

ADVANCED REVIEW**WILEY**

Low-carbon transition risks for finance

Gregor Semieniuk^{1,2}  | **Emanuele Campiglio**³ | **Jean-Francois Mercure**^{4,5,6}  | **Ulrich Volz**^{2,7}  | **Neil R. Edwards**^{5,8} 

¹Political Economy Research Institute & Department of Economics, University of Massachusetts Amherst, Amherst, Massachusetts

²Department of Economics & SOAS Centre for Sustainable Finance, SOAS University of London, London, UK

³Institute for Ecological Economics, Vienna University of Economics and Business, Vienna, Austria

⁴Global Systems Institute, University of Exeter, Exeter, UK

⁵Cambridge Centre for Energy, Environment and Natural Resource Governance (C-EENRG), Department of Land Economy, University of Cambridge, Cambridge, UK

⁶Cambridge Econometrics Ltd, Cambridge, UK

⁷German Development Institute, Bonn, Germany

⁸Environment, Earth and Ecosystems, The Open University, Milton Keynes, UK

Correspondence

Gregor Semieniuk, Political Economy Research Institute & Department of Economics, University of Massachusetts Amherst, Amherst, MA; and Department of Economics, SOAS University of London, London, UK.
Email: gsemienuk@econs.umass.edu; gs53@soas.ac.uk

Funding information

Natural Environment Research Council, Grant/Award Number: NE/S017119/1; Oesterreichische Nationalbank: Grant 17641; Stiftelsen för Miljöstrategisk Forskning

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 in rising industries. Studies on previous industrial transitions have shed light on the financial transition risks originating from rapidly rising “sunrise” industries. In contrast, a similar conceptual understanding of risks from declining “sunset” industries is currently lacking. We substantiate this claim with a critical review of the conceptual and historical literature, which also shows that most literature either examines structural change in the real economy, or risks to financial stability, but rarely both together. 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 and on the feedback from the financial system into the rest of the economy. We also review the state of play of policy aiming to protect the financial system from transition risks and spell out research implications.

This article is categorized under:

Climate Economics > Economics and Climate Change

KEYWORDS

financial stability, low-carbon economy, stranded assets, structural change, sunset industries, transition risks

Edited by Julie Rozenberg, Domain Editor, and Mike Hulme, Editor-in-Chief

1 | INTRODUCTION

Climate change mitigation requires the rapid decarbonization of the economy. Climate change is already threatening society through altered patterns of extreme weather events and through impacts on critical ecosystems. 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, 2019). 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.

Decarbonizing 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 toward promising paths for decarbonization (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. While there has been a rapid expansion of concepts and evidence concerning transition risks from academia, private industry, and regulators (e.g., 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 article 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 shifts are linked to finance (Freeman & Louca, 2001; Perez, 1983; Schumpeter, 1939). We find that the overwhelming majority of this literature has focused on how financial risks develop in sunrise industries, that is, the rising sectors, where bubbles could develop and then burst, with detrimental impacts on wider 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 developing in sunset industries (carbon-intensive ones, in this case). For instance, a widespread preoccupation concerns the financial repercussions of asset stranding, that is, the unexpected devaluation or write-off of assets from the balance sheets of economic agents (Caldecott, 2018; van der Ploeg & Rezai, 2019). The “focus shift” between past literature on transitions and the current debate leaves us without a well-defined comprehensive framework to understand and address how low-carbon transition financial risks develop in sunset sectors and interact with those in sunrise industries.

To advance the debate and contribute to filling this conceptual gap, we develop a minimal but consistent framework of low-carbon transition risks for finance. We distinguish: (a) drivers of transition risks; (b) the economic costs that the transition could impose on non-financial agents in terms of loss of income and asset stranding; (c) 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 (d) the wider macroeconomic effects leading to a loss of aggregate demand

and recession. Finally, we outline and comment on the current state of policies pursued by central banks and other actors seeking to stabilize the financial system without interfering with the transition itself, in the fast-evolving policy community on climate-related financial risks.

The remainder of the article is organized 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. Section 5 discusses actual and possible policies aimed at mitigating transition risks. Section 6 concludes with potential research avenues.

2 | THREATS TO FINANCIAL STABILITY FROM THE RISE AND FALL OF INDUSTRIES

For the purposes of analyzing 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 (Syrquin, 2010).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 relation, we turn to the literature on financial crises and on innovation as the process underlying structural change.

2.1 | 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 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 behavioral change, tends to omit systemic financial aspects; recent exceptions are Callegari (2018) and Geddes and Schmidt (2020). 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, that is, how the 2007–2008 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 these two fields. Perhaps the oldest such program of continued relevance is to be found in Marxist crisis theories (Basu, 2018; Shaikh, 1978), 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) and 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.

Real business cycle theory models (negative) shocks from technological change 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, 2018). The only theoretical approach placing the interaction of finance and structural change front and center appears to be the Schumpeterian one.²

2.2 | 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 risks overestimating sunrise industries’ growth potential (Schumpeter, 1939). Over-indebtedness and defaults can result from the exhaustion of an innovation cluster, and generate a financial crisis. One instance that this theory can 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 development of financial instability, and Schumpeter (1939) explicitly states that the negative effects of bankruptcy and decline in the sunset industries is overcompensated by the growth in the new industries. In other words, as long as growth opportunities in the sunrise sector exist, systemic economic and financial stability are not compromised by a failing sunset sector. This does not preclude sunset capital owners from losing their investments during periods of “structural crises of adjustment” that also spell unemployment and decline in living standards for a significant share of the population (Freeman & Louca, 2001). A recent example relevant to the low-carbon transition is the layoffs and declines in living standards in coal-mining communities catalyzing demands for a “just transition” (Rosemberg, 2010).

Subsequent work by Schumpeterian scholars emphasizes 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 Minsky’s (1975, 1986) financial instability hypothesis, which describes how the financial sector continuously drives itself toward 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.

2.3 | Risks associated with sunset industries

To the best of our knowledge, to date, there is little theory that explains financial instability caused by sunset industries. 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, Godin, and Lucarelli (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. The slightly neglected work by Szostack (1995) demonstrates that process innovations in sunset sectors combined with a lack of new product innovations can explain rising unemployment in the Great Depression, but stops short of linking this account to the financial collapse.

The 1930s and 1940s see the discussion of the microeconomic problem of “premature abandonment”, an earlier term for asset stranding (Caplan, 1940). This literature is related to vintage capital models of growth and fluctuations, which remain somewhat disconnected from financial stability (see, e.g., Benhabib & Hobbijn, 2003). A neo-Schumpeterian vintage capital model allows for costly reallocation of factors of production between industries, but has not analyzed 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. Individual industries, such as cotton or steel suffered from chronic overcapacity after 1920, and government programs were instituted to scrap uncompetitive machines to reduce capacity (Lazonick, 1984; Tolliday, 1987). Banks that had lent during the uptick of domestic demand in 1919–1920 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 of specific industries contributed to vulnerabilities in the financial sector (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 it is recognized that 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 destabilize the economy and induce systemic financial instability. The underlying logic argues that while some companies and even financial institutions 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.

3 | 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 to achieve the Paris agreement targets, many 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; McGlade & Ekins, 2015; Meinshausen et al., 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 engender 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 2007–2008 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 it is 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 expected to be 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 (which saw share prices drop by 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), 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”.⁵

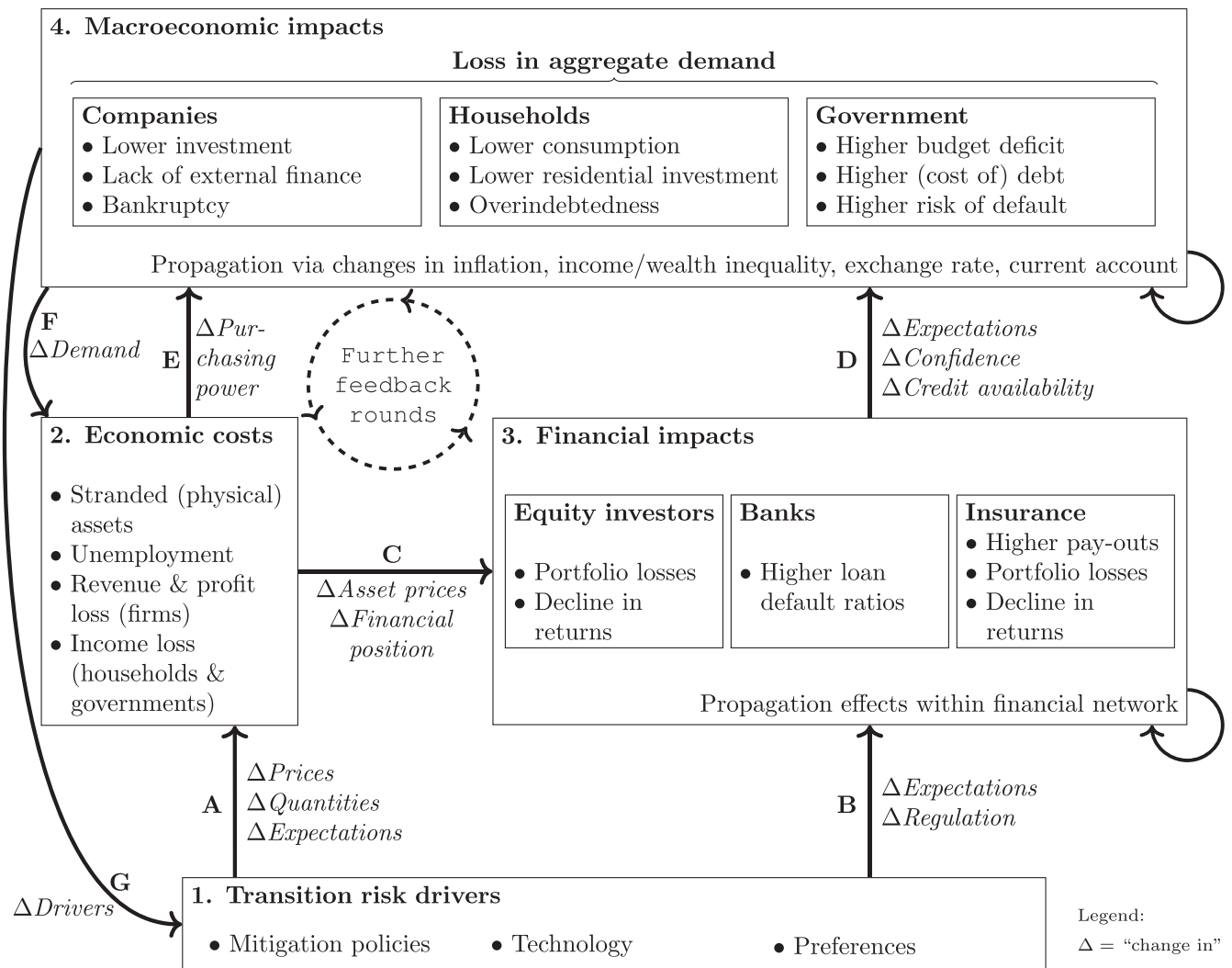


FIGURE 1 Schematic view of chain of causation from risk drivers to impacts (boxes) via transmission channels (arrows)

However, the current debate suggests that such a sunrise industry-induced financial instability, if it materializes, may be preceded by and interact with systemic risks realized in sunset industries.

4 | 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 conceptually, but the contrary is true of declining industries. Conversely, attention in the low-carbon transition is on sunset industries, but sunrise industries are largely ignored. To improve an understanding of possible channels whereby risks are transmitted from both sets of industries, we classify them to identify the drivers, costs, and impacts and their logical connection via transmission channels. The summary of the logical argument is mapped in Figure 1. We review evidence for each of these as we describe them.

4.1 | Transition risk drivers

Transition risk drivers (Figure 1, box 1) create economic costs and financial impacts via changing relative prices or market demand/supply in favor 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). Most drivers affect sunset industries negatively, for example, by altering relative prices in favor of low-carbon products. By implication they affect sunrise industries and expectations about them positively, so could drive—at least in the medium-term—sunrise risk from speculation, too. Key drivers are climate change mitigation policy, technological change, and changes in consumer taste (PRA, 2015). These are reviewed in turn as follows.

4.1.1 | Climate change mitigation policies

Policy seeking to internalize the carbon externality is a key driver of risks. The central plank of most climate change mitigation strategies consists of incentive-based regulation that prices carbon either via taxes or cap-and-trade schemes. The suite of scenarios limiting global warming to 1.5°C in the recent IPCC (2018) assessment 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 Five-Year Plan (National Development and Reform Commission, 2016) or Europe's Green Deal (European Commission, 2019), include mandating, subsidizing, 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 such as differentiated prudential requirements, lending quotas, or targeted refinancing lines by the central bank regulate the financial sector directly (Campiglio et al., 2018; Volz, 2017). 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.

4.1.2 | Technological change

Cost-saving technological innovations, possibly incentivized by earlier climate policies, further lower the prices of low-carbon technologies (Kavlak, Mc Nerney, & Trancik, 2018; Nemet, 2019). This is a nonlinear 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). Technological trajectories can also influence policy by opening up policy space through newly affordable alternatives (Schmidt & Sewerin, 2017) and closing it down through path dependencies (Fouquet, 2016). Conversely, of course, policies and the politics behind them influence which technologies are developed and deployed (Stirling, 2014).

4.1.3 | Preference change

Buyers' preferences can drive demand and prices. Preferences are endogenous to institutions and their changes (Bowles, 1998) and as more people use a technology, network effects 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). Moving beyond private consumption choices, preference changes can stir political movements, putting broader pressure on policy making and changing what is politically feasible.⁶ The public

mobilization 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.

4.2 | Transition costs

Transition drivers translate into transition costs (Figure 1, box 2) via two transmission channels (Figure 1, arrow A). Price and quantity changes lead to adjustments in all sectors, affecting revenues of producers, the real income of households via unemployment and loss of earnings on investment, and state tax and state-owned enterprise revenue. Fossil fuel price changes can be complex (Box 1). But importantly, the drivers also operate via expectations about future revenue streams, especially if policy and preference changes are credible and long-lasting (Helm, Hepburn, & Mash, 2003). This is not guaranteed, 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 uncertainty concerning their implementation (den Elzen et al., 2019; Pauw, Castro, Pickering, & Bhasin, 2019). However, if expectations change, asset stranding can occur.⁷

4.2.1 | Physical asset stranding

A growing literature analyses high-carbon physical assets at risk of stranding. The risk that excess reserves of fossil-fuel companies pose 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, Schneider, Stevenson, and Fox (2019).⁹ Davis, Caldeira, and Matthews (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; Tong et al., 2019). Yet, uncertainty remains: Rozenberg, Davis, Narloch, and Hallegatte (2015) calculate that for a 2°C warming scenario any fossil fuel asset built after 2017 cannot start operating if existing assets are prioritized 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 warm 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 occur virtually anywhere in the economy. Cahen-Fourot, Campiglio, Dawkins, Godin, and Kemp-Benedict (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, 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.

BOX 1 The effect of a carbon price on fossil fuel prices

A price on carbon is 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, 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, they might decide to flood the market in the short-run in a race to the bottom, to sell whatever they can (Sinn, 2008).⁸ This can also have consequences for the distribution of stranded assets, as lower-cost producers capture what is left of the declining market (Mercure et al., 2018).

Research has been conducted on systematically valuing the loss of assets due to stranding. Mercure et al. (2018) estimate losses of \$1 tn–\$4 tn 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 \$0.957 tn of power sector asset stranding up to 2050 was found in a bottom-up assessment by Saygin, Rigter, Caldecott, Wagner, and Gielen (2019). One of the most cited works in this area is in the gray literature: for the IEA's Below 2 Degree scenario, Carbon Tracker and UNPRI 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 \$10 tn stranded over the period 2015–2050, which increases to \$20 tn in a scenario of delayed transition policies. Dietz, Bowen, Dixon, and Gradwell (2016) calculate *value at risk* from the transition to be 0.4% of global financial assets, or \$0.6 tn. Recent analytical models show how, depending on the type and stringency of the policy implemented, some asset stranding in the form of under-utilization 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.

4.2.2 | 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 stabilizing 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; moreover, stranded workers may not be easily re-employed (Heim, 1984). 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 lose tax and other revenue from plunging sales 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 toward investments outside the fossil energy sector to keep the fiscal stance sustainable.

Real incomes of households could shrink due to rising prices, in addition to loss of employment, and 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 if implemented without countervailing redistribution. In such a case, Fremstad and Paul (2019) estimate that US households in the poorest deciles would 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.

4.3 | Financial impacts

Drivers impact the financial sector (Figure 1, box 3) directly via changing expectations about transition costs and rules (arrow B), and indirectly via transition costs (arrow C). There are two principal impacts: credit and market risks. 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 nonperforming loans could in turn reduce the profitability of the lending bank, affect its market valuation, and, if the phenomenon is significant enough, lead to a bank run and its default (Dafermos & Nikolaidi, 2019b; Diamond & Dybvig, 1983). The magnitude 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). Transition

costs, or expectations thereof, 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 on private financial markets could go well beyond the direct exposure of investors to carbon-intensive sectors, due to financial contagion (Allen & Gale, 2000). Financial systems have featured deeply connected networks throughout history (Graeber, 2011), and international financial liberalization since the 1970s has only reinforced this interconnectedness (Christophers, 2013). Besides being exposed to the same stranded assets, financial institutions also 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 with, academia (e.g., HSBC, 2019; Mercer, 2019; UNEP FI, 2019). Two types of analytical approaches are employed (Campiglio, Monnin, & von Jagow, 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 characterized by sudden changes of “sentiments” leading to unexpected volatility of prices. PRA (2018) calls the eventuality of fluctuations of the investor sentiments concerning the likelihood of future transition scenarios a “climate Minsky moment”.¹¹ To grasp these effects, a second research approach uses the “stress testing” conceptual framework to analyze 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).

Sanguine expectations about returns in sunrise sectors (operating mainly via arrow B) could in principle lower the financial sector repercussions just described as more investors are hedging their exposure to high-carbon assets with investments in lower-carbon alternatives (Andersson, Bolton, & Samama, 2016; Engle, Giglio, Kelly, Lee, & Stroebel, 2020). However, as we have seen in Section 2, it might also be possible—at least in the medium term—that a “mania” about low-carbon risks ultimately destabilizes the financial system. Moreover, the bigger the low-carbon sector is, the more credible the threat that production patterns could quickly switch away from high-carbon sectors. How important hedging could be for transition risks, and how soon low-carbon sectors could become widespread objects of speculation is hard to say, and finance journals have only recently started to pay attention to this problem (Diaz-Rainey, Robertson, & Wilson, 2017; Hong, Karolyi, & Scheinkman, 2020).

Table 1 summarizes outputs from the few academic and a selection 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*, that is, 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).

4.4 | Macroeconomic impacts

Transition costs and financial impacts could each cause macroeconomic impacts (Figure 1, box 4 via arrows D and E) that reduce aggregate demand. We highlight some of the possible channels.

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

#	Study	Region and Channel	Scenario (with value in parentheses as a share of regional GDP)
1	Giuzio et al. (2019)	First 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, and the USA to high environmental risk	Outstanding loans amount to 1.6 trillion 2014 USD (3.1% of GDP of selected countries)
3	Battiston et al. (2017)	First- and second-round exposure of top 50 EU banks to high-carbon assets	100% loss of fossil fuel & utility sector portfolio wipes out 13.5% of top 50 banks' equity (32.7% of European Union GDP)
4	Vermeulen et al. (2018)	First- and second-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)
<i>Physical risk studies for comparison</i>			
5	Dietz et al. (2016)	Global assets at risk under DICE BAU versus mitigation scenario	99th percentile of total assets at risk amounts to 24.2 trillion 2013 USD (31.5% of global GDP)
6	Lamperti, Bosetti, Roventini, and Tavoni (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.

4.4.1 | Banking channel

The increase in nonperforming 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 could in turn lead to a drop in investment levels of both firms (new capital assets), households (new real estate), and governments (new public capital assets and infrastructure).

4.4.2 | Confidence 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 capitalization to book value ratio lowers investments.¹² If the crisis affects the entire economy, these effects may also reduce investment in low-carbon sectors, as uncertainty raises the option value of waiting (Dixit & Pindyck, 1994).

4.4.3 | Consumption channel

Reduced income from unemployment and reduced wealth from revaluations of assets held for example, via pension funds, could shrink 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, 2019).

4.4.4 | Public debt channel

Government expenditure is likely to initially react counter-cyclically to the reduction in other expenditure categories due to automatic stabilizers, 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).

4.4.5 | Other macroeconomic effects

Additional macroeconomic impacts could alter inflation rates, trade balances, and exchange rates, which in turn could generate dynamics to re-assess existing international economic agreements (such as on trade) and propagate aggregate demand reductions. The international spill-overs of financial instability can generate volatility in foreign investment positions and exchange rates that can lead to follow-on debt crises, especially in developing countries. These impacts are, at the moment, hard to quantify and - like all other effects - subject to stabilization efforts by governments at the time of the crisis.

The combined effect of these impacts most likely decreases aggregate demand. This could in turn amplify transition costs (arrow F) in all sectors and generate further financial impacts, in the worst case sending the economy into a downward spiral of negative real-financial interactions with negative macroeconomic multipliers amplifying initial losses. A credit crunch likely also affects financing for sunrise industry investments, and transition drivers (arrow G). The only study that currently attempts to connect transition financial impacts with macroeconomic impacts is Vermeulen et al. (2018), highlighting that most literature either examines structural change in the real economy, or risks to financial stability but rarely both together. Financial sectors are also missing from integrated climate change scenarios (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 modeling efforts can use these as benchmarks.

4.5 | Two stylized scenarios

To better illustrate our theoretical framework, we conclude this section with two stylized scenarios using the concepts and channels presented above. We distinguish between: (a) a smooth orderly transition; (b) a disruptive transition. Both scenarios start from the same point. Renewable electricity and heat, low-emission transport, energy-efficient retrofits, and other low-carbon products proliferate as relative prices tilt in their favor, driven by climate policies, technological change, and changes in preferences and behavior.

A disruptive transition scenario could ensue if an ever-larger discrepancy arises between this direction of technological trajectory and sunset industry investment. Firms continue developing fossil reserves, building pipelines, transformation plants, and internal combustion engine factories, possibly egged on by beliefs of oil demand rebound, that are shared by a sufficient number of financial investors. These beliefs could in turn be supported by uneven and erratic climate policies, highly publicized low-carbon technological setbacks, vested interests bound up with at least a semblance of “business as usual” in the high-carbon sectors and biased information as prominent forecasters and scenarios reinforce shared beliefs. As large investments become sunk and committed, returns do not materialize due to tougher low-carbon competition. Thus, persistently low fossil fuel prices and insufficient demand for high carbon products erode cash flows and destabilize large balance sheets. Stock market valuations, still reflecting the belief of a high-carbon future, become vulnerable to sudden changes in expectations.

Disorder could then be triggered by, for instance, a disruptive event affecting one of the transition drivers. This could be a large-scale climatic event (e.g., unprecedented heat waves) that creates a generalized sense of urgency, leading to an “inevitable policy response” (PRI, 2020). This might take the form of a rapid and unanticipated increase in the price on the carbon content of goods or highly restrictive regulation. Transition costs jump upwards and firms re-evaluate their earnings prospect and write off assets. Banks re-assess the performance of their fossil-related loans and write off substantial shares of their assets in turn. Equity investors may react faster, anticipating the market-woes, and

jettison high-carbon firm financial investments, whereby market valuation collapses. At this point, the full chain of events described in the previous subsections could play out.

A smooth transition avoids the divergence between the direction of investments and that of the transition drivers. First, climate change mitigation policies are introduced gradually and at regular intervals with increasing degrees of ambitions. Their implementation is announced with enough warning for economic agents to prepare appropriately. They are backed by a large social and political majority, with low risk of policy reversal after changes in government. Several institutions (government, central bank, financial regulators, and others) concur in creating a harmonized policy effort, also across borders. Second, low-carbon technological progress continues at high speed but without major unanticipated breakthroughs or setbacks, and this progress is well communicated (possibly with appropriate government policies), so that market participants are aware of current technological trends and industry advancements. Third, consumers gradually shift their preferences toward low-carbon goods and services. Finally, the wider socio-economic context is also free of major disruptions (no wars, no pandemics, no disruptive climate-related physical impacts).

If these conditions are met, non-financial firms will recalibrate their new investments toward low-carbon technologies, while gradually phasing out existing high-carbon capital stock. Some firms will be less successful than others, but widespread default is avoided with enough companies having diversified and transitioned into low-carbon industries. Facilitated by firms' increasing climate risk disclosure and other financial sector regulations (see section 5), financial institutions will also gradually reallocate their investments toward firms with a lower carbon intensity. The high-carbon sector effectively manages its shrinking balance sheet, so that banks continue to receive interest payments until loans are repaid. Insurance companies are spared from major transition-triggered disruptions. For these reasons, the full set of transition impacts is never set in train.

These two scenarios bound a spectrum of transition scenarios of increasingly abrupt changes in expectations. Managing a smooth yet successful transition will be difficult due to time constraints, as currently existing and planned capital stock is likely already capable of producing emissions beyond the 2°C carbon budget. The challenge for policy-makers will be to use the small window of opportunity to manage a controlled transition where both climate damage and transition costs are minimized.

5 | POLICY RESPONSES TO MITIGATE FINANCIAL TRANSITION RISKS

While some policies drive the transition, others seek to reduce 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 a scrutinizing discourse on their role in safeguarding financial stability, and their mandate more broadly (e.g., Dikau & Volz, 2020; 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 centered 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; Beirne, Rhenzi, & Volz, 2020; Buhr et al., 2018; Kling et al., 2018). 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 incentivizing 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 “dirty” 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 revaluation. In January 2016, the Financial Stability Board established a Task Force on Climate-related Financial Disclosures (TCFD), which published 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, that is, high-carbon penalizing 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 65 central banks and supervisors (as of July 2020), 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 among firms to analyze their exposure. The second step is the assessment of climate risks at both the micro- and macro-prudential level, that is, 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) emphasizes that climate change-related financial risks “are best mitigated through an early and orderly transition.”

Existing stabilization policy has been criticized by academic studies as inadequate. In particular, researchers have criticized 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, Drummond, Bisaro, Grubb, and Chenet (2019) argue, based on interviews with investors, that disclosure by itself is insufficient to change investment behavior, as the argument rests on the unrealistic efficient market hypothesis (that financial markets price in all information). Monasterolo, Battiston, Janetos, and Zheng (2017) note the difficulty of disclosing supply-chain carbon exposure. And disclosure may help re-classify fossil fuel assets as junk, but does not make their associated systemic risk disappear (Mercure, 2019). More generally, the complexity of financial systems interlinkages limits the ability of regulators to address systemic risk (Battiston, Caldarelli, May, Roukny, & Stiglitz, 2016), which can be exacerbated rather than mitigated by internationally integrated financial markets (Stiglitz, 2010). 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 favor green over dirty assets (e.g., Weidmann, 2019). With reference to the market neutrality principle, central banks have thus far also resisted calls for green quantitative easing, where central bank asset purchases would be used to foster a green transition. In general, 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 (Dikau & Volz, 2020; D'Orazio & Popoyan, 2019; 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 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

Finally, it is important to mention that appropriate redistributive and industrial policy can also reduce financial risks indirectly by mitigating transition costs. 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 more in absolute terms, feebates turn carbon prices into a progressive instrument (Boyce, 2018). Just transition policies could

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 via existing public development banks seasoned in financing industrial policy that 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 compromise the ability of those nations to support the low-carbon transition through fiscal means.

6 | CONCLUSION

Low-carbon transition risks for finance arise from the abrupt structural change toward low-carbon industries that alters expectations about future revenue streams in high-carbon industries. A comprehensive theoretical framework explaining such sunset industry systemic risks for finance has hitherto been lacking because the theoretical and historical literature has tended to focus instead on historically more important risks from sunrise industries. Current academic research into transition risks tends to address either the real-economy structural change, or the financial impact, but does not typically connect the two. We contribute to the conceptual understanding of transition risks 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.

High-carbon industries could abruptly become uncompetitive due to a rapid change in climate-mitigation policy, low-carbon technology or preferences, or a widespread change in expectations of their impacts. These transition drivers cause physical assets to lose their ability to generate revenue, and if this is unanticipated, they become stranded. Asset stranding combines with other transition costs, notably unemployment, losses in profits, and reductions in real incomes from price changes 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: 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 policies, however, can dampen some transition risks by direct regulation of the financial sector.

What this article highlights is the need to understand in detail the transition risks for the macroeconomy and the financial system. This calls for contributions from a number of different fields of research.

6.1 | Theory and History

We have tried in this article to start developing a conceptual framework, but more work would be welcome. Rich literatures on business cycles and structural change already provide building blocks, some of which we reviewed in Section 2. But they need to be connected. A clearer focus on the role of declining industries in triggering or exacerbating instability would help root much of the discussion about stranded assets and financial risks in consistent theoretical frameworks. Historical research with a lens on how declining sectors fared in downturns and may have contributed to financial and economic crises could provide valuable insight and validation of theoretical frameworks. Moreover, it would also be important to understand how—at least in the longer term—sunset and sunrise sector investments may interact to either mitigate or exacerbate transition risks.

6.2 | Modeling

At the moment few, if any, modeling frameworks are capable of capturing the complexity of interactions described above. Besides lack of theoretical connections, model assumptions (e.g., rational expectations, banks as pure intermediaries), methods (e.g., no network analysis) and poor data access (most academics cannot afford access to proprietary

financial databases, many of which in turn are not made for large data queries) complicate integration of all relevant model components. Progress is being made on all of these fronts, and benefits from the bigger shift toward research on financial instability following the Great Recession (Campiglio, Godin, Kemp-Benedict, & Matikainen, 2017), yet much more effort is needed to integrate these strands.

6.3 | Institutions and governance

Research on the role of institutions and governance is in some ways most advanced thanks to the regulatory attention that was reviewed in Section 5, and has stimulated attempts at modeling. Making progress in the other areas could in turn generate useful insights on the appropriate regulatory roles and actions; ideally moving beyond a focus on disclosure to investigate what “unconventional” measures might be conducive to smoothing the transition. Research could also usefully elucidate how the varying institutional conditions in different parts of the world, and importantly in non-high income countries influence transition risks and feasible policy responses.

ACKNOWLEDGMENTS

The authors thank Ryan Barrett, Yannis Dafermos, Duncan Foley, Roger Fouquet, Carol Heim, Thomas Herndon, Kate Jobson, David Kotz, Carlota Perez, Edo Schets, Romain Svartzman and Isabella Weber as well as three anonymous referees for insights, helpful feedback, and comments. Remaining errors are solely the authors'. G. S., J.-F. M., and N. R. E. acknowledge funding from Natural Environment Research Council Grant NE/S017119/1 “Financial risk and the impact of climate change”. E. C. acknowledges the financial support of the Swedish Foundation for Strategic Environmental Research (Mistra) and the Oesterreichische Nationalbank (OeNB).

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Emanuele Campiglio: Conceptualization; funding acquisition; investigation; writing-original draft; writing-review and editing. **Jean-Francois Mercure:** Conceptualization; funding acquisition; investigation; writing-original draft; writing-review and editing. **Ulrich Volz:** Conceptualization; investigation; writing-original draft; writing-review and editing. **Neil Edwards:** Conceptualization; funding acquisition; writing-review and editing.

ORCID

Gregor Semieniuk  <https://orcid.org/0000-0002-2747-595X>

Jean-Francois Mercure  <https://orcid.org/0000-0003-2620-9200>

Ulrich Volz  <https://orcid.org/0000-0001-9917-8068>

Neil R. Edwards  <https://orcid.org/0000-0001-6045-8804>

ENDNOTES

¹ Cherp, Vinichenko, Jewell, Brutschin, and Sovacool (2018) show that for other purposes adopting a more multi-disciplinary definition can be productive.

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

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

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).

⁵ Discussions of green bubbles have to date taken place mainly outside academia, for example, in central banking circles (Regelink, Reinders, Vleeschhouwer, & van de Wiel, 2017). If anything, academic research has considered the reverse direction of causation, how the recent financial crisis has either slowed the progress of the green transition (Falcone, Morone, & Sica, 2018; Geels, 2013) or accelerated it through subsequently low interest rates that lowered the costs of capital intensive low-carbon power generation (Schmidt et al., 2019).

- ⁶ This effect cuts both ways. While “Fridays for Future” and “Extinction Rebellion” protests that started in 2019 may make stringent policy more feasible (Horton, 2019), protests may also constrain the rollout of climate policy (Jewell & Cherp, 2020).
- ⁷ In a rational expectations framework, stranded assets occur under policy time-inconsistency (Kalkuhl, Steckel, & Edenhofer, 2019).
- ⁸ Note that the extent to which this increases cumulative emissions relative to a world without a carbon price and so causes a situation termed the “green paradox” is subject to model assumptions, and existing empirical evidence tends to refute it (Jensen, Mohlin, Pittel, & Sterner, 2015).
- 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).
- 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, Jaffe, Lont, and Dominguez-Faus (2015) discuss reasons for the lack of response of investors to news about impending stranded assets, and Sen and von Schickfus (2020) suggest high-carbon firms expect compensation for anticipated stranding. Christophers (2019) reports and analyses investors’ views.
- 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 materialize (Tracker & UNPRI, 2018; Bond, 2018). Scenarios charting pathways to meet the Paris targets also see global fossil fuel demand peaking in the 2020s (Rogelj et al., 2018).
- 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).
- ¹⁴ See, for instance, Batten, Sowerbutts, and Tanaka (2016), ESRB (2016), Finansinspektionen (2016), Regelink, Reinders, Vleeschhouwer, and van de Wiel (2017), PRA (2018), and NGFS (2019).
- ¹⁵ For an overview of policy tools available to central banks and supervisors see Dikau and Volz (2019).
- 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, 2015).
- 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).

RELATED WIREs ARTICLES

[From climate finance toward sustainable development finance](#)

[Differentiating regions for adaptation financing: The role of global vulnerability and risk distributions](#)

[Mobilizing private finance for coastal adaptation: A literature review](#)

REFERENCES

- Allen, F., & Gale, D. (2000). Financial Contagion. *Journal of Political Economy*, 108(1), 1–33. <https://doi.org/10.1086/262109>
- 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, No. 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*, 160(4), 565–589. <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*, 2018(1), 1–20. <https://doi.org/10.21033/ep-2018-1>
- Andersson, M., Bolton, P., & Samama, F. (2016). Hedging climate risk. *Financial Analysts Journal*, 72(3), 13–32. <https://doi.org/10.2469/faj.v72.n3.4>

- 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/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/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: 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., Caldarelli, G., May, R. M., Roukny, T., & Stiglitz, J. E. (2016). The price of complexity in financial networks. *Proceedings of the National Academy of Sciences of the United States of America*, 113(36), 10031–10036. <https://doi.org/10.1073/pnas.1521573113>
- 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*, July 1, 1–33. <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*, 66, 102083. <https://doi.org/10.1016/j.cpa.2019.04.004>
- Beirne, J., Rhenzi, N., & Volz, U. (2020). Feeling the Heat: Climate Risks and the Cost of Sovereign Borrowing. *Asian Development Bank Institute Working Paper*, 1159.
- Benhabib, J., & Hobbijn, 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, NJ: Princeton University Press.
- Berg, A. O., Clapp, C., Lannoo, E., & Peters, G. (2018). *Climate scenarios demystified. A climate scenario guide for investors. CICERO Report*. Oslo, Norway: 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*. Basel, Switzerland: 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>
- Bond, K. (2018). *2020 vision: why you should see peak fossil fuels coming*. London: Carbon Tracker Initiative.
- 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. *Journal of Economic Literature*, 36(1), 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. M., 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*. London: Imperial College London.
- 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., Drewniak, 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/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*. 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/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., Godin, A., Kemp-Benedict, E., & Matikainen, S. (2017). The tightening links between financial systems and the low-carbon transition BT. In P. Arestis & M. Sawyer (Eds.), *Economic policies since the global financial crisis*. Cham: Springer International Publishing https://doi.org/10.1007/978-3-319-60459-6_8
- Campiglio, E., Monnin, P., & von Jagow, A. (2019). *Climate risks in financial assets [Discussion]*. Zurich: Council on Economic Policies.
- 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*. Hoboken, NJ: 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), 17140. <https://doi.org/10.1038/nenergy.2017.140>
- 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. In P. Arestis & M. Sawyer (Eds.), *Frontiers of heterodox macroeconomics*. London: Palgrave Macmillan. 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.
- 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). Geneva: 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*, 140, 111195. <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>
- Diamond, D. W., & Dybvig, P. H. (1983). Bank runs, deposit insurance, and liquidity. *Journal of Political Economy*, 91(3), 401–419.
- Diaz-Rainey, I., Robertson, B., & Wilson, C. (2017). Stranded research? Leading finance journals are silent on climate change. *Climatic Change*, 143(1), 243–260. <https://doi.org/10.1007/s10584-017-1985-1>
- 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 (2015). 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.
- Dixit, A., & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton, NJ: Princeton University Press.
- 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>
- Dosi, G. (1982). Technological paradigms and technological trajectories. *Research Policy*, 11(3), 147–162.
- Engle, R. F., Giglio, S., Kelly, B., Lee, H., & Stroebel, J. (2020). Hedging climate change news. *The Review of Financial Studies*, 33(3), 1184–1216. <https://doi.org/10.1093/rfs/hhz072>
- ESRB. (2016). *Too late, too sudden: Transition to a low-carbon economy and systemic risk. Report of the Advisory Scientific Committee*, 6. Frankfurt, Germany: 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.
- Fisher, J., Johnson, D., Latner, J., & Smeeding, T. (2019). Estimating the marginal propensity to consume using the distributions of income, consumption, and wealth. Federal Reserve Boston Research Department Working Papers 19-4.
- 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). Elgar: Cheltenham, UK.
- Fouquet, R. (2016). Path dependence in energy systems and economic development. *Nature Energy*, 1, 16098. <https://doi.org/10.1038/nenergy.2016.98>
- 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. (2020). Integrating finance into the multi-level perspective: Technology niche-finance regime interactions and financial policy interventions. *Research Policy*, 49(6), 103985. <https://doi.org/10.1016/j.respol.2020.103985>
- 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/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, F. 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/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/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)*. Frankfurt: 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, pp. 609–639). Amsterdam: Elsevier. [https://doi.org/10.1016/S0169-7218\(10\)01014-2](https://doi.org/10.1016/S0169-7218(10)01014-2)
- Heim, C. E. (1984). Structural transformation and the demand for new labor in advanced economies: Interwar Britain. *The Journal of Economic History*, 44(2), 585–595. <https://doi.org/10.1017/S0022050700032150>
- 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 and 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>
- Hong, H., Karolyi, G. A., & Scheinkman, J. A. (2020). Climate Finance. *The Review of Financial Studies*, 33(3), 1011–1023. <https://doi.org/10.1093/rfs/hhz146>
- 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/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.
- IPCC. (2018). *Global Warming of 1.5 Degree Celsius*. Geneva: IPCC.
- IRENA. (2017). *Stranded assets and renewables: How the energy transition affects the value of energy reserves, buildings and capital stock*. Abu Dhabi: International Renewable Energy Agency.
- 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/leep/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, 89–102. <https://doi.org/10.1016/j.techfore.2014.02.028>
- 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*, 100, 102214. <https://doi.org/10.1016/j.jeem.2019.01.012>
- Kavliak, G., McEnerney, J., & Trancik, J. E. (2018). Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy*, 123, 700–710. <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. (2021). The impact of climate vulnerability on firms' cost of capital and access to finance. *World Development*, 137, 105131. <http://dx.doi.org/10.1016/j.worlddev.2020.105131>.
- 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: Lazard.
- 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 of the United States of America*, 105, 1786–1793.
- Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Shellnhuber, H. J. (2019). Climate tipping points - too risky to bet against. *Nature*, 575, 592–595.
- 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/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>
- McGlade, C., & Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature*, 517, 187. <https://doi.org/10.1038/nature14016>
- 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*. New York, NY: 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. *Annual Review of Resource Economics*, 12, In press. <https://doi.org/10.1146/annurev-resource-110119-031134>
- 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 & 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/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/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/10.1016/j.rser.2014.10.060>
- National Development and Reform Commission. (2016). *The 13th five-year plan fo 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*. London: Routledge.
- NGFS. (2019). *A call for action: Climate change as a source of financial risk*. Paris: 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>
- 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/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/10.1016/0016-3287\(83\)90050-2](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, UK: 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/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), 054019. <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 UKinsurance sector*. London, UK: Prudential Regulation Authority, Bank of England.
- PRA. (2018). *Transition in thinking: The impact of climate change on the UKbanking sector (September)*. London, UK: Prudential Regulation Authority, Bank of England.
- PRI. (2020). The inevitable policy response. Principles for Responsible Investment. Retrieved from <https://www.unpri.org/download?ac=9833>.
- Regelink, M., Reinders, H. J., Vleeschhouwer, M., & van de Wiel, I. (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, NJ: 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), 095006. <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*, 100, 102183. <https://doi.org/10.1016/j.jeem.2018.10.005>
- Saygin, D., Rieger, 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>
- Schmidt, T. S., & Sewerin, S. (2017). Technology as a driver of climate and energy politics. *Nature Energy*, 2(6), 1–3. <https://doi.org/10.1038/nenergy.2017.84>
- Schmidt, T. S., Steffen, B., Egli, F., Pahle, M., Tietjen, O., & Edenhofer, O. (2019). Adverse effects of rising interest rates on sustainable energy transitions. *Nature Sustainability*, 2(9), 879–885. <https://doi.org/10.1038/s41893-019-0375-2>
- Schumpeter, J. A. (1939). *Business cycles: A theoretical, historical, and statistical analysis of the capitalist process* (Vol. 1). New York and London: McGraw-Hill.
- Semieniuk, G., & Mazzucato, M. (2019). Financing green growth. In R. Fouquet (Ed.), *Handbook on Green Growth*. Elgar: Cheltenham, UK.
- 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/10.1016/j.jeem.2019.102277>
- Shaikh, A. (1978). An Introduction to the history of crisis theories. In B. Steinberg (Ed.), *U.S capitalism in crisis*. New York: Union for Radical Political Economics.
- Shiller, R. J. (2001). *Irrational exuberance*. Princeton, NJ: 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>
- Sinn, H. W. (2008). Public policies against global warming: A supply side approach. *International Tax and Public Finance*, 15(4), 360–394. <https://doi.org/10.1007/s10797-008-9082-z>
- 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. (2010). Contagion, liberalization, and the optimal structure of globalization. *Journal of Globalization and Development*, 1(2), 1–47. <https://doi.org/10.2202/1948-1837.1149>
- Stiglitz, J. E. (2018). Where modern macroeconomics went wrong. *Oxford Review of Economic Policy*, 34(1–2), 70–106. <https://doi.org/10.1093/oxrep/grx057>
- Stirling, A. (2014). Transforming power: Social science and the politics of energy choices. *Energy Research & Social Science*, 1, 83–95. <https://doi.org/10.1016/j.erss.2014.02.001>
- Sweezy, P. (1970). *Theory of capitalist development*. New York: Monthly Review Press.
- Syrquin, M. (2010). Kuznets and Pasinetti on the study of structural transformation: Never the twain shall meet? *Structural Change and Economic Dynamics*, 21(4), 248–257. <https://doi.org/10.1016/j.strueco.2010.08.002>
- 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.
- Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., ... Davis, S. J. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature*, 572(7769), 373–377. <https://doi.org/10.1038/s41586-019-1364-3>
- UNEP Finance Initiative. (2019). *Changing course*. Geneva: UNEP Finance Initiative.
- Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, 28(12), 817–830. [https://doi.org/10.1016/S0301-4215\(00\)00070-7](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, PA: University of Pennsylvania Press.
- van der Ploeg, F., & Rezai, A. (2020). Stranded assets in the transition to a carbon-free economy. *Annual review of resource economics*, 12(1). <http://dx.doi.org/10.1146/annurev-resource-110519-040938>.
- van der Ploeg, F., & Rezai, A. (2020). The risk of policy tipping and stranded carbon assets. *Journal of Environmental Economics and Management*, 100, 102258. <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, Occasional Studies 1607*. Amsterdam: De Nederlandsche Bank.
- Vermeulen, R., 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., 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.
- von Hayek, F. A. (1931). *Prices and production*. New York: Augustus M. Kelley.
- 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.

How to cite this article: Semieniuk G, Campiglio E, Mercure J-F, Volz U, Edwards NR. Low-carbon transition risks for finance. *WIREs Clim Change*. 2020;e678. <https://doi.org/10.1002/wcc.678>