, Nowzohour, and Van Den Heuvel 2021).

Finally, experimental methods can be used to examine how people are likely to behave during a low-carbon transition. Such methods include subjecting individuals to "treatments" that are administered online, in a laboratory setting, or in the field (e.g., Hagmann, Ho, and Loewenstein 2019; Maestre-Andrés et al. 2021). These methods would be especially useful for understanding the barriers to more environmentally sustainable choices and the policies needed to incentivize such choices, as well as the possible drivers and transmission channels of transition-related disruptions.

Improve Macroeconomic Modeling of Transitions

As discussed above, more research is needed to develop methods to improve models of future macroeconomic, financial, and transition dynamics. It is encouraging that the climate and energy modeling community is already collaborating with macroeconomic and financial modelers to apply dynamic methods to climate-related questions (Bertram et al. 2021). Moreover, this research has gone beyond traditional methodological boundaries, with both neoclassical and nonneoclassical approaches being used to explore macrofinancial transition dynamics.

Research concerning such prospective modeling is needed in three areas to better understand endogenous transition disruption dynamics.[10] First, we need to develop a better understanding of how risk and uncertainty affect transition dynamics. Second, production and financial networks need to be incorporated into models to examine how transition costs (or benefits) could spill over across firms, sectors, and countries. Third, we need to develop an approach that accounts for the heterogeneity of beliefs and expectations.

Policy Priorities

Finally, the data, models, and other diagnostic tools we have at our disposal should be used to provide guidance to policy makers concerning the best policies and how to implement them in the least disruptive way. During the transition to a low-carbon economy, some economic agents or even entire economic systems will likely be made worse off. Indeed, both firms and households will be negatively affected by increases in the prices of energy, materials, and carbon-intensive products.

We would argue that two main policy strategies can certainly be considered appropriate at the moment. First, a price on carbon should be introduced, through either a tax or an emission permit market, to correct the market failure linked to GHG emissions and climate change. However, this needs to be done clearly and carefully to avoid the socioeconomic disruptions associated with an unexpectedly forceful policy action (e.g., Allen et al. 2020). Second, the information available to financial and nonfinancial firms should be expanded to help them correctly price climate-related risks. This could be achieved by developing better risk assessment methods and disclosing their results (NGFS 2019).

As we have discussed, the extent to which more proactive policies aimed at financial markets (e.g., a low-carbon orientation of monetary or prudential policies) would be desirable

[10] As discussed above, the current approach to transition disruption dynamics is to treat them as being driven by exogenous shocks (e.g., an unanticipated introduction of a carbon tax).

and effective remains unclear. Expanding policies to go beyond carbon pricing and information provision might require a restructuring of the underlying institutional framework, especially in jurisdictions with independent central banks and supervisors. Although transferring policy functions and powers to independent authorities could help establish credible forward-looking carbon price schedules, more research is needed on the optimal institutional framework that would support a rapid and smooth transition to a low-carbon economy.

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