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Low-carbon transition risks for finance

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Abstract

Transition risks for finance arise from the transition to a low-carbon economy, which can disrupt the ability of carbon-intensive industries to meet their financial obligations and lead to abrupt changes in asset valuations of affected firms and default on their debt. An understanding of these risks is key for any ambitious emissions reduction programme, such as that implied by the Paris Agreement. Insight from theory and study of past transitions is of limited help, as these see financial risks mostly flowing from speculation with rising industries propped up by a set of new vastly more productive technologies. The current transition instead requires policy to quickly render a set of currently productive high-carbon industries unprofitable, stranding their assets, so the risks are located in the declining industries. Absent a unified framework of the interaction of real and financial aspects of the transition, one set of studies conceptualises and quantifies asset stranding and other transition costs in declining industries, and a separate one estimates the potential impact of these transition costs on the financial system. Combining these two research strands and modelling the feedback of financial distress on the real economy will require more research, which could help integrate transition risks into the cost analysis of mitigation in integrated assessment models. An important insight from the past transitions literature is that once low-carbon industries are rendered more profitable than high-carbon ones, financial risks could also build in these newly rising industries due to speculation.

Keywords: Transition risks, low-carbon economy, declining industries, stranded assets, financial distress

JEL classification: E32, E44, G17, G32, L16, N2, O3.

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Introduction

Climate change impacts the financial system via two main channels: physical and transition risks (PRA, 2018).¹ Physical risks for finance arise from losses due to adverse physical consequences of climate change, for humans and the economy, such as increased flooding or extreme heat. Transition risks arise from the transition to a low-carbon economy, which can disrupt the ability of carbon-intensive industries to meet their financial obligations and lead to abrupt changes in asset valuations of affected firms and their creditors. These changes ultimately heighten systemic financial risks due to the financial sector's interconnectedness. To some extent, physical and transition risks are complementary. The more mitigation is delayed and climate change advances, the more it engenders physical risks (Allen and Stocker, 2014). A delayed transition must be faster and more disruptive to still reach a low carbon economy (Luderer *et al.*, 2013). This increases transition risks. But to some extent these risks are also substitutes. Notwithstanding that physical risks follow a statistical distribution with a substantially long tail towards high damages (Weitzman, 2009, 2011), maintaining global average temperatures below 1.5°C above pre-industrial averages most likely limits physical risks to manageable levels (Holden *et al.*, 2018), but will rapidly and deeply transform the economy. An understanding of transition risks is key for any ambitious emissions reduction programme, such as that implied by the Paris Agreement.²

At the root of the low-carbon transition lies a transformation in the industrial production structure that is driven by changes in market conditions, technological change (in short: innovation), policy and regulation, expectations about innovation, and preferences (Markard, 2018; Fouquet, 2019). To analyse risks for finance, we define the transition as structural economic change. The industrial composition of the whole economy changes: some parts grow and others decline in relative importance (Syrquin, 2010).³ To meet emissions reduction targets, low-carbon industries must grow at speed and scale, while high-carbon industries must decline swiftly, which can precipitate and interact with other structural changes in the economy (Ciarli and Savona, 2019). Low-carbon industries include: i) consumption and capital goods industries with low emissions in the production process (both in the direct process of production and in the supply chain); ii) consumption good industries whose output produces low emissions while being used by consumers, e.g. electric vehicles; iii) capital goods producing industries whose products reduce the emissions of other industries and production processes, e.g. wind turbines, energy-efficient machines, or 'smart' energy-saving digital technology. Low-carbon transition risks for finance can then be defined as the risks to financial actors and the financial system as a whole stemming from this specific type of (rapid) structural change. Risks can originate both in rising low-carbon and declining high-carbon industries.

Theoretically, we locate transition risks for finance at the intersection of business cycle research into financial instability, and the theory of financing innovation. We find that financial risks are associated with rising industries based on vastly more productive technology due to speculation. Declining industries, though important in the real economy,

¹ A third category, liability risk, is sometimes distinguished (PRA, 2015). Liability risks concern legal claims when parties seek to recover losses due to physical or transition from other parties they hold responsible. We follow NGFS (2019) in subsuming liability risks under the other channels.

² Existing reviews treat both physical and transitions risks, and the latter in less depth, or with a focus on the non-academic literature (Hjort, 2016; Batten, 2018; Campiglio, Monnin and von Jagow, 2019).

³ Cherp *et al.* (2018) show that for other purposes adopting a more multi-disciplinary definition can be productive.

are not found to destabilise the financial sector through their decline, as it is buffered by the rise of the new industries. As a result, no ready-made theoretical framework is available for analysing the current transition, which requires policy to quickly render a set of currently productive high-carbon industries unprofitable. In the absence of a unified framework of the interaction of real and financial aspects of the transition, one set of studies conceptualises and quantifies asset stranding and other transition costs in declining industries, and a separate literature estimates the potential impact of these transition costs on the financial system. Combining these two research strands and modelling the feedback of financial distress on the real economy will require more research. Here we classify and review the types of risks and impacts such a combination will likely have to consider.

The next section situates transition risks for finance in the theoretical literature and section 3 reviews the Schumpeterian tradition to understanding the link between structural change and financial risks. Section 4 contrasts theory with the current debate, concluding that the low-carbon transition is different from past ones in that there is no readily available high-productivity alternative, yet the transition must be made. Section 5 classifies declining industry transition drivers, costs, and impacts, while reviewing the evidence on each component. A penultimate section reviews policies for mitigating transition risks. Section 7 concludes.

Combining Finance and Structural Change

Research on financial instability and research on structural change have been carried out by two different groups with limited overlap. Scholars of financial distress rarely venture into the technological origins of such distress. Charles Kindleberger (1978), the classic reference on historical crises, eschews the details of the technical change that underlies several of his documented financial *manias*, and the only technological change Reinhart and Rogoff (2009) refer to is the *financial* innovation of changing from coin to paper money.⁴ The theoretical analysis of financial instability is also predominantly concerned with macroeconomic aggregates: expenditure, debt-to-GDP levels, unemployment, but not industry-level changes in the composition of these aggregates.

Innovation scholarship, which studies structural change due to technological and behavioural change, tends to omit systemic financial aspects (Callegari, 2018; Geddes and Schmidt, 2018). Even when the topic is 'financing innovation', researchers take a microeconomic perspective on how market failures prevent innovative firms from getting enough funding (Hall and Lerner, 2010), which precludes considering problems of aggregate nature, such as financial stability. If anything, research considers how the recent financial crisis has affected innovation negatively (Giebel and Kraft, 2019) or how subsequent economic stimulus affected it positively (Mundaca and Richter, 2015).

Where the two research programmes overlap is in research on recessions, depressions and (financial) crises in multi-sectoral economic models. Perhaps the oldest such programme of continued relevance is to be found in Marxist crisis theories (Basu, 2018), building on Karl Marx's unique attention to technology as explaining social change (Rosenberg, 1982). Key is Marx's idea to differentiate the economy into capital and consumption goods producing

⁴ The same focus only on financial innovation is on display for the 2007-08 financial crisis, where the innovation is the collateralized debt obligation to refinance mortgage backed securities (Brunnermeier, 2009).

sectors (departments 1 and 2), where both underconsumption (Shaikh, 1978) or over-investment (Brenner, 2006) can lead to a crisis. This can account, for instance, for the 2007-08 financial crisis (Kotz, 2013). In principle, this could provide a framework for analysis, however, existing contributions disregard industries *within* the capital goods producing sector: both low and high carbon industries are subsumed under it.

More recently, real business cycle theory has attempted to explain aggregate fluctuations purely from real shocks, such as technological change (Plosser, 1989). Where these models are multi-sectoral, they can analyse impacts of industry-specific technological change on the utilization of specialized inputs (Davis, 1987). The underlying general equilibrium approach can provide another framework for studying asset (and worker) stranding and financial consequences. But to date, the focus has been on unemployment and not capital stranding (Davis, Haltiwanger and Schuh, 1996), and technology shocks are typically conceived as random, not linked to secularly declining or rising industries (Azariadis and Kaas, 2016). Moreover, integrating a meaningful financial sector into these models, would require major changes to the theoretical framework (Stiglitz, 2014; Romer, 2016).

A more “old-fashioned real business cycle theory” (De Long, 1990) that considers industry-level innovation and finance is put forward by Joseph Schumpeter.⁵ In Schumpeter’s theory, innovation and structural change drive economic productivity growth, and must be financed by a financial sector.⁶ The interaction between finance and a clustering of innovations leads to swings around the growth trajectory, including a “depression” with a financial crisis (Schumpeter, 1934, 1939). This theory, developed further by followers of Schumpeter, yields good insights into the relevant risk categories and the next section takes a closer look.

Schumpeterian explanations of transition risks

In the Schumpeterian theory, a cluster of vastly more productive technologies causes a transition. Risks from the rising industries are responsible for much of the potential financial upheaval. Uncertainty about what technological design will ultimately prevail and about the scale at which the growing industry saturates, creates the potential for speculation, overinvestment and ‘irrational exuberance’ (Shiller, 2001). In contrast, the theory has no theoretical explanation of how declining industry risks could destabilise the financial sector. Economic history confirms theory by suggesting that declining industries have not caused for systemic financial distress in the past. While losers: firms, their financiers and swathes of unemployed workers suffered, the financial sector as a whole did not collapse as it sailed on the new industries’ wave that buoyed the aggregate economy. Transition risks from declining sectors must be seen as being caused by unprecedented policy intervention in what are profitable industries.

Risks associated with rising industries

In Schumpeter (1939), banks play a crucial role in helping innovators (the entrepreneur) finance their new enterprises by creating new credit. While this credit creation function of banks is key to innovation and leads to output expansion, problems for finance can arise from subsequent borrowing for speculating with financial assets of new industries. This ‘secondary wave’ of the business cycle carries the risk of overestimating rising industries’

⁵ Hayek (1931), like Marxist authors, only distinguishes consumption and capital goods sectors.

⁶ For important theoretical influences on Schumpeter’s thinking see Reinert (2002) and Hagemann (2003).

growth potential (Schumpeter 1939, p. 147). If speculators calculate wrongly, over-indebtedness and defaults could become the consequences exhaustion of a 'cluster' of innovation activity, and generate a financial crisis. Transition risks for finance are firmly linked to rising industry speculation.

According to Schumpeter, these waves of entrepreneurial activity occur at intervals. For transitions with widespread structural change, the most important is the about 50 year lasting long wave or cycle, named after Nikolai Kondratieff (Kondratieff, 1979[1925]).⁷ Examples include railway transport and steam shipping, based on steam engine diffusion in the second half of the 19th century; the adoption of electricity and heavy engineering (chemicals, steel) around the turn of the century; or the organisation of mass production and widespread diffusion of internal combustion engines based on oil from the 1930s/40s onwards (Freeman and Perez, 1988); and not least IT as the most recent of these waves.

Subsequent work by Schumpeterian scholars emphasises the important role of government policy and social change in assimilating the new technologies, which was assumed to happen somewhat automatically by Schumpeter (Perez, 1983; Freeman and Louca, 2001). The role of finance in these "technological revolutions" that change the "techno-economic paradigm" is developed by Carlota Perez (2002). Key is the turning point from the frenzied part of the "installation period" with intense financial speculation on various versions of the new technologies to the "deployment period" of orderly diffusion and stable economic growth based on the application of the new technologies and their paradigm across the whole economy until they reach maturity. This turning point follows a financial collapse that reveals the social problems resulting from the changes, witnesses anger, revolt and populism on both extremes. It highlights the need for a new set of regulations and institutions that establish a direction for innovation and investment, spreading the new technologies in socially beneficial ways.⁸ One example is the 1929 financial crisis, which involved a bubble in radio, electricity, airplanes, automobile and petrochemical industries (Freeman & Louca 2001). Similarly, the intense investment booms for the expansion of railways in the 19th century, were at the root of financial crises in several countries in the mid-1800s (Vague, 2019), and the new IT industry at the centre of the 2011 "dotcom" bubble.

Technology-based financial instability can be seen as a special case of Hyman Minsky's (1975, 1986) financial instability hypothesis, which describes how the financial sector continuously drives itself towards financial crises through the creation of increasingly complex financial structures, the accumulation of debt and financial innovation. Although innovation and technological change are exogenous in Minsky, his understanding of the relation of profit opportunities and financial speculation adds important insights to transition risks stemming from the fast development of rising industries.⁹

Risks associated with declining industries

To the best of our knowledge, there is little theory that explicitly associates financial risks with declining industries. Schumpeter thought that the death of old industries would not

⁷ See Freeman & Louca (2001) on the slow reception of Kondratieff's work in non-Russian speaking academia and Bernard et al. (2014) for a recent review of the named business cycles of different length and associated theories.

⁸ Note the parallels with the Marxist social structure of accumulation and regulation theories as a crisis being the turning point in the transition between two forms of capitalism (Kotz, 1990).

⁹ For a recent survey of Minskian models see Nikolaidi and Stockhammer (2017), for an application to the 2008 financial crisis see e.g. Taylor (2012) .

suffice to destabilise the economy. As long as entrepreneurial activity lead to aggregate growth, any crisis would be caused by speculation and slowing innovative activity (Schumpeter, 1939, pp. 134–5). The techno-economic paradigm literature highlights “structural crises of adjustment” that emphasise the struggle of both new and old industries equally (Freeman and Perez, 1988), however the focus is more on unemployment, and the transmission channels to financial risks of declining industries are left unexplored (Freeman and Louca, 2001).¹⁰ In line with this theoretical view, formal models of Schumpeterian dynamics do not provide an explanation of risks from declining industries. Dosi et al. (2017) explicitly model Schumpeterian dynamics and financial crises, but their focus is on the interaction of aggregate demand and innovation, not structural change. Carvalho & Di Guilmi (2019) analyse rising household debt from labour-saving technical change without distinguishing industries. Caiani et al. (2014) show that declining industry risk can be shown mathematically to cause financial distress, but more theoretical effort is needed to determine under what conditions asset scrapping is triggering a financial crisis.

In the 1980s and 1990s, neoclassical endogenous growth theory incorporated “creative destruction”, introduced in a later book by Schumpeter (1942). While “destruction” suggests more insight into declining industry risk, a closer look reveals that the theory explains the economy’s growth performance with the decision of entrepreneurs in the rising industries on how much to innovate (Aghion and Howitt, 1992; Francois and Lloyd-ellis, 2003; Aghion, Akcigit and Howitt, 2015). The idea of costly “reallocation” of factors of production would clearly allow a study of stranded assets (Caballero and Hammour, 1996). Yet, as before, there is no discussion of conditions under which such reallocation would become so important as to destabilise the financial system.

Institutional economic history of the secular decline of the British economy offers a different lens on the relative unimportance of declining industries for financial risks. It is well documented that individual industries, such as cotton or steel suffered from chronic overcapacity after 1920, and that government programmes were instituted to scrap uncompetitive machines in order to reduce capacity (Lazonick, 1984; Tolliday, 1987). Banks that had lent during the uptick of domestic demand in 1919-20 found themselves in a precarious position in the subsequently stagnating British economy. But the main thrust of this literature is to establish the influence of finance on British manufacturing industries’ decline, not the other way around (Best and Humphries, 1984; Higgins and Toms, 2003). A theoretical literature from the 1930s and 1940s discusses the microeconomic problem of ‘premature abandonment’, an earlier term for asset stranding (Caplan, 1940).¹¹ This literature evolved into vintage capital goods models of growth and fluctuations and the modern measurement of capital stock, but remains somewhat disconnected from structural change and in particular from financial risks (Eisner, 1972; Hulten, 1992; Greenwood, Hercowitz and Krusell, 1997; Benhabib and Hobijn, 2003; Diewert, 2005).

¹⁰ While they attribute unemployment to the declining sectors, Freeman and Louca broadly follow Schumpeter’s perspective emphasising the instability and euphoria triggered by “the tempestuous growth of the new industries” (2001, p. 259) as the root cause of financial crises.

¹¹ More recent microeconomic work has not connected this to finance. The ‘product life cycle’ has brought insights about financial volatility for young industries but neglects decline (Klepper, 1997; Mazzucato, 2002). Industrial organisation research on the efficiency of plant closures in declining industries (Baden-Fuller, 1989) is motivated by game theoretical predictions (Ghemawat and Nalebuff, 1990) on the impact of firm size on the survival chances of individual plants and firms (Lieberman, 1990).

In summary, theory and economic history strongly point to paying attention to rising industries for locating risks for the financial sector, or at least have not investigated risk from declining industries. This may appear puzzling: as we will review next, in the current transition the focus is fully on the risks posed by the declining high-carbon industries such as fossil fuels, but also the industries strongly relying on their input, such as cement and internal combustion engine cars. The theoretical review offers an important insight for this focus. A declining industry creates losses for the owners, and unemployment for its employees. But this hardly brings down the financial system, which is backed up by opportunities in the rising industries, which in turn only cause the fast decline of the previous set of industries because they are so much more productive. If losers are systemically or politically important enough, the asset owners' loss may be softened by subsidies or payoffs (Brainard and Verdier, 1997). This still exposes workers to unemployment, but creates fewer disruptions for equity and debt holders of the affected companies. To make declining industries the locus specifically of *financial* distress requires a deviation from this 'regular' pattern.

Research on the current transition's risks

Despite the theoretical predictions, attention to a speculative boom from rising low-carbon industries is scant. On the contrary, the academic literature has focused exclusively on how private investors could be coerced and cajoled into providing more finance for the new industries (Cárdenas Rodríguez *et al.*, 2015; Hall, Foxon and Bolton, 2017; Mazzucato and Semieniuk, 2017, 2018; Polzin, 2017; Mielke, 2019; Naidoo, 2019; Polzin *et al.*, 2019), and on obstacles from adverse market conditions, such as higher costs or rising interest rates that would penalise capital intensive low-carbon technologies (Egli, Steffen and Schmidt, 2018; Halstead *et al.*, 2019; Schmidt *et al.*, 2019).¹² The Schumpeterian lens proposes that the financial disruptions culminating in the 2001 and 2008 financial crises may already have constituted the turning point of the information techno-economic paradigm, so the key challenge is to assimilate IT to enable green growth (Perez, 2013, 2019). In short, the academic literature pays little attention to risks from low-carbon industries. Discussions of "green bubbles" or regulatory loopholes occur mainly outside of academia, e.g. within the central banking community (DNB, 2017).¹³

The ongoing low-carbon transition debate focusses almost exclusively on financial risks from declining industries. The possibility of 'stranded assets' in particular has galvanised attention (Leaton *et al.*, 2013; McGlade and Ekins, 2014). In the context of transition risks, these are sunk investments that rapidly depreciate due to changes in expectations, the regulatory environment and innovation (Caldecott, 2017). Since most industrial operations involve large capital investments, industrial capital (physical capital goods) must operate for at least their accounting lifetime in order to pay back for invested finance and generate a return. If they become stranded, they impact company cash flow and balance sheets, endangering debt

¹² One potential channel for transition risks arising from extensive government support might be the sustainability of government debt, especially in developing countries. However, the relevance and extent of debt sustainability is itself the subject of ongoing controversy (Wyplosz, 2011; Herndon, Ash and Pollin, 2014; Epstein, 2019).

¹³ If anything, academic research has considered the reverse direction of causation, how the recent financial crisis has slowed the progress of the green transition (Geels, 2013; Falcone, Morone and Sica, 2018).

repayment and depressing share prices and the banking system. If enough of such stranding occurs, this clearly constitutes a financial transition risk.

For fossil fuel producers, for instance, the value of investments in fossil fuel extraction depends critically on sufficiently high present and future demand for oil many years in the future, as the average useful lifetime of fossil fuel infrastructure is 40 years (Smith *et al.*, 2019). However, part of existing fossil fuel reserves that companies expect to extract and sell in the coming decades may need to remain underground, given that the carbon budget available to achieve climate mitigation targets is small relative to emissions embodied in reserves (Allen *et al.*, 2009; Meinshausen *et al.*, 2009). In a scenario limiting global warming to 2°C, McGlade and Ekins (2015) estimate that a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves would become 'unburnable' before 2050,¹⁴ and the associated plant, machinery and procuring equipment would become useless. Therefore, with ambitious climate policy, a substantial part of the global existing fossil fuel capital stock could be stranded.

The current transition considers something different from the theoretical literature. There is no new industry with vastly superior productivity. On the contrary, low-carbon industries are close substitutes for existing high-carbon products. At best they are a little cheaper, but so far provide hardly any new services that could excite investors and the general public. When the car replaced railways, it promised much greater individual mobility. Early applications of IT technology revolutionised long-distance communication and photography and movie production and delivery, with progress still ongoing (Brynjolfsson and McAfee, 2014). Current low-carbon technologies lack these advantages. Low-carbon electricity, the most advanced low-carbon substitute, provides hardly any new services compared to high-carbon electricity, on the contrary intermittency can cause a reduction in value as the share of intermittent renewable sources becomes large (Hirth, Ueckerdt and Edenhofer, 2016). Similarly, while electric cars may have a superior acceleration and conversion efficiency, they do not change the concept of mobility unlike the potential of IT to revolutionise transport via driverless cars. The upshot is that if high-carbon sectors were forced today into decline anyway so as to arrest climate change, this would not be buoyed by the bigger wave of a boom in low-carbon that generates so much new activity and profit that the old industry wipe-out can be absorbed in the aggregate. In this way, declining industries pose a more substantial risk for financial stability than in past transitions.

In the next section, we review what "transition drivers" could cause such a forced decline and how it may play out. But it is important to realise that the seeming inapplicability of existing theory to low-carbon transition risks stems from the fact that current low-carbon technologies do not present themselves (yet) as a clustering of superior productivity innovations. If they do, however, as low-carbon industries have been forced into decline and the possible immediate financial repercussions are overcome, the usual warning about rising industry risks applies, and a green bubble may build. In that sense, both rising and declining industry risks may be important.

¹⁴ Due to methane leakage, even more gas reserves than calculated by McGlade and Ekins must remain underground (Hendrick, Cleveland and Phillips, 2017).

A classification of declining industry risks

So far, we have established that mechanisms causing risks for finance from new industries are fairly well understood, but the contrary is true of declining industries. To improve an understanding of possible channels whereby declining industry risks may operate, here we classify them to identify the drivers, costs and impacts and their logical connection via transmission channels (summarised in figure 1). We review evidence for each category as we describe it.

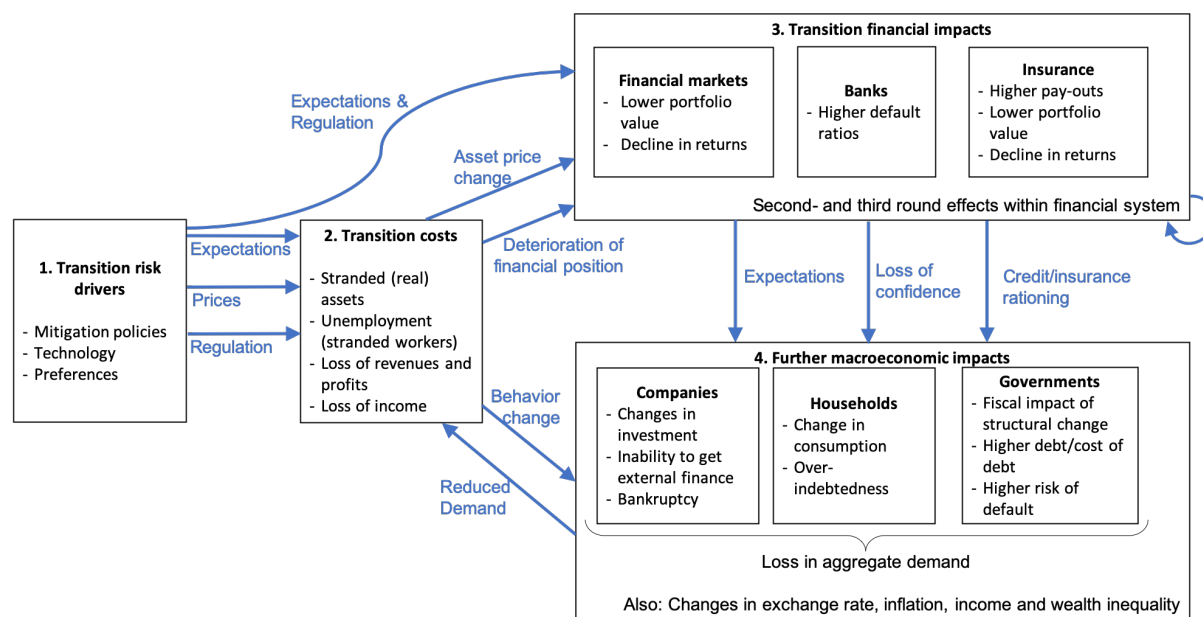


Figure 1: Schematic overview over chain of causation from risk drivers to impacts (black boxes) via transmission channels (blue arrows).

Transition risk drivers

Mitigation policies

The key driver of transition risks is undoubtedly policy. In theory, policy could forbid any emissions of CO₂ immediately and thereby grind the entire economy to a halt. Short of such drastic zero quotas, the central plank of any policy response is a price of carbon either via taxes or cap-and-trade schemes. The suite of scenarios limiting global warming to 1.5°C in the recent IPCC report a median global carbon price of \$91/tCO₂ (metric ton of CO₂) in 2025 and \$179/tCO₂ in 2030, with the interquartile range reaching \$175/tCO₂ and \$361/tCO₂ respectively on all emissions (calculations based on Huppmann *et al.*, 2018). In 2018, only half of CO₂ emissions in G20 and OECD countries were priced at all, and less than 8% at levels at or above \$91/tCO₂ (Kalkuhl *et al.*, 2018). Effective mitigation policies would therefore drastically change prices in the near future. Additionally, regulations may directly affect trade in high carbon products. Ten countries have recently set specific times for bans on new internal combustion engine cars, some as soon as 2030 (Meckling and Nahm, 2019).

In addition, large public investments could change market and incentive structures. Comprehensive policy approaches for 'green growth' in the US (Pollin *et al.*, 2014) or Europe

(Adler, Wargan and Prakash, 2019), and China's recent 5 year plans can be seen as ultimately making low carbon products cheaper by subsidising or carrying out investments and installing enabling infrastructure with the state effectively creating new markets (Block and Keller, 2011; Mazzucato, 2018). Some policies can also directly affect the financial system such as differentiated prudential requirements, lending quotas or targeted refinancing lines by the central bank (Campiglio *et al.*, 2018). However, we believe that policies indirectly impacting finance are likely to play a larger role for transition risks.

Technology

Fast decline in the prices of low-carbon technologies additionally changes price ratios, and can be further accelerated through policy incentives (Gallagher *et al.*, 2012; Kavlak, Mc Nerney and Trancik, 2018). The cheaper a new technology becomes, the more widely it is used, and through scale and learning effects becomes even cheaper, until it emerges as the 'new normal' (Arthur, 1989), altering the technological paradigm (Dosi, 1982). Even without cost differences, the more people use a technology, network externalities may accelerate further adoption (Rogers, 2003; Pettifor, Wilson, Axsen, *et al.*, 2017; Pettifor, Wilson, McCollum, *et al.*, 2017). Structural change between technologies and the change in the ratio of relative demand can thus accelerate over time in a non-linear fashion (Fouquet, 2016; Grubler, Wilson and Nemet, 2016; Sovacool, 2016), which has led to underestimating the rate of adoption of low-carbon technologies (Creutzig *et al.*, 2017).¹⁵

Preferences

Besides factors affecting cost and quantity, buyers' preferences and the public's support for particular products and policies can drive transition risks. For instance, McCollum *et al.* (2018) have simulated scenarios showing that fast adoption of electric vehicles is only feasible with a change in consumer preferences (which implies being willing to pay more for an electric vehicle). Public mobilisation can also operate via reputational channels. The public mobilisation against nuclear fission provides a cautionary story for other technologies (Boudet, 2019). Preference changes can stir political movements that can put broader pressure on policy making and change what is politically feasible.¹⁶ Through their demand-pull effect, preferences can also affect the pace and direction of technological change. In sum, the risk drivers can be mutually reinforcing.

Transition costs

Any combination of the transition drivers identified above is likely to translate into transition costs for firms, households and governments via two transmission channels. The contemporaneous change in relative product prices is self-evident (see also sidebar 1). This leads to adjustments in all sectors, affecting revenues of producers, the real income of households, and state tax revenue (on carbon tax revenue see next section). But the drivers also affect expectations about future revenue streams, if policy and preference changes are credible and long-lasting (Helm, Hepburn and Mash, 2003). For example, some of the car bans discussed above lack credible enforcement mechanisms (Plötz *et al.*, 2019), and current 'nationally determined contributions' under the Paris agreement, are subject to

¹⁵ But see Farmer and Lafond (2016) for data-driven efforts at predicting technological progress.

¹⁶ Of course, this blade cuts both ways. While 'Fridays for Future' and 'Extinction Rebellion' protests of 2019 may make stringent policy more feasible (Horton, 2019), protests may also constrain the rollout of climate policy (Jewell and Cherp, 2020).

implementation (den Elzen *et al.*, 2019; Pauw *et al.*, 2019). But if expectations do change, they cause the most widely discussed casualty of the low-carbon transition: stranded assets.

Sidebar 1 title: The effect of a carbon price on fossil fuel prices

Carbon taxes are likely to have two opposite effects on fossil fuel prices. In the short run, consumer prices will rise, lowering demand, while producers will earn less revenue per unit sold, a typical consequence of a tax increase in a partial equilibrium setting. In the long run, profit opportunities from cheaper low-carbon substitutes could induce an accelerated structural change away from fossil fuels (notably towards renewable electricity as opposed to coal/gas) which could lower prices due to lack of demand. If fossil fuel producers expect demand not to recover in the long run, but to decline further, they might decide to flood the market in the short-run in a race to the bottom, to sell whatever they can. This accelerates the price decline as the lowest cost producers capture what is left of the declining market (Mercure *et al.*, 2018).

Asset stranding

A growing literature analyses high-carbon assets at risk of stranding. The initial focus was on the reserves of fossil fuel companies and their valuation, briefly reviewed in section 4. Recent contributions to this research stream show that widespread deployment of carbon capture and storage could allow 50% more fossil fuels to be burned in the same time period while respecting the carbon budget (Budinis *et al.*, 2018). The inconsistency that arises between the valuation of these resources by fossil fuel companies, and the valuation consistent with climate change mitigation is discussed by Bebbington *et al.* (2019). But stranded assets go beyond reserves, and include any long-lived asset not compliant with a future low-carbon regulatory regime, such as plants, equipment and infrastructure not equipped to function in a high carbon economy. In short, both land and produced capital inputs can strand.

Davis *et al.* (2010) calculate that existing fossil fuel assets in 2009 would emit about 500 Gt of CO₂, or about half the carbon budget then remaining. These assessments have since been refined for fossil electricity assets and show an increasingly slim opportunity for new build non-stranded assets (Davis and Socolow, 2014; Johnson *et al.*, 2015; Pfeiffer *et al.*, 2018). Yet, uncertainty remains: Rozenberg *et al.* (2015) calculate that for a 2°C warming scenario any fossil fuel asset built after 2017 cannot start operating if existing assets are prioritised and the carbon budget is to be respected, while Smith *et al.* (2019) find that current fossil fuel infrastructure does not yet commit the world to warming of 1.5°C. Part of this range arises from the uncertainty about the size of the carbon budget itself (Rogelj *et al.*, 2019).

Asset stranding reaches beyond the fossil energy sector. Considering the relevance of fossil fuels as input factors in mining and manufacturing processes, which then provide crucial intermediate inputs to downstream sectors, stranding of physical assets could take place virtually anywhere in the economy. Cahen-Fourot *et al.* (2019) show how moving away from fossil fuels as input factors could create significant ‘cascades’ of asset stranding across the production network of European economies. In the building sector (including residential housing), retrofitting costs may exceed private returns (Muldoon-Smith and Greenhalgh, 2019). Unruh (2000) coined the term ‘carbon lock-in’.

Less academic research has been conducted on systematically *valuing* the loss of assets due to stranding. Exception are Mercure et al.'s (2018) estimate of \$1tn-\$4tn under various scenarios including the current trajectory of low-carbon technology, and a \$0.957tn of power sector asset stranding until 2050 from a bottom up assessment by Saygin et al. (2019). But one of the most cited works in this area is in the grey literature: for the IEA's 'below 2 degree', Carbon Tracker and PRI estimate one third of business as usual investments into oil and gas, or \$1.6tn, would be stranded in the period 2018-2025 (Carbon Tracker and UNPRI, 2018).¹⁷ Recent stylised models show mechanisms of stranding and policy trade-offs (Rozenberg, Vogt-Schilb and Hallegatte, 2018; Van Der Ploeg and Rezai, 2018; Kalkuhl, Steckel and Edenhofer, 2019). There are also some numerical estimates based on highly stylised models (Monasterolo and Raberto, 2018; van der Ploeg and Rezai, 2019), and precise numerical estimates for specific investors (e.g. Monasterolo, Zheng and Battiston, 2018). None of these studies models the impact of asset stranding on the financial sector.

Other transition costs

Along with asset stranding, workers could also become 'stranded'. Although net aggregate job changes in a rapid transition would be positive even in large-scale fossil fuel producing countries, high-carbon sectors are likely to suffer from significant unemployment (Pollin, 2015; Bastidas and Mc Isaac, 2019). Without stabilising government policy, high cost fossil fuel producers could even lose up to 3% (USA) and 8% (Canada) of employment (Mercure et al. 2018). As reviewed in section 3, transitional unemployment is well documented for structural change.

High-carbon companies (including state-owned ones) would lose revenue due to lower demand for their products from higher prices (induced through carbon prices).¹⁸ Transition drivers would negatively affect the revenues of certain companies or governments, especially those involved in the extraction and distribution of fossil fuels, but also in high-carbon sectors. For instance, Malova and van der Ploeg (2017) calculate that if prices of oil and gas deteriorate due to a lack of demand in line with a 2°C scenario, the Russian government would need to divert an additional 0.9% of GDP in oil revenue a year towards investments outside the fossil energy sector in order to keep the fiscal stance sustainable. Regulations, such as production quotas, may also restrict revenue.

Real incomes of households could shrink due to rising prices, in addition to loss of employment, declining return on investments and transfer payments if government finances are affected. These costs apply unequally. As poor households spend a larger fraction of their incomes on high-carbon products, a carbon tax would be regressive without countervailing redistribution. For the US, Fremstad and Paul (2019) estimate that households in the poorest deciles incur 50% more additional costs as a fraction of their expenditure than households in the highest decile. Strict low-carbon building and appliance regulations, while not 'stranding', may affect the value of residential housing unequally, and disproportionately impact the financial position of households struggling to raise the capital for retrofitting existing houses (Brown, Sorrell and Kivimaa, 2019; Cabrera Serrenho *et al.*, 2019; Schleich, 2019).

¹⁷ Dietz et al. (2016) calculate value at risk from physical risks but implicitly give the value at risk from the transition to be 0.4% of global financial assets, or \$0.6tn.

¹⁸ Note that in the short run, inelastic demand may lead to revenue increases, but this would abate as more substitution possibilities emerge.

Financial impacts

Transition costs can cause two main financial impacts. First, the loss of assets and income are likely to increase default on debt; therefore, banks would likely see their share of non-performing loans grow. Higher ratios of non-performing loans would in turn reduce the profitability of the lending bank, affect its market valuation and, if the phenomenon is significant enough, lead to its default (Dafermos and Nikolaidi, 2019b). The significance of this effect depends on how exposed the banking system is to industries that will have to decline as part of the low-carbon transition (see Vermeulen et al. (2019) and Giuzio et al. (2019) for data concerning Dutch and Euro Zone banks).

Second, institutional investors and other institutions holding financial assets could suffer negative portfolio effects due to the revaluation of assets triggered by the transition process (Campiglio, Monnin and von Jagow, 2019). The transition costs reviewed above, or expectations about their realisation, would induce financial analysts to revise the expected discounted cashflow that carbon-intensive firms will offer in the future, thus leading to a reduction in the current value of financial assets.¹⁹ The revaluation could also take place 'endogenously', as a result of the application of new valuation models by financial analysts. Whoever holds the devalued financial assets will see their wealth diminished.

The impact of the transition on private financial markets could go well beyond the direct exposure of investors to carbon-intensive sectors, due to second-round effects. First, modern financial systems are deeply interconnected. Financial institutions tend to be heavily exposed amongst each other. In particular, many financial assets are used as collateral in short-term repurchase agreements (repos), so any decline in asset prices can cause liquidity problems. This means that a financial institution might be strongly negatively affected by the low-carbon transition even if not directly exposed to carbon-intensive sectors (Battiston *et al.*, 2017). Second, a further decline of asset prices could occur due to fire sales; episodes in which too many companies simultaneously sell off assets to try to pay off excessive debt in order to avoid bankruptcy. This could prompt a vicious cycle of asset price falls and sell-outs, so-called debt-deflation (Fisher, 1932).

The overall effect of such revaluation of financial assets is still unclear, and addressed by a nascent research literature published mostly outside of, or in collaboration with, academia (e.g. HSBC, 2019; Mercer, 2019; UNEP FI, 2019). This tends to offer two types of analytical approaches (Campiglio et al., 2019). First, studies looking at the long term usually project transition scenarios to the future, derive sectoral economic gains/costs, and transform them into changes in financial asset prices. This approach is implicitly based on the representation of the low-carbon transition as a relatively smooth process of reallocation of resources from certain sectors to others, with financial investors placidly following. However, financial sector dynamics are often characterised by sudden changes of 'sentiments' leading to unexpected volatility of prices. PRA (2018) calls the eventuality of fluctuations of the sentiments of investors concerning the likelihood of future transition scenarios a 'climate Minsky moment'.²⁰ In order to grasp these effects, a second research approach uses the 'stress

¹⁹ The extent of current mis-valuation is contested. Byrd and Cooperman (2018) argue coal asset stranding is already priced into investors' expectations, while Silver (2017) avers that stranded asset risk is invisible to institutional investors. Griffin et al. (2015) discuss reasons for the lack of response of investors to news about impending stranded assets.

²⁰ The timing of the change in expectations is contingent on the drivers, but the 2020s were highlighted as the most likely period in which the carbon bubble may burst and carbon risks

testing' conceptual framework to analyse the reaction of asset prices to certain types of shocks (e.g. a change in consumer preferences) and the effect of these changes on the portfolios of financial institutions (Vermeulen *et al.*, 2019).

Further macroeconomic impacts

Transition costs and financial impacts could each trigger further macroeconomic impacts; in particular aggregate demand may fall. This could in turn amplify transition costs and financial impacts, sending the economy into a downward spiral of negative real-financial interactions. We highlight some of the possible channels for demand reductions:

Banking channel. The increase in non-performing loans could lead to credit rationing. Even if the origin of the shock lies in fossil-intensive sectors, credit rationing might affect all sectors irrespective of their carbon intensity. This might translate into higher interest rates, or a quantitative rationing of credit, which would in turn lead to a drop in investment levels of both firms (new capital assets), households (new real estate) and governments (new public infrastructure).

Investment channel. In addition to having limited access to credit, firms might have less appetite for investments if the transition has led to a drop in their market valuation (which might happen also for low-carbon sectors if the crisis is systemic), although the old 'Tobin's q' theory, whereby a low market capitalisation to book value ratio lowers investments, is subject to qualifications (Altissimo *et al.*, 2005; Jovanovic and Rousseau, 2014).

Consumption channel. Reduced income and wealth levels could reduce household consumption levels. Widening income and wealth inequality in combination with stronger credit rationing may additionally impact consumption expenditure negatively, due to higher propensities to consume and inability to smooth consumption of poorer households (Amromin, De Nardi and Schulze, 2018; Jonathan Fisher *et al.*, 2018).

Public debt channel. Government expenditure is likely to initially react positively (counter-cyclically) to the reduction in other expenditure categories due to automatic stabilisers, public support to failing industries, and not least for the bail-out of failing financial institutions. However, higher public debt could translate a lower capacity to spend in the future, especially in countries highly dependent on international credit markets.²¹ A worsening of sovereign credit ratings would also raise corporate cost of capital, as both tend to be related (Kling *et al.*, 2019).

Other macroeconomic effects. The low-carbon transition, especially if implemented in an uncoordinated way at the global level, could lead to changes in inflation, trade balances and exchange rates, which in turn could generate dynamics to re-assess existing international economic agreements (such as on trade). These impacts are, at the moment, very hard to adequately quantify.

The combined effect of these impacts most likely decreases aggregate demand, which in turn could further exacerbate transition costs, and financial impacts. While in principle, rising industry activity could lift the economy, once the negative feedback loop leads to a full-blow credit crunch, rising industry firms may find it hard to finance investment in the short run. The

materialise (UNPRI, 2019; Bond, 2019). Scenarios charting pathways to meet the Paris targets also see global fossil fuel demand peaking in the 2020s (Rogelj *et al.*, 2018).

²¹ The problem of crowding-out would seem less relevant as a crisis-ridden and transforming economy is likely to be far from full capacity (Heim and Mirowski, 1987; Deleidi, Mazzucato and Semieniuk, 2020).

only study that currently attempts to connect transition financial with macroeconomic impacts is Vermeulen et al. (Vermeulen *et al.*, 2018). Of course, many of the channels from finance to real economy and vice versa are explored widely in the macroeconomic literature, so any future modelling efforts can use these as benchmarks.

Summary

Table 1 summarises outputs from the few academic and a select number of central bank studies that report exposure of banks to high-carbon sectors, (row 1,2), and stress tests in the sense that 2nd round effects are traced (3) and feedback to the economy is considered (4). The last two rows show value at risk, and a scenario study for physical risks as a comparison. The studies are difficult to compare, as they use various system boundaries. But it is clear that only looking at direct exposure (1,2) gives much lower values than when tracing second-round effects (3,4), and the latter are in the same order of magnitude. However, one cannot deduce from these numbers how ‘high’ transitions risks are relative to physical risks, as it is unclear just how to compare them quantitatively. But there are good reasons to believe that transition risks are easier to understand and manage: transition risks can be computed directly from economic models, whereas physical risks are likely to do much more damage, including casualties, that cannot easily be quantified economically (Nolt, 2015) and typically rely on speculative damage functions (Farmer *et al.*, 2015). Transition risks are also controllable in that they involve fewer poorly understood tipping points in the global economy (Lenton *et al.*, 2019). Moreover, transitions risks are short-term. If the transition is successful, they are ‘one time’ so they should be less difficult to take into account for policy making. Lastly, while transitions risks are likely to be net negative in the short run, there is an upside of new industries rising instead of the old ones.

That said, modelling the global economy including the financial sector is fiendishly complicated, and requires additional research. For instance, none of the transition studies in Table 1 has a sophisticated generator of stranded assets, and only Vermeulen et al. (2018) attempt to model feedback effects into the real economy for a single country. Similarly, the otherwise very detailed and advanced assessment scenarios reported in the IPCC reports do not yet include transition risks as modifying the costs of mitigation: an integrated analysis of the macroeconomy and finance is not yet in the literature (Farmer *et al.*, 2015). Here, more theoretical clarity and stylised facts about declining sector risks would help assess and interpret numerical results generated by large models.

Table 1: Estimates of potential maximal financial exposure to transition risks, and comparison with physical impact estimates

#	Region & Channel	Channel	Scenario (with value in parentheses as a share of regional GDP)
1	Giuzio et al. (2019)	1 st round exposure of 40 European banks	Exposure to 20 largest emitting firms amounts to 1.8% of 40 banks’ assets (---)
2	Nieto (2019)	Outstanding syndicated loans in China, Europe, Japan, Switzerland, USA to high environmental risk	Outstanding loans amount to 1.6 trillion 2014 USD (3.1% of GDP of selected countries)

3	Battiston et al. (2017)	1 st & 2 nd round exposure of top 50 EU banks to high-carbon assets	100% loss of fossil fuel & utility sector portfolio wipes out 13.5% of top 50 banks' equity (32.7% of European Union GDP)
4	Vermeulen et al. (2018)	1 st & 2 nd round impacts on portfolios of 80 Dutch financial institutions	Loss of up to 0.16 trillion 2018 EUR when combining technology and policy shocks (up to 18% of Dutch GDP)
5	Dietz et al. (2016)	Global assets at risk under DICE BAU vs mitigation scenario	99th percentile of total assets at risk amounts to 24.2 trillion 2013 USD (31.5% of global GDP)
6	Lamperti et al. (2019)	Global bank failures from physical risks	Additional government expenditure needed to rescue banks (5-15% of global GDP)

Note: Where possible, the comparison with GDP was calculated by using regional GDP figures in current national currency or USD from the IMF.

Policy responses

Costs and impacts are subject to policy attempting to prevent them. It is useful to distinguish policy aiming directly at financial sector impacts, implemented by financial regulators, from more indirect policies.

Policies directed at the financial sector

Following the 2008 financial crisis, central banks and financial supervisors have intensified efforts to strengthen financial regulation and identify systemic financial risks in order to mitigate these. Central banks in particular were subject to an intensive discourse on their role in safeguarding financial stability, and their mandate more broadly (G30, 2015; Volz, 2017; Dikau and Volz, 2020). Building on early academic contributions on the role of financial governance in addressing climate-related financial risks (Campiglio, 2016; Volz, 2017), since 2016 monetary and financial authorities have started to include climate change among these systemic risks and consider adequate policy responses to mitigate these.²² Most attention has been devoted to the risk of abrupt changes in asset valuations due to stranded assets. Hence, much of the discussion on policy responses has centred around ways to mitigate declining sector risk. Growing attention is now also being paid to impacts on sovereign risks and how these can be mitigated (Buhr *et al.*, 2018; Kling *et al.*, 2018; Battiston and Monasterolo, 2019). There has also been a discussion on the role of financial policies in scaling up investment in green activities, such as green supporting factors in financial regulation or green asset purchases by central banks (e.g. Vaze, Meng and Giuliani, 2019). This discourse has largely ignored potential risks from rising industries. Moreover, much policy discussion looks at physical and transition risks jointly.

Regulatory responses are mainly preventive in that they aim at providing information and incentivise the move away from high-carbon assets, so that any future transition driver has less impact. They include suggestions for enhancing transparency through taxonomies of

²² See, for instance, Batten et al. (2016), ESRB (2016), Finansinspektionen (2016), Regelink et al. (2017), PRA (2018) and NGFS (2019).

“green” and “brown” assets and a (mandatory) disclosure of risks (Volz *et al.*, 2015; HLEG 2018), climate-related stress testing at both micro and macro prudential level, and climate calibrated capital rules or collateral frameworks.²³ Initially, the focus was on a disclosure of financial risks from climate change, which would help firms manage, and financial markets price in these risks and thus avoid rapid revaluation. In January 2016, the Financial Stability Board established a Task Force on Climate-related Financial Disclosures (TCFD). In its report in 2017, the TCFD makes recommendations on disclosures at the firm level (TCFD, 2017). Risks that are thus disclosed can then be assessed under different scenarios of the future (see also section 5.3), and firms can use these for risk management (TCFD, 2016; Berg *et al.*, 2018). The financial sector is to use the disclosures for adequate pricing. There have also been proposals for introducing risk differentials in financial regulation, i.e. high-carbon penalising or low-carbon supporting factors (Dafermos and Nikolaidi, 2019a).

The current thinking of policy makers is captured in the work of the Central Banks and Supervisors Network for Greening the Financial System (NGFS), a group of more than 50 central banks and supervisors, established at the Paris One Planet Summit in December 2017. In April 2019, the NGFS (2019a) put forward a high-level framework for the integration of climate-related factors into prudential supervision, comprising five elements. According to this framework, the first step is to raise awareness of climate-related risks and build capacity amongst firms to analyse their exposure. The second step is the assessment of climate risks at both the micro and macro prudential level, i.e. at the level of individual financial institutions and the financial system as a whole. Examples include the assessment of financial institutions’ exposure to high-carbon sectors, or possible impacts of tightening energy efficiency regulation on the valuation of energy inefficient homes. Climate-related stress tests could be conducted at the level of financial institutions and of the system at large.

The third step is to provide guidance to regulated firms on appropriate approaches to governance, strategy and risk management to mitigate climate-related risks. Step four is about climate-related disclosures to enhance transparency and promote market discipline. This may include an integration of climate-related disclosure requirements in line with the TCFD recommendations into Pillar 3 of the Basel III banking regulations. The fifth and final step is to consider additional capital charges related to climate risks. This could include an integration of climate-related capital surcharges into the minimum capital requirements under Pillar 1 of the Basel III regulatory framework, or special capital requirements for firms that exhibit higher risk concentration in their balance sheet or that do not comply with supervisory expectations under Pillar 2.

Existing policy has been criticised by academic studies as inadequate. For instance, Ameli *et al.* (2019) argue, based on interviews with investors, that disclosure by itself is insufficient to change investment behaviour, as the argument rests on the unrealistic efficient market hypothesis (that financial market price in all information). Monasterolo *et al.* (2017) note the difficulty of disclosing supply-chain carbon exposure, and D’Orazio and Popoyan (2019) show that high-income countries are lagging behind others in macroprudential policy implementation. These sentiments are reflected in the IPCC’s recent assessment that effective mitigation would require an evolution of the global financial system (de Coninck *et al.*, 2018). Against this, some central bankers have, while acknowledging their role as financial regulators by enhancing transparency and stress testing, insisted that central banks

²³ For an overview of policy tools available to central banks and supervisors see Dikau and Volz (2019).

ought to adhere to the principle of market neutrality in the conduct of monetary policy and not favour green assets over brown (Weidmann, 2019). Proposals for risk differentials in financial regulation or collateral policies, and any activist policies aimed at incentivising green fostering a green transition, have been controversial (Dikau and Volz, 2019).

Wider policy landscape

Dealing with the entire set of costs and impacts outlined in section 5 of course draws on the entire palette of economic stabilisation policy, especially macro-development policy (Ocampo, Rada and Taylor, 2009). Two policy tools analysed in the recent literature that aim to mitigate specific transition costs are briefly highlighted.

Directed (private and public) investment into low-carbon industries could help reduce transition risks by diverting new projects away from declining industries (Mazzucato and Semieniuk, 2017). One vehicle are public banks, multilateral development banks and development finance institutions (Griffith-Jones and Ocampo, 2018). Often equipped with an explicit mandate to promote environmental sustainability and “green growth”, development banks’ primary motivation is not the maximisation of returns (Geddes, Schmidt and Steffen, 2018). This enables them to take on a higher level of risk and (co-)finance projects that may otherwise not get funded by commercial banks (Mazzucato and Penna, 2016). As such, they could smoothen economy-wide structural change by mobilising investment into rising industries, especially in declining industry dominated areas with opportunities of reconversion investments.²⁴ In practice development banks have been pursuing low-carbon investments to different extents (Steffen and Schmidt, 2018). These directed investments could be coupled with an eponymous just transition program for fossil fuel sector employees with reemployment or pension guarantees, amounting to modest costs compared to overall low-carbon investment needs (Pollin and Callaci, 2018). Public initiatives are supposed to draw in private funds by ‘de-risking’ investments. One weakness of this strategy is that the risk does not disappear but is transferred to the public sector. This riskiness limits the applicability of derisking without the state also sharing appropriately in the rewards of investments, especially for budget constrained governments of low- and middle-income countries (Mazzucato *et al.*, 2018).

Government revenue from carbon taxes or auctioned-off emission permits can be used as a tool to mitigate transition costs for households. This tax and dividend or ‘feebate’ redistributes the revenue earned from a carbon price equally or even more progressively among citizens and since richer households spend more in absolute terms, feebates turn carbon prices into a progressive instrument (Boyce, 2018, 2019). Experimental evidence shows that using revenues for public good provision improves acceptance of carbon taxes (Beiser-McGrath and Bernauer, 2019), and the carbon taxes in Canadian provinces have received more acceptance *after* they had been implemented with revenue recycling (Murray and Rivers, 2015). Government revenue could also be used to maintain minimum company solvency during the transition (Caldecott and Dericks, 2018).

Conclusion

Low-carbon transition risks for finance are likely to be generated mainly from major and rapid changes in policy, but also from technology and preferences and their interaction with each

²⁴ An example of reconversion finance is the European Investment Bank’s co-financing of the reconversion of coal mines in regions with a challenging transition path via a Just Transition Fund.

other. In this review we established that the low-carbon transition is different from past transitions, where speculation with financial assets of the new rising industries of superior productivity regularly created destabilising financial risks. In the present transition, the risks come primarily from financial assets in declining, high-carbon industries. Their current valuation is only justified under continued carbon-intensive production trajectories, just as their debts can only be repaid under such trajectories. However, with rapid structural change away from high-carbon and towards low-carbon sectors, the underlying physical assets lose their ability to generate revenue. Asset stranding combines with other transition costs, notably unemployment, losses in revenue, profits and reductions in real incomes that generate significant risks for portfolio losses and debt default. Financial actors might become unable to service their own debts and obligations, creating important second- and third-round effects. The adverse impact of credit tightening and lack of confidence as well as the direct impact of transition costs on the macroeconomy, could lead to a general economic crisis with further risks for finance. None of this suggests that financial markets would be better off without or with a limited transition: financial sector exposure to physical risks under unmitigated climate change would be high and, unlike transitional risks of a policy change, this exposure would be 'here to stay'. Policy can mitigate some transition risks by direct regulation of the financial sector, as well as intervention at the transition cost stage.

The current academic research on these topics works out either the transition costs, or the financial impact, but does not yet connect the two, and no readily available framework for theorising this connection exists. Past literature has only identified rising (i.e. low-carbon) sectors as posing risks to the financial system and worked on stylised facts for these. What the current transition needs is a set of theoretical propositions and stylized facts about the link between fast depreciation and financial impact. These could be implemented in multi-sectoral models with a financial sector, of which there are already several. Putting together real and financial economic mechanisms would allow exploring the whole set of interlinked parts of transition drivers, costs and impacts to arrive at benchmarks both of losses and effects of policy measures. Such research could inform calculations of integrated assessment models that already calculate other costs of mitigation, but not those of transition risks. An important insight from existing theory on financial risks of transition is that once policy has established the higher productivity and thereby new profit opportunities in low-carbon industries, the potential for financial trouble also starts lurking there.

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