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Abstract

The macro-financial transition risks that result from disorderly transitions to a carbon-free or low-carbon economy may entail significant costs due to the risk of stranded assets, defaults, collapse in stock market value, both for financial firms and non-financial firms. The effects of networks, contagion, and higher-round effects of stranding may exacerbate the problem. But green monetary and prudential policy and governance reforms may mitigate the problem. The qualitative, empirical, modelling, policy and institutional research on this topic is surveyed and various avenues for future research are identified.

JEL codes: E00, E58, E44, G01, G18, P18, Q35, Q43, Q48, Q54

Keywords: climate transition risks, stranded assets, default, carbon premium, networks, contagion, green financial and prudential policy, institutional and governance reform

1. Introduction

Reaching net-zero greenhouse gas (GHG) emissions in a way compatible with the Paris temperature targets involves decarbonising the global productive system (IPCC, 2014). Transitioning to a carbon-free economy will require the share of low-carbon activities and technologies to expand[3] and that of high-carbon activities and technologies to decline[4]. This helps to identify two key macro-financial implications of the low-carbon transition. First, the expansion of low-carbon productive activities requires significant low-carbon physical and financial investments. Non-financial firms need to produce and install low-carbon capital whilst financial institutions need to invest in and lend to low-carbon firms. Second, high-carbon sectors need to be phased out in a controlled manner. New high-carbon physical and financial investments need to rapidly decline until they stop. Additionally, a strategy is required to deal with the existing stocks of high-carbon physical and financial assets (van der Ploeg and Rezai,

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[3] Low-carbon activities include electrification of productive processes now based on fossil fuel use, production of electricity through renewable energy sources, improvement of the energy efficiency of buildings and industry, and other similar activities.

[4] High-carbon activities include fossil extraction and distribution, production of electricity using fossil-fuelled plants, manufacturing processes in the steel, cement, chemical, and other carbon-intensive industries, fossil-fuelled transportation, and other activities producing high-carbon emissions.

2020ab). To what extent could they become 'stranded' and lose their value, and how could this affect the wider stability of the economic and financial system?

These questions have raised the concern of prominent policymakers, especially in central banks and financial institutions. This is not surprising given the historical inexperience of human societies in dealing with controlled processes for technological shifts. Past technological transitions were mainly driven by the emergence of more productive technologies to which market actors 'naturally' moved to, including fossil-fuel ones (Fouquet, 2010). This is not the case (yet) for low-carbon technologies, since policies to help with and incentivize green investments in line with the Paris agreements are needed. Furthermore, we still lack a consistent body of research on the macro-financial implications of technological transitions, especially for what concerns the so-called 'sunset' industries (Semieniuk et al., 2021). Several fields of study are relevant (climate economics, macroeconomics, finance, innovation systems, and others) but they have been seldom applied together to this specific question, and usually in an unconnected fashion.

Our aim is to contribute to the development of a broader knowledge on how the low-carbon transition might affect macro-financial stability and the policy strategies to mitigate transition risks. We critically discuss the expanding literature on the topic and offer suggestions for promising further research avenues. We identify four current research areas in the field.[5]

First, several contributions have focused on the development of conceptual frameworks and qualitative analyses of possible futures, with the aim of understanding the potential boundaries and features of a 'disorderly transition' scenario. The focus is at connecting transition risk drivers (e.g. unexpectedly reduction in the relative cost of renewable energy) to economic impacts on non-financial firms, which are then transmitted to the financial system, possibly triggering wider macroeconomic volatility and financial instability. Both transition and climate physical risks are thought to be able to trigger large-scale macro-financial volatility, often referred to as a 'climate Minsky moment' (Carney et al., 2019) or a 'Green Swan' event (Bolton et al., 2020).

Second, an emerging empirical literature aims to quantify the physical and financial exposure to transition risks. While useful in catalysing public debate, the conceptual frameworks being developed still must be properly quantified and tested. To do so, we first need an empirical understanding of the present able to act as a base for the exploration of possible futures. We identify here three lines of work: i) the analysis of the exposure of physical assets (fossil reserves and capital stocks) to transition risks; ii) the analysis of the exposure of financial assets to transition risks; iii) the study of financial asset prices to capture the extent to which transition risks are already internalised by investors.

Third, several studies have used dynamic modelling to study possible macro-financial transition patterns. While solid empirical analysis is key to understand the current context, it can only rely on past evidence, and is thus unable to fully capture the features of historically

[5] Our survey is related to van der Ploeg (2021), who also discusses the empirical, modelling, and policy literatures on transition risks.

unprecedented phenomena (such as a green swan). To develop quantitative dynamic investigation of possible futures we must rely also on prospective modelling techniques. We identify a methodological dichotomy: a supply-side neoclassical approach, based on optimising forward-looking agents and clearing markets, aimed at the identification of optimal transition paths; and a demand-led complexity approach, based on macro-econometric relations and adaptive expectations, aimed at studying potential system behaviours.

Finally, a growing number of studies identify policy and institutional strategies aimed at ensuring an orderly transition. A first stream of work is devoted to designing and discussing policies to mitigate physical and transition risks, with the main debate lines revolving around the instrument type and stringency of such policies. A second stream is instead aimed at discussing the institutional implications of a low-carbon transition, with a particular focus on central banks and financial regulators, and their relationship with both the government and private financial actors.

The remainder is structured as follows. Section 2 discusses the conceptual framework behind the current research on disorderly transitions. Section 3 focuses on the empirical analysis aimed at understanding the exposure to and internalization of transition risks. Section 4 discusses prospective transition modelling methodologies. Section 5 analyses policy strategies to achieve a smooth and rapid low-carbon transition and their institutional feasibility. Section 6 offers suggestions for future research and concludes.

2. Disorderly transitions to the carbon-free economy

The recent literature on transition risks has sketched detailed depictions of possible negative future transition scenarios to understand and prevent them. The key concept here is the one of a 'disorderly' transition, i.e. a process of technological shift accompanied by large socioeconomic costs and financial volatility. This is often decomposed into various dimensions (NGFS, 2019; Semieniuk et al., 2021): transition risk drivers; impacts on non-financial firms; impacts on financial firms; wider macro-financial impacts. Three drivers of transition risk are usually distinguished.

First, mitigation policies can be introduced in an unanticipated manner causing an abrupt re-evaluation of the profitability of fossil fuel extraction and other carbon-intensive sectors, which in turn may lead to a fall in the price of their financial assets. Anticipated but very stringent policies could also trigger similar effects: if the policy-driven emission pathway is faster than the one implied by the 'natural' lifetime of existing productive assets, some of them will have to remain idle, possibly affecting the market valuation of the firm. Second, unanticipated or very rapid changes in technological progress can also have economic and financial implications, irrespective of the climate policies implemented, making existing capital stock prematurely obsolete and leading to a sudden drop in share prices of these assets. Similar considerations apply to negative emission technologies (e.g., carbon capture and storage or direct air removal of CO_2), which might become competitive in the future and contribute to the survival of fossil-based technologies while respecting temperature targets. Third, rapid swings in the preferences and expectations of individuals, in their role as consumers, entrepreneurs, or financial investors, could affect businesses' profitability and financial asset prices. The spread of environmental awareness and social movements (e.g. "Fridays for the Future") could be one such driver. The sudden realization of the public opinion of the urgency of decarbonization in the wake of a particularly violent climate-related event is another.

Whatever the transition risk driver and the way it materializes, we identify two main potential effects on non-financial companies: i) a decrease in revenues or increase in cost resulting in a decline in business profitability ('flow effect'); ii) a change in the valuation of assets present in the balance sheet of the companies ('stock effect'). Two main types of physical assets are at risk of becoming 'stranded' in a disorderly a low-carbon transition: reserves of fossil fuels might remain unextracted; and long-lived stocks of high-carbon capital may remain unutilized or must be prematurely decommissioned. Economic impacts can propagate from carbon-intensive activities to other sectors via the inter-firm production network.

The combination of both stocks and flow economic effects on non-financial firms can have two types of financial implications. First, the probability of default of carbon-intensive firms may increase, thus worsening the non-performing loan ratios of commercial banks and putting banks themselves at risk. Second, a sudden downward revision of expected profits from such firms triggers a revaluation of their outstanding financial assets (e.g. bonds and stocks), thereby negatively affecting the portfolios of financial investors holding the assets. The financial effects of a disorderly low-carbon transition depend on various factors including the degree and distribution of the exposure of financial institutions to affected productive sectors, the strength of financial network propagation mechanisms, and the extent to which transition risks have already been included in financial asset prices.

Finally, the compound economic and financial dynamics, if strong enough, can trigger additional dynamics in the wider macroeconomic setting. Semieniuk et al. (2021) mention, among others: increase in firms' financing cost; reduced demand for credit; loss of confidence of households, firms and banks; reduced income and consumption; unemployment; increase in public debt and worsening of sovereign borrowing financing conditions; financial instability; and economic recession. These dimensions are all part of a potential transition-triggered green swan moment. Additional insights could be offered in this respect by the qualitative literature on socio-technical transitions, which however, despite some recent exceptions (e.g. Geddes and Schmidt, 2020), still lacks a well-developed integration of financial dimensions.

3. Empirical evidence

What evidence is available to justify the conceptual framework sketched above? How likely is a green swan? Three streams of empirical studies attempt to answer these questions. The first stream studies the amount and type of physical assets (either fossil reserves or productive capital stocks) at risk of losing value or becoming unutilized because of a low-carbon transition. The second stream studies the direct and indirect exposure of financial institutions towards high-carbon activities. The third steam, mainly rooted in finance, assesses the degree to which transition risks are priced in asset returns. This is of key importance, because the extent to which investors have already priced in risks determines the magnitude of potential future volatility. We examine these three strands of literature in turn.

3.1. Physical stranded assets and their economic implications

Reserves of oil, gas and coal may remain partly unutilized if mitigation policies are introduced, or if technological progress makes fossil-based technologies obsolete. While there is substantial uncertainty on the exact size of a 1.5°C or 2°C carbon budget[6] (Meinshausen et al., 2009; Rogelj et al., 2019), it is clear that this budget is lower than the amount of emissions that would result if all reserves were to be extracted. McGlade and Ekins (2015), for instance, use a partial equilibrium model to identify the cost-efficient distribution of reserves to leave in the ground. They show that, assuming that CCS is not available, around 35% of oil, 52% of gas and 88% of coal must remain unextracted at the global level, with large variations across regions. Not being able to extract as much fossil fuel to limit global warming and the loss of associated revenues will have international economic repercussions. Mercure et al. (2018), for instance, study the macroeconomic implications of both a 2°C transition and a transition driven by technological diffusion without policy support. Both lead to significant stranding of fossil reserve assets, which triggers GDP losses for some regions (mainly large fossil exporters like US and Canada) and positive ones for others (importers such as China and EU).

A second type of asset at risk of stranding is productive capital stock that uses fossil fuel to operate either as an intermediate input or to create heat. These include electricity plants, blast furnaces, cement kilns, chemical plants, buildings, transport infrastructure, and other types of long-lived capital stocks. One can compute the amount of emissions 'committed' by their existence, assuming certain lifetimes and utilization rates, and compare them to 1.5°C or 2°C carbon budgets. Tong et al. (2019) calculate the committed CO_2 emissions from existing and proposed infrastructure in electricity, industry, transport and other fossil-burning sectors. Their results suggest that these might be already above the 1.5°C carbon budget and around two thirds of the 2°C budget. Similarly, IEA (2020) finds that global CO2 emissions locked in by existing energy-related assets are already close to the emissions produced in its Sustainable Development Scenario.

This mismatch between committed emissions and carbon budgets implies that new investments in high-carbon capital assets should be immediately or rapidly discontinued. Furthermore, it implies that a significant proportion of existing carbon-intensive capital stock is in danger of being stranded. Physical capital stranding can take several forms. First, assets might have to be retired before their 'natural' end of their life. Second, they could be utilized at a lower-than-full capacity rate with consequent adverse implications for their profitability. Third, they may have to be retrofitted at a cost to make them less carbon-intensive or carbon-free through carbon capture or other technologies.

[6] We define the 'carbon budget' as the cumulative emissions that can be produced while still keeping temperature below its target level.

Numerical Integrated Assessment Models (IAMs) have been used to study how and to what extent stranding might originate because of a technological transition. These studies typically find that cost-effective pathways to 1.5°C or 2°C entail a reduction of 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 worsens asset stranding, especially in China and India[7]. Smaller-scale Ramsey growth models have also been employed to study optimal stranding pathways under a carbon budget with a large proportion of dirty capital stocks unutilized (Baldwin et al., 2020; Coulomb et al., 2019; Rozenberg et al., 2020). No explicit financial dimension is introduced in any of these models.

Most of these contributions focus on specific sectors that have a high risk of stranding (mostly mining or coal- or gas-fuelled electricity production). However, the impact of transition risks extends beyond these sectors, affecting other productive activities which employ their products as intermediate inputs, and ultimately having a detrimental impact on the entire economic system. Cahen-Fourot et al. (2021) combine multi-regional production networks and sector-specific capital stock data to compute a set of marginal 'stranding multipliers'. These give an estimate of the stock of capital at risk of remaining underutilized due to a marginal negative shock taking place in the fossil sector of some region. Their results suggest that the international exposure to physical stranding risk is significant and also affects downstream sectors via second-round effects taking place within the production network. However, more work is needed to incorporate the insights being offered by the economics literature on production networks dynamics (Acemoglu et al., 2012; Carvalho and Tahbaz-Salehi, 2019) into the analysis of disorderly low-carbon transition.

3.2. Financial implications: exposure, defaults, and networks

The financial exposure question was first posed by Leaton (2011) and Leaton et al. (2013). They compare the 2°C carbon budget with the amount of fossil reserves owned by the top 200 fossil listed on world's stock exchanges, and find that the latter is much larger than the former. This indicates that fossil companies may be riding a 'carbon bubble' and be overvalued compared to their true worth in a 2°C world. This was followed by several other contributions, often from researchers of central banks, that assess the exposure of financial institutions to specific sectors with different degrees of sophistication. Giuzio et al. (2019), for instance, study the exposure of Euro area banks to climate-sensitive sectors; Faiella and Lavecchia (2020) look at the carbon content of Italian loans; Delgado (2019) provides a similar analysis for Spanish banks; and EIOPA (2020) maps the exposure of European insurers to a transition shock scenario.

These analyses typically cover only direct exposure of sectors deemed to be at risk at a specific time. One can go further by applying a network perspective to financial systems, following a similar logic to the one developed above for production networks. Given the strong interconnectedness of financial networks, where all financial firms are to some extent exposed

[7] Their analytical structure, based on a looser or stricter emission targets in the short-term (2030) followed by the unanticipated implementation of a long-term 2°C-consistent policy, has been subsequently adopted also by Bertram et al. (2020).

to each other via financial contracts, firms can via such networks be vulnerable to transition risks even if not directly exposed towards fossil-intensive sectors (Battiston et al., 2017; Stolbova and Battiston, 2020). Roncoroni et al. (2021), for instance, explore the implications of a climate policy shock for the Mexican financial system, including several rounds of effects: i) losses suffered by banks and investment funds due to direct exposure (bonds and loans) to climate-related risks; ii) revaluation of intra-financial claims driven by increased risk of banks' default, computed using a contagion model; iii) fire sales of external assets by banks and investment funds, causing further asset price decline; and iv) losses too large to be absorbed by banks and transmitted to external creditors.

3.3. What do asset returns tell us

It is crucial whether and to what extent financial institutions are aware of their exposure to transition risks and price them in financial assets. If and when a transition shock hits, the reaction of the financial system is likely to be more violent if investors fail to internalize transition risks. This empirical question is not easy to answer and the current empirical literature offers contrasting results.[8]

Some contributions suggest that high-carbon companies must pay a 'carbon premium' to investors to convince them to accept the transition risks faced by carbon-intensive firms. Bolton and Kacperczsyk (2020) combine financial and carbon emission data for a large sample of US listed companies in 2005-2017. After controlling for the usual variables affecting stock market returns (the so-called Fama-French factors), they show that a one-standard-deviation increase in the level of scope 1, 2 and 3 emissions would lead to an increase of 15, 24 and 33 basis points in stock returns, respectively, equivalent to a 1.8%, 2.9% and 4.0% annualized increase. This suggests that financial markets are, 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, thus suggesting that companies capable of cutting emissions have easier access to capital. Bolton and Kacperczyk (2021) perform a similar exercise for firms in 77 countries and find empirical evidence for a positive and rising carbon risk premium in stock market returns. They find that the premium is stronger 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, wild-fires and droughts. Atanasova and Schwartz (2020) use a sample of 600 North American oil firms for the years 1999-2018 to show that growth of 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.

This carbon premium is also associated with year-by-year changes in emissions, as one-standard-deviation increase in the change of scope 1, 2 and 3 emissions lead to an increase of 26, 18 and 31 basis points, respectively, equivalent to an annualized increase of 3.1% 2.2% and 3.8%. This suggests that companies capable of cutting emissions have easier access to capital. They also show that the carbon premium has only materialized in recent years, as there is no evidence for it in the 1990s. Bolton and Kacperczyk (2021) perform a similar exercise for firms

[8] For a more comprehensive literature on the topic see Daumas (2021) and Campiglio et al. (2019).

in 77 countries and find empirical evidence for a positive and rising carbon risk premium in stock market returns. At the global level, a one-standard-deviation increase in the level of scope 1 emissions leads to a 2.34% increase in annualized results. They find that the premium is stronger 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, wild-fires, and droughts. With a longer time series, the carbon premium in the US is larger (2.85%) than the one found in Bolton and Kacperczsyk (2020), which would confirm the claim that carbon premiums have been increasing in recent years. Atanasova and Schwartz (2020) use a sample of 600 North American oil firms for the years 1999-2018 to show that growth of 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. For instance, they find that a one-standard-deviation increase in the growth of undeveloped reserves reduces the market value of firms by 2.6%.

A different empirical approach is taken by Sen and von Schickfus (2020). They exploit the gradual implementation of a particular German climate policy proposal aimed at reducing electricity production from coal to empirically estimate the effect of this policy on the valuation of energy utilities. Their evidence suggests that investors take account of stranding risk in their valuation, but they also expect to be compensated by the government for it, and hence not to be financially affected. Only the announcement of possible hurdles to compensation triggered a reaction in financial markets, which led to a loss in 5-day cumulative abnormal returns of more than 20% for three major German utilities. This suggests that litigation for compensation when firms are faced with disorderly climate policy changes needs further investigation.

Other contributions focus instead on the provision of syndicated bank loans, showing that a one-standard-deviation increase in the fossil fuel reserves of a firm increases the loan spread by 25.3 basis points (Delis et al., 2021) and that a one-standard-deviation increase in scope 1 emission intensity imply a carbon risk premium of around 17 basis points (Ehlers et al., 2021). Ilhan et al. (2021) also find evidence for a carbon premium in the options market.

However, the jury on carbon premiums may still be out, since other studies find instead higher returns associated with low-carbon investment strategies which indicates that the risk associated with carbon emissions is under-priced. In et al. (2019), for instance, find empirically 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 under-price carbon risk to such an extent that green responsible investors perform better than non-green 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. Hence, the debate on the degree of internalisation of transition risks in asset prices has not yet been settled.

An alternative approach to capture investors' perception on transition risks elicits opinions through surveys. This suggests that, despite several obstacles, investors increasingly take account of climate-related risks, including transition ones (Amel-Zadeh, 2019; Harnett, 2017; Krueger et al., 2020).

4. Forward-looking analysis of macro-financial transition risks

While empirical analysis is crucial in understanding past and present conditions, giving a perception of how exposed macro-financial systems are to transition risks, one cannot rely on backward-looking analysis alone as changing conditions may lead agents and the system to react differently to a same shock at different time periods, thus making it impossible to entirely rely on past evidence to understand future dynamics. Furthermore, some of the envisioned scenarios, such as a green swan, are historically unprecedented, and we have insufficient empirical evidence to rely on. To assess future macro-financial dynamics associated with orderly or disorderly low-carbon transitions, one must incorporate the economic, financial and climatic dimensions in an integrated and consistent manner via forward-looking prospective modelling methodologies (Svartzman et al., 2020). We now review the current literature on the topic.

4.1. Available modelling options

We identify three main prospective modelling approaches and related streams of literature. The first stream consists of models exploring the interactions between the economy, energy systems, and climate dynamics. We can further distinguish between: large-scale numerical models with a detailed representation of energy technologies and pollutants, driven by welfare maximisation or cost minimisation (integrated assessment models or IAMs); multi-regional models with a granular representation of international and inter-sectoral flows (computable general equilibrium models or CGEs); and small-scale analytical models aimed at identifying optimal rules for policy and for private sector behaviour (analytical IAMs). While different in many respects, all of them fit in with the neoclassical modelling paradigm with clearing of markets, homogenous rational agents, and optimal behaviour. The large numerical models 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 at the moment mainly used to provide reference emission, energy and carbon price pathways to be incorporated in other models with a more sophisticated representation of macro-financial dynamics (e.g., Allen et al., 2020; Bertram et al., 2020). Given their relative simplicity, analytical IAMs with a Ramsey-type growth setting might be more promising in incorporating stylized macro-financial dynamics, and they have indeed been gradually moving towards the adoption of macroeconomic and financial dimensions.

The second stream is rooted in neoclassical macroeconomic and financial modelling. We can here distinguish between: dynamic models with representative rational agents reacting to stochastic shocks, with or without nominal rigidities (real business cycle (RBC) or dynamic stochastic general equilibrium models (DSGE)); and financial models aimed at capturing optimal asset prices along the transition (e.g. capital asset pricing models (CAPMs)). These approaches are interested in identifying optimal transition paths or optimal reactions to exogenous shocks. They have only recently focused their attention to environmental questions by incorporating climate variables (e.g., a carbon budget, or a climate damage function) or transition-related variables (e.g., a distinction between green and dirty sectors). The first contributions with an RBC setting were aimed at comparing the macroeconomic and welfare effects of different mitigation policies in the presence of productivity shocks or at studying the degree of procyclicality of optimal mitigation policies (Fischer and Heutel, 2013). These were followed by contributions introducing frictions and nominal shocks, as typical of the New-Keynesian DSGE approach, to study how monetary policies and financial regulation can be used to supplement climate policies (Annicchiarico and Di Dio, 2015; Benmir and Roman, 2020; Carattini et al., 2021; Comerford and Spiganti, 2020). Both DSGE and asset pricing models have also been used to study optimal asset pricing behaviour under uncertainty and the effects of risk premia of green and carbon-intensive assets along the transition towards a low-carbon transition economy (Hambel et al., 2020; Karydas and Xepapadeas, 2019). A key insight is that capital may not be run down completely 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. Typically, the carbon premium is positive and rising. Current research is concerned with how uncertainty about the future ambition of climate policy leads to carbon premia in asset prices, as found in empirical work, and cuts holdings of carbon-intensive assets in the portfolio. Provided there are intersectoral and intertemporal adjustment costs for investments, such models can also explain the mechanism behind the risk of stranded assets. These models rely on exogenous shocks to perturb a stable, unique equilibrium, have commercial banks only as pure intermediaries, and do not allow for underutilization of input factors or other demand-led dynamics.

The third stream originates from complexity theory and system dynamics modelling approaches. We can here distinguish between: models based on the interacting balance sheets of institutional sectors (stock-flow consistent (SFC) models; and models fully adopting a complexity perspective and introducing heterogeneity within sectors (agent-based models or ABMs). Both approaches tend to model economic systems as demand-led markets out of equilibrium and without market clearing (Mercure et al., 2019). Economic decisions take place under radical uncertainty and rely on macro-econometric estimation rather than welfare maximization; expectations are usually adaptive and backward-looking. These contributions usually originate from non-neoclassical schools of economic thought such as post-Keynesian, evolutionary or ecological economics (Dafermos et al., 2018; Dunz et al., 2021; Kemp-Benedict, 2018; Ponta et al., 2018; Safarzyńska and van den Bergh, 2017). Given their complexity, SFC models and ABMs are typically solved numerically to investigate a set of simulation scenarios. They are often hard to estimate and calibrate, and their results may not be easy to interpret. Their reliance on adaptive expectations, which is the result of both methodological preferences and the desire to ease computational complexity, does not permit the economy reacting in anticipation to future changes in technology or climate policy.

4.2. How well do models capture transition risks?

While able to offer valuable insights into the features of a low-carbon structural change, we highlight three limitations that apply to all modelling approaches.

First, there is still a weak understanding of the endogenous nature of transition risk drivers (Daumas, 2021). A disorderly transition is typically obtained in models by assuming an unanticipated and abrupt increase in carbon prices. The representative scenarios of the Network for Greening the Financial System (NGFS), for instance, include a 'disorderly transition' marker scenario where a carbon price is unexpectedly introduced in 2030 and subsequently rises at the rate of $35/tCO2 per year. This is contrasted with an 'orderly transition' scenario, which corresponds to the introduction of a carbon price in 2020 which subsequently rises at the lower rate of $10/tCO2 per year (Bertram et al., 2020). The unforeseen climate policy shock approach draws on the stress-testing literature which analyses 'severe but plausible' scenarios, and has been used in several recent studies (Allen et al., 2020; Carattini et al., 2021; EIOPA, 2020; Vermeulen et al., 2018). Technological tipping is rarer as a transition risk driver in models, but it is also usually treated as exogenous when present (Allen et al., 2020; Vermeulen et al., 2018). The third main type of transition risk drivers discussed in section 2 - the swings in sentiments and expectations of individuals and firms - is the least investigated. We argue that the transition-related literature would benefit from developing closer links to the one investigating the role of heterogeneous expectations, social norms and sentiments in macroeconomic dynamics (e.g. Bordalo et al., 2018; Hommes, 2021). Several additional potential transition disruption drivers are not currently being studied. For instance, despite the absence of clear evidence of a 'green bubble' so far, macro-financial disruptions might originate from an overvaluation of green financial assets. Endogenous disruptions could also surface during an orderly transition process, similarly to the building up of debt levels during the 'great moderation' period, eventually bursting and affecting the shape of the transition itself.

Second, treating transition risk drivers as unexpected shocks does not fully allow for the role of expectations concerning policy implementation and the related uncertainty. A policy might have implications on investment behaviour and asset prices well before it is introduced, or even announced, just because forward-looking agents might already attach some probability to the possibility of its implementation. So far, only a few small-scale general equilibrium models have explicitly studied how uncertainty about the timing of policy or technological breakthroughs might affect macro-financial and transition dynamics (e.g. Barnett, 2019; Bretschger and Soretz, 2018; Campiglio et al., 2020; Fried et al., 2021; Jaakkola and Ploeg, 2019; van der Ploeg, 2020; van der Ploeg and Rezai, 2020b). More work is needed in this direction.

Third, we still lack a comprehensive quantitative vision of transition risks, capturing the complexity of technological, economic, financial, and climatic dynamics. Most of the contributions so far focus on specific dimensions or develop stylized models to offer insights on key dynamics. However, a full understanding of macro-financial transition risks will require a systemic perspective. This is very hard to achieve as a consistent configuration of several moving components would be needed. For instance, production and financial networks tend to be separated from prospective dynamic modelling. Not even a static multi-layer production-financial network perspective is fully developed yet. The most advanced numerical exercises in this direction include Allen et al. (2021), who combine three numerical IAMs to offer pathways for energy mixes, carbon prices and other similar variables, a New-Keynesian macroeconomic model to calculate macroeconomic variables (GDP, employment, interest rates) for a set of aggregate regions, a production network model (Devulder and Lisack, 2020) to transform aggregate macroeconomic dynamics into sector-specific results, and a suite of Banque de France financial models to compute probability of default and the change in the price of financial assets (bonds and stocks). They show 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, adding also a study of the exposure of financial institutions to transition risks. However, even these contributions fall short of offering a complete picture, e.g. they lack a feedback mechanism from financial dynamics back to transition pathways.

5. Policies and institutions for a rapid and orderly transition

Previous sections have highlighted how several drivers could trigger transition-related disruptions, affecting macro-financial stability through a variety of transmission channels. How could policies help to mitigate the risk of a disorderly transition? This is a hard question because policies themselves can be the trigger of transition disruptions. One answer is early implementation of a sufficiently high carbon price, and then a gradual and credible increase of the price in the coming years as this gives the right incentives for firms and households to make the necessary investments for the green transition and avoid carbon-intensive investments. However, ambitious carbon pricing is difficult (World Bank, 2020) due to its unpopularity (see the *gilet jaunes* movement in France) and hence poor electoral returns for policymakers. Furthermore, additional market failures in financial systems suggest that carbon prices by themselves may not be sufficient to convince investors to reallocate their portfolios in an orderly manner (Campiglio, 2016). What other policy options are available? And are they institutionally feasible? We will address these questions in turn.

5.1. Policies directed at financial investors

There are two complementary strategies for supporting low-carbon investments while avoiding sudden wake-up moments with associated market swings. First, financial investors can be gently pushed to internalize transition (as well as physical) risks to gradually become aware of their exposure and not be surprised when change materializes. This can be done in various ways. Financial institutions need to feel sure about the definitions and rules of the game. Initiatives in this direction include the development of 'sustainability taxonomies' to clarify what activities are sustainable, and the definition of green bond standards or climate-related benchmarks (e.g., a 'Paris-aligned' benchmark). Also, financial institutions need to be able to assess the exposure of their business or portfolio to climate-related risks. Currently, this is not easy due to lack of data and appropriate methodologies. Hence, policy and industry initiatives have been directed towards the development of risk assessment methodologies for non-financial firms, financial firms, and financial systems (e.g., climate stress testing). Furthermore, once exposure to climate-related risks is assessed, it needs to be disclosed to the rest of market participants in a standardized manner (TCFD, 2017). This allows market discipline to do its job, i.e., to efficiently include risks into financial asset prices. Additional strategies include raising awareness, capacity-building activities, data sharing and international cooperation (NGFS, 2019).

While positive, these measures are unlikely to be enough by themselves to either shift investments to a sufficient degree or to protect financial institutions against climate-related risks (Ameli et al., 2020; Christophers, 2017). Most of them are voluntary and, due to methodological complexities highlighted in previous sections, may be unable to offer a comprehensive and commonly accepted risk assessment technique. Since full assessment of exposure to climate-related risks may be infeasible, a precautionary approach for central banks and supervisors when dealing with climate-related risks is called for (Chenet et al., 2021).

5.2. Greening policies of financial institutions

Second, policies directly aimed at financial institutions can be implemented to gradually push banks and other financial institutions towards low-carbon activities so that they will not be unprepared if and when a policy shock arrives, even in the absence of a carbon price. We identify the following strategies.[9] Financial prudential regulation can be designed to offer economic incentives to financial institutions investing in low-carbon firms (D'Orazio and Popoyan, 2019). For instance, Basel III capital requirements for banks could depend on the carbon intensity of borrowing firms to offer a higher leverage space and associated larger profits to banks if they lend sustainably. Carattini et al. (2021) and Benmir and Roman (2020) find that introducing macroprudential instruments can have positive effects on the low-carbon transition and associated macro-financial dynamics. However, the literature still must get to grips with a fundamental asymmetry. Although it may be good tighten capital requirements for carbon-intensive firms that are subject to transition risk, it is not a good idea to loosen capital requirements for green firms as this carries the danger of higher volatility, more defaults and welfare losses.

Similar considerations apply to monetary policy and other conventional central banking policy instruments. For instance, requirements to hold reserves at central banks can be eased for banks that lend to green sectors, as done by the Banque du Liban. The same could be done for the interest rate applied to central bank financing of banks (Böser and Colesanti Senni, 2020). Van't Klooster and van Tilburg (2020) propose a green version of targeted longer-term refinancing operations. Alternatively, the central bank collateral framework (the rules governing eligibility of and haircuts to be applied to financial assets deposited at the central bank by commercial banks as collateral) might include climate-related considerations (McConnell et al., 2020; Oustry et al., 2020). Instead of using market-based incentives, central banks could request banks to allocate their credit respecting certain sectoral quotas as done by the Reserve Bank of India and the Bangladesh Bank (Campiglio et al., 2018).

Finally, central banks may steer 'quantitative easing' (QE) programmes towards purchases of financial assets of low-carbon sectors. Since a significant proportion of the bond market is

[9] Governments themselves can of course participate to financing low-carbon investments, for instance through the action of national and multilateral banks (Mazzucato and Semieniuk, 2018). We focus here only on policies directed at private financial actors.

composed of assets issued by large carbon-intensive firms, market-neutral strategies are likely to reinforce this carbon-intensive bias (Matikainen et al., 2017; van't Klooster and Fontan, 2020). Ferrari and Nispi Landi (2020) find only a small but positive effect of green QE on environmental variables and welfare. Papoutsi et al. (2021) use micro data on bond holdings, firm characteristics and emissions, the portfolio of the European Central Bank is tilted towards carbon-intensive sectors relative to a market portfolio of sectoral capital stocks.

5.3. Institutional coordination and governance frameworks

A wide range of policies can thus be implemented to support the orderly reallocation of both physical and financial investments towards low-carbon activities. But whether these policies will be implemented depends on the type and quality of institutions and governance.

Informational policies such as taxonomies, disclosure, and stress testing are applied in many jurisdictions. Although proactive policies aimed at steering financial investments into low-carbon sectors are often observed in emerging economies, this is less so in high-income countries (Campiglio et al., 2018; Dikau and Ryan-Collins, 2017). Baer et al. (2021) suggest that this difference is due to public financial regulators differing in their control of private financial dynamics and to different degrees of independence of financial regulators from the government. In emerging economies such as China private financial dynamics are affected by the pervasive presence of public regulators (e.g., the People's Bank of China) that align their activities to development strategies defined by the government. In contrast, in the high-income countries of the European Union public regulators try not to distort functioning of financial markets to maintain efficient resource allocation. Regulators such as the European Central Bank are sufficiently independent from governments not to be forced to align to their strategies if these go against their stated mandates.

In jurisdictions characterized by independence of delegated authorities, financial policies cannot be used to allocate credit to green sectors unless there is evidence that dirty sectors are riskier than green ones from a financial perspective. This evidence is currently unavailable and may not be available in the future. This led to the proposal of introducing a 'green supporting factor' on banks' capital requirements, initially supported by the European Commission (Dombrovskis, 2017), only to be rebuffed by European financial supervisors (Enria, 2019).

There are increasing signs that central banks, even in high-income countries, intend to move beyond market neutrality and adopt an explicit promotional stance (Lagarde, 2021; Schnabel, 2020). Taking account of climate-related risks may be necessary to ensure central banks' primary objectives and fiduciary responsibilities are attained (Dikau and Volz, 2021; Svartzman et al., 2020). Undesirable outcomes may include a 'green technocracy', whereby unelected officials shape development strategies with no mandate and outside of democratic control, or a reappropriation by the government of policy areas now under the control of delegated authorities, with detrimental effect on their ability to achieve their primary objectives (Baer et al., 2021).

An alternative option, if credible carbon pricing by governments is infeasible, is to establish an additional delegation revolving around the achievement of carbon price schedules (Delpla and

Gollier, 2019; G30, 2020; Helm et al., 2003). Emission reduction targets would be defined by government, but the mandate of maintaining a carbon price compatible with the targets would be assigned to an independent authority (a 'carbon central bank' or 'carbon council'). Alesina and Tabellini (2007) show that delegation to independent bureaucrats is called if the tasks are technical for which ability is more important than effort or if there is uncertainty about whether politicians have the required ability. This seems to be the case for the task of keeping cumulative emissions below a certain target, hence this suggest the case for an independent carbon central bank.

6. Future research and policy directions

We have surveyed the academic and policy literature studying the macroeconomic and financial risks of a low-carbon transition. Several crucial gaps in understanding still exist, suggesting that more sophisticated pieces of analysis will be developed in the coming years. The most developed line of research is probably the one that develops qualitative understanding of possible future transition scenarios. Most efforts detail worst-case scenarios involving large macro-financial disruptions ('disorderly transition', 'green swan', 'climate Minsky moment'). While insightful, further efforts are needed to obtain a reliable compass for policies.

First, more empirical research is needed to better understand the exposure of the current macro-financial system to transition risks. Existing work on physical assets suggests that a 2°C target is incompatible with full depletion of fossil reserves and continued investments in high-carbon capital stocks, so there is a risk of stranding of productive infrastructure in both upstream and downstream sectors. A parallel line of work finds a relatively small direct financial exposure to carbon-intensive sectors but a larger and potentially systemic indirect exposure via financial networks. Furthermore, the latest and most sophisticated econometric research on asset returns and interest on corporate loans suggests that transition risks are increasingly priced in by the market albeit that there is competing research that suggest the presence of a green premium instead of a carbon premium. But if companies more heavily exposed to transition risks (e.g. the ones producing more direct and indirect carbon emissions or owning more fossil fuel reserves) are increasingly required to pay an additional premium to their banks and financial investors, the carbon premium is increasing in time. Hence, adopting a strategy of hedging against transition risk may no longer be as cheap as suggested by Andersson et al. (2016).

Second, more work is needed on prospective modelling to obtain the expectational dynamics of transition risk. Approaches based on neoclassical macroeconomics including finance and growth theory need to take account of tail risk, contagion, production and financial networks, and systemic risks while those based on complexity economics need to take account more of forward-looking behaviour. Rather than treating transition risk drivers as exogenous, they could be treated as endogenous and build on the literature of stochastic tipping and of sentiments and heterogenous expectations. A more pluralistic approach might thus be the most sensible way forward to better understand disorderly transitions to the green economy.

Finally, more research is needed on the synergies between climate policies and financial and prudential policies, on the one hand, and on governance and institutional reforms to minimize systemic risks and disorderly green transitions, on the other hand. Several academic and policy contributions already exist ranging from voluntary assessment of exposure to climate-related risks to proactive reallocation of credit by public authorities. Given the evidence for an increasing carbon premium trend, stringent public interventions might become partially redundant, or even detrimental if they contribute to fuelling a 'green bubble'. Also, if the market is indeed pricing in transition risk, the prudential tasks of financial regulators may be less onerous. However, internalization of transition risks may be due to the increasing moral suasion conducted by central banks and international initiatives such as the NGFS or the TCFD and could fade without it. Central banks and financial regulators are increasingly doing the best they can within their mandate to prepare the ground for implementing greener monetary and prudential policies without triggering excessive financial volatility. However, the main responsibility for ensuring an orderly green transition is in the hands of government who should commit to a serious and credible carbon pricing policy, for which there is no monetary, financial or prudential substitute.

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