

Low-carbon transition risks for finance

Gregor Semieniuk, Emanuele Campiglio, Jean-Francois Mercure,
Ulrich Volz and Neil R. Edwards

Working paper

No. 233

March 2020

The SOAS Department of Economics Working Paper Series is published electronically by SOAS University of London.

ISSN 1753 – 5816

This and other papers can be downloaded free of charge from:

SOAS Department of Economics Working Paper Series at
<http://www.soas.ac.uk/economics/research/workingpapers/>

Research Papers in Economics (RePEc) electronic library at
<https://ideas.repec.org/s/soa/wpaper.html>

Suggested citation

Semieniuk, Gregor, Emanuele Campiglio, Jean-Francois Mercure, Ulrich Volz and Neil R. Edwards (2020), “Low-carbon transition risks for finance”, SOAS Department of Economics Working Paper No. 233, London: SOAS University of London.

Department of Economics
SOAS University of London
Thornhaugh Street, Russell Square, London WC1H 0XG, UK
Phone: + 44 (0)20 7898 4730
Fax: 020 7898 4759
E-mail: economics@soas.ac.uk
<http://www.soas.ac.uk/economics/>

© Copyright is held by the author(s) of each working paper.

Low-carbon transition risks for finance

Gregor Semieniuk^{*}

Emanuele Campiglio[†]

Jean-Francois Mercure[‡]

Ulrich Volz[§]

Neil R. Edwards^{**}

Abstract

The transition to a low-carbon economy will entail a large-scale structural change. Some industries will have to expand their relative economic weight, while other industries, especially those directly linked to fossil fuel production and consumption, will have to decline. Such a systemic shift may have major repercussions on the stability of financial systems, via abrupt asset revaluations, defaults on debt and the creation of bubbles. Studies on previous industrial transitions have shed light on the financial transition risks originating from rapidly rising ‘sunrise’ industries. In contrast, we argue here, based on a critical review of the literature, that a comprehensive theoretical framework to analyse how declining ‘sunset’ industries might affect financial stability in the current low-carbon transition, via stranded assets or otherwise, is still lacking. We contribute to filling this research gap by developing a consistent theoretical framework of the drivers, transmission channels and impacts of the phase-out of carbon-intensive industries on the financial system as well as its feedback into the rest of the economy.

Keywords: Transition risks, low-carbon economy, sunset industries, stranded assets, financial stability, structural change

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

Acknowledgements: The authors thank Yannis Dafermos, Duncan Foley, Roger Fouquet, Carol Heim, Thomas Herndon, Kate Jobson, David Kotz, Carlota Perez, Edo Schets and Isabella Weber for helpful feedback and comments. Remaining errors are solely the authors’.

GS, JM and NE acknowledge funding from Natural Environment Research Council Grant NE/S017119/1 “Financial risk and the impact of climate change”. EC acknowledges the

^{*} Political Economy Research Institute & Department of Economics, University of Massachusetts; Department of Economics, SOAS University of London. gsemieniuk@umass.edu

[†] Institute of Ecological Economics, Vienna University of Economics and Business, emanuele.campiglio@wu.ac.at

[‡] Department of Geography, University of Exeter, J.Mercure@exeter.ac.uk

[§] SOAS Centre for Sustainable Finance & Department of Economics, SOAS University of London; German Development Institute, uv1@soas.ac.uk

^{**} Environment, Earth and Ecosystems, The Open University, UK, neil.edwards@open.ac.uk

financial support of the Swedish Foundation for Strategic Environmental Research (Mistra) and the Oesterreichische Nationalbank (OeNB).

Introduction

Climate-change mitigation requires the rapid decarbonisation of the economy. Climate change is already threatening society through altered patterns of extreme weather events and impacts on critical ecosystems, and the best climate projections to date indicate that catastrophic impacts could arise in the near future from nonlinear effects leading to ‘tipping-points’ in the Earth system, such as the collapse of ice sheets or tropical rainforests (Lenton et al., 2008). The 2015 Paris agreement enshrines the need to avoid such consequences with a goal of stabilizing temperature increases well below 2°C above pre-industrial levels, with the aim of limiting negative climate change impacts at manageable levels, although substantial climate variability would still remain (Holden et al., 2018). To avoid warming of the global average temperature exceeding 1.5°C, evidence gathered by the Intergovernmental Panel on Climate Change suggests that decreasing net carbon emissions to zero by mid-century is likely to be necessary (IPCC, 2018). Consequently, governments and sub-national entities have started adopting laws requiring carbon neutrality by or before mid-century.

Decarbonising the economy quickly is not trivial. It will involve large-scale structural change, with some sectors having to rapidly expand their relative production/market shares, and others having to entirely transform their technological basis or, alternatively, shrink and potentially disappear. This last category of sectors comprises activities directly related to the extraction and distribution of fossil fuels, but also, and perhaps most importantly because it implicates a far larger proportion of the economy, sectors producing goods and services using fossil fuels as a crucial input in their production process. In some cases, such as power production, a low-carbon alternative is available that is increasingly competitive with the incumbent (Lazard, 2019). Increasing electrification of end-use technologies, such as passenger transport, also points towards promising paths for decarbonisation (IEA, 2019). But in other industries, such as steel or air travel, development is only at an early stage, and a significant proportion of firms still lack a strategic plan to face the low-carbon transition (Dietz et al., 2020).

A fast transformation of economic structure is likely to have significant financial impacts. A lively debate has been developing around the threats of a low-carbon transition for the stability of financial institutions, and for the financial system as a whole, with central banks occupying a prominent position. While there has been a rapid expansion of concepts and evidence concerning transition risks from academia, private industry and regulators (Bolton, Despres, Pereira Da Silva, Samama, & Svartzman, 2020; NGFS, 2019), a comprehensive theoretical framework linking the low-carbon structural change to financial dynamics is still missing. It is not yet clear what the risk drivers, sectoral origins and transmission channels will be, or how their effects will propagate to the wider macroeconomy.

The aim of this paper is to shed some light on how risks for financial stability relate to the transition’s underlying structural change. First, we survey the literature for insights on the general links between structural change and finance. The low-carbon transition is certainly not the first systemic technological shift in recent history, and several authors have discussed the issue of how these paradigm shifts are linked to finance (Freeman & Louca, 2001; Perez, 1983; Schumpeter, 1939). We find that the overwhelming majority of this literature has focused on the financial risks stemming from the sunrise industries, i.e. the rising sectors, where bubbles could develop and then burst, with detrimental impacts on the rest of society.

Turning to the low-carbon transition, we notice how, contrary to this historical perspective, most of the current debate on transition-related financial risks focuses on the risks raised by sunset industries (carbon-intensive ones, in this case). For instance, a widespread preoccupation concerns the financial repercussions of asset stranding, i.e. the devaluation or write-off of assets from the balance sheets of economic agents (Caldecott, 2018; van der Ploeg & Rezai, 2019). We argue that this difference is likely because the transition has not yet advanced far enough for low-carbon investment opportunities to be able to stabilize the financial system, while climate-change mitigation policy remains focused on attempts to accelerate the phase-out of high carbon sectors. Be that as it may, the ‘focus shift’ between past literature on transitions and the current debate leaves us without a well-defined comprehensive framework to understand and address low-carbon transition financial risks.

To advance the debate and contribute to filling this conceptual gap, we develop a minimal but consistent framework of low-carbon risks for finance originating in sunset industries. We distinguish: i) drivers of transition risks; ii) the economic costs that the transition could impose on non-financial agents in terms of loss of income and asset stranding; iii) the impacts that these costs would create on financial institutions and financial stability, in terms of non-performing loans, loss in portfolio values and higher expenditures; and iv) the wider macroeconomic effects leading to a loss of aggregate demand and recession. Finally, we outline and comment on the current state of policies seeking to stabilize the financial system without interfering with the transition itself pursued by central banks and other actors in the fast-evolving policy community on climate-related financial risks.

The remainder of the article is organised as follows. Section 2 discusses the economic literature linking structural change, innovation and finance. Section 3 focuses on the ongoing debate around the risks of a low-carbon transition. Section 4 presents our conceptual framework on transition risks for finance originating in sunset industries. Section 5 discusses actual and possible policies aimed at mitigating transition risks. Section 6 concludes.

Threats to financial stability from the rise and fall of industries

For the purposes of analysing transition risks to finance, we define the low-carbon transition as structural economic change: some parts of the economy grow and others decline in relative importance, as a result of deliberate policy, changing preferences and ongoing technological change.¹ To meet emissions-reduction targets, low-carbon sunrise industries must grow rapidly, while high-carbon sunset industries must decline rapidly. This process can precipitate and interact with other structural changes in the economy (Ciarli & Savona, 2019). Low-carbon transition risks for finance can then be defined as the threat to financial stability from this specific type of (rapid) structural change. For a conceptual understanding of this process, we turn to the literatures on financial crises and on innovation as the process underlying structural change.

Finance and innovation: A neglected subfield

At the outset, it is important to note the relative conceptual neglect of the problem. Scholars studying financial crises rarely venture into the details of technological change, but focus on aggregate fluctuations. Kindleberger (1978), the classic reference on historical financial crises, eschews the details of the technical change that underlies several of his documented

¹ Cherp et al. (2018) show that for other purposes adopting a more multi-disciplinary definition can be productive.

financial *manias*. The only technological change Reinhart and Rogoff (2009) refer to is the *financial* innovation of changing from coin to paper money. Similarly, innovation scholarship, which studies structural change due to technological and behavioural change, tends to omit systemic financial aspects; recent exceptions are Callegari (2018) and Geddes and Schmidt (2018). Even students of 'financing innovation' tend to adopt a microeconomic perspective on how market failures prevent a small set of innovative firms from getting enough funding (Hall & Lerner, 2010), but neglect innovation's interaction with financial stability. If anything, research in this area considers the opposite direction of causation, i.e. how the 2007-08 financial crisis and subsequent stimuli have affected innovation (Giebel & Kraft, 2019; Mundaca & Richter, 2015).

Multisectoral theories of technological change lie in the small intersection of both fields. 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). Marx's differentiation of the economy into sectors producing capital and consumption goods (departments 1 and 2) allows for both underconsumption (Sweezy, 1970) or over-investment (Brenner, 2006) to generate a crisis. But existing Marxist literature tends to disregard industries *within* departments: both low-carbon and high-carbon industries are subsumed in each department.

More recent real business cycle theory explains (negative) shocks through technological change also in multi-sectoral settings (Davis, 1987). But technology shocks are typically random, not linked to secularly declining or rising industries (Azariadis & Kaas, 2016). Moreover, integrating a meaningful financial sector into these models would require major changes to the theoretical framework (Stiglitz, 2014). The only theoretical framework placing the interaction of finance and structural change front and centre appears to be the Schumpeterian one.²

The Schumpeterian perspective

In the Schumpeterian theory of the business cycle, innovative agents (entrepreneurs) create new clusters of vastly more productive technologies, collectively cause socio-technical transitions, and generate structural change through 'creative destruction' of less competitive products and industries.³ Examples where this theory applies include railway transport and steam shipping, based on steam engine diffusion, replacing canal and sailing ship transport in the second half of the 19th century; the internal combustion engine based on oil displacing steam-powered transport in the early 20th century (Freeman & Perez, 1988); or more recently electronics revolutionizing data processing (Mowery & Rosenberg, 1998).

The financial sector and specifically banks play a crucial role in enabling entrepreneurs to finance their new enterprises by creating credit (Schumpeter, 1939). Only with the support of financial institutions can entrepreneurs acquire the resources for executing their innovative plans and creating sunrise industries. While the credit creation function of banks is key to innovation and leads to output expansion in a 'primary wave', the increasingly profitable sunrise industries become objects of financial speculation. This 'secondary wave' of the business cycle carries the risk of overestimating sunrise industries' growth potential (Schumpeter 1939, p. 147). Over-indebtedness and defaults can result from the exhaustion of an innovation cluster, and generate a financial crisis. One instance that this theory can

² Hayek (1931), like Marxist authors, only distinguishes consumption and capital goods sectors.

³ Reinert (2002) and Hagemann (2003) discuss important theoretical influences on Schumpeter's thinking.

explain is the 1929 financial crisis, which involved a bubble in radio, electricity, airplanes, automobile and petrochemical industries (Freeman & Louca, 2001). Similarly, the 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 2001 'dotcom' bubble burst even carries a sunrise industry's name. In practice, the distinction between speculative and conventional investment may be partly artificial, the key being a miscalculation of risk that is only revealed retrospectively. Nevertheless, these examples illustrate the link between structural change and transition risks for the financial sector.

In Schumpeter's theory the origin of these risks lies in sunrise industries. Uncertainty about what technological design will ultimately prevail and about the scale at which the growing industry saturates, creates the potential for speculation and over-investment that have been characterized as 'manias' (Kindleberger, 1978) and 'irrational exuberance' (Shiller, 2001). Once the bubble bursts, and the financial crisis starts, it can be exacerbated by the failure of financially unstable sunset firms. However, the theory largely ignores the contribution of sunset industries to the *onset* of financial instability, and Schumpeter explicitly states that the negative effects of bankruptcy and decline in the sunset industries is overcompensated by the growth in the new industries (Schumpeter 1939, p. 134-5). In other words, as long as a strong sunrise sector exists, systemic economic and financial stability are not compromised by a failing sunset sector, even though sunset capital owners lose out and periods of 'structural crises of adjustment' spell unemployment and decline in living standards for a significant share of the population (Freeman & Louca, 2001). A recent example that is also relevant to the low-carbon transition is the layoffs and declines in living-standards in coal-mining communities catalysing demands for a 'just transition' (Rosemberg, 2010).

Subsequent work by Schumpeterian scholars emphasises the important role of government policy and social change in the assimilation of new technologies, which was assumed to happen automatically by Schumpeter (Freeman & Louca, 2001; Perez, 1983). The role of finance in these technological revolutions that change the 'techno-economic paradigm' is developed by Carlota Perez (2002). Her work highlights how the aftermath of the financial collapse that marks the end of the initial speculation with sunrise industry reveals the social problems resulting from the changes and generates anger, revolt and populism. A new set of regulations and institutions are needed at this turning point to establish a direction for innovation and investment, spreading the new technologies in socially beneficial ways.⁴ An important take-home message from this literature is the role of government in regulating and managing economic instability arising from structural change.

Technology-based financial instability can also be seen as a 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 (recent discussions include Nikolaidi & Stockhammer, 2017; Taylor, 2012). 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.

Risks associated with sunset industries

⁴ 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).

To the best of our knowledge, to date there is little theory that explains financial instability caused by sunset industries.⁵ The Schumpeterian literature locates the crisis mechanism in the sunrise industries, while the contribution to financial risks from declining industries is left largely unexplored. Caiani et al. (2014) show that systemic risk from sunset industries can be shown mathematically to cause economic distress, but more theoretical effort is needed to determine under what conditions asset scrapping can trigger a financial crisis.

A theoretical literature from the 1930s and 1940s discusses the microeconomic problem of 'premature abandonment', an earlier term for asset stranding (Caplan, 1940). 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 (see e.g. Benhabib & Hovijn, 2003; Eisner, 1972). A neo-Schumpeterian vintage capital model allows for costly reallocation of factors of production between industries, but has not analysed under what conditions such reallocation could destabilize the financial system (Caballero & Hammour, 1996).

Institutional economic history of the secular decline of the British economy offers a different lens on the contribution of sunset industries to 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 focus of this literature is again on the reverse causal direction, namely to investigate how the nature of the British financial system influenced British manufacturing industries' decline, not how decline conditioned financial instability (Best & Humphries, 1984; Higgins & Toms, 2003).

In summary, economic theorists and historians have identified sunrise industry speculation as the trigger of financial crises, but have not substantially investigated systemic risks originating in sunset industries, even though the latter may contribute to the severity of the crisis once it is unleashed. Our conceptual review offers an important insight for the current low-carbon transition. An industry with declining demand generates losses for its owners, unemployment for its employees, and quite possibly a default on its loans. However, theory suggests this is not enough to destabilise the economy and induce systemic financial instability. The underlying logic argues that while some companies and even financial institution go under, the financial system as a whole is diversified and profitable enough to weather this shock thanks to the dynamic sunrise industries. It is only when the sunrise industries mature, and a bubble in their financial assets pops, that theory predicts the onset of crisis.

Low-carbon transition risks from sunset industries

In contrast with what has just been reviewed, the current debate on the low-carbon transition has so far focused on financial risk from sunset industries. The simple reason is that in order to achieve the Paris agreement targets, lots of currently productive enterprises have to radically alter their production. In particular, a good share of the emissions from currently known fossil fuel reserves must be suppressed (Carbon Tracker, 2013; Meinshausen et al.,

⁵ Szostack's (1995) analysis of the Great Depression goes into detail about sunset industries but does not link to financial stability.

2009). The cash flow of industries supplying or using fossil fuels would be impacted. If this impact is unanticipated by investors, their assets would prematurely depreciate or ‘strand’ (Caldecott, 2018) and if the stranding is widespread enough, it could lead to a financial instability and crisis (Monasterolo, 2020; van der Ploeg & Rezai, 2019).

Consideration of sunrise industry risks, on the other hand, is absent from the debate. While observer bias and timing may help explain some of this neglect (for instance, before the 2007-8 crash few commentators pointed to a looming housing crisis), there is also some hard evidence to cite: Investment in low-carbon technologies has been increasing in recent decades, but they are still far away from the scale necessary to compensate for the phase-out of fossil-based technologies under a 1.5°C scenario (CPI, 2019; McCollum et al., 2018; Semieniuk & Mazzucato, 2019). Nor are the investments yet vastly more profitable – support policies have so far been required to attract private investors even in the advanced power supply sector (Mazzucato & Semieniuk, 2018; Polzin, Egli, Steffen, & Schmidt, 2019). Of course, the fast market capitalization growth in some low-carbon companies such as Ørsted, market leader in offshore wind projects, or Tesla, an electric car maker, are examples of (so far) successful sunrise companies to point to (Financial Times, 2020a, 2020b). And there have already been instances of initially hyped low-carbon companies collapsing just as if their potential had been overestimated by Schumpeterian ‘speculators’, including photovoltaic cell makers Solarworld in Germany and Solyndra in the US. However, these instances hardly triggered systemic financial instability, just as the burst of the YieldCo bubble in the US in 2015 (share prices dropped 60%) did not destabilize wider stock markets (CPI, 2016). In short, at this moment, there does not yet seem to be a general ‘mania’ in the low-carbon sunrise industries.

The timeline and scale of structural change implied by proposed climate-change mitigation then appears to make this transition different. The aim is to correct an externality using deliberate policy intervention (Foley, 2009; Nordhaus, 2013), rather than to let a more or less evolutionary trajectory guide the transition. Past theory does caution that, if the transition is managed well and innovation in low-carbon technologies is fast, then the world might soon find itself in the ‘typical’ situation whereby there are fast-growing low-carbon sunrise industries, that pose the risk of a ‘green bubble’.⁶ However, the current debate suggests that such a sunrise industry-induced financial instability, if it materialises, may be preceded by systemic risks realised in sunset industries.

A model and classification of low-carbon transition 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, 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.

⁶ Discussions of green bubbles have to date taken place mainly outside academia, e.g. in central banking circles (DNB, 2017). If anything, academic research has considered the reverse direction of causation, how the recent financial crisis has slowed the progress of the green transition (Falcone, Morone, & Sica, 2018; Geels, 2013).

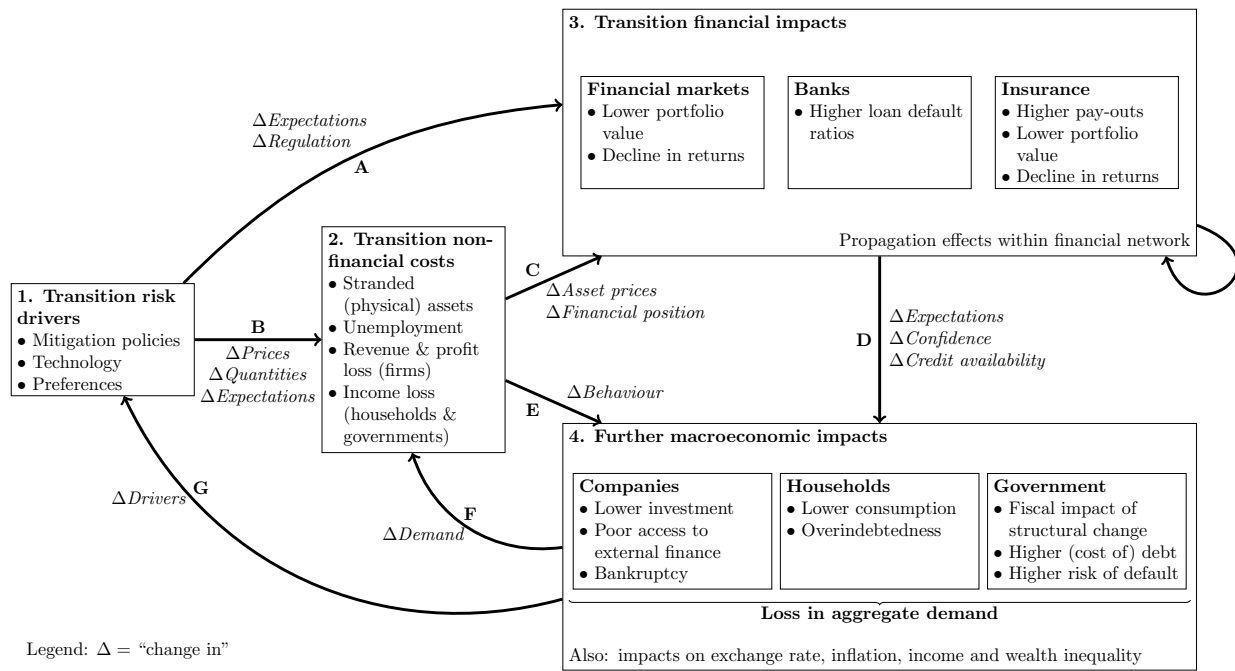


Figure 1: Schematic view of chain of causation from risk drivers to impacts (boxes) via transmission channels (arrows).

Transition risk drivers

Transition risk drivers (Figure 1, box 1) can be conceptualised as changing relative prices or market demand/supply in favour of low-carbon goods and services, either immediately or over time. In the latter case, expectations about future changes may still create risks in the present (van der Ploeg & Rezai, 2020). Hence, Figure 1 can be read both as the potential unfolding of actual transition impacts and as a mental map of expected future impacts of transition drivers. Key drivers are climate change mitigation policy, technological change and changes in consumer taste (PRA, 2015). These are reviewed in turn below.

Climate change mitigation policies

Policy seeking to internalise the carbon externality is a key driver of risks. The central plank of most climate change mitigation strategies consists of incentive-based regulation that generates a carbon price either via taxes or cap-and-trade schemes. The suite of scenarios limiting global warming to 1.5°C in the recent IPCC report reports a median global carbon price of \$91/tCO₂ (metric ton of CO₂) in 2025 and \$179/tCO₂ in 2030, with the interquartile range reaching up to \$175/tCO₂ and \$361/tCO₂ respectively (calculations based on Huppmann et al., 2018). In April 2019, only 20% of global greenhouse gas emissions were priced at all, and less than 5% of these were in line with Paris Agreement compatible levels (World Bank, 2019). Effective mitigation policies could therefore drastically increase industry and consumer prices for high-carbon products in the near future. Regulation may also directly limit the sale of high-carbon products. Ten countries have recently set specific times for bans on new internal combustion engine cars, some as soon as 2030 (Meckling & Nahm, 2019).

In addition, public subsidies, regulations and investments help lower prices of low-carbon products. Comprehensive policy approaches for 'green growth' such as China's 13th 5-year plan (National Development and Reform Commission, 2016) or Europe's Green Deal

(European Commission, 2019), include mandating, subsidising or directly carrying out investments into low-carbon products and installing enabling infrastructure. This makes low-carbon products more competitive by creating markets, financing and helping innovation proceed at pace or simply altering prices directly (Block & Keller, 2011; Mazzucato & Semieniuk, 2017). Some policies can also directly affect the financial system such as differentiated prudential requirements, lending quotas or targeted refinancing lines by the central bank, indicated by arrow A in Figure 1, or alter the financial sector's expectations (Volz, 2017; Campiglio *et al.*, 2018). It is important not to confuse the policy here seeking to accelerate the transition (mitigation policy) with policy aimed at stabilizing the financial system, which we review in the next section.

Technological change

Cost-saving technological innovations, possibly incentivised by earlier climate policies, further lower the prices of low-carbon technologies (Kavlak, McNerney, & Trancik, 2018; Nemet, 2019). This is a non-linear process often approximated by s-curves of adoption. (Rogers, 2003). 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). Structural change between technologies and the change in the ratio of relative demand can thus accelerate over time, which has led to underestimating the rate of adoption of low-carbon technologies (Creutzig *et al.*, 2017). Since technology diffusion self-reinforces and evolves endogenously, once set in train, it can contribute substantially to price changes even without any new policy changes. As a new socio-technical regime gradually establishes itself, it requires decreasing amounts of external support to diffuse further (Geels, 2002).

Preference change

Buyers' preferences and the public's support for particular products and policies can drive demand and prices. Preferences are endogenous to institutions and their changes (Bowles, 1998) and the more people use a technology, network externalities may accelerate further adoption (McShane, Bradlow, & Berger, 2012; Pettifor, Wilson, Axsen, Abrahamse, & Anable, 2017). Through their demand-pull effect, preferences can also affect the pace and direction of technological change, which can interact with government procurement policies (Boon & Edler, 2018). Lastly, preference changes can stir political movements, putting broader pressure on policy making and changing what is politically feasible.⁷ The public mobilisation against nuclear fission provides a cautionary story for other technologies (Boudet, 2019). Therefore, changes in preferences can lead both to price changes and quantity restrictions.

Transition costs

Transition drivers translate into transition costs (Figure 1, box 2) via two transmission channels (Figure 1, arrow B). Price and quantity changes lead to adjustments in all sectors, affecting revenues of producers, the real income of households, and state tax revenue. Although prices of high-carbon production may rise, market price behaviour may be more complex (see Sidebar 1). But the drivers also transmit via expectations about future revenue streams, especially if policy and preference changes are credible and long-lasting (Helm,

⁷ 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 & Cherp, 2020).

Hepburn, & Mash, 2003). For example, some of the car bans discussed above lack credible enforcement mechanisms (Plötz, Axsen, Funke, & Gnann, 2019), and current Nationally Determined Contributions under the Paris agreement, are subject to implementation (den Elzen et al., 2019; Pauw, Castro, Pickering, & Bhasin, 2019). But if expectations do change, they can do so quickly and across the board due to herd effects, also directly affecting the financial sector (arrow A).⁸ This leads to asset stranding.

Sidebar 1: 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 as firms pass costs on to consumers, lowering demand, while producers 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, which could lower prices due to lack of demand and oversupply. 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, the 'green paradox' (Jensen, Mohlin, Pittel, & Sterner, 2015). This accelerates the price decline as the lowest-cost producers capture what is left of the declining market (Mercure et al., 2018).

Physical asset stranding

A growing literature analyses high-carbon physical assets at risk of stranding. The risk that excess reserves of fossil-fuel companies poses for their valuation was briefly reviewed in Section 3. 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).⁹ Davis *et al.* (2010) calculate that existing fossil-fuel sector 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 & Socolow, 2014; Johnson et al., 2015; Pfeiffer, Hepburn, Vogt-Schilb, & Caldecott, 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. Meanwhile, Smith et al. (2019) find that current fossil fuel infrastructure does not yet commit the world to warming beyond 1.5°C. Part of this range arises from the uncertainty about the size of the carbon budget itself (Rogelj, Forster, Kriegler, Smith, & Séférian, 2019).

Asset stranding can spill out of the fossil energy sector. Considering the relevance of fossil fuels as inputs 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 (Fowlie, Greenstone, & Wolfram,

⁸ In a rational expectations framework, stranded assets occur under policy time-inconsistency (Kalkuhl, Steckel, & Edenhofer, 2019).

⁹ Research supported by the fossil fuel producer Shell suggests the deployment of carbon capture and storage could allow significantly more reserves being exploited while respecting the carbon budget (Budinis, Krevor, Dowell, Brandon, & Hawkes, 2018).

2018; Muldoon-Smith & Greenhalgh, 2019), and IRENA (2017) projects the building sector to hold the most stranded assets. Unruh (2000) coined the term 'carbon lock-in'. In short, both land and produced capital inputs can become stranded.

Research has been conducted on systematically valuing the loss of assets due to stranding. Mercure *et al.* (2018) estimate losses of \$1tn-\$4tn in the fossil in the fossil fuel sector in the period 2016-2035 under various scenarios including the current trajectory of low-carbon technology without additional policy measures, while \$0.957tn of power sector asset stranding until 2050 was found in a bottom up assessment by Saygin *et al.* (2019). One of the most cited works in this area is in the grey literature: for the IEA's Below 2 Degree scenario, 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 & UNPRI, 2018). IRENA (2017) calculates an economy-wide \$10tn stranded over the period 2015-50, which increases to \$20tn in a scenario of delayed transition policies. Dietz *et al.* (2016) calculate *value at risk* from the transition to be 0.4% of global financial assets, or \$0.6tn. Recent analytical models show how, depending on the type and stringency of the policy implemented, some asset stranding in the form of underutilisation of installed capital is not only likely, but also optimal from a social perspective (Coulomb, Lecuyer, & Vogt-Schilb, 2019; Rozenberg, Vogt-Schilb, & Hallegatte, 2018). None of these studies model 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 could be positive even in large-scale fossil fuel producing countries, high-carbon sectors are likely to suffer from significant unemployment (Bastidas & Mc Isaac, 2019; Pollin, 2015). 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), when including multiplier and knock-on effects of income and spending changes across the economy. As reviewed in Section 2, transitional unemployment is well documented for structural change. A fast-growing policy literature considers prospects and costs for retraining workers to ensure a 'just transition' (ILO, 2015; Oei *et al.*, 2020; Pollin, 2019).

Governments could also lose tax and other revenue from plunging sales and incomes of their domestic industries (not to be confused with carbon price revenue reviewed in section 5), especially, but not exclusively for fossil fuel exporters. For instance, Malova and van der Ploeg (2017) calculate that low oil and gas demand, in line with a 2°C scenario, would require the Russian government to divert an additional 0.9% of GDP a year towards investments outside the fossil energy sector in order to keep the fiscal stance sustainable. Regulations, such as production quotas or standards, may also restrict revenue.

Real incomes of households could shrink due to rising prices, in addition to loss of employment, declining return on investments. 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 & 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, & Kivimaa, 2019; Cabrera

Serrenho, Drewniok, Dunant, & Allwood, 2019; Schleich, 2019). Since poorer households are at a higher risk of defaulting on loans, such regressive impacts can create further risks for the financial sector.

Financial impacts

Transition costs impact the financial system (Figure 1, box 3) via two transmission channels: credit and market risks (Figure 1, arrow C). First, the loss of assets and income increases the likelihood of default on debt; therefore, banks could see their share of non-performing loans grow. Higher ratios of non-performing loans could 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 & 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 eurozone 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, & von Jagow, 2019). The transition costs reviewed above, or expectations about their realisation, could 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.¹⁰ 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. Economic theory is gradually incorporating transition-related risks into both growth and asset pricing theory (van der Ploeg & Rezai, 2020), and precise numerical estimates for specific investors are being estimated (e.g. Monasterolo, Zheng, & Battiston, 2018).

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. Financial systems have featured deeply connected networks throughout history (Graeber, 2011), and international financial liberalisation since the 1970s has only reinforced this interconnectedness (Christophers, 2013). Financial institutions tend to be heavily exposed to each other (Battiston, Puliga, Kaushik, Tasca, & Caldarelli, 2012). 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 could be strongly negatively affected by the low-carbon transition even if not directly exposed to carbon-intensive sectors by 'second-round effects' (Battiston, Mandel, Monasterolo, Schütze, & Visentin, 2017). 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 and avoid bankruptcy. This could prompt a vicious cycle of asset price falls and sell-outs, known as debt-deflation (Fisher, 1932).

The overall effect of such revaluations of financial assets remains unclear, but is being addressed by a nascent research literature published mostly outside of, or in collaboration

¹⁰ 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, and Sen & von Schickfus (2020) suggest high-carbon firms expect compensation for anticipated stranding. Christophers (2019) reports and analyses investors' views.

with, academia (e.g. HSBC, 2019; Mercer, 2019; UNEP FI, 2019). Two types of analytical approaches are employed (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'.¹¹ In order to grasp these effects, a second research approach uses the 'stress 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).

Table 1 summarises outputs from the few academic and a selected number of central bank studies that report exposure of banks to high-carbon sectors (rows 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*, i.e. from climate change itself. The studies cannot be directly compared, 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).

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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (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)
Physical risk studies for comparison:			

¹¹ 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 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).

5	Dietz <i>et al.</i> (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 <i>et al.</i> (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.

Further macroeconomic impacts

Transition costs and financial impacts could each trigger further macroeconomic impacts (Figure 1, box 4, and arrows D and E); 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 with negative macroeconomic multipliers amplifying initial losses. We highlight some of the possible channels for demand reductions as follows.

Banking channel. The increase in non-performing loans could lead to credit rationing by commercial banks. Even if the origin of the shock lies in carbon-intensive sectors, credit rationing could 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). Lower investment would reduce aggregate demand, affecting in turn expenditure in all sectors.

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 depressing confidence and expectations. Behind this lies ‘Tobin’s q’ theory, which suggests that a low market capitalisation to book value ratio lowers investments.¹² If the crisis affects the entire economy, these effects may also reduce investment in low-carbon sectors.

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, & Schulze, 2018; Fisher, Johnson, Latner, & Smeeding, 2018).

Public debt channel. Government expenditure is likely to initially react counter-cyclically to the reduction in other expenditure categories due to automatic stabilisers, public support to failing industries, and not least through the bail-out of failing financial institutions. However, higher public debt could translate into a lower capacity to spend in the future, especially in countries highly dependent on international credit markets.¹³ A worsening of sovereign credit ratings would also raise the corporate cost of capital, as the two tend to be related (Kling, Lo, Murinde, & Volz, 2018; Kling, Volz, Murinde, & Ayas, 2020).

¹² The original theory is subject to qualifications (Altissimo *et al.*, 2005; Jovanovic & Rousseau, 2014).

¹³ The problem of crowding-out would seem less relevant as a crisis-ridden and transforming economy is likely to be far from full capacity (Deleidi, Mazzucato, & Semieniuk, 2020; Heim & Mirowski, 1987).

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 (arrow F), financial impacts. A negative feedback loop from asset stranding in sunset industries could lead to a full-blown credit crunch, which could make it hard for sunrise industry firms to finance investment in the short run and in turn affect transition drivers (arrow G). The only study that currently attempts to connect transition financial impacts with macroeconomic impacts is Vermeulen *et al.* (2018), highlighting the absence of possible financial cost in integrated climate change scenarios, both with and without mitigation (Farmer, Hepburn, Mealy, & Teytelboym, 2015). However, many of the channels from finance to the real economy and vice versa are explored widely in the macroeconomic literature, so any future modelling efforts can use these as benchmarks.

Policy responses to mitigate transition risks

While some policies drive the transition, others seek to mitigate systemic financial impacts. 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 (e.g. Dikau & Volz, 2020; e.g. G30, 2015; Volz, 2017). Building on early academic contributions on the role of financial governance in addressing climate-related financial risks (Campiglio, 2016; Volz, 2017), monetary and financial authorities have started to include climate change among these systemic risks and consider adequate policy responses to mitigate them.¹⁴ 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 sunset sector risk. Growing attention is now also being paid to impacts on sovereign risks – stemming both from physical and transition risks – and how these can be mitigated (Battiston & Monasterolo, 2019; Buhr *et al.*, 2018; Kling *et al.*, 2018; Volz *et al.*, 2020). 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, & Giuliani, 2019). This discourse has largely ignored potential risks from rising industries.

Regulatory responses are mainly preventive in that they aim at providing information and incentivising 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 ‘green’ and ‘brown’ assets and a (mandatory) disclosure of risks (Thomä, Dupré, & Hayne, 2018; Volz *et al.*, 2015), climate-related stress testing at both micro and macro prudential level (Battiston *et al.*, 2017), and climate calibrated capital rules or collateral frameworks.¹⁵ Initially, the focus was on a disclosure of financial risks from climate change, which would help firms to manage, and financial markets to price in these risks and thus avoid rapid

¹⁴ See, for instance, Batten *et al.* (2016), ESRB (2016), Finansinspektionen (2016), Regelink *et al.* (2017), PRA (PRA, 2018) and NGFS (2019).

¹⁵ For an overview of policy tools available to central banks and supervisors see Dikau & Volz (2019).

reevaluation. 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, and firms can use these for risk management (Berg, Clapp, Lannoo, & Peters, 2018; TCFD, 2016). 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 & 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 (2019) 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 suggested by the NGFS 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. The NGFS (2019, p. 6) emphasises that climate change-related financial risks "are best mitigated through an early and orderly transition."

Existing stabilisation policy has been criticised by academic studies as inadequate. In particular, researchers have criticised too strong a focus on disclosure and the expectation that it will lead to an "efficient market reaction to climate change risks" (Carney, 2015, p. 12). For instance, (Christophers, 2017, p. 1124) contends that "there is something fundamentally awry with expecting enhanced disclosure to miraculously provide financial systemic safety." 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 markets price in all information). Monasterolo *et al.* (2017) note the difficulty of disclosing supply-chain carbon exposure. Lastly, disclosure may help re-classify fossil fuel assets as junk, but does not make their associated systemic risk disappear (Mercure, 2019). 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 ought to adhere to the principle of market neutrality in the conduct of monetary policy and

not favour green assets over brown (e.g. Weidmann, 2019). Proposals for risk differentials in financial regulation or collateral policies, and any activist policies aimed at fostering a green transition, have been controversial (Dikau & Volz, 2019). Nevertheless, a growing number of central banks and supervisors have started to implement micro and macro prudential measures to address transition risks (D’Orazio & Popoyan, 2019; Dikau & Volz, 2020; Frisari, Gallardo, Nakano, Cárdenas, & Monnin, 2019) or are considering doing so, going beyond disclosure and stress testing.

There is also a growing awareness of low-carbon transition risks for finance among finance ministries.¹⁶ A Coalition of Finance Ministers for Climate Action (CAPE) was established by 23 countries in April 2019 and has since grown to more than 50 members, all of which have signed the six “Helsinki Principles”, committing to national climate action and incorporating climate change into financial policies. While climate-related financial risks and impacts are included in the deliberations, to date the emphasis of CAPE has been primarily on fiscal policies.¹⁷

Lastly, and although we cannot go into depth, it is important to mention that appropriate redistributive and industrial policy can also reduce financial risks indirectly by mitigating transition costs (box 2). For a budget-neutral example, consider how government revenue from carbon taxes or auctioned-off emission permits could be used as a tool to mitigate transition costs for households. If part of this revenue is redistributed among citizens, and since richer households consume more carbon and thus pay a higher price in absolute terms, feebates turn carbon prices into a progressive instrument (Boyce, 2018), and just transition policies would further mitigate impacts. Government revenue could also be used to maintain minimum company solvency during the transition (Caldecott & Dericks, 2018), and industrial policy could direct (private and public) investments into sunrise industries to help reduce the amount of assets at risk of stranding. One vehicle for this is existing public development banks that have long experience with financing industrial policy and can strategically focus on structural change through their mandates and ability to function on lower operating margins than commercial lenders (Geddes, Schmidt, & Steffen, 2018; Griffith-Jones & Ocampo, 2018; Mazzucato & Penna, 2016). Note, however, that loss of substantial revenues from fossil-fuel royalties in major fossil-fuel producer countries could affect the ability of those nations to support the low-carbon transition through fiscal means.

Conclusion

Low-carbon transition risks for finance are likely to be generated mainly from unanticipated, stringent climate-mitigation policy, but also from technological and preference changes and their interaction with each other. The current academic research on these topics addresses

¹⁶ The French Ministry of Finance was among the first to address climate risk for the financial sector. Enacted in August 2015, Article 173 of the French Energy Transition Act introduced mandatory reporting requirements on climate-related financial risks and the measures adopted to mitigate them for listed companies and/or large non-listed firms, including both non-financial and financial firms (Direction Générale du Trésor, n.d.).

¹⁷ Helsinki Principle 5 (“Mobilize private sources of climate finance by facilitating investments and the development of a financial sector which supports climate mitigation and adaptation”) includes the identification of “strategies to incorporate climate risks and opportunities into investment decisions, such as supporting global efforts for transparency and disclosure of climate-related financial risks and impacts, identifying risks to financial stability posed by climate change, and considering ways to manage these risks” (CAPE, 2019, p. 3).

either the real-economy transition costs, or the financial impact, but does little to connect the two. A comprehensive theoretical framework of sunset industry systemic risks for finance is lacking as the theoretical and historical literature has focussed on risks from sunrise industries instead. We contribute to thinking about the conceptual issues in understanding transition risks from sunset industries by developing a consistent theoretical framework of the drivers, transmission channels and impacts of the phase-out of carbon-intensive industries on the financial system. An important insight from existing Schumpeterian theory on financial risks of transition, however, is that once low-carbon industries do become more productive, as the sunrise industries in previous transitions ultimately did, the potential for financial instability begins to threaten the low-carbon sector too.

High-carbon industries could abruptly become uncompetitive due to strong climate-change mitigation policy and the resulting price changes and expectations, reinforced by fast technological change and preference changes. These transition drivers cause physical assets to lose their ability to generate revenue and become stranded. 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 debt and obligations, creating loss propagation within the financial network. 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: several studies have clearly demonstrated that financial sector exposure to the transition already exists, and delaying climate-change action would only necessitate an even more rapid and potentially more damaging transition in the future, while exposure to physical risks under unmitigated climate change would be drastically increased. Targeted financial stabilization policies, however, can mitigate some transition risks by direct regulation of the financial sector, as well as intervention at the transition cost stage.

What the current transition needs is a set of theoretical propositions and stylized facts about the link between fast depreciation of capital and financial impact. These could be implemented in multi-sectoral models with a financial sector and vintage capital structure. Putting together real and financial economic mechanisms would make it possible to explore the whole set of interlinked parts of transition drivers, costs and impacts to arrive at benchmarks both of systemic risk and effects of policy measures.

References

- Altissimo, F., Georgiou, E., Sastre, T., Valderrama, M. T., Sterne, G., Stocker, M., ... Willman, A. (2005). Wealth and Asset Price Effects on Economic Activity. *European Central Bank Occasional Paper Series*, 29.
- Ameli, N., Drummond, P., Bisaro, A., Grubb, M., & Chenet, H. (2019). Climate finance and disclosure for institutional investors: why transparency is not enough. *Climatic Change*. <https://doi.org/10.1007/s10584-019-02542-2>
- Amromin, G., De Nardi, M., & Schulze, K. (2018). Household inequality and the consumption response to aggregate real shocks. *Economic Perspectives*. <https://doi.org/10.21033/ep-2018-1>
- Arthur, W. B. (1989). Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *The Economic Journal*, 99(394), 116–117.

- Azariadis, C., & Kaas, L. (2016). CAPITAL MISALLOCATION AND AGGREGATE FACTOR PRODUCTIVITY. *Macroeconomic Dynamics*, 20(2), 525–543. <https://doi.org/DOI:10.1017/S1365100514000236>
- Bastidas, D., & Mc Isaac, F. (2019). Reaching Brazil's Nationally Determined Contributions: An assessment of the key transitions in final demand and employment. *Energy Policy*, 135, 110983. <https://doi.org/https://doi.org/10.1016/j.enpol.2019.110983>
- Basu, D. (2018). Reproduction and Crisis in Capitalist Economies. In M. Vidal, T. Smith, T. Rotta, & P. Prew (Eds.), *The Oxford Handbook of Karl Marx*. Oxford University Press.
- Batten, S., Sowerbutts, R., & Tanaka, M. (2016). Let's Talk About the Weather: The Impact of Climate Change on Central Banks. *Bank of England Working Paper*, 603.
- Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., & Visentin, G. (2017). A climate stress-test of the financial system. *Nature Climate Change*, 7(4), 283–288. <https://doi.org/10.1038/nclimate3255>
- Battiston, S., & Monasterolo, I. (2019). A Climate Risk Assessment of Sovereign Bonds' Portfolio. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.3376218>
- Battiston, S., Puliga, M., Kaushik, R., Tasca, P., & Caldarelli, G. (2012). DebtRank: Too Central to Fail? Financial Networks, the FED and Systemic Risk. *Scientific Reports*, 2(541), 1–6. <https://doi.org/10.1038/srep00541>
- Bebbington, J., Schneider, T., Stevenson, L., & Fox, A. (2019). Fossil fuel reserves and resources reporting and unburnable carbon: Investigating conflicting accounts. *Critical Perspectives on Accounting*, (In Press). <https://doi.org/10.1016/j.cpa.2019.04.004>
- Benhabib, J., & Hobijn, B. (2003). Vintage Models, Fluctuations and Growth. In P. Aghion, R. Frydman, J. Stiglitz, & M. Woodford (Eds.), *Knowledge, Information and Expectations in Macroeconomics: Essays in Honor of Edmund S. Phelps*. Princeton: Princeton University Press.
- Berg, A. O., Clapp, C., Lannoo, E., & Peters, G. (2018). *Climate scenarios demystified. A climate scenario guide for investors*. CICERO Report: Centre for International Climate and Environmental Research.
- Best, M. H., & Humphries, J. (1984). The City and Industrial Decline. In *The Decline of the British Economy* (pp. 223–239). Oxford: Clarendon Press.
- Block, F., & Keller, M. R. (2011). *State of Innovation*. Oxford and New York: Routledge.
- Bolton, P., Despres, M., Pereira Da Silva, L. A., Samama, F., & Svartzman, R. (2020). *The green swan: Central banking and financial stability in the age of climate change*. Bank for International Settlements.
- Boon, W., & Edler, J. (2018). Demand, challenges, and innovation. Making sense of new trends in innovation policy. *Science and Public Policy*, 45(4), 435–447. <https://doi.org/10.1093/scipol/scy014>
- Boudet, H. S. (2019). Public perceptions of and responses to new energy technologies. *Nature Energy*, 4(6), 446–455. <https://doi.org/10.1038/s41560-019-0399-x>
- Bowles, S. (1998). *Endogenous Preferences: The Cultural Consequences of Markets and other Economic Institutions*. XXXVI(March), 75–111.
- Boyce, J. K. (2018). Carbon Pricing: Effectiveness and Equity. *Ecological Economics*, 150(April), 52–61. <https://doi.org/10.1016/j.ecolecon.2018.03.030>
- Brenner, R. (2006). *The economics of global turbulence: the advanced capitalist economies from long boom to long downturn, 1945-2005*. London; New York: Verso.
- Brown, D., Sorrell, S., & Kivimaa, P. (2019). Worth the risk? An evaluation of alternative finance mechanisms for residential retrofit. *Energy Policy*, 128(January), 418–430. <https://doi.org/10.1016/j.enpol.2018.12.033>

- Budinis, S., Krevor, S., Dowell, N. Mac, Brandon, N., & Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. *Energy Strategy Reviews*, 22(May), 61–81. <https://doi.org/10.1016/j.esr.2018.08.003>
- Buhr, B., Volz, U., Donovan, C., Kling, G., Lo, Y., Murinde, V., & Pullin, N. (2018). *Climate Change and the Cost of Capital in Developing Countries*.
- Byrd, J., & Cooperman, E. S. (2018). Investors and stranded asset risk: evidence from shareholder responses to carbon capture and sequestration (CCS) events. *Journal of Sustainable Finance and Investment*, 8(2), 185–202. <https://doi.org/10.1080/20430795.2017.1418063>
- Caballero, R. J., & Hammour, M. L. (1996). On the Timing and Efficiency of Creative Destruction*. *The Quarterly Journal of Economics*, 111(3), 805–852. <https://doi.org/10.2307/2946673>
- Cabrera Serrenho, A., Drewniok, M., Dunant, C., & Allwood, J. M. (2019). Testing the greenhouse gas emissions reduction potential of alternative strategies for the english housing stock. *Resources, Conservation and Recycling*, 144, 267–275. <https://doi.org/https://doi.org/10.1016/j.resconrec.2019.02.001>
- Cahen-Fourot, L., Campiglio, E., Dawkins, E., Godin, A., & Kemp-Benedict, E. (2019). Capital stranding cascades : The impact of decarbonisation on productive asset utilisation. *WU Institute for Ecological Economics Working Paper Series*, 18/2019.
- Caiani, A., Godin, A., & Lucarelli, S. (2014). Innovation and finance: A stock flow consistent analysis of great surges of development. *Journal of Evolutionary Economics*, 24(2), 421–448. <https://doi.org/10.1007/s00191-014-0346-8>
- Caldecott, B. (2018). Stranded Assets and the Environment: Risk, Resilience and Opportunity. In *Routledge Explorations in Environmental Studies*. Oxford: Routledge.
- Caldecott, B., & Dericks, G. (2018). Empirical calibration of climate policy using corporate solvency: a case study of the UK's carbon price support. *Climate Policy*, 18(6), 766–780. <https://doi.org/10.1080/14693062.2017.1382318>
- Callegari, B. (2018). The finance/innovation nexus in Schumpeterian analysis: theory and application to the case of U.S. trustified capitalism. *Journal of Evolutionary Economics*, 28(5), 1175–1198. <https://doi.org/10.1007/s00191-018-0601-5>
- Campiglio, E. (2016). Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics*, 121(C), 220–230. <https://doi.org/http://dx.doi.org/10.1016/j.ecolecon.2015.03.020>
- Campiglio, E., Dafermos, Y., Monnin, P., Ryan-Collins, J., Schotten, G., & Tanaka, M. (2018). Climate change challenges for central banks and financial regulators. *Nature Climate Change*, 8(6), 462–468. <https://doi.org/10.1038/s41558-018-0175-0>
- Campiglio, E., Monnin, P., & von Jagow, A. (2019). Climate Risks in Financial Assets. *Council on Economic Policies, Discussion*.
- CAPE. (2019). The Coalition of Finance Ministers for Climate Action. *Overview of the Santiago Action Plan for 2020, Madrid, 9 December*.
- Caplan, B. (1940). The Premature Abandonment of Machinery. *The Review of Economic Studies*, 7(2), 113. <https://doi.org/10.2307/2967474>
- Carbon Tracker. (2013). Unburnable Carbon 2013: Wasted capital and stranded assets. *Carbon Tracker Initiative & Grantham Research Institute on Climate Change and the Environment*.
- Carbon Tracker, & UNPRI. (2018). 2 degrees of separation: Company-level transition risk July 2018 update. *Carbon Tracker Initiative & UNPRI*.
- Carney, M. (2015). Breaking the tragedy of the horizon – Climate change and financial

- stability. *Speech given at Lloyd's of London, 29 September.*
- Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E., & Sovacool, B. (2018). Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Research and Social Science*, 37(January 2017), 175–190. <https://doi.org/10.1016/j.erss.2017.09.015>
- Christophers, B. (2013). *Banking Across Boundaries: Placing Finance in Capitalism*. Wiley.
- Christophers, B. (2017). Climate Change and Financial Instability: Risk Disclosure and the Problematics of Neoliberal Governance. *Annals of the American Association of Geographers*, 107(5), 1108–1127. <https://doi.org/10.1080/24694452.2017.1293502>
- Christophers, B. (2019). Environmental Beta or How Institutional Investors Think about Climate Change and Fossil Fuel Risk. *Annals of the American Association of Geographers*, 109(3), 754–774. <https://doi.org/10.1080/24694452.2018.1489213>
- Ciarli, T., & Savona, M. (2019). Modelling the Evolution of Economic Structure and Climate Change: A Review. *Ecological Economics*, 158(September 2017), 51–64. <https://doi.org/10.1016/j.ecolecon.2018.12.008>
- Coulomb, R., Lecuyer, O., & Vogt-Schilb, A. (2019). Optimal Transition from Coal to Gas and Renewable Power Under Capacity Constraints and Adjustment Costs. *Environmental and Resource Economics*, 73(2), 557–590. <https://doi.org/10.1007/s10640-018-0274-4>
- CPI. (2016). *Beyond YieldCos*. London: Climate Policy Initiative.
- CPI. (2019). *Global Landscape of Climate Finance 2019*. London: Climate Policy Initiative.
- Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, 2(9). <https://doi.org/10.1038/nenergy.2017.140>
- D'Orazio, P., & Popoyan, L. (2019). Fostering green investments and tackling climate-related financial risks: Which role for macroprudential policies? *Ecological Economics*, 160(February), 25–37. <https://doi.org/10.1016/j.ecolecon.2019.01.029>
- Dafermos, Y., & Nikolaidi, M. (2019a). An assessment of green differentiated capital requirements. *Mimeo, University of the West of England*.
- Dafermos, Y., & Nikolaidi, M. (2019b). *Fiscal Policy and Ecological Sustainability: A Post-Keynesian Perspective BT - Frontiers of Heterodox Macroeconomics* (P. Arestis & M. Sawyer, Eds.). https://doi.org/10.1007/978-3-030-23929-9_7
- Davis, S. J. (1987). Allocative Disturbances and Specific Capital in Real Business Cycle Theories. *The American Economic Review*, 77(2), 326–332.
- Davis, S. J., Caldeira, K., & Matthews, H. D. (2010). Future CO₂ Emissions and Climate Change from Existing Energy Infrastructure. *Science*, 329(5997), 1330–1333. Retrieved from <http://www.jstor.org.silk.library.umass.edu/stable/41075805>
- Davis, S. J., & Socolow, R. H. (2014). Commitment accounting of CO₂ emissions. *Environmental Research Letters*, 9(8), 84018. <https://doi.org/10.1088/1748-9326/9/8/084018>
- de Coninck, H., Revi, A., Babiker, M., Bertoldi, P., Buckeridge, M., Cartwright, A., ... Sugiyama, T. (2018). Strengthening and Implementing the Global Response. In *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*, (pp. 313–443). IPCC - The Intergovernmental Panel on Climate Change.
- Deleidi, M., Mazzucato, M., & Semieniuk, G. (2020). Neither crowding in nor out: Public direct investment mobilising private investment into renewable electricity projects. *Energy Policy*, 111195. <https://doi.org/https://doi.org/10.1016/j.enpol.2019.111195>

- den Elzen, M., Kuramochi, T., Höhne, N., Cantzler, J., Esmeijer, K., Fekete, H., ... Vandyck, T. (2019). Are the G20 economies making enough progress to meet their NDC targets? *Energy Policy*, 126, 238–250. <https://doi.org/10.1016/j.enpol.2018.11.027>
- Dietz, S., Bowen, A., Dixon, C., & Gradwell, P. (2016). 'Climate value at risk' of global financial assets. *Nature Climate Change*, 6(4), 676–679. <https://doi.org/10.1038/NCLIMATE2972>
- Dietz, S., Byrne, R., Gardiner, D., Gostlow, G., Jahn, V., Nachmany, M., ... Sullivan, R. (2020). *TPI State of Transition Report 2020*.
- Dikau, S., & Volz, U. (2019). Central Banking, Climate Change and Green Finance. In J. Sachs, W. Thye Woo, N. Yoshino, & F. Taghizadeh-Hesary (Eds.), *Springer Handbook of Green Finance: Energy Security and Sustainable Development* (pp. 81–102). New York: Springer.
- Dikau, S., & Volz, U. (2020). Central Bank Mandates, Sustainability Objectives and the Promotion of Green Finance. *SOAS Department of Economics Working Paper Series*, 232.
- Direction Générale du Trésor. (n.d.). The financial sector facing the transition to a low-carbon climate-resilient economy. In *Trésor-Economics 185*. Paris: Ministère de l'Économie et des Finances.
- DNB. (2017). Waterproof? An exploration of climate-related risks for the Dutch financial sector. *De Nederlandsche Bank*.
- Dosi, G. (1982). Technological paradigms and technological trajectories. *Research Policy*, 11(3), 147–162. Retrieved from <http://linkinghub.elsevier.com/retrieve/pii/0048733382900166>
- Eisner, R. (1972). Components of Capital Expenditures : Replacement and Modernization Versus Expansion. *Review of Economic Studies*, 54(3), 297–305.
- ESRB. (2016). Too late, too sudden: Transition to a low-carbon economy and systemic risk. *Report of the Advisory Scientific Committee*, 6, European Systemic Risk Board.
- European Commission. (2019). The European Green Deal. *COM(2019) 640 Final*.
- Falcone, P. M., Morone, P., & Sica, E. (2018). Greening of the financial system and fuelling a sustainability transition: A discursive approach to assess landscape pressures on the Italian financial system. *Technological Forecasting and Social Change*, 127, 23–37. <https://doi.org/10.1016/J.TECHFORE.2017.05.020>
- Farmer, J. D., Hepburn, C., Mealy, P., & Teytelboym, A. (2015). A Third Wave in the Economics of Climate Change. *Environmental and Resource Economics*, 62(2), 329–357. <https://doi.org/10.1007/s10640-015-9965-2>
- Financial Times. (2020a). Can Orsted be the first green energy supermajor? *February 3*.
- Financial Times. (2020b). Tesla's soaring share price defies the bears. *January 17*.
- Finansinspektionen. (2016). *Climate change and financial stability*. Stockholm: Finansinspektionen.
- Fisher, I. (1932). *Booms and Depressions*. New York: Adelphi.
- Foley, D. K. (2009). Economic fundamentals of global warming. In J. M. Harris & N. R. Goodwin (Eds.), *Twenty-First Century Macroeconomics. Responding to the Climate Challenge* (pp. 115–126). Cheltenham, UK: Elgar.
- Fowlie, M., Greenstone, M., & Wolfram, C. (2018). Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program. *The Quarterly Journal of Economics*, 133(3), 1597–1644. <https://doi.org/10.1093/qje/qjy005>
- Freeman, C., & Louca, F. (2001). *As Time Goes By*. Oxford and New York: Oxford

University Press.

- Freeman, C., & Perez, C. (1988). Structural crises of adjustment, business cycles and investment behaviour. In G. Dosi, C. Freeman, R. R. Nelson, G. Silverberg, & L. L. G. Soete (Eds.), *Technical Change and Economic Theory* (pp. 38–66). London and New York: Pinter.
- Fremstad, A., & Paul, M. (2019). The Impact of a Carbon Tax on Inequality. *Ecological Economics*, 163(July 2018), 88–97. <https://doi.org/10.1016/j.ecolecon.2019.04.016>
- Frisari, G. L., Gallardo, M., Nakano, C., Cárdenas, V., & Monnin, P. (2019). Climate Risk and Financial Systems of Latin America: Regulatory, Supervisory and Industry Practices in the Region and Beyond. *Inter-American Development Bank Technical Note, IDB-TN-018*.
- G30. (2015). *Fundamentals of Central Banking. Lessons from the Crisis*. Washington, DC: Group of Thirty.
- Geddes, A., & Schmidt, T. S. (2018). Theorizing finance in transitions studies – a multi-level perspective analysis of state investment banks' roles in mobilising finance for clean energy transitions. *International Sustainability Transitions Conference*. Manchester (UK).
- Geddes, A., Schmidt, T. S., & Steffen, B. (2018). The multiple roles of state investment banks in low-carbon energy finance: An analysis of Australia, the UK and Germany. *Energy Policy*, 115, 158–170. <https://doi.org/https://doi.org/10.1016/j.enpol.2018.01.009>
- Geels, F W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, 31(8–9), 1257–1274.
- Geels, Frank W. (2013). The impact of the financial–economic crisis on sustainability transitions: Financial investment, governance and public discourse. *Environmental Innovation and Societal Transitions*, 6, 67–95. <https://doi.org/https://doi.org/10.1016/j.eist.2012.11.004>
- Giebel, M., & Kraft, K. (2019). The Impact of the Financial Crisis on Investments in Innovative Firms. *Industrial and Corporate Change*, 28(5), 1079–1099. <https://doi.org/https://doi.org/10.1093/icc/dty050>
- Giuzio, M., Krusec, D., Levels, A., Melo, A. S., Katrin, M., & Radulova, P. (2019). Climate change and financial stability (Financial Stability Review). *European Central Bank*.
- Graeber, D. (2011). *Debt: The First 5,000 Years*. Brooklyn: Melville House.
- Griffin, P. A., Jaffe, A. M., Lont, D. H., & Dominguez-Faus, R. (2015). Science and the stock market: Investors' recognition of unburnable carbon. *Energy Economics*, 52, 1–12. <https://doi.org/10.1016/j.eneco.2015.08.028>
- Griffith-Jones, S., & Ocampo, J. A. (2018). *The Future of National Development Banks*. Oxford: Oxford University Press.
- Hagemann, H. (2003). SCHUMPETER'S EARLY CONTRIBUTIONS ON CRISES THEORY AND BUSINESS-CYCLE THEORY. *History of Economic Ideas*, 11(1), 47–67.
- Hall, B. H., & Lerner, J. (2010). Chapter 14 - The Financing of R&D and Innovation. In B. H. Hall & N. B. Rosenberg (Eds.), *Handbook of The Economics of Innovation*, Vol. 1 (Vol. 1, pp. 609–639). [https://doi.org/https://doi.org/10.1016/S0169-7218\(10\)01014-2](https://doi.org/https://doi.org/10.1016/S0169-7218(10)01014-2)
- Hayek, F. A. von. (1931). *Prices and production*. New York: Augustus M. Kelley.
- Heim, C. E., & Mirowski, P. (1987). Interest Rates and Crowding-Out During Britain's Industrial Revolution. *The Journal of Economic History*, 47(1), 117–139. <https://doi.org/DOI: 10.1017/S0022050700047446>
- Helm, D., Hepburn, C., & Mash, R. (2003). Credible Carbon Policy. *Oxford Review of Economic Policy*, 19(3), 438–450. <https://doi.org/10.1093/oxrep/19.3.438>

- Higgins, D., & Toms, S. (2003). Financial distress, corporate borrowing, and industrial decline: the Lancashire cotton spinning industry, 1918–38. *Accounting, Business & Financial History*, 13(2), 207–232. <https://doi.org/10.1080/0958520032000084996>
- Holden, P. B., Edwards, N. R., Ridgwell, A., Wilkinson, R. D., Fraedrich, K., Lunkeit, F., ... Viñuales, J. E. (2018). Climate-carbon cycle uncertainties and the Paris Agreement. *Nature Climate Change*, 8(7), 609–613. <https://doi.org/10.1038/s41558-018-0197-7>
- Horton, R. (2019). Offline: Extinction or rebellion? *The Lancet*, 394(10205), 1216. [https://doi.org/10.1016/S0140-6736\(19\)32260-3](https://doi.org/10.1016/S0140-6736(19)32260-3)
- HSBC. (2019). *Low-carbon transition scenarios: Exploring scenario analysis for equity valuations*. Retrieved from HSBC Global Asset Management website: <https://no.assetmanagement.hsbc.com/en/institutional-and-professional-investor/news-and-insights/low-carbon-transition-scenarios>
- Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Rose, S. K., ... Zhang, R. (2018). *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA*. <https://doi.org/https://doi.org/10.22022/SR15/08-2018.15429>
- IEA. (2019). *Global EV Outlook 2019*. Paris: International Energy Agency.
- ILO. (2015). *Guidelines for a just transition towards environmentally sustainable economies and societies for all*. Geneva: International Labour Organization.
- IRENA. (2017). *Stranded assets and renewables: how the energy transition affects the value of energy reserves, buildings and capital stock*.
- Jensen, S., Mohlin, K., Pittel, K., & Sterner, T. (2015). An Introduction to the Green Paradox: The Unintended Consequences of Climate Policies. *Review of Environmental Economics and Policy*, 9(2), 246–265. <https://doi.org/10.1093/reep/rev010>
- Jewell, J., & Cherp, A. (2020). On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5°C? *WIREs Climate Change*, 11(1), e621. <https://doi.org/10.1002/wcc.621>
- Johnson, N., Krey, V., McCollum, D. L., Rao, S., Riahi, K., & Rogelj, J. (2015). Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, 90(PA), 89–102. <https://doi.org/10.1016/j.techfore.2014.02.028>
- Jonathan Fisher, David Johnson, Jonathan Latner, & Timothy Smeeding. (2019). Estimating the marginal propensity to consume using the distributions of income, consumption, and wealth. *Federal Reserve Boston Research Department Working Papers*, 19(4).
- Jovanovic, B., & Rousseau, P. L. (2014). Extensive and Intensive Investment over the Business Cycle. *Journal of Political Economy*, 122(4), 863–908. <https://doi.org/10.1086/676405>
- Kalkuhl, M., Steckel, J. C., & Edenhofer, O. (2019). All or nothing: Climate policy when assets can become stranded. *Journal of Environmental Economics and Management*. <https://doi.org/https://doi.org/10.1016/j.jeem.2019.01.012>
- Kavlak, G., McNerney, J., & Trancik, J. E. (2018). Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy*, 123, 700–710. <https://doi.org/https://doi.org/10.1016/j.enpol.2018.08.015>
- Kindleberger, C. P. (1978). *Manias, Panics and Crashes*. London: Palgrave Macmillan UK.
- Kling, G., Lo, Y., Murinde, V., & Volz, U. (2018). Climate vulnerability and the cost of debt. *Mimeo, SOAS University of London*.
- Kling, G., Volz, U., Murinde, V., & Ayas, S. (2020). The impact of climate vulnerability on firms' cost of capital and access to finance. *Department of Economics Working Paper*.
- Kotz, D. M. (1990). *A Comparative Analysis of the Theory of Regulation and the Social*

- Structure of Accumulation Theory. *Science & Society*, 54(1), 5–28.
- Lamperti, F., Bosetti, V., Roventini, A., & Tavoni, M. (2019). The public costs of climate-induced financial instability. *Nature Climate Change*, 9(11), 829–833. <https://doi.org/10.1038/s41558-019-0607-5>
- Lazard. (2019). *Levelized cost of energy analysis - Version 13.0*. New York.
- Lazonick, W. (1984). The Cotton Industry. In *The Decline of the British Economy* (pp. 18–50). Oxford: Clarendon Press.
- Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences*, 105(6 LB-Lenton2008), 1786–1793.
- Malova, A., & van der Ploeg, F. (2017). Consequences of lower oil prices and stranded assets for Russia's sustainable fiscal stance. *Energy Policy*, 105(February), 27–40. <https://doi.org/10.1016/j.enpol.2017.02.022>
- Mazzucato, M., & Penna, C. C. R. (2016). Beyond market failures: the market creating and shaping roles of state investment banks. *Journal of Economic Policy Reform*, 19(4), 305–326. <https://doi.org/http://dx.doi.org/10.1080/17487870.2016.1216416>
- Mazzucato, M., & Semieniuk, G. (2017). Public financing of innovation: New questions. *Oxford Review of Economic Policy*, 33(1), 24–48. <https://doi.org/10.1093/oxrep/grw036>
- Mazzucato, M., & Semieniuk, G. (2018). Financing renewable energy: Who is financing what and why it matters. *Technological Forecasting and Social Change*, 127, 8–22. <https://doi.org/10.1016/j.techfore.2017.05.021>
- McCollum, D. L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., ... Riahi, K. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, 3(7), 589–599. <https://doi.org/10.1038/s41560-018-0179-z>
- McShane, B. B., Bradlow, E. T., & Berger, J. (2012). Visual Influence and Social Groups. *Journal of Marketing Research*, 49(6), 854–871. <https://doi.org/10.1509/jmr.11.0223>
- Meckling, J., & Nahm, J. (2019). The politics of technology bans: Industrial policy competition and green goals for the auto industry. *Energy Policy*, 126(May 2018), 470–479. <https://doi.org/10.1016/j.enpol.2018.11.031>
- Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., ... Allen, M. R. (2009). Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature*, 458(7242), 1158–1162. <https://doi.org/10.1038/nature08017>
- Mercer. (2019). Investing in a time of climate change. The sequel. *Mercer*.
- Mercure, J.-F. (2019). Toward Risk-Opportunity Assessment in Climate-Friendly Finance. *One Earth*, 1(4), 395–398.
- Mercure, J. F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., ... Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change*, 8(7), 588–593. <https://doi.org/10.1038/s41558-018-0182-1>
- Minsky, H. P. (1975). *John Maynard Keynes*. New York: Columbia University Press.
- Minsky, H. P. (1986). *Stabilizing an unstable economy*. New Haven; London: Yale University Press.
- Monasterolo, I. (2020). Climate Change and the Financial System. *SSRN Electronic Journal*. <https://doi.org/http://dx.doi.org/10.2139/ssrn.3479380>
- Monasterolo, I., Battiston, S., Janetos, A. C., & Zheng, Z. (2017). Vulnerable yet relevant: the two dimensions of climate-related financial disclosure. *Climatic Change*, 145(3–4), 495–507. <https://doi.org/10.1007/s10584-017-2095-9>

- Monasterolo, I., Zheng, J. I., & Battiston, S. (2018). Climate Transition Risk and Development Finance: A Carbon Risk Assessment of China's Overseas Energy Portfolios. *China and World Economy*, 26(6), 116–142. <https://doi.org/10.1111/cwe.12264>
- Mowery, D. C., & Rosenberg, N. (1998). *Paths of Innovation: Technological Change in 20th-Century America*. [https://doi.org/DOI: 10.1017/CBO9780511611957](https://doi.org/DOI:10.1017/CBO9780511611957)
- Muldoon-Smith, K., & Greenhalgh, P. (2019). Suspect foundations: Developing an understanding of climate-related stranded assets in the global real estate sector. *Energy Research & Social Science*, 54, 60–67. <https://doi.org/https://doi.org/10.1016/j.erss.2019.03.013>
- Mundaca, L., & Richter, J. L. (2015). Assessing 'green energy economy' stimulus packages_ Evidence from the U.S. programs targeting renewable energy. *Renewable and Sustainable Energy Reviews*, 42(C), 1174–1186. <https://doi.org/http://dx.doi.org/10.1016/j.rser.2014.10.060>
- National Development and Reform Commission. (2016). *The 13th Five-Year Plan for Economic and Social Development of the People's Republic of China*. Beijing: Central Compilation & Translation Press.
- Nemet, G. F. (2019). *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation*. Routledge.
- NGFS. (2019). A call for action: Climate change as a source of financial risk. *Network for Greening the Financial System*.
- Nieto, M. J. (2019). Banks, climate risk and financial stability. *Journal of Financial Regulation and Compliance*, 27(2), 243–262. <https://doi.org/10.1108/JFRC-03-2018-0043>
- Nikolaidi, M., & Stockhammer, E. (2017). MINSKY MODELS: A STRUCTURED SURVEY. *Journal of Economic Surveys*, 31(5), 1304–1331. <https://doi.org/10.1111/joes.12222>
- Nordhaus, W. D. (2013). *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. Yale University Press.
- Oei, P.-Y., Hermann, H., Herpich, P., Holtemöller, O., Lünenbürger, B., & Schult, C. (2020). Coal phase-out in Germany – Implications and policies for affected regions. *Energy*, 196, 117004. <https://doi.org/https://doi.org/10.1016/j.energy.2020.117004>
- Pauw, W. P., Castro, P., Pickering, J., & Bhasin, S. (2019). Conditional nationally determined contributions in the Paris Agreement: foothold for equity or Achilles heel? *Climate Policy*, 0(0), 1–17. <https://doi.org/10.1080/14693062.2019.1635874>
- Perez, C. (1983). Structural change and assimilation of new technologies in the economic and social systems. *Futures*, 15(5), 357–375. [https://doi.org/https://doi.org/10.1016/0016-3287\(83\)90050-2](https://doi.org/https://doi.org/10.1016/0016-3287(83)90050-2)
- Perez, C. (2002). *Technological revolutions and financial capital: the dynamics of bubbles and golden ages*. Cheltenham [England]: Edward Elgar.
- Pettifor, H., Wilson, C., Axsen, J., Abrahamse, W., & Anable, J. (2017). Social influence in the global diffusion of alternative fuel vehicles – A meta-analysis. *Journal of Transport Geography*, 62, 247–261. <https://doi.org/https://doi.org/10.1016/j.jtrangeo.2017.06.009>
- Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*, 13(5). <https://doi.org/10.1088/1748-9326/aabc5f>
- Plötz, P., Axsen, J., Funke, S. A., & Gnann, T. (2019). Designing car bans for sustainable transportation. *Nature Sustainability*, 2(7), 534–536. <https://doi.org/10.1038/s41893-019-0328-9>

- Pollin, R. (2015). *Greening the Global Economy*. Cambridge, MA: MIT Press.
- Pollin, R. (2019). Green Economics and Decent Work : A Viable Unified Framework. *Development and Change*, 51(2), 711–726. <https://doi.org/10.1111/dech.12559>
- Polzin, F., Egli, F., Steffen, B., & Schmidt, T. S. (2019). How do policies mobilize private finance for renewable energy ?— A systematic review with an investor perspective. *Applied Energy*, 236(May 2018), 1249–1268. <https://doi.org/10.1016/j.apenergy.2018.11.098>
- PRA. (2015). The impact of climate change on the UK insurance sector. *Prudential Regulation Authority, Bank of England*.
- PRA. (2018). Transition in thinking : The impact of climate change on the UK banking sector. *Prudential Regulation Authority, Bank of England*, (September).
- Regelink, M., Reinders, H. J., Vleeschhouwer, M., & Wiel, I. van de. (2017). *Waterproof? An exploration of climate-related risks for the Dutch financial sector*. Amsterdam: De Nederlandsche Bank.
- Reinert, E. S. (2002). SCHUMPETER IN THE CONTEXT OF TWO CANONS OF ECONOMIC THOUGHT. *Industry and Innovation*, 9(1–2), 23–39. <https://doi.org/10.1080/13662710220123608>
- Reinhart, C. M., & Rogoff, K. S. (2009). *This Time Is Different*. Princeton University Press.
- Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J., & Séférian, R. (2019). Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, 571(7765), 335–342. <https://doi.org/10.1038/s41586-019-1368-z>
- Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., ... Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, 8(4), 325–332. <https://doi.org/10.1038/s41558-018-0091-3>
- Rogers, E. M. (2003). *Diffusion of innovations*. New York: Free Press.
- Rosemberg, A. (2010). Building a Just Transition: The linkages between climate change and employment. *International Journal of Labour Research*, 2(2), 125–162.
- Rosenberg, N. (1982). Marx as a Student of Technology. In N. Rosenberg (Ed.), *Inside the Black Box: Technology and Economics*. Cambridge, New York and Melbourne: Cambridge University Press.
- Rozenberg, J., Davis, S. J., Narloch, U., & Hallegatte, S. (2015). Climate constraints on the carbon intensity of economic growth. *Environmental Research Letters*, 10(9). <https://doi.org/10.1088/1748-9326/10/9/095006>
- Rozenberg, J., Vogt-Schilb, A., & Hallegatte, S. (2018). Instrument choice and stranded assets in the transition to clean capital. *Journal of Environmental Economics and Management*. <https://doi.org/https://doi.org/10.1016/j.jeem.2018.10.005>
- Saygin, D., Rigter, J., Caldecott, B., Wagner, N., & Gielen, D. (2019). Power sector asset stranding effects of climate policies. *Energy Sources, Part B: Economics, Planning, and Policy*, 14(4), 99–124. <https://doi.org/10.1080/15567249.2019.1618421>
- Schleich, J. (2019). Energy efficient technology adoption in low-income households in the European Union – What is the evidence? *Energy Policy*, 125(July 2018), 196–206. <https://doi.org/10.1016/j.enpol.2018.10.061>
- Schumpeter, J. A. (1939). *Business Cycles: A Theoretical, Historical, and Statistical Analysis of the Capitalist Process, Volume 1*. New York and London: McGraw-Hill.
- Semieniuk, G., & Mazzucato, M. (2019). Financing Green Growth. In R. Fouquet (Ed.), *Handbook on Green Growth*. Cheltenham, UK: Elgar.
- Sen, S., & von Schickfus, M.-T. (2020). Climate policy, stranded assets, and investors'

- expectations. *Journal of Environmental Economics and Management*, 100, 102277. <https://doi.org/https://doi.org/10.1016/j.jeem.2019.102277>
- Shiller, R. J. (2001). *Irrational exuberance*. Princeton [etc.]: Princeton University Press.
- Silver, N. (2017). Blindness to risk: why institutional investors ignore the risk of stranded assets*. *Journal of Sustainable Finance and Investment*, 7(1), 99–113. <https://doi.org/10.1080/20430795.2016.1207996>
- Smith, C. J., Forster, P. M., Allen, M., Fuglestedt, J., Millar, R. J., Rogelj, J., & Zickfeld, K. (2019). Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming. *Nature Communications*, 10(1), 1–10. <https://doi.org/10.1038/s41467-018-07999-w>
- Stiglitz, J. E. (2014). Reconstructing macroeconomic theory to manage economic policy. *Fruitful Economics: Papers in Honor of and by Jean-Paul Fitoussi*, 20–56. <https://doi.org/10.1057/9781137451057.0005>
- Sweezy, P. (1970). *Theory of Capitalist Development*. New York: Monthly Review Press.
- Szostack, R. (1995). *Technological Innovation and the Great Depression*. Boulder and Oxford: Westview Press.
- Taylor, L. (2012). *Maynard's Revenge*. Cambridge, MA, and London: Harvard University Press.
- TCFD. (2016). The use of scenario analysis in disclosure of climate-related risks and opportunities. *Technical Supplement, Task Force on Climate-Related Financial Disclosures*.
- TCFD. (2017). *Recommendations of the Task Force on Climate-related Financial Disclosures*. Task Force on Climate-related Financial Disclosures.
- Thomä, J., Dupré, S., & Hayne, M. (2018). A Taxonomy of Climate Accounting Principles for Financial Portfolios. *Sustainability*, 10(328).
- Tolliday, S. (1987). *Business, Banking and Politics*. Cambridge, MA and London, England: Harvard University Press.
- UNEP FI. (2019). Changing course. *UNEP Finance Initiative*.
- Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, 28(12), 817–830. [https://doi.org/https://doi.org/10.1016/S0301-4215\(00\)00070-7](https://doi.org/https://doi.org/10.1016/S0301-4215(00)00070-7)
- Vague, R. (2019). *A Brief History of Doom: Two Hundred Years of Financial Crises*. Philadelphia: University of Pennsylvania Press.
- van der Ploeg, F., & Rezai, A. (2019). Stranded Assets in the Transition to a Carbon-Free Economy. *CESifo Working Paper*, 8025.
- van der Ploeg, F., & Rezai, A. (2020). The risk of policy tipping and stranded carbon assets. *Journal of Environmental Economics and Management*, 100. <https://doi.org/10.1016/j.jeem.2019.102258>
- Vaze, P., Meng, A., & Giuliani, D. (2019). *Greening the Financial System: Tilting the Playing Field: The Role of Central Banks*. London: Climate Bonds Initiative.
- Vermeulen, R., Schets, E., Lohuis, M., Kölbl, B., Jansen, D.-J., & Heeringa, W. (2018). An energy transition risk stress test for the financial system of the Netherlands. *De Nederlandsche Bank, Occasional Studies*, 16–7.
- Vermeulen, Robert, Schets, E., Lohuis, M., Kölbl, B., Jansen, D.-J., & Heeringa, W. (2019). The Heat Is on: A Framework for Measuring Financial Stress Under Disruptive Energy Transition Scenarios. *DNB Working Paper*, 625. <https://doi.org/10.2139/ssrn.3346466>
- Volz, U. (2017). On the role of central banks in enhancing green finance'. *UN Inquiry Working Paper*, 17/01.

- Volz, U., Ambrosio, N., Beirne, J., Fenton, A., Mazzacurati, E., Rhenzi, N., & Stampe, J. (2020). *Climate Change and Sovereign Risk*. London, Tokyo, Singapore and Berkeley, CA: SOAS University of London, Asian Development Bank Institute & Four Twenty Seven.
- Volz, U., Böhnke, J., Eidt, V., Knierim, L., Richert, K., & Roeber, G. M. (2015). *Financing the Green Transformation – How to Make Green Finance Work in Indonesia*. Houndmills, Basingstoke: Palgrave Macmillan.
- Weidmann, J. (2019). Consistency as a mandate: Speech at the ceremony to commemorate “250 years of the Pfandbrief.”
- World Bank. (2019). *State and trends of carbon pricing 2019*. Washington, DC: World Bank Group.