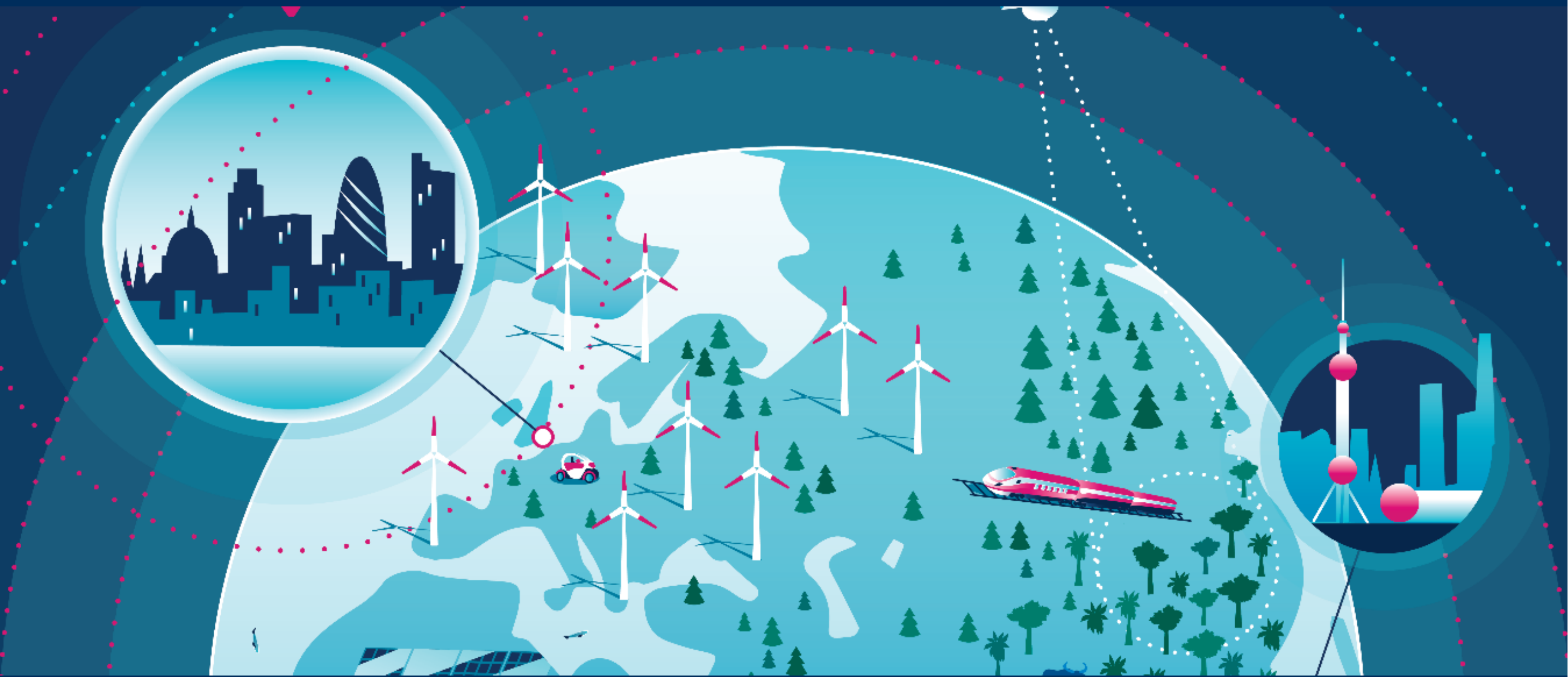
Low-Carbon Transitions and Systemic Risk



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Executive Summary

The low-carbon transition has been cited by policymakers as a potential driver of systemic risk that could lead to financial instability and negative macroeconomic outcomes. Transition risk refers to the economic and financial risks associated with a disorderly transition to a low-carbon economy. Policymakers have highlighted that the systemic nature of transition risk could lead to an adverse impact on financial stability. In particular, several have warned of the potential for a transition-driven 'Minsky moment' whereby a disorderly transition leads to a sudden collapse in asset prices.[1]

This work draws on the frameworks of central banks and academic studies to identify the channels through which an adverse shock can lead to a realisation of systemic risk. Systemic risk can be defined as the risk of a shock that has negative externalities on economies and financial systems via networks. This risk can be realised when a large number of financial market participants are impacted simultaneously or when a sector-specific shock leads to contagion and feedback loops that amplify the impact. The realisation of systemic risks can also be more likely when the source of risk is not well understood. This makes it inherently challenging to identify them ex ante, but therefore important to consider the multiple possible channels and work through their potential implications.

The report then considers the channels through which systemic risk could materialise under a low-carbon transition. The main sources of risk identified in the context of a low-carbon transition are a sudden downward repricing of carbon-intensive (or low-carbon) assets and energy price shocks. The repricing of assets would lead to losses for those directly and indirectly exposed. Feedback loops can also amplify the initial losses and have a negative impact on the wider economy. Further, a disorderly transition could lead to an energy price shock which has a large negative impact on economic growth. Within these main sources, we outline the detailed transmission channels for systemic risk stemming from overlapping portfolios, lending between financial market participants, and the interaction between the financial system and the real economy.

While there is an extensive literature on systemic risk, the literature on systemic risk in relation to a low-carbon transition is still in early stages of development. Since the financial crisis, there has been a growing emphasis in the literature on assessing the systemic financial risk triggered by unexpected shocks, such as the bursting of the subprime mortgage bubble in the US. Approaches include the development of market-based indicators that capture the build-up and materialisation of systemic risk, general equilibrium models and stress testing frameworks. While the literature focussing on transition risk in particular is more limited, there are studies which have employed networks approaches to estimating systemic risk in the context of a low-carbon transition.

We identify the main gaps in existing methodologies for estimating the systemic risk posed by a low-carbon transition and recommend areas for future research. First, further data collection is required to better assess the exposure of assets to transition risk. In addition, policymakers should work to develop more comprehensive climate-related stress testing exercises, with more of a focus on second round impacts. Where possible, these exercises could draw on historical events with similar characteristics, such as a large swing in energy prices. Further, the development of more comprehensive approaches such as multi-layered models of financial and production networks, and frameworks that include both the impact of rising and declining industries have the potential to improve the assessment of systemic risk.

[1] This was cited in an open letter by Governor of the Bank of England, Mark Carney (at time of writing), Governor of Banque de France, François Villeroy de Galhau, and Chair of the Network for Greening the Financial System, Frank Elderson.

Contents

List of figures

1 Introduction

Transition risk refers to the economic and financial risks associated with a disorderly transition to a low-carbon economy. Transition risk could be driven by a shift in climate policy, a break-through in technology, a shift in market preferences, or a change in societal norms (Bolton et al., 2020). This is because these factors may lead to a misalignment between the expectations of financial market participants and other agents (such as policymakers, producers or consumers). If these participants abruptly revise their expectations, it could result in a sudden repricing of financial assets, which has the potential to trigger a systemic disruption, amplifying the initial impact on the financial system and economy as a whole. Such a scenario could also manifest itself as a broader macroeconomic shock that impacts many market participants simultaneously.

A number of policymakers have identified the systemic risks associated with the transition to a low-carbon economy. In recognition of the fact that the transition could potentially destabilise financial markets, a group of policymakers set up the Taskforce for Climate-related Financial Disclosures (TCFD) in 2015, which encourages companies to disclose climate-related financial risks (TCFD, 2016). In addition, the Network for Greening the Financial System (NGFS) was set up in 2017 to assist in managing the financial risks posed by climate change and to mobilise capital for 'green' and low-carbon investments (NGFS, 2019). An open letter from three of the founding members explicitly makes a commitment to avoid a 'Minsky moment' whereby a disorderly transition leads to a sudden fall in asset prices (Carney, Villeroy de Galhau and Elderson, 2019). Individual central banks are also undertaking research into this area, with the ECB conducting analysis suggesting that climate-related risks have the potential to become systemic in the Euro Area (ECB, 2019).

This has led to a number of central banks undertaking stress tests involving an adverse transition scenario. Stress tests are designed to test the resilience of individual banks and the banking system to adverse shocks. The De Nederlandsche Bank (DNB) has developed stress test scenarios for the Netherlands based on climate policy shocks, energy technology shocks and confidence shocks. In addition, the Bank of England is currently developing a stress testing exercise based on three scenarios: early policy action, late policy action and no additional policy action. The European Banking Authority and the IMF have also committed to conducting climate-related stress tests. Further details are provided in section 5.1.2.

This report provides a survey of the literature on potential channels and modelling approaches for systemic risk, with a particular focus on assessing transition risk. While there is an extensive literature on systemic risk (particularly following the 2008 financial crisis), there is a limited but growing number of academic studies on the systemic risks associated with a low-carbon transition. We provide a detailed assessment of the indicators and modelling frameworks in the systemic risk literature, as well as methods used to evaluate transition risk specifically. We also highlight the main gaps in the literature on modelling systemic transition risks and areas for future research. Given this report focuses on transition risk, we do not consider the channels of and approaches to modelling physical risk. The rest of the report is structured as follows:

- Chapter 2 defines systemic risk and highlights the various types identified by researchers.
- Chapter 3 identifies the transmission channels for systemic risk.
- Chapter 4 provides an overview of indicators and models used to assess systemic risk.
- Chapter 5 discusses the approaches used to assess the systemic risk associated with a low-carbon transition.
- Chapter 6 identifies the main gaps in the literature and suggests areas for further research.
- Chapter 7 reports the main conclusions.

2 Defining systemic risk

While there is no one definition of systemic risk, a number of policymakers and academics have sought to define this concept. The ECB broadly defines systemic financial risk as the risk that financial instability becomes so widespread that it impairs the functioning of a financial system to the point where economic growth and welfare suffer materially (ECB, 2010). Based on a review of the literature, Smaga (2014) concludes that definitions of systemic financial risk tend to include a transmission of disturbances between interconnected elements of the financial system which can then impact the real economy, and a disruption of the financial system's performance and functions such as financial intermediation. According to LSE (2019), systemic risk is realised when there is an endogenous feedback loop that amplifies risk. For example, when the distress of one particular agent causes them to sell off assets leading to the distress of other agents.

Various sources also categorise systemic risk into different forms, with a degree of overlap between types. Studies distinguish between exogenous and endogenous forms of systemic risk, macro and micro forms, as well as the build-up and materialisation of risks. For example, the ECB (2010) identifies three forms of systemic risk:

- Exogenous macro shocks, where shared exposure causes simultaneous problems.
- An endogenous build-up of financial imbalances which leads to asset bubbles that can unravel suddenly.
- Contagion risk, whereby an idiosyncratic problem has a more widespread impact when financial activities are highly interconnected.

Smaga (2014) notes that systemic risk can be caused by an exogenous source (such as a severe recession) or an endogenous source (such as the collective behaviour of financial institutions). Nier (2009) distinguishes between macro and micro dimensions of systemic risk, with the former reflecting correlated exposures across institutions to macroeconomic risks and the latter referring to the failure of a systemically important financial institution leading to an adverse impact on the rest of the financial system. Systemic risk can also be categorised across a time dimension, with an endogenous build-up of imbalances occurring over time and the transmission of a macro or micro shock occurring at a given point in time. The various types of systemic risk can overlap. For example, a macroeconomic shock that leads to correlated risks across institutions can exacerbate the risk of failure for a particular institution, which can lead to contagion and trigger the unravelling of financial imbalances.

In addition to risks propagated through the financial system, there is also evidence for the risk of spillovers in production networks. For example, Cahen-Fourot et al. (2019) consider a scenario of physical capital stranding in upstream sectors and emphasise that spillovers to the rest of the production network could be large, leading to a systemic disturbance across the economy.

Given the sources investigated above, we define systemic risk as the risk of a shock (either exogenously or endogenously generated) that has negative externalities on economies and financial systems via networks (i.e. second round effects).

3 Transmission Channels

3.1 Identifying broad channels for systemic risk

We draw on the general risk frameworks set out by the ECB and the Federal Reserve Board to identify the broad process through which a low-carbon transition could lead to systemic risk (ECB, 2018, FRB, 2019). In particular, we begin by considering exogenous shocks that can trigger the transmission of systemic risk. We then outline the vulnerabilities of a financial system that can build up over time and have the potential to cause distress when realised or to amplify the initial impact of an exogenous shock. Finally, we discuss how risks can spread throughout the financial system and the economy via contagion.

3.1.1 Exogenous Shocks

When adverse events or shocks hit an unstable financial system, there can be large negative impacts on the system and the economy as a whole. Exogenous shocks that can trigger the transmission of systemic risk include a severe domestic or external recession, a disorderly Brexit or a sharp adjustment in climate policy. As explained in chapter 2, such shocks may be widespread, resulting in a simultaneous negative impact across the system, or begin as a localised shock that spreads. While a stable financial system is often able to absorb these shocks, when shocks hit an unstable system, they can have large effects on the level of lending and therefore investment, income, employment and economic activity. Therefore, understanding the vulnerabilities of a financial system is important in understanding the channels through which a shock can exacerbate systemic risk.

3.1.2 Endogenous Build-up of Vulnerabilities

Systemic risk can materialise from a build-up of vulnerabilities in the financial system. Such a build-up could exacerbate the impact of an exogenous shock or reach a tipping point, triggering an endogenous disruption that is transmitted to the wider financial system. A build-up of risk can be characterised by increasing financial imbalances, excessive leverage, financial exuberance, maturity mismatch or a misalignment in asset prices. The key vulnerability to monitor in the case of a low-carbon transition is the potential misalignment in asset prices resulting from a failure to price in the risks associated with such a transition. In other words, there may be a bubble in the valuation of assets exposed to the transition (Thomä and Chenet, 2017). Other vulnerabilities in the system, such as excessive leverage, could also exacerbate the risks associated with the transition.

3.1.3 Contagion

A build-up in financial vulnerabilities and subsequent disruption can lead to contagion. The degree of contagion depends on the extent to which economic and financial systems are connected and the ease with which market agents can withdraw from these connections. Systems that are highly connected tend to be characterised by large volumes of funding and lending between participants and overlapping portfolios (ECB, 2018). In terms of transition risk, the strength and rigidity of connections between carbon-intensive production (or potentially low-carbon production), the production of other goods and services and financial institutions will determine the risk of contagion.

3.2 Identifying specific channels for systemic transition risk

Next, we draw on the literature to identify the specific channels through which a transition shock could lead to a systemic disruption. While some studies focus on the sources of risk at a high level, others provide more detail on the specific transmission mechanisms between market participants and the real economy.

ESRB (2016) identifies two key sources through which a low-carbon transition scenario can lead to systemic risk. First, an energy price shock triggered by a change in climate policy would likely impact a large number of participants simultaneously. In the absence of sufficient renewable energy infrastructure to supply energy at a reasonable cost, an abrupt restriction on fossil-fuel based energy production could lead to an increase in energy costs, and thus an increase in production costs across the economy. Second, if financial market participants fail to price in a more stringent path for climate policy, there is the potential for an abrupt repricing of emissions-intensive assets, particularly in the energy and land-use sectors. A sudden repricing of emissions-intensive assets (such as those in oil, gas, coal, electricity generation, transportation or ruminant meat production) would likely reflect a localised shock that could spread.

The potential for a 'green' bubble is another source of systemic risk that could be present during a low-carbon transition. In addition to declining industries, Semieniuk et al. (n.d.) recognises the potential for systemic risk from rising industries, stemming from overinvestment and 'irrational exuberance' towards low-carbon industries. For example, some new green technologies may be overvalued if markets overestimate the ability of such technologies to be cost-competitive in the long-run. Further, sudden reversals of government promises could lead to agents revising expectations on the value of green technologies. Assets backed by green technologies could therefore also be vulnerable to a bubble and a sudden downward repricing which has negative externalities on economic and financial systems.

Semieniuk et al. (n.d.) highlight a number of channels through which declining and rising industries impact the financial system and the broader economy. First, falling asset values and potential revenue loss could lead to an increase in defaults for non-financial firms. This would increase the share of non-performing loans for banks, leading to a drop in banks' market valuation and potentially default themselves. This would lead to a fall in asset prices and potentially a fire sale of assets, prompting a vicious cycle of asset price decreases. The reduction in portfolio values would also lead to losses for equity holders of those financial assets. The study then considers the channels through which the wider economy is affected, including the:

- Banking channel: An increase in the share of non-performing loans in banks' portfolio could lead to credit rationing and/or an increase in interest rates, which would in turn decrease investment levels.
- Investment channel: A decrease in firms' market valuation could decrease the appetite for physical investment.
- Consumption channel: The reduction in wealth of those holding affected financial assets could lead to lower household consumption levels (this could also be exacerbated by credit rationing).
- Public debt channel: There could be an initial increase in government expenditure to counteract the reduction in other expenditure categories. However, higher public debt could lead to higher interest rates and lower capacity to spend in the future. This could be exacerbated by lower tax revenue.

ESRB (2016) highlights the debt channel which negatively impacts those financing production processes exposed to the transition. A repricing of assets could lead to debt repricing and in turn losses for the bank lenders or investors who hold this debt. The shock could therefore spread to the corporate bond market and the higher risk leveraged loan market, as well as the sovereign bond market in countries which are heavily dependent on fossil fuels. If the shock was to spread to the sovereign bond market and result in a sovereign debt downgrade, empirical evidence suggests this could lead to a decrease in capital inflows and an increase in capital outflows, and therefore lower investment (Gande and Parsley, 2004; Violante, 2016). The risks generated via these channels could also be exacerbated by existing financial fragilities. For example, there is evidence to suggest that some exporters of fossil fuels already have relatively high levels of government debt and a higher share of non-performing loans in total assets (Feyen et al., 2020).

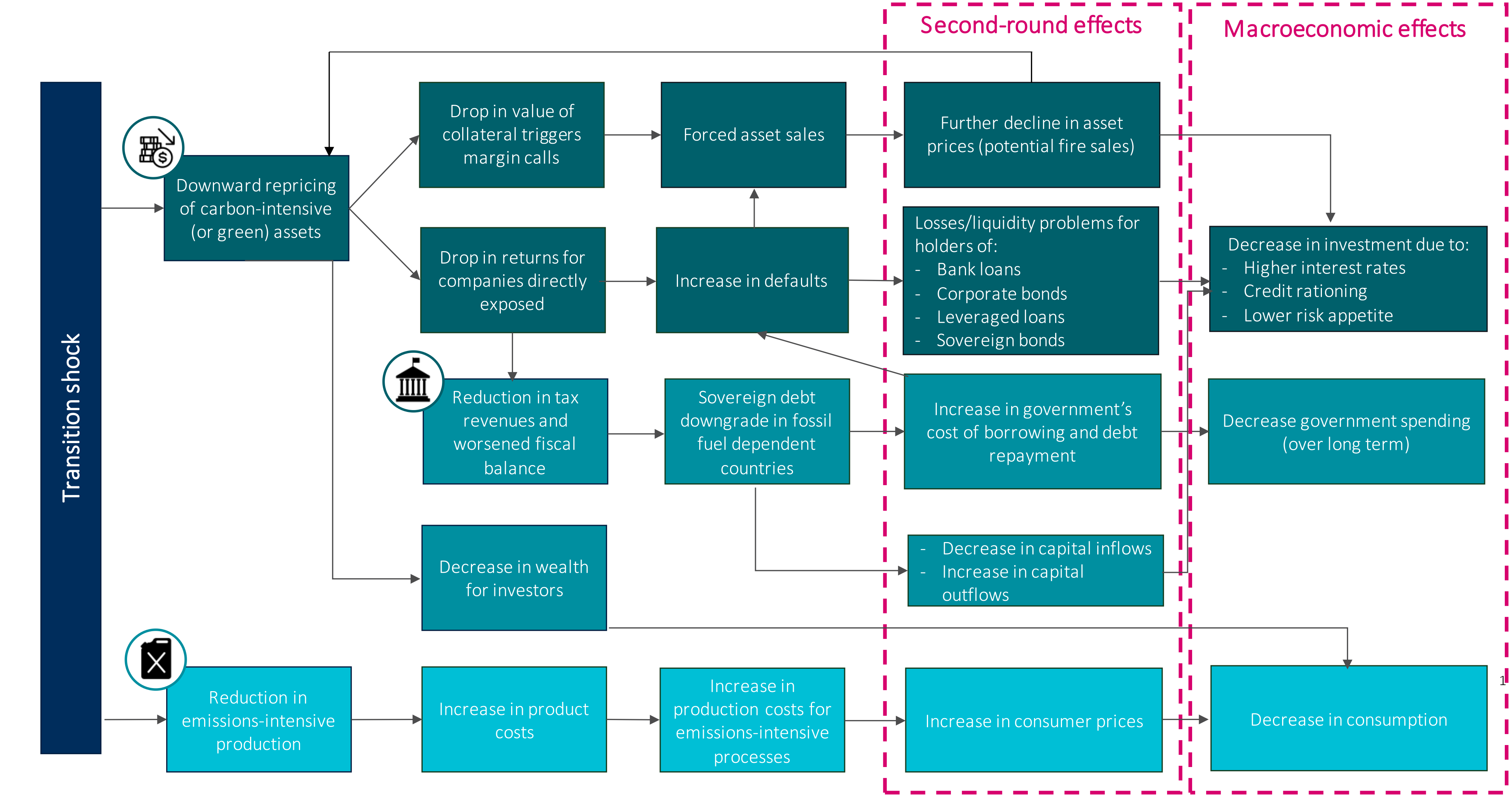
Bolton et al. (2020) identifies key systemic risks driven by a higher likelihood of defaults, a change in investor appetite, lower collateral values, lower liquidity and a repricing of insurance products. The key categories discussed that are relevant for transition risk include:

- Credit risk: A decrease in borrowers' ability to repay debts can lead to a higher probability of default. A depreciation in collateral could also trigger margin calls, leading to further price declines.[2]
- Market risk: A change in investors' perception of profitability could lead to a fire sale of assets.
- Liquidity risk: Banks' balance sheets hit by credit and market risks may be unable to refinance in the short term.
- Insurance risks: The under-pricing of new insurance products covering green technologies.

Figure 1 provides a graphical representation of the main channels discussed above.

[2] Margin calls force companies to post more collateral in order to maintain their position. In the event that companies cannot post more collateral, they will be forced to sell assets, leading to further price declines (Clerc et al., 2016).

Figure 1 Transmission channels for systemic risk following a transition shock



Source: Vivid Economics

4 Approaches to assessing systemic risk

There are a number of approaches in the existing literature that are used to assess systemic risk. Some approaches develop risk indicators and test whether these can be used to predict adverse financial and macroeconomic outcomes. In addition, general equilibrium models are used to assess the impact of shocks while accounting for the feedback between the real economy and the financial system. Further, stress testing frameworks focus on testing the resilience of financial systems, using both bottom-up approach and top-down models.

4.1 Market-based Indicators

Market-based indicators have evolved from measuring the risk for individual firms to include a systemic dimension. Prior to the 2008 financial crisis, banking regulators focussed on indicators which monitored risk at the individual institution level, such as Value-at-Risk (VaR), estimating the maximum loss of an individual asset or portfolio at a given confidence level. The crisis showed the importance of considering potential clusters of risk and the exposure of institutions to the wider economic and financial system. This led to regulators developing methods to identify systemically important financial institutions (SIFIs). For example, the global systemically important banks (G-SIB) methodology developed by the Basel Committee on Banking Supervision assigns a systemic risk score to banks based on their size, interconnectedness, the lack of available substitutes for services provided, their global activity and complexity (BIS, 2014). The crisis also drove the development of new indicators that place a higher weight on the systemic component of financial risk, such as conditional value-at-risk (CoVaR).

Conditional value-at-risk (CoVaR) measures have been shown to be driven by vulnerabilities such as leverage and maturity mismatch. Building on the VaR measure, Adrian and Brunnermeier (2016) developed CoVaR, which estimates the value-at-risk of a financial system conditional on institutions being under strain. The difference between the CoVaR conditional on the distress of an institution and the CoVaR conditional on the median state of that institution (ΔCoVaR) measures the institution's contribution to systemic risk. The study also shows that characteristics such as leverage, size, maturity mismatch, and asset price booms significantly predict ΔCoVaR.

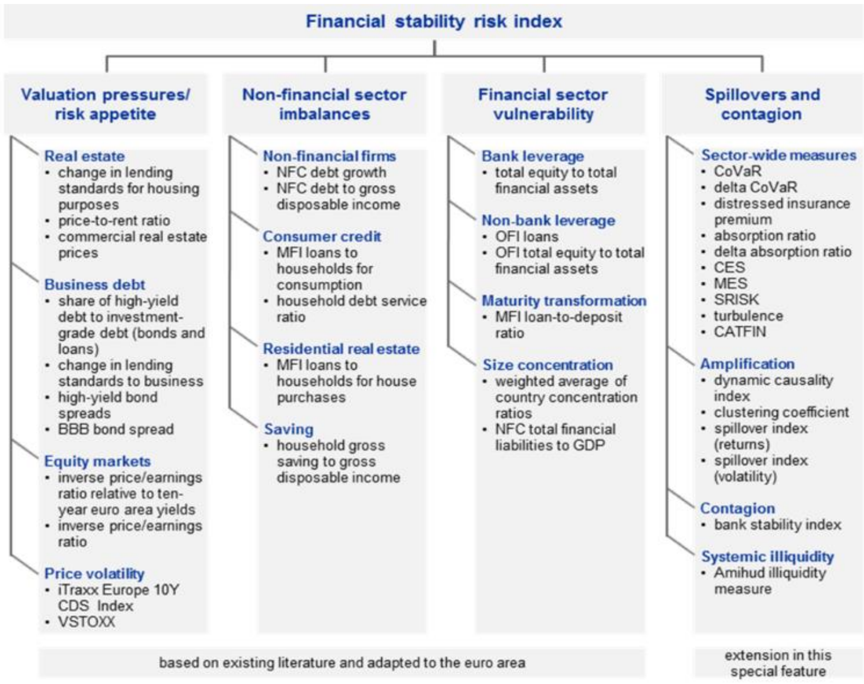
Connectedness metrics can be used to measure contagion and spillover risk to the wider financial system. Diebold and Yilmaz (2009) generate a 'Spillover Index' based on a volatility forecast error variance, which measures the spillovers between US stocks, bonds, foreign exchange and commodities. Diebold and Yilmaz (2014) go further and use a connectedness index which captures spillovers between individual financial institutions. Billio et al. (2012) also construct a metric of connectedness in the financial system, the 'Dynamic Causality Index', based on principal component analysis and Granger causality networks. This index helps estimate the number and importance of common factors driving the returns of these financial institutions and identifies the statistically significant relations among these institutions.

Measures based on capital shortfalls have also been shown to predict worsening economic conditions. For instance, Brownlees and Engle's (2017) metric SRISK measures the capital shortfall of a firm conditional on a severe market decline, which is a function of its size, leverage and risk. This study suggests that an increase in SRISK predicts future declines in industrial production and increases in the unemployment rate, with the predictive ability stronger at longer horizons.

4.2 Composite market-based indicators

The Financial Stability Risk Index (FSRI) uses a large number of indicators (including those discussed in 4.1), as well as partial quantile regression to predict near-term adverse shocks to the real economy (ECB, 2018). The index is made up of indicators which reflect cyclical and cross-sectional financial vulnerabilities. The measure is derived by using quantile regression to extract co-movement from a large set of indicators across four classes (Figure 2). The index has been shown to have predicative power for shocks to quarterly real GDP growth one quarter ahead.

Figure 2 ECB financial stability indicators



Source: ECB (2018)

4.3 General equilibrium models

A number of studies have used general equilibrium models to outline the theoretical framework for systemic risk channels. For example, the model developed by Goodhart et al. (2006) features a commercial banking sector with capital requirements, incomplete markets, money and endogenous default. The model incorporates heterogeneous agents in the form of many commercial banks and endowed investors. In contrast to models which reflect a single 'representative' bank, this approach can capture the contagion from a single bank failure to other banks, asset markets and the real economy. The authors identify a number of channels for contagion captured in the model, such as the collapse of the banking sector's equity value in secondary markets, which reduces its expected profitability. This in turn lowers the income of the investors holding shares of those banks, who now have reduced repayment rates on loans and asset deliveries. Kiyotaki and Moore (1997) develop a model showing how small and temporary shocks to technology or income distribution can result in large and persistent changes in output and asset prices. In the model, agents can borrow provided that their debts are collateralised with durable assets such as land. Changes in the land value spurred by technology or income distribution shocks reduces the agents' ability to borrow and invest. Credit chains through the economy cause the shock to propagate to other firms, who then experience financial difficulties. While these studies provide a theoretical framework to better understand systemic risk, they do not provide quantitative insights into the size of contagion and its effects on the economy.

Other models have used a framework similar to that developed by Kiyotaki-Moore to quantify financial contagion through the channel of credit. Boissay (2016) develops a model to analyse the propagation of a shock through a network of firms that borrow and lend to each other. The contagion spreads through the financial system when the default of one firm causes creditors to incur financial difficulties. The theoretical framework is then applied to the US financial market over the period 1986-2004. The study finds that the probability of a sound firm becoming financially distressed through credit defaults ranges from 4.1% to

12.8%. Financial contagion through credit defaults are estimated to reduce US GDP by at least 0.4% over the whole period considered. This increases to 0.9%-2.3% when considering data in the second half of the 1990s.

4.4 Macroprudential stress testing

In addition to monitoring vulnerabilities in the financial system, central banks and supervisory authorities conduct stress tests to explicitly test the resilience of financial institutions to adverse shocks. A concurrent bank stress test is a simultaneous stress test of several banks carried out under the direction of a central bank or banking system regulator. By exposing banks to a common and simultaneous shock, a concurrent stress test predicts how different banks respond to the same scenario, as well as the speed and spread of the shock throughout the financial system (Dent et al., 2016). Authorities may also be interested in exploring a specific risk involving a subset of financial institutions, and consequently run a narrower stress scenario. The stress-test results are used for macroprudential policy purposes, such as changes in the system-wide capital buffer requirements for financial institutions.

While some stress-testing approaches are based on top-down models, others are based on bottom-up frameworks. The Bank of Japan uses a Financial Macro-econometric model to assess the impact of stress scenarios, including the feedback effects between the financial system and the real economy (Kitamura et al., 2014). In addition, the Bank of Canada has employed a suite of models, including the Macro Financial Risk Assessment Framework (MFRAF), which quantifies second round effects from an adverse shock, such as funding liquidity risk, fire-sale losses and interbank contagion risk (MacDonald, C. and Traclet, V, 2018). While the Bank of England has employed top-down models in the past that have included feedback mechanisms (Burrow et al., 2012), it now employs a range of models developed by participating financial institutions alongside other in-house models. Its most recent methodological note on the stress testing process suggests that it is still developing its capability to model amplification mechanisms and spillovers (BoE, 2015).

5 Approaches to assessing systemic risk from a transition shock

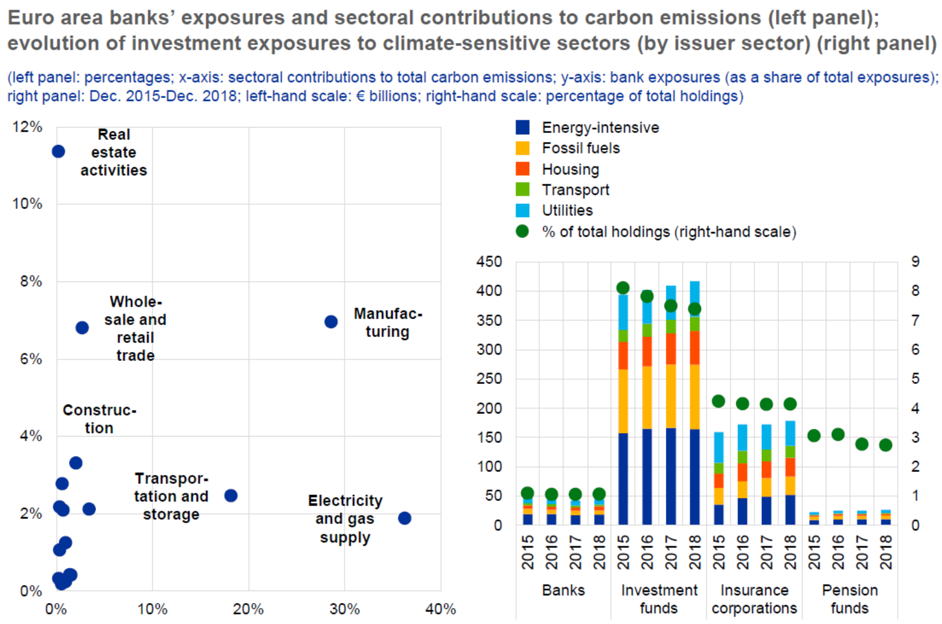
We consider approaches to assessing systemic transition risk employed by policymakers, as well as studies which estimate the risk of losses at various stages following a transition shock. Approaches employed by policymakers include monitoring indicators of exposure to fossil fuels and stress testing. The wider literature includes modelling approaches which estimate the first round and second round effects of a transition scenario.[3] Given the studies which include second round impacts are limited, we also report studies which estimate the first round impacts only (i.e. excluding material spillovers to other parts of the economic and financial network).

5.1 Approaches of Policymakers

5.1.1 Monitoring Indicators

To tailor risk management practices towards transition risk, policymakers have begun to monitor indicators of banks' exposure to high-carbon sectors. For example, the ECB has estimated eurozone bank exposures to various sectors alongside their contribution to total emissions. It has also calculated more detailed exposures from banks, investment funds, insurance corporations and pension funds to emissions-intensive industries, drawing on the methodology from Battiston et al. (2017) (see Figure 3). Another aspect considered by the ECB is the concentration of banking exposures to the largest emitters across European countries, in order to gauge in which countries, the large emitters are more systemically relevant (see Figure 4).

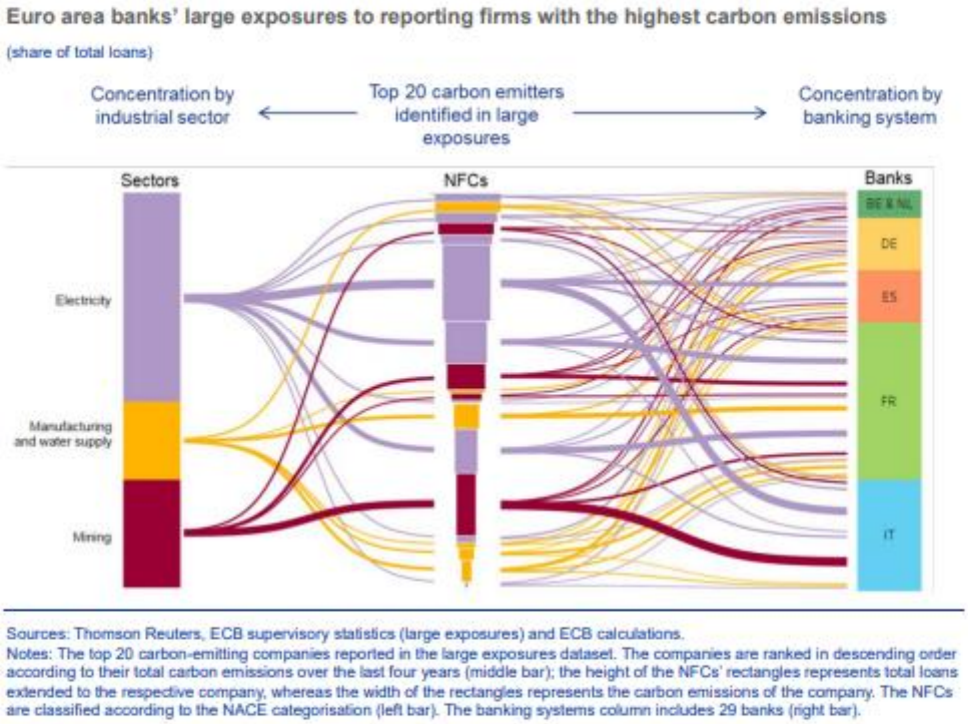
Figure 3 Sectoral exposure statistics can provide a first comprehensive approximation of transition risk



Source: ECB (2019)

[3] We note that it can be difficult to distinguish between categories.

Figure 4 Large exposures to reporting firms with the highest emissions



Source: ECB (2019)

5.1.2 Climate-related stress testing

Many central banks and supervisory authorities are now applying scenario-based stress tests, to examine the extent to which the financial system and wider economy is exposed to transition risk. A stress test which reflects a disorderly transition could involve generating scenarios with varying paths for temperature increases, policy actions, technological breakthroughs and confidence levels. The impact on different sectors or market participants can then be estimated under different scenarios.

The DNB estimates the potential losses for Dutch financial institutions across several transition scenarios (Vermeulen et al., 2019). Four disruptive transition scenarios were specified: an active climate policy shock, a renewable energy technology shock, a double shock which combines the previous two scenarios and a confidence shock to reflect caution in the absence of clear developments on policy or low-carbon technology. Industry-level transition vulnerability factors are then constructed to identify the industries affected by transition risk. These are based on the embodied emissions of the final goods and services in each industry and vary across scenarios to reflect the particular risk factors present in each scenario. Next, macroeconomic impacts of each scenario are derived from a macro-econometric model and the vulnerability factors are applied to estimate the industry-specific impacts on equity values. The authors conclude that disruptive energy transition scenarios can have sizeable negative consequences on the Dutch financial sector as a whole, with portfolio values declining by up to 11%. The DNB also conducted an earlier analysis which quantifies the impact of a disruptive energy transition at industry-level, with Utilities and Mining being the sectors most severely hit by policy and technology shocks respectively (Vermeulen et al., 2018).

The Bank of England has announced that its 2021 Biennial Exploratory Scenario (BES) will focus on stress testing under three climate-related scenarios (BoE, 2019). The BES will test the resilience of the UK's largest banks and insurers balance sheets under three different scenarios:

- **Early policy action scenario:** The transition to a carbon-neutral economy starts early and the increase in global temperature stays below 2^{o}C, in line with the Paris Agreement.

- **Late policy action scenario:** The global climate goal is met but the transition is delayed and must be more severe to compensate for the late start.
- **No additional policy action scenario:** No policy action beyond that which has already been announced is delivered. Therefore, the transition is insufficient for the world to meet its climate goal.

This work appears to place the responsibility of modelling on the participants of the stress test and therefore the extent to which systemic risks will be captured is unclear.

Other financial institutions plan to use stress test methodologies to size the financial stability challenges due to climate change. The European Banking Authority has committed to conducting a climate related stress test, although few details have been provided on the methodology (EBA, 2019). In addition, the IMF is conducting a pilot program to assess financial stability risks associated with the transition to a low-carbon economy (Adrian et al. (2020)). The analysis will be carried out for an oil-producing advanced economy through the Financial Sector Assessment Program (FSAP). The IMF intends to learn from the lessons of the ongoing pilot program to extend transition risk assessments to a larger number of countries, in collaboration with the World Bank and supervisory agencies.

5.2 Literature on first-order impacts

A number of studies use Integrated Assessment Models (IAMs) to assess the first-order financial risk from a low-carbon transition. Mercer (2019) draws on an IAM to estimate the value gains and losses for various asset types under a 2-degree scenario, with the cumulative impact to 2030 varying between -59% and 106% based on the sector. In addition, Carbon Delta (2019) draws on the technology- and policy-based price estimates from IAMs (such as REMIND) to estimate the company-level costs associated with meeting emission reduction targets. These are then used alongside datasets for publicly listed companies to estimate the climate-value at risk (CVaR) from policy adjustments. Under a 2-degree scenario, the transition CVaR was estimated to be 8.16%, although this is reduced if the opportunities presented by low-carbon technologies are considered (UNEP FI, 2019).

Vivid Economics (2019) completed a study which quantified the first order financial impacts on a range of financial assets under an 'Inevitable Policy Response' scenario. This work draws on the macro-economic model G-Cubed, the energy model TIAM-Grantham and the Land-use model MAgPIE to translate climate policy shocks into real economic shocks. Vivid's Net-zero toolkit is then used to apply this shock to companies both directly, for example through a higher carbon price, and through indirect channels, such as changes in demand for a company's products. The financial impacts are quantified in terms of changes in these direct and indirect asset value streams, accounting for companies' areas of activity and market exposure. The model also describes the likely reactions of companies to the shocks, including implementation of abatement opportunities, cost pass-through to consumers and other competition dynamics. The work concludes that a scenario based on probable policy and technological developments could lead to a decrease in the iShares MSCI ACWI ETF by 3.1% or $1.6trn. At a sub-sector level (RBICS level 2), it finds impacts of valuations ranging from –38% to +7%. At a company level, the worst-performing decile suffer losses exceeding 60%, while the best-performing decile have gains ranging from 50% - 100%.

Weyzig et al. (2014) estimate the exposure of EU financial institutions to fossil fuel firms and commodities, analysing the first-order impacts of a bursting carbon bubble on the financial system. The direct exposure of EU financial institutions to fossil fuel firms and commodities were estimated to be over €1 tn, of which 44% is held by banks, 32% by insurance companies and the remainder by pension funds. Exposure is calculated across equity investments, corporate loans, corporate bonds, pension fund investments and assets of insurance companies. The authors then model the potential losses connected to a 'quick transition' scenario, in which the transition to a low-carbon economy is rapid and definite. They find that losses as a percentage of total asset ownings vary between 0.4% for banks and up to 3.4% for pension funds. While these exposures are sizeable, it was suggested that this would not be sufficient to be a source of systemic risk. However, pre-existing fragilities in the financial system could increase the destabilising power of a carbon bubble.

5.3 Literature on second round impacts and contagion

The existing studies which quantify the second round impacts from a low-carbon transition draw on network theory and can be broadly categorised into two branches 1) financial networks; 2) production networks. The first branch explores how the first-round impacts of a low-carbon transition spread across the financial network through lending and ownership relationships (Battiston et al., 2017; Stolbova et al., 2018). The second branch investigates the transmission of a transition shock through the production network and the subsequent changes to the structure of production. Important contributions in this stream of research include Cahen-Fourot et al. (2019) as well as Bastidas and Florent (2019). These contributions are described in greater detail below.

Battiston et al. (2017) employs network analysis to investigate the interconnectedness between different investor types and uses this to estimate the first and second round impacts of a climate shock. The authors derive shareholders for a pool of companies, construct a portfolio for each of them and then group shareholders into 8 different investor types. From here they are able to derive the relative exposure of each investor type to 'climate-relevant' sectors, which include suppliers and users of fossil fuels and electricity.[4] The ratio of the exposure to climate relevant sectors over total equity of each investor is computed. This gives an upper bound on the relative first round losses on capital that an investor would suffer, in case of a shock to those sectors. The analysis also considers second round effects stemming from the devaluation of interbank obligations of investors exposed to the first round, which can have a negative impact on the portfolios of those who hold such obligations. The analysis concludes that, while direct exposures to the fossil fuel sectors are small (3-12%), the combined exposures to climate-relevant sectors are large (40-54%) and amplified by large indirect exposures via financial counterparties (30-40%). The authors define the main channel of contagion for each investor type, depending on their specific portfolio composition. In the case of banks, contagion from carbon-intensive sectors is channelled mainly through the loan market, while investment funds and pension funds are exposed largely through the channel of equity holdings.

Stolbova et al. (2018) use a macro-network approach to identify the feedback loops between the financial sector and the real economy from a climate policy shock to the Euro Area. The climate shock considered is a late-and-sudden introduction of climate policies against a baseline where the same climate policies are implemented early and gradually. The authors consider eight institutional sectors in the Euro-area (non-financial firms, banks, investment funds, other financial institutions, government, households, and insurance and pension funds) and study their relative exposure to climate shocks through financial instruments such as bonds, equity, loans, insurance and pension scheme guarantees, using empirical data on financial exposures. The existence of chains of financial contracts enables the shock to transmit through the financial network, including feedback loops due to closed chains of financial exposures among institutional sectors. The study focuses on the transmission channel to securities valuation, stemming from a decrease in the value of equity holdings and debt securities holdings, as well as the decrease in value of banks' assets from depositors withdrawing funds and the subsequent decrease in creditworthiness. Results show that a small negative climate policy shock hitting the banking system could lead to a great amplification in losses via the bank-household connection. This eventually results in great losses for the banking system and negative implications for the real economy.

Cahen-Fourot et al. (2019) assesses the exposure of European sectors to the risk of physical capital stranding using a combination of input-output (IO) theory and networks. The metrics developed capture the direct and indirect impacts of a low-carbon transition on the stranding of assets. The study estimates multipliers to assess the sector's total impact on asset stranding, the external impact this has on other sectors and the exposure of particular sectors to asset stranding. The work also assesses the cascading impact of asset stranding from the mining sector through to the other sectors across 10 European countries and develops a lower bound estimate of the total proportion of assets at risk of stranding. The sectors that were found to be

[4] While fossil fuels sectors tend to be negatively impacted by climate policies, the other categories can be affected positively or negatively depending on the energy source used (such as suppliers of renewable energy).

most affected by capital stranding were electricity, gas, coke, refineries, basic metals and transport. Although, the shocks also cascade into chemicals, metal products, motor vehicles, water and waste, wholesale and retail trade and public administration. Different results were also documented across countries, with Austria estimated to have 0.8% of capital at risk (driven by the mining sector), while Slovakia was estimated to have 8.2% of capital at risk driven by the electricity and gas sectors.

Bastidas and Florent (2019) consider the case of Brazil to analyse the changes in production needed to meet the country's NDCs as well as its economic growth objectives. They combine input-output data, GHG emissions data by industry and employment data to assess the impact on employment and production under an NDC scenario. They find that primary industries (such as agriculture and livestock), services and education are booming throughout the transition period. On the other hand, the production of extracting activities, most manufacturing activities and some of the services activities are expected to decline.

6 Gaps in existing methodologies and areas for future research

There are still gaps in existing methodologies for estimating the systemic risk associated with a disorderly low-carbon transition. Potential areas for further research include:

- Improved data collection and monitoring of exposure to carbon-intensive (and green) assets.
- Detailed transition risk scenarios in stress tests that account for feedback loops between financial market participants, and between the financial system and the real economy.
- More comprehensive modelling approaches which include both production and financial networks, as well as the impact from rising and declining industries.

6.1 Data collection

Improved data collection on the exposure to carbon-intensive and green assets will assist in assessing systemic risk. Despite the ECB reporting a number of useful indicators on exposure to fossil fuels, it acknowledges that more comprehensive data on climate-related exposures is required to better assess the levels of systemic risk (ECB, 2019). The estimated exposures could be improved through additional data collection for each institutional sector, especially with regard to investment funds which tend to lack information on the industry classification of the ultimate exposures (Vermeulen et al., 2019). Data on exposure to new low-carbon technologies would also be useful in monitoring the risk from rising industries. The participation of both the public and private sector is important to developing these new data collection frameworks. To facilitate the collection of such information, the NGFS and TCFD are already setting out frameworks which encourage firms to disclose exposures to climate-related financial risk.

Where possible, the assessment of transition risk should seek to draw on data which have been used to assess systemic risk in the past. It may be possible to apply some of the indicators discussed in section 4.2 to the transition risk context, for example through tracking debt growth or debt to assets ratios of carbon-intensive and green companies. While the ESRB (2016) has cited statistics which suggest that carbon-intensive companies are highly leveraged,[5] this needs to be monitored on a more frequent basis, disaggregated by sector, and compared with other sectors to gauge whether debt levels are high in relative terms.

Reporting of exposures should also cover the fossil fuels producers themselves and include carbon stocks in fossil fuel reserves. Many companies have started voluntarily providing information on their annual direct carbon emissions and those associated with the use of their products. However, efforts to disclose annual carbon flows should be paired with requirements to report carbon stocks represented by fossil fuel reserves. A failure to disclose this information could pose a long-term systemic risk through asset mispricing. Disclosure should also be carried out in an integrated way, moving away from standalone reports. This would allow for cross-company and cross-country comparisons of carbon stocks, flows and exposures, which facilitates monitoring and better informs policy action (Carbon Tracker, 2011; Russell, 2016).

[5] There is evidence to suggest that there has been a large increase in the debt to assets ratio for smaller US companies and state-owned companies in EMEs (Domanski et al.,2015). In addition, carbon-intensive companies are said to make up one third of the high risk leveraged loan market (PRA, 2015).

6.2 Stress testing

Incorporating 'worst-case' transition scenarios into regular stress testing exercises would improve the understanding of transition risk. The climate stress tests could arguably include more extreme scenarios than those in the plans that have been outlined, reflecting a 'worst-case' transition shock to the financial system, as well as the interaction with other adverse shocks. The regular scenarios employed could reflect a sudden downward repricing of exposed assets and/or an upward shock in the price of non-renewable energy sources with the positive balance sheet effects for energy producers turned off (ESRB, 2016). Other scenario inputs could include variations in climate sensitivity, economic growth and the costs of decarbonisation.

In particular, stress tests should aim to incorporate the potential financial risks associated with the development of innovative green technologies. High levels of uncertainty surround new green technologies, both in terms of the necessary costs to develop them and the outcomes of their implementation at scale. Therefore, there is the potential for policymakers to direct high levels of investment towards risky projects. For example, in the U.S. solar PV market, the rise of international competition led a large US firm, Solyndra, to declare bankruptcy, after receiving large amounts of public funding (Rodrik, 2014). This confirms that technological developments and commercial trends in the market for green technologies can be highly uncertain. Even once green technologies are proven to be cost-effective at scale, the substitutability with existing technologies may be a further source of disruption to economic and financial systems. Policymakers should therefore incorporate such risks into their stress testing methodologies.

Historical events, particularly in relation to commodity price swings, can also be used to inform and calibrate the modelling of future shocks in stress testing exercises. There is a recognised difficulty in the systemic risk literature of measuring the risk associated with events that have never been seen. However, we can draw on systemic crises that have occurred in the past which display similar characteristics. For example, Reinhart and Rogoff (2008) study the history of financial crises, examining the major transmission channels and impacts from a range of shocks, including commodity price swings. The same approach could be used to infer the direction and magnitude of the economic and financial impacts from energy price shocks. In fact, the Bank of England has previously estimated the financial impact of large movements in commodity prices (oil in particular) as part of their stress testing exercises (BoE, 2015). The results from such exercises could be used in future calibrations. These scenarios could involve estimating an upward shock to commodity prices with the positive balance sheet effects turned off (as suggested in ESRB, 2016) or a downward shock to commodity prices with the cost pass-through channel turned off.

Stress tests can also be further developed to better capture amplification and feedback loops (i.e. second round effects). While studies which focus on the first-order financial impact of a low-carbon transition suggest the risks are limited, the empirical evidence on second round effects from a disorderly transition shock suggest that there could be substantial amplification of first round losses (Battiston et al. 2017). However, Borio et al. (2014) suggests that most of the stress testing techniques available still lack the necessary capabilities to capture adequate feedback and amplification mechanisms, and that the only way to generate systemic outcomes within current stress testing frameworks is by enlarging the size of the initial shock, despite this size often becoming inconsistent with empirical evidence.

6.3 More comprehensive modelling frameworks

A multi-layered approach that includes both production and financial networks would lead to a more comprehensive approach to estimating systemic risk. While the effects of a low-carbon transition spread to the wider economic system through a number of mechanisms, these can be classified under two main layers: propagation through the production network and through the financial network. Future research should aim at developing a multi-layer network approach that brings together these two layers of transmission within a dynamic framework. Examining these networks simultaneously could lead to further insights on the spillovers between financial and production networks and therefore improve the assessment of systemic risk in the context of a transition shock.

Future research should also aim to develop modelling approaches that estimate the risks from both rising and declining industries. As previously mentioned, studies such as Semieniuk et al. (n.d.) differentiate between the financial risks from rising and declining industries during the transition to a low-carbon economy. These impacts are important to consider using a combined framework as there is a counterbalancing impact on risk. In other words, when risks for declining industries are high, risks for rising industries decline and vice versa. There are gaps in the literature regarding both types of industry classification. The risks associated with rising industries and innovation have been widely covered in the existing literature. For example, Perez (2013) argues that a new direction for innovation and industry is often associated with over-investment. However, so far, little attention has been paid to estimating the risk from rising industries in the context of a low-carbon transition, likely because the transition is still in its early stages. On the other hand, while the risks posed by declining industries have been closely examined in the transition risk context, there has been limited research on the risks posed by declining industries in other contexts, and therefore, this area lacks a theoretical structure from previous literature. Future research should aim to better describe the risks from rising industries under a low-carbon transition, leveraging the existing literature on innovation, and develop a comprehensive theoretical framework for assessing the risk from declining industries.

7 Conclusion

There has been a growing emphasis in the literature on the potential for systemic risk following a transition shock. Many studies identify the channels through which a low-carbon transition can lead to systemic risk. This includes a failure to price in the risks associated with declining and rising industries exposed to the transition. If financial market participants revise their expectations on these risks, potentially due to a climate policy shock, this could lead to a fire sale of assets and stress in debt markets which ultimately result in lower levels of investment and government spending. In addition, energy price shocks driven by an abrupt restriction on fossil-fuel based energy production, have the potential to result in systemic risk through increases in energy and production costs across the economy, which will likely dampen consumption levels. Given the potential for these transmission channels, policymakers and academic studies have developed approaches to assessing systemic risk from a low-carbon transition. For policymakers, these include indicators of banks' exposure to high-carbon sectors and stress testing methodologies. The academic literature has focused on network modelling to study the propagation of a transition shock throughout financial and production networks.

More research is required from policymakers and academia to develop modelling approaches which quantify the extent of systemic transition risks. While the channels of systemic risk have been well documented, quantifying the extent of systemic risk associated with a low-carbon transition still represents a challenge. Greater collection of detailed data on the exposure of portfolios and lenders to carbon-intensive (and green) assets can assist in producing a more accurate assessment of systemic risk and inform modelling efforts. Stress testing frameworks could be further developed to better quantify second round effects, and to incorporate a broader range of transition-related risks. Historical events with some similar characteristics can also be used to inform the design and calibration of stress tests. Further, more comprehensive approaches that model financial and production networks in detail, and capture both the risk from declining and rising industries, will likely provide a more holistic assessment of systemic risk.

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