FAERE Working Paper, 2021.05

Should we fear transition risks? A review of the applied literature

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March 22, 2021

Abstract

The transition to a low-carbon economy will entail sweeping transformations of energy and economic systems. To such an extent that a growing literature has been worrying about the effect of such strain on the stability of financial system. This "financial transition risk" literature has highlighted that the conjunction of climate policy, technological change and changing consumption patterns may propagate to financial markets. If too brutal or unexpected, such dynamics may result in a "Climate-Minsky" moment of systemic implications. Yet, recent historical developments have shown that financial markets can prove resilient to shocks onto transition-exposed industries such as fossil fuel producers. Should we thus fear transition risks? To answer this question, I propose a critical review of the relevant applied modelling and econometric literatures. Three sub-fields will be examined: the asset stranding literature, the financial econometrics of the low-carbon transition and the direct assessment of transition risks through prospective models. I will expound some key results of these literatures, and critically assess underlying methodologies.

Keywords: Review, Stranded assets, Financial Stability

JEL Codes: G01, Q50

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1 Introduction

Climate change poses an unprecedented challenge to human societies. Because adverting potentially disastrous outcomes will require massive societal changes within a relatively short time window, significant strain will be imposed upon economic systems. This could go as far as entailing the ”stranding”, *i.e*, the premature devaluation of significant parts of the capital stock. On top of possible macroeconomic costs already highlighted by the literature (Clarke et al., 2015), such developments may also destabilise financial systems. As highlighted by former Bank of England Governor Mark Carney (2015), mitigation policies, technological breakthrough and more frugal consumption patterns subject financial systems to “transition risks”. If severe enough, such risk may lead to a so-called ”Climate-Minsky” moment. Financial stability could be put at risk, especially if agents cannot anticipate sudden changes in regulation, technology or other. The stakes are important, as financial disorders may in turn hamper the achievement of climate goals, or reframe political agendas away from environmental issues (Geels, 2013).

A growing literature has emerged to tackle such questions. An example would be the vulnerability of fossil fuel companies to transition dynamics, and how these exposure could ripple off to financial markets (Curtin et al., 2019). Yet, history has shown that significant market devaluations could be withstood by fossil extractors and utilities, and their investors. According to IEA (2020), Chevron, BP, Shell, Eni and Total wrote down altogether up to $50 billion of their fossil assets in December 2019. This represented some 5 to 15% of their market capitalisation. Hence that large companies may be able to bear important shocks to their balance sheets within short time periods. Yergin and Pravettoni (2016) report that negative oil price shocks over the 2010s have triggered large asset devaluations for fossil industries, without causing disorders. Finally, the Covid-19 shock has represented a major blow for fossil companies, without major financial disturbances so far. As a result, the financial system looks quite resilient, and investors seem to have included in their expectations the end of the carbon era (IEA, 2020).

If markets can accommodate such large shocks, should we, then, fear transition risks at all?

In fact, that markets can withstand important downward shocks is reassuring, but should not lead to undue optimism. The examples above raise two objections. Such devaluations did not occur for environmental reasons, but because of low oil prices (IEA, 2020). These write-downs could be offset if oil prices are expected to go up again (Christophers, 2019). They are not permanent balance-sheet losses due to structural changes, which questions companies' ability to withstand irreversible changes. Plus, oil price dynamics do not represent the full spectrum of possible transition dynamics. However, if transitional efforts are sizeable, they remain overly insufficient to meet climate targets (UN, 2019), with the most disruptive elements of the transition yet to be implemented.

Hence important uncertainties surrounding how financial system will react to the transition, which interrogates the magnitude of transition risks and of how they can be estimated. To answer these questions, this article will propose a critical review of the applied literature on financial transition risks. I will cover the main results of this literature, and critically examine underlying methodologies. I will finally proposing some ways forward. In particular, the literature is yet to fully account for some uncertainties inherent to forward-looking methodologies. It is also yet to come up with conceptual and quantitative definitions of financial instability in the context of the low-carbon transition.

The review will be structured around three axes.

A first step will be to quantify the extent to which structural changes can negatively affect financial markets. This leads us to study the literature on "stranded assets" (Jackson, 2018). This questions in turn how such devaluation can propagate to financial markets, a question still hardly answered. Second, it is important to know how financial markets currently treat the low-carbon transition. The literature has emphasised that financial markets could be able to navigate transition risks if they can shape adequate expectations (van der Ploeg, 2020). Hence the need to study financial markets' current vision of the transition.

Yet, these two literatures cannot provide estimates of transition risk magnitude. They rather propose insights on the magnitude of structural changes that may have financial consequences, or on how financial markets may react to climate commitments. To reach direct quantifications of transition risks (default probabilities, asset price decreases...), forward-looking methodologies accommodating links between transition changes in real-economy sector and financial markets must be resorted to. They represent the third research strand I will cover in this study.

To the best of my knowledge, no such exercise has been carried out, although focuses on particular sub-problems have been proposed. Jackson (2018) proposes an in-depth review of the applied stranded asset literature (see also Curtin et al. (2019) and Fisch-Romito et al. (2020)), while van der Ploeg (2020) and Semeniuk et al. (2020) provide more theoretical reviews on asset stranding and financial transition risks. Finally, Breitenstein et al. (2020) have provided a review of how the financial sector deals with environmental concerns, ranging from risk to Environmental and Social Governance (ESG) aspects. My contribution proper lies in the critical focus on methodological aspects and the covering of all three key problems mentioned above altogether.

The remainder of this article will be organised as follows. Section 1 will present some theoretical elements and provide a short overview of the applied literature. Section 2 will review the applied "stranded asset" literature both methodologically and theoretically. Section 3 will focus on the financial econometrics of the low-carbon transition. Section 4 will turn to the study explicitly trying to assess financial transition risks through forward-looking, scenario approaches, and discuss their methodology. Before concluding, Section 5 will summarise and discuss my findings, by questioning how the literature will have to deal with uncertainties inherent to forward-looking approaches.

2 Transition risks for finance: An overview of the applied literature

2.1 Some theoretical elements

The idea of "transition risk" can be originated from Meinshausen et al.'s (2009) proposal and analysis of 2°C-consistent carbon budgets. The study showed that the remaining carbon emission space (1550-2100 Gt CO_2) was smaller by a factor of 1.5 to 2 to the emissions that would be entailed by the full use of existing carbon reserves alone (2500-3000 Gt CO_2). The concept was further popularised through the "carbon bubble" hypothesis defended by the Carbon Tracker Initiative (CTI) think tank, according to which "unburnt" fossil reserves could see their value suddenly collapse to zero, and trigger financial disorders (Schoenmaker and Van Tilburg, 2016). The "transition risk" term was coined by Mark Carney in his 2015 "Tragedy of the Horizon" speech. On this occasion, he highlighted that climate change posed three main risks to financial stability. "Physical risks" relate to climate change impacts upon production structures. "Liability risks" refer to the possible compensations some entities and countries may ask for after suffering climate damage. This review will focus on "transition risks", which describe the instability generated by the shift to a low-carbon economy. Carney further highlights a trade-off between physical and liability risks on the one hand, and transition risks on the other. Going too slow and failing to achieve climate targets would jeopardise financial stability due to high climate damage and compensation. But transitioning too fast may bring about severe devaluations in some economic sectors, that may then propagate to financial systems.

2.1.1 Transition risk drivers

Three main drivers can bring about transition risks (Semeniuk et al., 2020) : policies, especially if briskly implemented, shifts in consumer preferences, and technological breakthroughs, especially if they are unexpected[1]. All three "transition" drivers" will harm some productive structures, and could propagate to financial systems through four channels (Bolton et al., 2020). *Market risks* refer to asset depreciation on financial markets, that may lead to balance-sheet losses. *Credit risks* imply higher default probability that may become problematic if leverage is high. *Liquidity risks* describe

[1] Caldecott et al. (016b) expands the list to other drivers like supply bottlenecks on key mineral inputs.

the reduced ability to exchange assets and to get refinanced in the short run in case of balance sheet hit or expectation downturns. Finally, *insurance risks* relates to potential underpricing of derivatives on transition-exposed assets. Wilkins (2018) extends the list to two other kinds of risks. *Reputational risks* are signal effects that may lead partners or customers not to renew their contracts. Finally, *litigation risks* relate to the exposure of companies and Nation-States to legal actions due to failures to achieve climate goals or respect environmental norms. A summary is provided in Table 1.

Table 1: Typology of Financial Risks

	Description	Transition-risk example
Market Risk	Loss in asset prices	Decrease in fossil company shares
Credit Risk	Default on debt	Increase in default probability of carbon-itensive firms
Liquity Risk		
Position	Difficulty to get refinanced in the short-run	Increased risk premium on short-term debt to carbon-intensive firms
Market	Difficulties to trade an asset	Strong decrease in demand for securities from carbon-intensive firms
Insurance Risk	Potential mispricing of insurance contracts (derivatives)	Important obligations on high-carbon firm derivatives, or transition-sensitive commodities (fossil fuels...)
Reputation Risk	Signal effect entailing loss in customers and partners	A fund know for its high-carbon investment may find difficulties to get financed
Litigation Risk	Charges of legal action due to non-compliance with climate regulations	A financial firm not complying or frauding on disclosure

The framing in terms of ”risk” is related to the realisation of a given event drawn from a probability distribution. This event is usually considered as an exogenous shock, that affects a given system or agent. However, all the risks above may interact on financial markets and lead to endogenous amplifications (Carney, 2015; ESRB, 2016), and even interact with other kinds of risks (Monasterolo, 2020b).

2.1.2 Behaviours and structures

The basic intuition of financial transition risks is that, under certain conditions, the transition to a low-carbon economy can bring about financial disturbances, ranging from inconsequential asset repricing systemic risks to proper systemic collapse.

Given the unprecedented scope and pace of required changes (Masson-Delmotte et al., 2018), financial systems, which are still embedded in a fossil-dependent economic system, may incur losses from such structural change. Perez (2003) provides one of the only theoretical links between structural change and financial instability through technological change. For her, the conjunction of the rise of new technologies and ensuing financial exhilaration and of the downfall of old techniques can create financial instability due to losses in “sunset industries” and heightened risk-taking in “sunrise industries” (Semeniuk et al., 2020). Yet, as far as the transition is concerned, the focus has mostly been on “sunset industries” like fossils, given the slow progress of low-carbon investments. This focus relates to how the high-carbon structure of current economic systems may represent perils for financial instability through investment irreversibility, frictions and other transformations of socio-economic systems. Yet the behavioural response of economic agents must also be accounted for (van der Ploeg, 2020). In particular, asset valuations depend also on expectations which themselves depend on the availability of relevant information. A problem of the transition risk literature is to assess the relative importance of the “lock-in” into a carbon-intensive production structures (Unruh, 2000) and agents’ ability to deal with it on financial markets. In this respect, the literature has emphasised the threat that a “disorderly” transition, in which expectations would not have had time to get aligned, could represent with respect to an “orderly” course of events (Carney, 2015; van der Ploeg, 2020), in which climate policy and economic changes unravel smoothly (Bertram et al., 2020; NGFS, 2020).

2.1.3 What is financial instability?

Beyond mechanisms and narratives, it should be noted that virtually no definition of “financial instability” can be found in the literature. This is surprising given the amount of scholarship on the matter, both theoretical (Minsky, 1986; Schinasi, 2004; Allen and Wood, 2006; Nikolaidi, 2017) and applied (Barrell et al., 2010; Schularick and Taylor, 2012). True, coming up with an unequivocal battery of financial instability indicators is a daunting task given the subject’s complexity. Yet, a reflection in terms of significance of some metrics, or even indicative thresholds could have been expected.

Such gap reduces research to measures of losses against a chosen baseline, which are usually expressed in terms of losses on portfolios returns, balance-sheet valuations or increased default probabilities. Assessing their significance is not made according to established criteria. It often boils down to the study’s authors’ appreciation, which is an important weakness. At best are “common sense” criteria summoned, for instance about the business models of different financial institutions (Weyzig et al., 2014).

The absence of quantitative reflection comes also along a lack of qualitative thinking about what "financial instability" means in narrative or theoretical terms. Schinasi (2004) defines financial instability very broadly as:

> "(i) A financial system is entering a range of instability whenever it is threatening to impede the performance of an economy.
> (ii) A financial system is in a range of instability when it is impeding performance and threatening to continue to do so."(Schinasi, 2004, p.10)

Schinasi defines "performance" very loosely as welfare improvements and talks about "ranges" of instability. This suggests an understanding of financial instability as a spectrum. History is indeed full of examples of financial instability with different degrees of macroeconomic relevance. Along well-known large financial crises, they range from innocuous macroeconomic effects altogether, like the small banking crises of the 1960-70s (Minsky, 1986) to economic slowdowns, like the European Monetary System crisis of the ealry 1990s. Financial crises can also be contained to a certain area of the globe without rippling off to the worldwide financial system. This was the case, for instance, for the Asian crisis of the 1990s (Giraud, 2014) which remained mainly circumscribed to South-East Asia. Finally, disorders can take forms going beyond financial market crashes. Balance of payment and exchange rate crises represent in this respect major threats for developing economies. In that light, the notion of financial crises should not be twisted by the legitimate concern for central financial systems like the US, the EU or the UK's.

Whether the transition risk literature refers to all of these is unclear. Most authors seem to have in mind a systemic crisis scenario, consistently with the reinforcing of financial supervision after 2008 (Carney, 2015; Caldecott et al., 2016; Battiston et al., 2017; Scialom, 2020). It also matches the oft-drawn distinction between "orderly" and "disorderly" transitions mentioned above (2020). However, such view does not explore other financial instability narratives and thus hardly depletes the content of the concept. This invites to consider a broad range of narratives.

2.2 Three main approaches

The applied literature can be classified into three main categories : the study of asset stranding, the evaluation of financial markets' attitude towards the low-carbon transition and the direct estimation of transition risks through forward-looking approaches.

2.2.1 Asset stranding and financial instability

According to Caldecott et al. (2013), stranded assets can be defined as follows:

> "Stranded assets" are assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities. (Caldecott et al., 2013, p.2)

The term designates those assets that will lose value due to the low-carbon transition and ensuing changes in economic conditions (Jackson, 2018). They can be divided into three categories, summarised in the following table.

Table 2: The three kinds of stranded assets

Stranded resources	Stranded capital	Stranded paper
Fossil resources (Coal, oil)	Extraction and production capital (Power generation, high-carbon industries)	Financial assets (Bond, equities, loans, derivatives)

What I call "stranded paper"[2] designate losses in value on financial markets. Stranded *resources*, on the other hand, used to be the focus of some academic articles (Meinshausen et al., 2009; McGlade and Ekins, 2015; Caldecott et al., 2013) and of institutions and NGOs interested in the "carbon bubble" hypothesis, and its possible effects on market capitalisation. Finally, stranded *capital* refers to these production assets in extraction and other sectors (industry, transports...) that will lose value, or whose conservation will be costly due to refurbishment and reconversion (Hambel et al., 2020).

Stranded assets is therefore a cross-sectoral matter, any kind of "dirty" capital, be it extraction, power-related, or industrial, being potentially subjected to devaluations. To the extent that such balance-sheet shocks could propagate through the investment chain up to investors and financiers (Curtin et al., 2019), they represent a sizeable part of possible transition risks.

[2] Taking inspiration from Perez's "paper profits" (2003)

2.2.2 Financial asset pricing

A second strand of the literature has applied statistics to elucidate the current stance of financial markets towards the transition. An important question is whether they incorporate transition risks correctly into prices by adequately valuing associated risks and opportunities. Three methods have been applied so far.

A sub-part of this literature has surveyed investors and financial institutions on how they see the transition (Amel-Zadeh, 2018; Krueger et al., 2020), and how these entities deal with subsequent data and methodological challenges (Bingler et al., 2020). Such works make for a microeconomic picture that expands over traditional assumptions, by elucidating broader behavioural factors and studying institutional barriers to the right pricing of transition risks and the processing of relevant information (Ameli et al., 2020).

Another strand has adopted a more mesoeconomic focus by studying the behaviour of markets themselves. Starting from asset price observations, this research has applied extended versions of traditional asset-pricing models including environmental indicators such as carbon emissions (Bolton and Kacperczyk, 2020b).

Finally, other econometric studies have used event-studies in order to assess how financial markets react to transition-related events, which mostly take the form of technological news or policy announcements and implementations. Albeit circumscribed in terms of external validity, such research nonetheless provides valuable insights on how financial institutions see future transition shocks and how the shock will be dealt with by other parties like governments (Sen and von Schickfus, 2020). It is also informative on longer-run expectations, such as technological development (Barnett et al., 2020).

2.2.3 Direct transition risks assessments

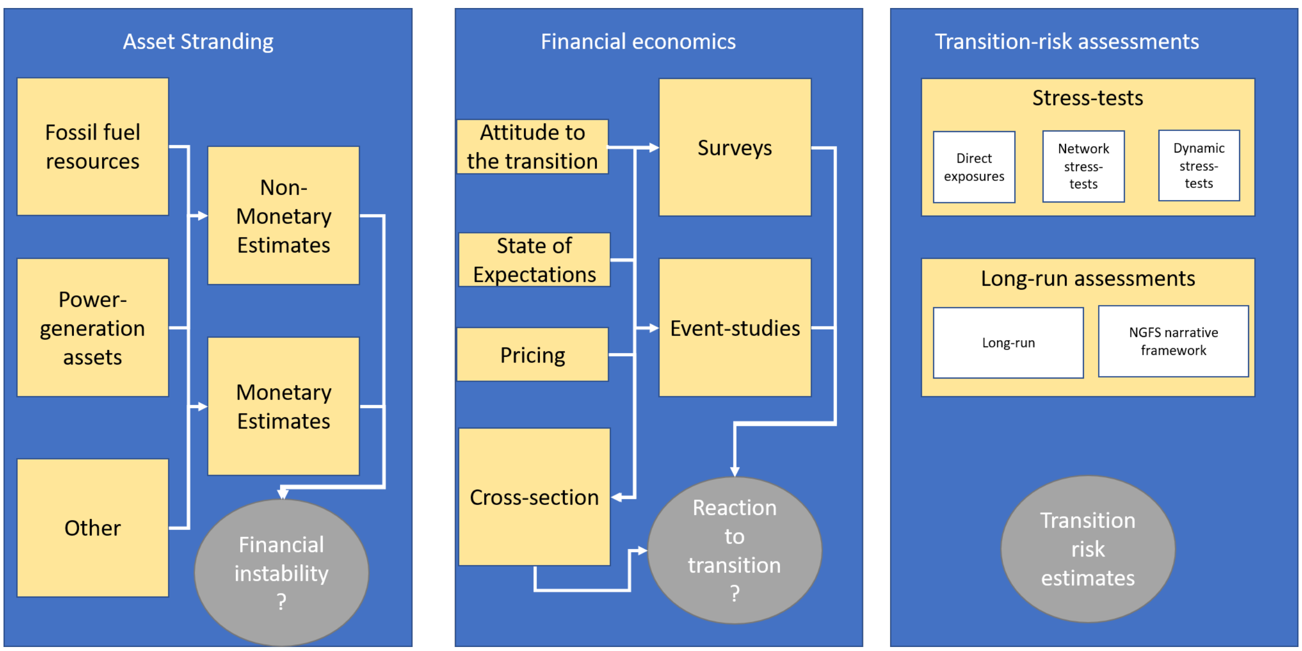
The latter are by definition backward-looking. As such, if they are informative on how financial markets could react to some transition developments, they cannot instruct us on how transition risks will unravel along transition paths. Hence the need for forward-looking approaches.

Building on the vision of the transition as a shock, financial climate stress-tests have been proposed as the privileged method. Stress-tests originate from(Borio et al., 2014). They seek to assess the

resilience of system to a strong exogenous shock. Such techniques have gained popularity in the wake of the Great Financial Crisis (GFC) amongst practitioners to assess financial fragility. As transition risks can take the form of a brisk policy or technology shock, the method have proven attractive and fruitful in assessing the extent of climate-related risks.
However, stress-tests are confined to the short-run, while the transition is a long-term process. Other studies have tried to assess the extent of financial transition risks along existing mitigation pathways as provided by various institutions (IPCC, IEA, IRENA...).

The remainder of this article will review all three approaches and critically assess their methodologies. Figure 1 summarises all them as well as the main methods mobilised in the three strands.

Figure 1: Overview of the literature



All three categories will structure my review in Sections 2 to 4.

3 Asset stranding and financial instability: the missing link

Asset stranding has elicited growing interest in the literature over the past decade. This section aims at presenting the literature's main results, and to assess existing methodologies. The most importance issue, though, is theoretical. The transmission channels from asset stranding to financial instability are far from clear, henceforth limiting estimates' heuristic range.

3.1 A quick overview: methods and asset types

Applied studies use forward-looking scenarios generated by different models to estimate asset stranding. While most have studied directly exposed sectors, extracting industries and high-carbon power assets, a few papers have focussed on other stranding sources like in housing (Muldoon-Smith and Greenhalgh, 2019) or agriculture (Caldecott et al., 016b).

3.1.1 Power sector and fossil reserves

Applied studies have made use of forward-looking scenarios to estimate the extent of asset stranding and shown important potential for balance-sheet losses on fossil and power companies. A handful of backward-looking studies also exist, quantifying assets that have already been stranded. Such studies represent the bulk of the literature on the matter, and will compose most of the references gathered in Tables 3-7.

3.1.2 Other assets

If the literature has mostly explored asset stranding in the extraction and power sectors, it has recently proposed estimates for other assets. Cahen-Fourot et al. (2019) suggest that asset stranding can flow in cascades from extraction activities to downstream sectors depending on the structure of the economy. Muldoon-Smith and Greenhalgh (2019) and Saygin et al. (2019) highlight that housings that would fail to adopt environmental and energy norms can suffer considerable devaluation. If estimation methods are still frail, they point at important stranding potentials. Housing is particularly relevant in terms of transition risks given its historical links with financial instability (Jordà et al., 2015). Transportation infrastructures and assets (such as thermal-engine cars) are also sometimes included, *e.g* Mercure et al. (2018).

3.2 Metrics, methods and stories

A consequence of the large variety of possible stranded assets is that there is currently no well-established and unequivocal metric measuring asset stranding (Fisch-Romito et al., 2020). Beyond hampering result comparability (Monasterolo, 2020b), this diversity is not neutral when it comes to assess the financial instability potential of resource and physical stranding. More precisely, each metrics relates to different mechanisms, on stocks and flows. As a result how they relate to their underlying decarbonation scenarios begs clarification.

3.2.1 Non-monetary estimates

The first studies aimed to quantify the amount of ”unburnable” carbon (McGlade and Ekins, 2015), related to the “carbon bubble” hypothesis. This has extended to the quantification of power assets at loss in a non-monetary way Saygin et al. (2019), and notably Fisch-Romito et al. (2020) propose summaries of the existing literature. The latter, in particular, highlight the high number of non-monetary metrics, which range from committed emissions, to GW of necessarily decommissioned capacities, through the age of the capital stock. Some studies are static, that is, measure a year-to-year stranding potential based on a given target (Pfeiffer et al., 2016; Farfan and Breyer, 2017). Yet, most studies are forward-looking and based on mitigation scenarios (CTI, 2011; Coulomb et al., 2019).

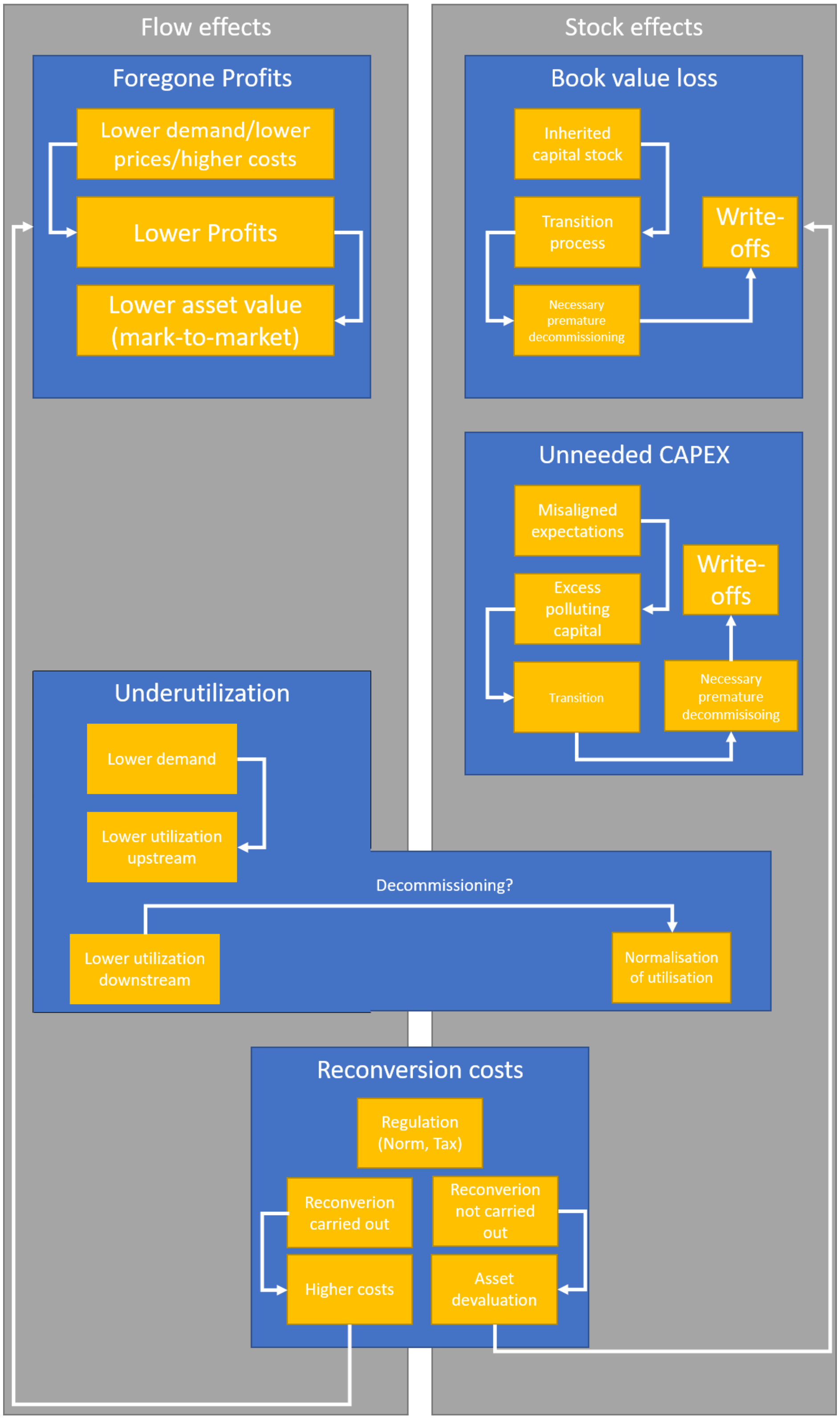
This literature, however, because it remained focused on quantities, is silent on how stranded resources can affect finance. Lacked a reflection on how the actual valuation of those assets would change (Helm, 2015), beyond upper-bound hypotheses of a collapse of the value of unburnable carbon (CTI, 2011).

3.2.2 The five measures of monetary estimates

I therefore focus on monetary estimates, which provide a more direct idea of how asset stranding may affect the balance sheet of relevant companies. The literature has so far relied on five metrics, summarised in Figure 2.

All categories will be defined and further studied in the following.

Figure 2: Measure of asset stranding in the literatures - Overview



Foregone Profits Foregone profits were used in two studies, reported in Table 3. Against a baseline, authors compute the spread at each point in time between the profit flows accruing to companies on this baseline and on a mitigation pathway. The differences between the two can arise from lower demand, losses in market shares or increased operating costs due, for instance, to carbon pricing. Those spreads are then summed and discounted over the study's horizon. Under the assumption that asset-pricing is forward-looking, the value of production assets is the discounted sum of expected profits. Then, the spread between baseline and scenario gives an estimate of how much carbon assets will have to be depreciated by.

Table 3: Foregone Profit Studies - Summary

Authors /Year	Exposed sectors	Geographical coverage	Methodology	Reference Scenario(s)	Underlying model(s)	Expectation structure	Value
Caldecott, Dericks & Mitchell (2015)) Report	Coal Utilities and Generation assets	Australia	Cost of closing all plants at a 5, 10 and 15 year horizon Conservative scenario for projected variables	Irr.	Irr.	Irr.	AUD$ 8.4-18.3 bn
Mercure et al. (2018) *Nature Climate Change*	Fossil assets incl. transportation means	World	Model-based runs with several "Green paradox" modalities Distributional effects computed	Homemade Baseline & 2°C IEA Expectation	E3ME-FTT-GENIE	Myopic Foresight	Yearly 340 bn foregone income on average for IEA Expectations and 250 bn per year with Homemade 2°

Note: Irr. Stands for "Irrelevant", bn for "billion", "tn" for trillion. Monetary values are constant from a given date depending on the study.

This metric relates to how a diminution of profit flows entails a decrease in asset value on the balance sheets of a given company. Over short time periods, as in Caldecott et al. (2013), the metrics is interesting in that it gives an idea of the profitability shock (that may translate or not into asset valuations) that companies will have to face if they do not provision against the start of the transition. Over longer time spans, as in Mercure et al. (2018), results are less easy to interpret. The authors report that, under several assumptions, "approximately US$12 trillion (in 2016 US dollars, which amounts to US$4 trillion present value when discounted with a 10% corporate rate) of financial value could vanish off their balance sheets globally in the form of stranded assets" by 2035. Such losses can be interpreted as upper bounds. Possible real-world dynamics could first entail a series of downward shocks to fossil fuel companies' profits. Then, when lower profitability will have been integrated in agents' expectations for the existing stock of fossil assets, a downward revaluation would occur, but of a lesser magnitude than Mercure et al.'s headline (undiscounted) \$9 to \$12 trillion loss.

Underutilization Underutilization relates to the possibility, for a firm, to diminish the production flow from this asset while not decommissioning it altogether. This variable is often used in Post-Keynesian studies, in which economies are assumed to be structurally in a state of underemployment. In such a context, companies typically keep some slack at hand in order to face surges in demand (Lavoie, 2014) or create entry barriers (Palley, 2021). Jackson (2018) proposes a Post-Keynesian stock-flow consistent model of asset stranding in which the (exogenous) transition to a low-carbon economy leads to a transitory underutilization of high-carbon capital. Capacity utilization has also been used in neoclassical models of asset stranding, to figure a situation in which investment being irreversible, companies are forced to produce below full-capacity in presence of carbon taxes(Rozenberg et al., 2020; Coulomb et al., 2019).

Table 4: Underutilization - A summary of the literature

Authors /Year	Exposed sectors	Geographical coverage	Methodology	Reference Scenario(s)	Underlying model(s)	Expectation structure	Value
Cahen-Fourot et al. (2020) Working Paper	All	European Union (Individual Countries)	I-O Analysis allowing for exogenous shock propagation Stranding is measured as a percentage of utilization (capital-output ratio) loss due to a marginal shock on the mining and quarrying sector	Irr.	Gosh IO Model (Supply-Side)	Irr.	Between 0.1% (Belgium) and 70% (UK) of Mining stranding, between 1.2% (Belgium) and 35.7% (UK) in Elec/Gas
Cahen-Fourot et al. (2021) AFD Research Paper	All	European Union (Individual Countries), US, Canada, China, Indonesia, India, Taiwain, Norway	Cross-country I-O analysis allowing for exogenous shock propagation from the Mining and Quarrying Sector Stranding is measured as a percentage of utilization (capital-output ratio) loss due to a marginal shock on the mining and quarrying sector	Irr.	Multi-regional Gosh IO Model	Irr.	Up to 60% loss in utilization in the Power sector, 20%in the coke and petroleum sector Large cross-countrty exposures for USA, Canada and Japan

Note: Irr. Stands for "Irrelevant", bn for "billion", "tn" for trillion. Monetary values are constant from a given date depending on the study.

The sole applied study using this metric so far was proposed by Cahen-Fourot et al. (2019, 2021), who illustrate how a downward shock to the utilization of capital in the Mining and Quarrying sector affects the utilization of downstream sectors in European economies. In this context, underutilization is a short-run measure which relates both to stocks and flows. A drop in utilization may lead to lower profits, hence a dynamic, forward-looking effect on asset value. On the other hand, it also gives a measure of the capital that should be decommissioned to reach a ”normal” level of utilization[3]. As such, the underlying story is not very clear. On the one hand, this measure provides an idea of the actual magnitude of a demand or supply shock to the economy. Given the complexity of production networks, and the lack of transparency about value chains, many agents may not be able to anticipate fully such short-term shocks. However, much of the total effect belongs to the medium-run, that is, to the process by which utilization is brought back to its normal level. The authors warn in this respect that their multipliers should be considered as marginal exposure measures. They provide more information on the structure of the network than on the stranding dynamics along a transition path.

Unneeded CAPEX Unneeded CAPEX consists in itemising existing investment projects (power plants, exploration, etc.) which will represent excess capital if the world economy is assumed to respect a carbon budget, usually drawn from canonical mitigation pathways. This excess would have to be written off from companies” balance sheet and therefore degrade their financial positions.
It measures investments that will not be recouped by the time the corresponding assets will be decommissioned and written down. This can happen in two ways. Either the investment becomes unprofitable in its development phase, before assets are fixed, or the use of the asset does not allow to fully recoup CAPEX. Estimates are most often upper bounds. As most studies only measure CAPEX, without hypotheses on decommissioning, it is impossible to know the amount that will have to be effectively written-down. Exceptions are Johnson et al. (2015) and Löffler et al. (2019), who explicitly model decommissions along mitigation pathways, with different hypotheses on expectations. Studies are summaries in Table 5.

This way to measure stranded assets directly relates to *ex ante* deviations from decarbonation pathways. It estimates how some investors and businesses' expectations go against the needs of the transition. Unneeded CAPEX is a measure of ”certain losses” in the case of transition since these investments have been sanctioned with transition-contrarian expectations.
Potentials for financial instability are therefore important. By considering 2030 carbon budgets from the IEA, CTI (2019) suggests that many major companies sanctioned in 2018 a \$50 billion of projects falling outside of a 1.7-1.8 °C world, and sanctioned in 2019 another \$60 billion in

[3]Which, in most developed countries neighbours 0.75 at the macroeconomic level (Botte, 2017)

Table 5: Unneeded CAPEX studies

Authors /Year/Publication	Exposed sectors	Geographical coverage	Methodology	Reference Scenario(s)	Underlying model(s)	Expectation structure	Value
Caldecott & McDaniel (2014) Report	Energy (Gas)	European Union	Inventory of gas write-downs and valuation	Irr.	Irr.	Irr.	€6 bn
Carbon Tracker Initiative (b) Report	Energy (Gas)	World	Value of projects in surplus in 2025 compared to a low-demand scenario	IEA/Shell	IEA/Shell	Irr.	$283 bn
Carbon Tracker Initiative (a) Report	Extractive (Coal/Gas/Oil)	World	Unneeded CAPEX to remain within Carbon Budget	IEA 450 Scenario	World Energy Model	Perfect foresight	$1.3 tn oil $0.5 tn gas $0.2 tn coal
Ceres, 2ii, ETA, and CTI (Ceres et al.) Report	Extractive (Gas/Oil)	World	Value of capex deferred or cancelled in 2014	Irr.	Irr.	Irr.	$200 bn
Iyer et al. (2015) *Environmental Research Letters*	Energy	World	Unneeded CAPEX in a delayed action (no-Paris) scenario according to 2°C scenarios due to early retirement	IPCC and Paris-Agreement scenario	GCAM	Perfect foresight	$400 - 700 bn unneeded CAPEX in 2031-2035 in a delayed action scenario
Johnson et al. (2015) *Technological Forecasting and Social Change*	Coal-fired power plants	World	Model runs without CSS along 8 scenarios featuring different climate-policy stringency. Endogenous early capital requirement	AMPERE Database + Homemade variants	MESSAGE-MACRO	Myopic Foresight	$165-550 bn
IEA (2017) Report	Energy Utilities	World	Comparison of delayed and smooth scenarios	IEA Scenarios	WEM	Perfect foresight	$1.3 tn
Pfeiffer et al. (2018) *Environmental Research Letters*	Energy Utilities	World	Comparison of committed emissions to carbon budget	IPCC	Irr.	Irr.	$ 7tn unneeded CAPEX
Löffler et al. (2019) *Energy Strategy Reviews*	Energy utilities	European Union	Model runs without CCS with and without limited foresight	Homemade 2°C consistent scenarios	GENeSYSMOD	Perfect Foresight	€200-250 bn with political constraints and limited foresight 150 bn with only limited foresight
Carbon Tracker Initiative (2020) Report	Fossil extractive assets	World	Inventorise fossil extraction prjects inconsistent with 1.5°C target, including with CCS	1.6 °C Carbon budget	Irr.	Irr.	$2tn

Note: Irr. Stands for ”Irrelevant”, bn for ”billion”, ”tn” for trillion. Monetary values are constant from a given date depending on the study.

non-compliant projects (CTI, 2020). Finally, The Production Gap (2020), shows that current fossil fuel production plans entail a yearly 2% increase, which is in total contradiction with sustainability goals, which suppose, on average, a yearly 6% *decrease*.

Book Value Losses The ”Book Value Loss” metric (see Table 6) is quite close to the ”Unneeded CAPEX” one, as it also measures a pure shock to companies' balance sheets, and has been so far the most widespread type of study. The difference lies in that it relates to investments that were carried out before the introduction of explicit decarbonation goals, except if the transition requires transitory technologies that are bound to be decommissioned before the end of the economic lifetime (Coulomb et al., 2019). Effects are therefore likely to be similar to that of the ”Unneeded CAPEX” indicator. Their magnitude will depend on how accelerated depreciation will be handled and provisioned for. Saygin et al. (2019) show that stranding potential, even in early-action scenarios, *in models with perfect foresight*, are sizeable between 2020 and 2050: $1 trillion worldwide for

Table 6: Book Value Losses - Summary

Authors /Year	Exposed sectors	Geographical coverage	Methodology	Reference Scenario(s)	Underlying model(s)	Expectation structure	Value
Caldecott et al. (2016) Report	Coal Utilities and Generation assets	Japan	Inventorise future decommissioned existing and to-be-built plants in excess of stock replacement requirements	Irr.	Irr.	Irr.	$61.6-80.2 bn (23-29% of market capitalisation)
Shearer et al. (2016) Report	Pipelined capital expenditures for coal-fired power plants	World	Assuming no new coal plants will be needed in the future, compute the "wasted money" associated with such expenses	Irr.	Irr.	Irr.	$981 bn
Muttit (2016) Report	Planned extraction and transportation projects	World	Inventorise future decommissioned existing and to-be-built plants in excess of carbon budget and without CCS development	IEA	Unclear	Irr.	10 tn in extraction 3 tn in transportation
Kefford et al. (2018) Energy policy	Fossil power assets	World	Power Sector: Model runs 2010-2060 computation of early decommissioning an comparison to "full lifetime" use of capital Baseline, delayed action, early action Rest: Annex computations	IEA 2DS	NREAL-SAC for EOL retirement	Irr.	$541-773 bn stock losses due to premature decommisionning. Lower bound given IEA hypotheses
Saygin et al. (2019) Energy Source	Power Sector Extractive assets Real Estate	World	Power Sector: Model runs 2010-2060 computation of early decommissioning an comparison to "full lifetime" use of capital Baseline, delayed action, early action Rest: Annex computations	IRENA scenarios	IRENA Model	Perfect Foresight	Power Sector: Delayed: $1.8 tn (ar.50 bn/year) Early: $927 bn (ar. 25 bn/year) Real Estate: Delayed : $11 tn (300 bn/year) Early:$ 5.5 tn (150 bn/year) Extractive: Delayed: $7 tn (215 bn/year) Early: $4 tn (100 bn/year)
Binsted (2020) Environmental Research Letter	Fossil power assets	Latin America	Model runs (2020-2050) computation of early decommissioning an comparison to "full lifetime" use of capital. 4 scenarios (NDCs, 1.5, 2°C)	Homemade NDC-1.5-2°C scenarios	GCAM	Perfect Foresight	Around $90 bn in worst-case scenarios (NDC to 1.5°C)

power assets and fossil reserves. For the power sector, this corresponds to 20-30% of the current investment volume in thermal generation.

Reconversion costs Part of the literature has also considered asset reconversion (from high- to low-carbon) as a possible metric of asset stranding. It indeed represents additional investment spending necessary to comply with regulation or keep asset value afloat, that may not have been provisioned for beforehand. As a result, such investment expenses do not increase the total amount of capital, but merely change its structure. A straightforward example could be the extra spending needed to graft a Carbon Capture and Storage (CCS) module onto an existing power plant. Reconversion of thermal engine to electrical or hydrogen technologies, or house refurbishing are other tell-tale illustrations.

So far, the concept has mostly been applied in theoretical models (Campiglio et al., 2020; Hambel et al., 2020) in which a portion of polluting ("brown") capital can be turned at a premium into less polluting ("green") assets. Such measure of asset stranding thus gauges the cost of the stickiness of capital reallocation, and therefore of the degree of investment irreversibility. It can also be taken as a measure of accelerated depreciation to the extent that it prevents the depreciation of capital, but leaves net investment unchanged.

Table 7: Reconversion - Summary of the literature

Authors /Year/Publication	Exposed sectors	Geographical coverage	Methodology	Reference Scenario(s)	Underlying model(s)	Expectation structure	Value
Muldoon-Smith & Greenlagh (2019) Energy Research & Social Science	Real-estate assets	World	Back of the envelope calculation	Irr.	Irr.	Irr.	\$16 tn for residential assets \$5 tn for commercial assets

The applied literature, by contrast has so far not explicitly linked reconversion costs to the asset stranding phenomenon. This could be attributed to the fact that reconversion expenses can also be construed as higher production costs, in the sense that they transitorily or permanently involve higher expense for the same production. As a result, they may feed into the “foregone profit” category of asset stranding, and reduce asset value through lower discounted profits if higher costs cannot be passed onto consumers. Yet, this only holds if companies do invest in low-carbon technologies for their current stock of capital. Transition-adverse expectations or other obstacles (liquidity or cognitive biases for housing refurbishment, for instance (Grubb et al., 2014)) may entail that some agents will not incur immediate reconversion costs, but may suffer from balance sheet loss in the longer run. In other words, reconversion costs can also provide an *ex ante* measure of future capital losses, and thus relate also to the ”Book value loss” metric. This method was applied by Muldoon-Smith and Greenhalgh (2019), to roughly estimate asset stranding in the housing sector. This study, reported in Table 7, is to the best of our knowledge the only one taking conversion costs as measure of asset stranding.

3.2.3 Stranding magnitude across metrics

In spite of the large diversity of metrics, the studies mentioned in Tables 3-7 allow for a general picture of asset stranding potentials. As reads, across scopes and methods, the applied literature estimates sizeable asset stranding along decarbonation scenarios. Overall, stranded assets at a global scale tend to amount, across studies, to \$US 1 trillion for power assets, mainly coal, and around \$US 4 trillion for resources. For the sake of comparison, this corresponds to several multiples of financial losses incurred during the 2008 financial crisis (Mercure et al., 2018) As expected, delayed-action scenarios yield higher estimates (Saygin et al., 2019), as well as those assuming a rapid fall in fossil fuel prices (Mercure et al., 2018). However, the amount of stranded assets remains high even in early-action scenarios, suggesting that financial disorders may also arise in case of desirable policy course. In other words, no assumptions about policy timing, coordination or the unexpectedness of transition drivers are necessary to give rise to stranded assets.

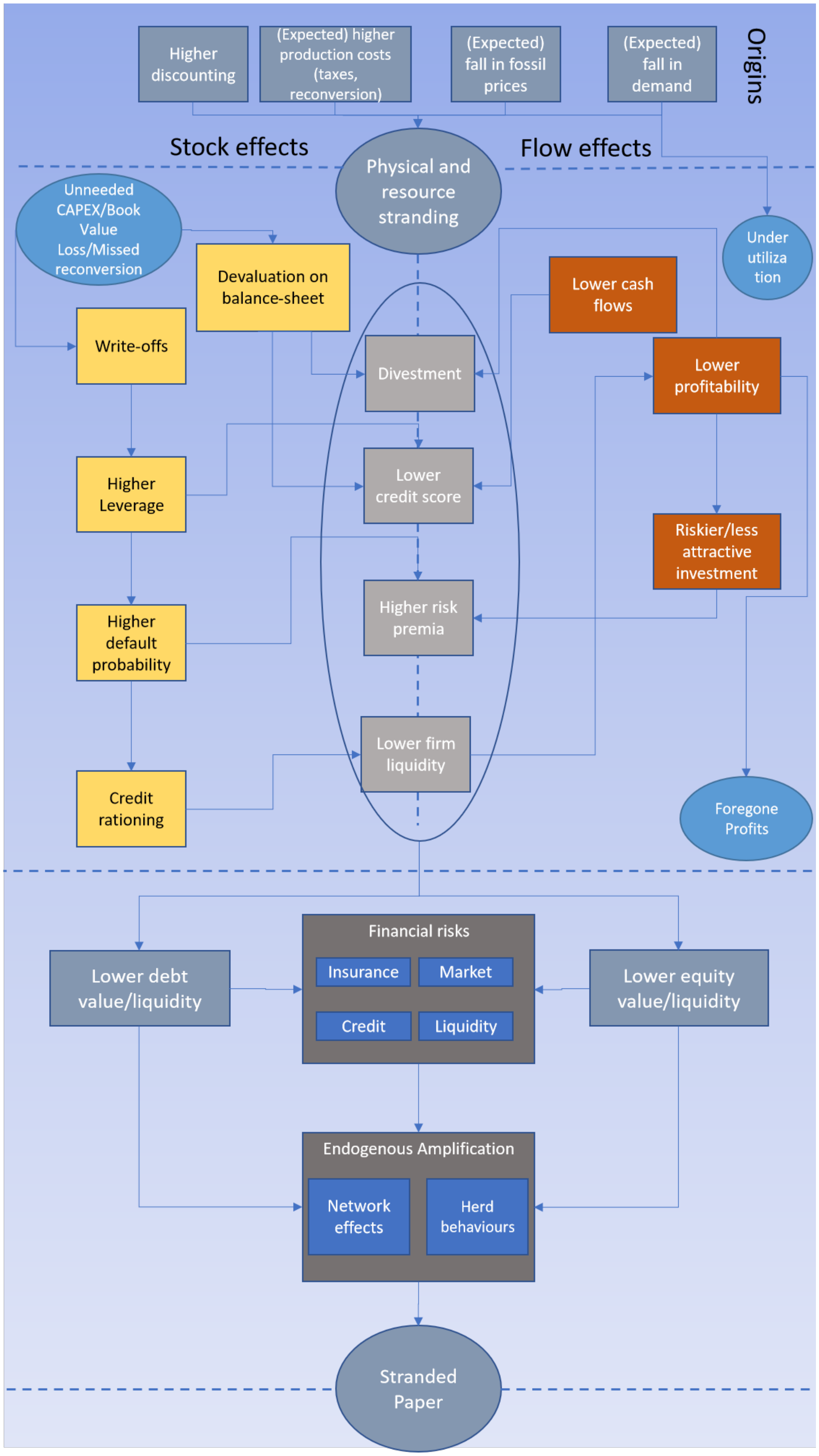
Also noteworthy is that assumptions about agents' foresight do not significantly lead to different results. One could to the contrary expect that due to perfect-foresight, agents can more easily reallocate capital, and therefore limit stranding. (Saygin et al., 2019), using a perfect foresight model, yields amongst the highest estimates at the world level. Johnson et al. (2015), working explicitly with myopic expectations, reaches stranding in the coal sector comparable to perfect foresight studies such as Scott and Barrett (2015). This is significant, as it suggests that even in case of perfect behavioural response to the transition process, the magnitude of stranded assets remains preoccupying. This suggests that structural determinant, like investment irreversibility, stickiness in capital reallocation and other "lock-ins" may play a more important role than behaviours.

Asset stranding studies estimates exhibit impressive numbers, suggesting that transition risks for finance may be substantial. This is all the more important since sizeable stranding can be estimated along early-action, desirable scenarios. In other words, no assumptions about policy timing, coordination, agents' (lack of) rationality or the unexpectedness of transition drivers are necessary to give rise to stranded assets, in contrast with many theoretical analyses on the matter (Kalkuhl et al., 2020; Rozenberg et al., 2020; Van der Ploeg et al., 2020).

3.3 From stranded resources and capital to stranded paper: A gap yet to be bridged

Now, if these works are useful in deriving insights on resource or physical stranding, they say little on how this would translate into financial value. Transmission channels from asset stranding to financial instability in applied studies have remained at best blurred. A financial crisis is usually presented as a possible threat (Mercure et al., 2018), but precise transmission channels are less understood (Curtin et al., 2019). Hence a need to elucidate them. I propose a summary in Figure 3.

Figure 3: Theoretical transmission channels from physical and resource stranding to stranded paper



A first distinction is between stock and flow effects. Flow effects relate to how diminished demand, prices and market shares feed into market valuation, default probabilities, etc. Stock effects, on the other hand, relate to balance-sheet shrinking. They relate to how changing asset without corresponding diminution in liabilities (debt) for one agent may translate in the end into lower market valuations for other agents or broader financial disorders (Nikolaidi, 2017). In all these processes, it is also important to identify catalysts and counteracting elements. For instance, aligned expectations may indeed play as a counteracting influence, while information gaps can be seen as catalysts.

Flow effects are well-mapped by the literature. Changes in market conditions, relative prices, technological competition, evolving regulation and possible divestment from fossils on the part of investors feature in most research that I will review in Section 4. However, how fossil assets' liquidity may change in the course of the transition is comparatively unexplored. Indeed, if liquidity is higher for financial assets, it is also much more variable than for fixed investments. If, over the course of the transition, fossil assets become less marketable (higher liquidity premium, lesser number of buyers, etc.), their value will fall. In a catastrophic course of events, the market for some fossil assets (short-term bonds, derivatives) could even dry up, leaving an these assets unpriced.

Stock effects are by contrast less understood. A direct hit to a balance sheet increases the company's leverage, making it more fragile. This may also force it into contracting more debts to cover operating expenses, ensure sufficient cash flows or even meet some liabilities. Moreover, asset stranding also includes those recent investment whose capital expenditures will be lost, or partially recouped. This configuration may lead to a classical Minskian mechanism if fossil companies' indebtedness is high. For extractors, Heede and Oreskes (2016) recall that most reserves are in the hand of non-listed public actors, suggesting that some Nation-State could have to, eventually, take the blow on their balance sheets. How far Nation-States will bear the full cost will depend on the State of public finances, especially in countries that depend on capital inflows and proceeds from fossil production to fund their expenditures (Jaffe, 2020). Phenomena scarcely mentioned in the literature, such as balance-of-payment issues could arise.

Another aspect of the issue are the feedback-loop effects between flow and stock effects in asset stranding, and how financial markets may amplify or accelerate the process through diverse channels. Most fossil companies and utilities are very capital-intensive businesses, and are therefore very sensitive to interest risk. This includes higher risk premiums. If these companies face tighter funding conditions in time of distress, disorders may ensue (Jackson, 2018). Asset stranding may feed asset stranding (Cahen-Fourot et al., 2019). In that course of event, more than the "directly fossil" sectors would be hit, which could represent a larger shock to the financial system.

The magnitude of such effects on the financial sphere will depend on financiers' stranding expectations, the good functioning of markets (sufficient liquidity, relevant information), but also the pace at which decommissioning will have to occur. If financial markets can in principle navigate asset stranding if the transition is orderly and gradual (van der Ploeg, 2020), a large amount of simultaneous shock onto companies' balance sheets may be difficult to hedge in any kind of transition. Saygin et al. (2019) show that the time distribution of asset stranding depends on the technology considered, with stranded coal being stranded early, and gas stranding peaking by 2045 in early-action scenarios. As most transmission channels are not easy to reproduce in applied studies, a general model linking asset stranding to financial instability being yet to be proposed (Jackson, 2019; Mercure et al., 2018).
Finally, an important, often disregarded point, is the extent to which industries and financiers alike will be able to diversify their portfolios and reap the fruits of the low-carbon transition (Jackson, 2018). Only looking at losses is not enough (Monasterolo, 2020b). Rather, how possible diversification will be given evolving structural constraints would be worth studying. Cormack et al. (2020) show for the EU that utilities with healthy finances *ex ante* are better able to reorient their production portfolios and navigate transition risks. It is the case even if they are highly carbon-intensive at the start of the transition.

The stranded asset literature shows important potentials for financial instability that emerge from escaping carbon lock-in. It therefore focuses less on financial *instability* as such than on sources of financial *instability*. This important distinction was proposed by Wolfson (1990) according to whom the latter results from the former. Wolfson goes further by arguing that systems are not fundamentally financially unstable. Rather, they can become more and more financially frail. Fragility emerges progressively as imbalances build up though time. An important question for the financial transition risk literature is the extent to which asset stranding will be a decisive source of imbalances that may degenerate into financial instability.

Yet, due to many theoretical uncertainties, the effect of resource and physical asset stranding on financial stability is still unexplored beyond flow effects. This calls for the use of integrative methods able to accommodate a balance-sheet view of firms and financial institutions, and model the interaction between the two (Monasterolo and Raberto, 2016; Dafermos et al., 2018).

An important question is also that of the balance between the magnitude of asset stranding and the ability economic agents to cope with them. This calls for an evaluation of how financial markets deal with transition risks. If markets misprice transition risks, financial agents will not be able to hedge and avert possible losses. I then propose an overview of the empirical literature on the financial economics of the low-carbon transition.

4 Financial markets and the transition: A study of the empirical literature

Gauging whether markets include financial risks poses methodological challenges. Given the relative paucity of data and indicators, inference is complex. Different approaches have been proposed. Surveys of financial institutions have shed light on their investment practices with respect to the low-carbon transition. Econometric asset-pricing approaches have tried to infer pricing behaviours based on market prices. Finally, event-studies have been proposed to measure investors' reaction to policy shocks and news.

4.1 Are investors concerned about the transition?

Little data or survey studies are available on the way financiers perceive the low-carbon transition as such and the materiality of transition and climate risks. Yet, a handful of studies have provided valuable insights on this issue.

This small literature has shown that investors are growingly considering climate risks. The TCFD reports that between 2017 and 2020, the number of financial operators concerned by climate-related risks has grown by more than 85% (TCFD, 2020b). This trend started after the Paris Agreement. Critchlow (2015) documented an "irrational apathy" on the part of the financiers she surveyed, who exhibited a lack of interest and information on climate issue. More recent studies tend to show an opposite attitude.

Amel-Zadeh (2018) demonstrates that financiers now do consider regulatory (including stranding) and physical risks as material enough to be accounted for in their funding decisions. He also shows that financiers and managers consider different types of risk. Management seems to regard physical operational risks as more important than others. Plus, numerous sectors, like IT, consider all climate risks as irrelevant to their business because of lack of information about the exposure of their value chain. Krueger et al. (2020) show a similar picture, while highlighting that investors' motivations for considering climate change can go beyond purely financial considerations. Indeed, reputational, legal or even moral issues turn out to be the most important motives in many instances. In this precise respect, Amel-Zadeh (2018) argues that surveys may lead to biased responses.

Most of these studies highlight that financiers have trouble translating such concerns into investment decisions, due to lack of exposure data, adapted methodology and readily usable insights from scientific productions (Harnett, 2017). It has been confirmed by surveys on the barriers to proper pricing and reallocation on financial markets. Ameli et al. (2020) and Monasterolo (2020a) show that the lack of rigorous methodologies for the pricing of transition risks, readable indicators and investment vehicles are major barriers for investors. Christophers (2019), Thomä and Chenet (2017) and Louche et al. (2019) suggest that institutional routines and information asymmetries all represent obstacles. The TCFD highlights the complexity involved in estimating physical and transition risks and has proposed some synthetic indicators (TCFD, 2017). However, Ilhan et al. (2019) show that while investors consider disclosure as important, they only find it relevant when it comes to assess physical-risk. Mésonnier and Nguyen (2021) nonetheless show that, in France, mandatory disclosures strongly encourage divestment from fossil-energy assets. However, the authors do not discuss whether divestment corresponds to a better understanding of transition or physical risks. Whom their assets were sold to is not questioned either.

This still incipient literature shows encouraging signs of a regain of interest for climate matters on the part of financiers. However, it does not tell much about how investors price risks.

4.2 Do investors price climate-related risks?

To gauge whether agents price climate risks, the literature has relied on econometric methodologies. They include cross-section analysis of asset returns and the application of asset-pricing models (CAPM, Fama-French) on excess returns from synthetic portfolios with different carbon contents. The latter is meant to derive carbon-specific risk premia or non-efficient pricing. Some studies also use event-studies, that is, measures of investors' reactions to transition events (policy, technological news...) shocks, and draw lessons on investor expectations.

4.2.1 Cross section and asset-pricing models

Cross-section analyses, with and without asset-pricing models, allow to test several hypotheses which all have their theoretical implications with these methodologies. Bolton and Kacperczyk (2020b) list three such research questions, which are not mutually exclusive, and that more or less structure this body of research.

The *carbon risk premium* hypothesis holds that agents price at least partly the risk associated with fossil exposures by asking for a premium when they buy assets. The expected outcome is that, in cross sections, higher returns should be associated with higher exposures, measured by carbon intensity (emission-sales ratio) or absolute emissions (Scope 1, 2 or 3[4]). This hypothesis can be tested for any kind of asset, from stocks (Hsu et al., 2020) to options (Ilhan et al., 2019). Taken as it is, this hypothesis suggests that risk premiums on carbon-intensive assets are higher than those known to be applied onto low-carbon technologies, notably renewables (Schmidt, 2014; Polzin et al., 2019).

The *market inefficiency* hypothesis suggests on the contrary that agents misprice carbon-related assets, by exhibiting an undue lack of interest for low-carbon assets (Bernardini et al., 2019; Cheema-Fox et al., 2019; Görgen et al., 2019; In et al., 2020). The expected pattern is that low-carbon portfolio evaluated with canonical asset-pricing models would perform better than the market and would exhibit positive "alphas"[5]. This would point at a market inefficiencies. On efficient markets, such "alphas" would be reduced to zero as all profit opportunities would already have been reaped at the moment of observation.

The *divestment hypothesis* takes carbon-intensive assets as "sin stock" some investors do not want to buy and even want to get rid off. As a result, the asset would be less demanded and more offered on the market. Hence lower prices and higher returns. This hypothesis would translate into similar observables to the carbon risk premium one, but is conceptually distinct, as it is a quantity rather than a price effect. It therefore requires a distinct identification strategies based on holdings rather than returns. If the divestment hypothesis is true, more carbon-intensive assets would be less held by institutional investors (Hunt and Weber, 2019; Bolton and Kacperczyk, 2020b; Mésonnier and Nguyen, 2021).

Part of literature seems to validate the "market inefficiency" hypothesis when it comes to stock holdings. Most portfolios studies show that "greener" portfolios exhibit positive alphas or outper-

[4]Emission "scopes" are different ways to measure the CO_2 emissions of a company at different range along their value chains. Scope 1 emissions are the emissions directly related to the production process. Scope 2 emissions include those attributable to energy consumption. Scope 3 emissions account for all other emissions along the value chain (outsourcing, transportation, etc.).

[5]In the traditional CAPM model, the expected return on a portfolio is goven by $r = r_f + \alpha + \beta(r_m - r_f)$ where r is the portfolio's return, r_f the return on the risk-free asset, r_m the market return and β is a mesure of undiversifiable risk. α is a measure of excess returns, which must be zero if markets are efficient.

form "browner" holding structures (Bernardini et al., 2019; Cheema-Fox et al., 2019; Görgen et al., 2019; Hentati-Kaffel and Ravina, 2020; In et al., 2020). Hsu et al. (2020) stands as an exception, by rejecting market inefficiency based on portfolio analysis, but is focused on local pollution.

This conclusion is not shared by Bolton and Kacperczyk (2020a), who consider cross-section regressions on actual returns with several controls instead of synthetic portfolios[6]. Gostlow (2019), using a factor-selection approach, shows that CO_2 emissions over net sales significantly feed into the pricing of environmentally friendly portfolios, but not of others. Most studies also show higher specific risk (beta) for the most polluting companies[7]. Results are robust across asset-pricing models (CAPM, Fama-French, Carhart). Similar conclusions were found for corporate bounds (Duan et al., 2020). Donadelli et al. (2019) also show that fossil companies most exposed to transition policies exhibit a lower market-to-book ratio. They further report that oil companies' valuation is getting increasingly unrelated to oil prices, their main fundamental. This suggests that fossil companies' valuation is getting driven by exposition to climate policies. Finally Atanasova and Schwartz (2019) report similar effect onto oil extraction firms. They show that companies investing in undeveloped proven reserves (new wells) face lower market valuation. These results vindicate the carbon risk premium hypothesis. Bolton and Kacperczyk (2020b) further show that carbon premiums do not vary much between Asia, Europe and North America. Using another metric for carbon risk, Görgen et al. (2019), to the contrary, do not find evidence of a carbon premium. Monasterolo and de Angelis (2020) document similarly that after the Paris Agreement, investors have been perceiving less risks on low-carbon technology, but have not priced-in higher risks for high-carbon assets. Finally, Faccini et al. (2021) show that climate-related risks are only partially priced in. Transition risks, in particular, are only accounted for over short-run horizons. What's more, investors only react to domestic (US) climate policy news.

[6] The authors nonetheless do not control for fossil fuel prices, which may be correlated to their main regressors (total emissions), and weigh on the returns of some key high-carbon companies.

[7] Although Bolton and Kacperczyk (2020a) show higher risks related to plain emissions instead of carbon intensity, a metric used in most studies.

Table 8: Asset-Pricing Studies on Transition Risks - Green Premium

Author/Year /Publication	Asset type	Assets' Sector	Geographical coverage/Period	Analysis type	Methodology	Measure of climate risk	Results
Cheema-Fox et al. (2019) Working Paper	Stocks	All	US (2010-2016)	Regression	Computation of returns from several portfolios consisting in various strategies	Sum of all emission scopes	Significant decarbonization alphas detected. Attributed to investors' lack of reaction
Gostlow (2019) Working Paper	Stocks	All	North America Europe Japan	Portfolio Analysis	Several portfolios including measures of physical and transition risks. Penalisation of over-specification	Carbon intensity	Transition risk indicators cannot explain returns on portfolio
Duan et al. (2020) Working Paper	Corporate bonds	All	Global (2005-2017)	Regression	Building of quintile portfolios, regression analysis with manyrobustness checks	Carbon intensity of revenue (Scope 1)	Presence of significant carbon alphas, attributed to investor's underreaction
Görgen et al. (2020) Working Paper	Stocks	All	Global (2010-2018)	Portfolio Analysis	Three portfolio, including a Green-minus-Brown one to disentangle low-carbon premium	Aggregate "greenness" indicator based on ESG metrics	Low-carbon portfolios outperform high-carbon one, especially in the extreme
				Regression	Panel regressions with increasing controls and fixed-effects. Estimate a "carbon beta"based on an aggregate factor.		Aggregate factor makes for many usual risk measures, but does not measure a carbon risk. Attributed to unpriced fundamental changes
Ihn et al. (2017) *IAEE Forum Issue*	Stocks	All	Global	Portfolio analysis	Green-minus-brown portfolios	Sum of all emission scopes	Low-carbon portfolios outperform high-carbon one
Monasterolo & de Angelis (2020) *Ecological Economics*	Stocks	Energy and fossil	EU & US (1999-2018, depends on the stock index)	Portfolio analysis	Fama-French model applied on several stock indices with a dummy before/after the Paris Agreement	Classification based on sectoral indices (Clean energy, oil& as, etc.)	After the Paris Agreement, companies have started revaluing green companies, but not brown companies
Ravina (2020) Working Paper	Bonds	All	EU (2008-2018)	Portfolio Analysis	Six portfolios with different degrees of greenness valued with a Fama-French 2-factor model augmented with a measure of returns associated with compliance to EU-ETS	"Green minus brown" factor: difference between weekly value-weight carbon portfolio returns from the weekly value-weight green bond portfolio returns from the beginning of Phase II	Significant coefficients on the "Green minus brown" factor, interpreted as a positive green premium
Ravina & Kaffel (2020) Working Paper	Stocks	All	EU (2008-2018)	Portfolio Analysis	Six portfolios with different degrees of greenness valued with a Fama-French 2-factor model augmented with a measure of returns associated with compliance to EU-ETS	"Green minus brown" factor: difference between weekly value-weight carbon portfolio returns from the weekly value-weight green bond portfolio returns from the beginning of Phase II	Significant coefficients on the "Green minus brown" factor, interpreted as a positive green premium
Bernardini et al. (2021) *Journal of Sustainable Finance*	Stocks	Utilities	Europe (2008-2016)	Portfolio Analysis	Three portfolio (Green, Green-minus-brown, Brown)	Emission intensity of production (Scopes 1 and 2)	Green portfolio performs better than brown minus green,which performs better than brown portfolios
				Regression	Estimation of carbon alphas and estimation of a corresponding risk premium.		Significant carbon alphas, linked to lower perceived risk on the low-carbon market
Faccini et al. (2021) Working Paper	Stocks	All	United-States (2000-2018)	Regression	Portfolio sorts analysis - Estimation of climate risks and excess returns with asset-pricing model	Textual analysis of climate news : shares of press articles covering climate topics in total press releases. Four topics are tested: short-run US climate policy, international climate policy, natural disasters and global warming	Positive alphas for portfolio long on high climate policy risks and short on high climate policy risks. Suggests hedging in favour of firms with low transition risks (climate betas) due to climate policy rollback. Other climate-related factors not priced in. Bottom line: only short-term domestic transition risks are priced in, mostly after 2012
				Regression	Fama-McBeth regressions (Robustness check)		
				Regression	Portfolio sorts analysis - Estimation of climate risks and excess returns with asset-pricing model	Narrative indicator of climate policy news : 3500 articles on US climate policy published between 2000 and 2018 are marked 1 if climate policy is tightening and -1 otherwise	

Note: A "green minus brown" portfolio is a portfolio structure long on green assets and short on brown assets. A "brown minus green" portfolio is the opposite.
We call "Portfolio analysis" the comparison of the performances of various portfolios.
The "Regression analysis" category comprises all kinds of methods estimating returns and/or stock prices with econometric models.

Table 9: Asset-Pricing Studies on Transition Risks - Carbon Premium

Author/Year /Publication	Asset type	Assets' Sector	Geographical coverage/Period	Analysis type	Methodology	Measure of transition risk	Results
Chava (2014) *Management Science*	Stock & Loans	All	Global (1992-2007)	Regression	Regression of environment-related metrics onto cost of capital (returns, loans)	Synthetic indicators of environmental performances and concerns, including carbon emissions	Higher returns required and higher credit spread for firms with higher emissions/environmental hazards- Even by controlling for key variables.
Matsumura et al. (2014) *The Accounting Revue*	Stocks	All	US (S&P 500) (2006-2008)	Regression	Link between firm value and emissions (Scope 1) Logit model of disclosure decision	Scope 1 emissions	Firms with higher Scope 1 emissions have a lower market value
Hsu et al. (2018) Working Paper	Stocks	All	US (1986-2014)	Portfolio Analysis	Five Portfolios with different degrees of greenness	Firm's polluting releases (Local pollution)	Higher emissionsimply higher returns (lower asset prices). Significant pollution premium,untampered by common measuresof systematic risks.
				Regression	Cross-section on returns with controls.		Lower emissions reduce profitability. Sensitivity to policy shifts.
Jung et al. (2018) Working Paper	Loans and bonds	All	Australia (2009-2013)	Regression	Regression analysis of carbon risk (emission intensity) and carbon awareness (reporting or not o carbon intensity)	Scope 1 emissions	Higher cost of capital for carbon-intensive risks. Higher costs negated by disclosing their carbon intensities.
Zhang et al. (2018) *Theoretical Economics Letters*	Stocks	Covered by Chinese (Shenzen) Pilot ETS system	China (2013-2015)	Portfolio Analysis	Three portfolios: clean, dirty, dirty-minus-clean	Firms receiving free carbon alowances	Negative abnormal returns on dirty portfolios
Anatasova & Schwartz (2019)	Stocks	Fossil firms	US & Canada	Regression	Time-series analysis with undeveloped proven reserves as regressors	Investment in undeveloped proven reserves	Higher cost of capital for firms investing in undeveloped proven reserves
Bolton & Kacpercykz (2020a) Working Paper	Stocks	All	Global (2005-2017)	Regression	Cross-section of returns with many controls Regression of climate-risk coefficient on traditional risk metrics	Scope 1,2 and 3 emissions Growth rate of Scope 1,2 and 3 emissions Emission intensity (Scope 1,2,3)	Significant carbon premium on absolute emissions (not carbon intensity) not explained by traditional measures
Bolton & Kacpercykz (2020b) Working Paper	Stocks	All	Global with disaggregation (2005-2017)	Regression	Cross-section of returns with many controls Regression of climate-risk coefficient on traditional risk metrics Regional disaggregation	Scope 1,2 and 3 emissions Growth rate of Scope 1,2 and 3 emissions Emission intensity (Scope 1,2,3)	Small regional differences in carbn premiums
Delis et al. (2020) Working Paper	Syndicated bank loans	All	Global (2007-2016)	Regression	Panel regressions with more and more controls and fixed-effects	Measure of climate policy exposure thanks to existingclimate policy index interacted with fossil-industry dummy	Increased spreads after 2015 (Paris agreement), mainly due to climate policy.
Ilhan et al. (2020) Working Paper	Options	All	US (2010-2017)	Regression	Cross-section analysis linking downard tail risk to carbon intensity	Emission intensity of market capitalisation (Scope 1)	Downward tail risk increase (very) sligtlywith industry's carbon intensity
Kolbel (2020) Working Paper	Credit-default swaps	All	Global (2010-2018)	Regression	Forecasting regressions on CDS spreads based on fowards-looking climate-risk measure	Measure of firms' future emissions based on mandatory disclosure (Forward-looking)	Transition risks increase CDS spreads especially after the Paris Agreement
Nguyen et al. (2020) Working Paper	Stocks and Loans	All	Australia (2002-2013)	Regression	Dynamic diff-in-diff study of the reaction to the Australian ratification of the Kyoto protocol	Dummy variable identifying emitters and non-emitters	Higher cost of capital for polluting firms after the ratification of the Kyoto Protocol
Wen et al. (2020) *Energy Economics*	Stocks	Covered by Chinese (Shenzen) Pilot ETS system	China (2013-2018)	Regression	Difference in difference with matching at the implementation of the Chinese Pilot ETS	Dummy variable identifying ETS participants and ETS outsiders	No significant difference in stock returns at the implementation of the Shenzen Pilot
				Portfolio Analysis	Three portfolios: clean, dirty, dirty-minus-clean	Firms receiving free carbon alowances	Negative abnormal returns on dirty portfolios

Note: A "green minus brown" portfolio is a portfolio structure long on green assets and short on brown assets. A "brown minus green" portfolio is the opposite.
We call "Portfolio analysis" the comparison of the performances of various portfolios.
The "Regression analysis" category comprises all kinds of methods estimating returns and/or stock prices with econometric models.

Concerning the divestment hypothesis Hunt and Weber (2019) show that divesting from carbon-intensive sectors yield higher returns for hypothetical portfolios in Canada. Trinks et al. (2018) and Plantinga and Scholtens (2021) report similar findings, by showing that divestment from fossil companies would not have diminished portfolio performances in the long-run. By contrast, Bolton and Kacperczyk (2020a) show that observed divestment effects concern the upper tail of the carbon emission distribution.

Table 10: Asset-Pricing Studies on Transition Risks - Divestment

Author/Year /Publication	Asset type	Assets' Sector	Geographical coverage/Period	Analysis type	Methodology	Results
Hunt & Weber (2018) *Organization and Environment*	Stocks	Fossil firms	Canada (2011-2015)	Portfolio analysis	Carhart four-factor model on divesment portfolios	Divesting from carbon-intensive sectors yield higher returns for hypothetical portfolios
Trinks et al. (2018) *Ecological Economics*	Stocks	Fossil firms	US (1927-2016)	Portfolio analysis	Carhart four-factor model on divesment portfolios	Divestment very modestly impacts financial performances
Bolton & Kacperczyk (2020a) Working Paper	Stocks	All	Global (2005-2017)	Pooled regression model	Effect of carbon intensity on fossil holdings	Divestment concentrated in directly affected companies (Fossil firms)
Platinga & Scholtens (2021) *Climate Policy*	Stocks	Fossil firms	Global (1973-2017)	Portfolio analysis	Fama-French four-factor model on divesment portfolios	Divestment does not impact significantly the risk-return profile of portfolios

Note: A "green minus brown" portfolio is a portfolio structure long on green assets and short on brown assets. A "brown minus green" portfolio is the opposite. We call "Portfolio analysis" the comparison of the performances of various portfolios.
The "Regression analysis" category comprises all kinds of methods estimating returns and/or stock prices with econometric models.

The literature verifies the carbon risk premium hypothesis on the credit (Delis et al., 2019), option (Ilhan et al., 2019) markets and CDS (Kölbel et al., 2020). It shows that regulatory risks are indeed priced in on those markets, although observable effects are weak in the case of credit. Nguyen et al. (2020) report a higher cost of capital for fossil firms in Australia, with a notable effect after the ratification by the country of the Kyoto Protocol in 2007.

The literature seems characterised by a number of uncertainties, mostly due to the variety of methods (cross-section v. portfolio) and indicators (policy exposures, returns, market-to-book ration, emissions, etc.). These uncertainties are heightened due to the paucity of studies, especially for asset classes other than stocks.
It must also be emphasised that risk-pricing is a mere risk-shifting operation. An agent will have to bear the costs in case of adverse outcomes. If such risk-shifting occurs only within financial markets, its overall stability may be left unchanged if exposure networks are dense enough (Battiston and Martinez-Jaramillo, 2018). What's more, financial markets also suffer from concentration, and some financial institutions have large market powers allowing them to shift risks onto less solid shoulders (Christophers, 2017). Most research in that field do suggest, however, that pricing behaviours seem to emerge in the wake of key policy events, like the Kyoto Protocol (2003) or the Paris Agreement (2015), highlighting the power of key policy announcements. Studying the effect of such announcements through event study is of key interest.

4.2.2 Event-studies

Building on a well-established method in financial economics (MacKinlay, 1997), event-studies consist in building an econometric model predicting market returns based on usual determinants. Predicted returns are then compared to real-world returns. Spreads between predicted and actual returns around the event define abnormal returns. A handful of studies, that I reference in Table 11, carry out such analyses[8].

The literature highlights that investors react to policy announcements, tightening climate policies being associated to negative abnormal returns for fossil companies Barnett (2019); Donadelli et al. (2019) or higher risk pricing on option markets Ilhan et al. (2019), and *vice-versa*. Varntanian and Pancera (2020) find such results, but insist on their small magnitude. Note that by using a different dataset (Datastream instead of Compustat in most studies), Batten et al. (2016) find insignificant abnormal returns for most climate policy events over 2011-2016, including the Paris Agreement. Hence uncertainty on data quality, and needs for robustness tests.

Some other studies contain broader insights about the behaviour of investors. Sen and von Schickfus (2020) study the reaction of German investors to the passing of a bill aimed at decommissioning lignite plants, hence triggering asset stranding. By using a granular event-study, they show that agents do care about asset stranding by underpricing exposed companies. However, they also show that investors expect a compensation for asset losses on the part of the State. Negative changes in abnormal returns were detected when the European Commission threatened to strike down the compensation scheme to be included in the bill. Finally, Byrd and Cooperman (2018) measure the reaction of investors to progress and setbacks in CCS technologies. They show that progress can be linked to positive and significant abnormal returns while setbacks cannot. They suggest that either agents have troubles pricing long-run technology risks, or do not consider climate policy to be credible in decreasing fossil fuel demand.

Event studies, though useful they may be, nonetheless suffer from certain limitations, and must be taken with precaution. First, considering daily returns around an event is perilous over long (over a week) time spans, as statistical biases can arise (Brown and Warner, 1985). Second, these studies are performed over short-run horizons. As such, discriminating actual changes in ”fundamentals”

[8] Some papers are present in Tables 9, 8 or 10, and 11 as some studies run both an event study and an asset-pricing analysis.

Table 11: Event Studies on Transition Risks

Author/Year /Publication	Asset Type/Sector	Geographical Coverage/Period	Event	Results
Griffin et al. (2015) *Energy Economics*	Stocks Oil Producers	US (2009-2013)	Test for ”unburnable carbon” news	1.5-2% loss in asset price for 63biggest oil-gas companies in the US
Byrd & Cooperman (2018) *Journal of Sustainable Finance & Investment*	Stocks Coal producers	North America (2011-2015)	CCS-related events (technological breakthroughs, setbacks)	Investors have priced strandedassets in, as they do not react much to CCS setbacks,but seem to be stillhoping for CCS breakthroughs,as they react positivelyto positive announces
Barnett (2019) PhD Thesis (University of Chicago)	Stocks & Commodity Oil	North America (1996-2017)	Test for several climate-policy events (Paris Agreement, Trump’s election)	Tighter climate policy associated with lower abnormal returns on oil prices and oil producer stocks. Larger and more significant coefficients associated to recent years
Donadelli (2019) Latvia Central Bank Report	Stocks All	2010-2018	Series of many climate events, effects averaged out	Abnormal losses(-1%) after 20 days
Ilhan et al. (2019) Working Paper	Stocks All	2016	Trump Election (Associated with climate policy rollback)	Trump election’s decreases downward risk
Nguyen et al. (2019) Working Paper	Stocks All	Australia (2007)	Kyoto Protocol Ratification	Lower abnormal returns for emitters’ stocks within 3 to 5 days before and after ratification
Hansen & Pollin (2020) *Review of Social Economy*	Stocks Fossil Firms	Global (2011-2018)	Analysis of the effect of divestment on fossil fuel share prices	Very limited effects on fossil firm share prices
Sen & Von Schickfus (2020) *Journal of Environmental Economics and Management*	Stocks Utilities	Germany (2015)	Decommissioning of lignite plants	Investors account for stranded assets but expect a compensation

that would be detected by investors or transitory reactions before mean-reversion in the longer run is not trivial. In that light,it is difficult to see whether asset devaluation mirror transition risks, which would require semi-strong market efficiency in the sense of Fama (1960). The assumption can be tested by looking at market reaction around the event date : if the market over- or undershoots before several time units around the event, semi-strong efficiency does not hold. That significant abnormal returns could be detected around event dates in most papers argues in disfavour of semi-strong efficiency. As a result, it seems fair to assume that pricing may be off the hypothetical efficient benchmark.

The literature offers contrasted evidence of the integration of transition risks into asset pricing. Risk-pricing behaviours seem uncertain for stocks, less so for other asset classes and the credit market. However, the small number of papers, notably for other asset types than stocks, and the small size of post-Paris time-series invites to prudence. Plus, on one side, the econometrics of asset pricing seem to point at emerging carbon premia on financial markets, event-studies and survey approaches invite to caution. They indeed highlight the difficulties coming along the computation of transition risks and possible transition-contrarian expectations.

The discrepancies across these studies, which point at a gap between the mesoeconomic behaviour of financial markets and individual responses to news and additional information, may suggest that a variable is missing. For instance, carbon intensity or emissions, which do seem to give rise to a “carbon premium”, may be correlated to other fundamentals. Bolton and Kacperczyk (2020b) show that carbon emissions are highly correlated to financial metrics. More polluting companies may find themselves in the lower tail of the productivity and capital vintage distribution. This may lead investors to apply a premium on those assets without it being related to transition risks, but simply to lower economic performances. Many studies have shown a positive link between greenness (measured by ESG factors and other metrics) and financial exposures (Breitenstein et al., 2020). Higher emissions may signal a greater exposure to fuel price volatility, which is a known market risk (Bagirov and Mateus, 2019). Hence, again, an additional carbon premium that may not be related to the transition.

4.3 Obstacle to pricing: are premiums adequate?

Another issue lies in that little can be said on whether this pricing is adequate. If the presence of carbon premia suggests that investors price in transition risks to a certain extent, their presence does not tell much on whether they are sufficiently high (or, to the contrary, low enough) regarding future transition developments. This question is virtually unanswerable given the lack of strong inference methods and theoretical uncertainties[9].

However, the literature has expressed worries about current pricing of climate-related risks being too low. Monnin (2020) and van der Ploeg (2020) suggest that financial markets may be under-pricing climate-related risks, both physical and transition-related. Despite progress, financial markets still exhibit a certain "blindness" with respect to transition risks (Silver, 2017; Thomä and Chenet, 2017; Louche et al., 2019).

Would increasing information disclosures and better assessment framework lead to better alignment and get market closer to efficient pricing? Theoretically, the literature is divided on the question, with Ryan-Collins (2019) and Kalinowski and Chenet (2020) criticising the TCFD's (2020b) sole call for better disclosure, and suggest a stronger, precautionary approach. The literature is also divided on the policy framework. Monasterolo (2020b) recommends that a unique and reproducible metric be found for climate-related risks. On the other hand, Bingler et al. (2020) calls for the adoption, by financiers, of a multi-criteria approach due to the multiplicity of existing evaluation frameworks.

Hence that the detection of a degree of transition-risk pricing should be taken with precaution. On top of methodological uncertainties, cognitive biases, informational gaps and radical uncertainty may prevent the full incorporation of transition risks into prices. Investment and hedging behaviours may then still be limited and inconsistent with future decarbonation efforts.

4.4 Interpretation and scope

Finally, two competing hypotheses cannot be disentangled based on the results above. On the one hand, failing to price higher carbon risks may signal that investors have not integrated the opportunities coming with the low-carbon transition. Yet, this suggests that financial agents will

[9]This directly relates to the "joint hypothesis" between market efficiency and adequate pricing highlighted by Fama (1991)

not be able to hedge their exposures once the transition starts. In other words, there is tension between seeing financial institutions as an *obstacle* to the transition or as *vulnerable* to it. This relates to what Kalinowski and Chenet (2020) call the “double materiality” of financial transition risks. Imperfect financial markets may hamper transitional efforts if they fail to ensure that low-carbon technologies and capitals are not backed. They may thus increase the extent of physical risks, which may in turn feed back onto transition risks as economic transformations get more rapid and pronounced (Monasterolo, 2020b). Conversely, the financial sector is vulnerable to the transition, due to its exposure to asset devaluations.

This important difficulty stems from the status of the transition itself with respect to the financial sector. A mistake would be to consider the transition process as external to financial systems and only affect it exogenously. Rather, the financial system will have to be part and parcel of the low-carbon transition, by channelling funds and supporting investments. In other words, higher transition risks associated with one sector will not mandatorily result in massive divestment from this sector, but in a selection of companies most able to cope with the transition (Allen et al., 2020). Exposures will therefore change along transition paths. The distribution and extent of transition risk will evolve as the transition goes. Pricing behaviours are endogenous to the transition itself.

In that light, the results presented above hold for a state of the world in which climate policies are still timid and low-carbon capital penetration low (UN, 2019). They do not inform us on long-run exposures of transition risks, but rather on how markets could react (or not) to transition shocks in the short run. Such results are therefore informative for stress-tests, as they provide insights on possible behavioural and market reactions. However, they are less informative for long-run assessment, as those may refer to different structural and macroeconomic conditions.

In view of these uncertainties, it seems safe to assume that financial markets may not be pricing transition risks sufficiently and adequately, and that they may be vulnerable to a shift to a transition path, all the more so if it is brisk and abrupt (Carney, 2015). It is therefore suited to study how financial instability is gauged as such.

5 Direct financial transition-risk assessments : Results and Methods

The applied literature on transition risks have mostly built on two methods. Some studies have made use of different kinds of "stress test" approaches, that have grown fashionable amongst practitioners. Another strand has adopted a more long-run approach aimed at characterising the effects of the transition in itself. Other kinds of studies have also been proposed, that I will review as well.

5.1 Stress tests

5.1.1 Mapping of direct exposures

Early studies (Weyzig et al., 2014; Bowen and Dietz, 2016) assessed financial institutions' direct exposure to sectors most exposed to climate policies. Such studies are useful in providing rough approximations (Batteson and Saccardi, 2020) within national (US, UK) and regional financial (EU) financial sectors.

As shown on Table 12, a significant part of the literature points at small losses as a fraction of total assets, with asset-type-specific proportions staying below 5%. Most discrepancies across studies depend on whether the "fossil" category includes more than extraction industries and commodity assets. However, loss estimates do not mean the same thing depending on the type of financial institution under scrutiny (Weyzig et al., 2014). A some hit a a fraction of total asset would affect banks and insurance companies more than pension funds for instance. Finally, the manageability of financial losses depends on the country's own mcro-financial fragility *ex ante* (Delgado, 2019; Nieto, 2019; Baer, 2020).

Most studies document pure exposures, henceforth offering an upper bound of direct losses due to climate-related risks (Delgado, 2019). They do not make hypothesis on the magnitude of a given transition shock. One study, Weyzig et al. (2014) chose to build scenarios contrasting different policy stances (implementation of climate policy or not) and timings (immediate or delayed).

Table 12: Mapping of exposures - Summary of the literature

Authors	Location of Financial Institutions/Period	Assets' class	Exposed financial sectors	Assets' Sectors	Methodology	Findings
Weyzig et al. (2014) EU Parliament Report	EU(2014)	All	Banks Pension funds Insurance companies	Fossil	Cartography of direct exposures	5% total assets across sectors Pension funds: 5% of all assets Insurance companies:4% Banks: 1.4%
					Scenario: Swift transition (Transition Risks)	Pension funds: 2.5-3.4% of all assets (Small) Insurance companies:2% Banks: 0.4% (Big)
Bank of England (2015) Working Paper	UK (2015)	Equity & Bonds	Insurance Sector	Fossil fuel companies, carbon-intensive sectors	Plain exposure of UK financial institutions	Global equity and fixed-income assets exposed to transition risk (Equities/IG Bonds/HY Bonds/Leveraged Loans) USD 75.3 trillion Tier 1: 6.0/2.6/0.5/0.3; Tier 2: 9.2/2.8/0.7/0.5; Other: 37.9/11.1/1.9/1.8
Bowen & Dietz (2016) Finansinspektionen Report	Sweden (2015)	All	All	Fossil fuel companies, carbon-intensive sectors	Plain exposure of Swedish financial instutitions	Overall low exposures
Gros et al. (2016) ESRB Report	EU (2015)	Equity & Bonds	All	Fossil fuel companies, carbon-intensive sectors	Plain exposure of EU financial institutions in aggregate, discussion on macroeconomic shocks	Total Assets: Banks: 1.3% Pension Funds: 5% Insurers: 4.4%
(Schotten, van Ewijk, Regelink, Diederik, and Kakes, Schotten et al.) DNB Report	Netherlands (2015)	All	Banks Insurers Pension Funds	Fossil fuel companies, power generation, basic industry, transport, agriculture	Plain exposure of Dutch financial instiutitions	Banks: 10% Insurers: 4.5% Pension funds: 12%
Bank of England (2018) PRA Report	UK (2018)	Debt	Banking Sector	Fossil fuel reserves, carbon-intensive sectors Housing Automotive	Qualitative assessment of exposures, key mechanisms	Transition risks significant to the UK banking sector, especially through housing. £20 million exposure to automotive sector Around £100 billion in exposure to coal industry
Delgado (2019) Banco de España - Revista de Estabilita Financiera	Spain (2010s)	Loans	Depost-taking institutions	All	Based on most fragile sectors (NPL), assessment of potential bank exposure	Spain economy still fragile, and potentially made more fragile by transition risks
Nieto (2019) *Journal of Financial Regulation and Compliance*	EU, USA, China, Switzerland, Japan (2014)	Syndicated Loans	Banks	All	Documents aggregate exposure to climate-relevant syndicated loans as percentage of total national sector asset, due to decrease in credit quality.	1.6 trillion total exposure US: 3.8% EU: 1.4% (50% of capital with 3% leverage ratio) China: 0.5% Japan: 2.2%
Baer (2020) CEENRG Working Paper	EU, USA, Canada, China, Switzerland, Japan, South Africa, India , Argentina, Brasil, Chile, Australia, Malaysia, Russia, New Zealand (2018)	Bonds, equity	All relevant	Fossil	Enhances previous approaches by accounting for diversification and risk and discussing geographical distribution of exposures	US financial system particularly exposed Around US$3 trillion of direct exposures, 7.5% bonds, rest equities.
Battiston et al. (2020) OeNB Financial Stability Report 40	Austria (2019)	Loans and bonds	Banks	Fossil Utilities Energy-Intensive Transportation Building Agriculture	Documents exposures based on OEnB's credit dataset and CPRS database (Vorbis)	Austrian banks exposed by 26% of the their assets. 16% housing, 10% rest
Faiella and Lavecchia (2020) *Journal of Sustainable Finance and Investment*	Italy (2018)	Loans	All loan-making institutios	First quintile of the average ranking of borrowers and emmitters	Document loan exposures of Italien financial system based on descriptive statistics and homemade metrics	40 to 55% of loans (exluding interbank lending) of banks exposed to high-carbon sectors. Corresponds to 10-15% of total assets.

Such research adopts a similar approach to the stranded asset literature, by showing instability potentials. Yet, they only account for direct exposures and leave aside the possibility for financial contagions across financial networks (Allen and Gale, 2000; Battiston and Martinez-Jaramillo, 2018). More elaborate stress test methods have therefore been proposed by the literature.

5.1.2 Static stress tests

Climate stress tests can be performed at the level of specific financial institutions. They can also be applied at the mesoeconomic level of whole financial systems. Their explicit endeavour is to gauge the magnitude of possible losses arising from a sudden and/or delayed, unanticipated and disorderly transition (Battiston et al., 2017). Such studies focus most often on equity and as such mostly tackle market risks. Baer (2020) insists in that respect that only accounting for the equity channel may be misleading, and calls for incorporating bond finance as well. Some studies have nonetheless extended to bonds and loans and explored credit risks (Monasterolo et al., 2018; Batteson and Saccardi, 2020). I review all approaches in the following. They are summarised in Table 13.

Table 13: Static stress tests - Summary of the Litterature

Stress-Test Type	Authors/Year/ Publication	Geographical Coverage/Period	Assets' Coverage	Depreciated Assets' class/Metric	Exposed financial sectors	Assets' Sectors	Methodology	Reference Scenario(s)	Underlying model(s)	Findings
Microeconomic	Monasterolo et al. (2018) Working Paper	China (2018)	Global	Syndicated loans	Two main development banks	Energy & Utility	Stress-test based on different scenario assumptions, with a shock in 2020-2030.	LIMITS Database	GCAM, WITCH	4%-22% of Chinese development banks' portfolio value
	Monasterolo & Battiston (2018) OeNB Conference Paper	Austria (2018)	Global	All	Central Bank (OeNB)	Energy, Utility & Sovereign	Stress-test based on different scenario assumptions, with a shock in 2020-2030. Risk premium of sovereign bonds based on GDP shocks	LIMITS Database	GCAM WITCH	Between -0.4% loss to 0.1% gain Underlying scenarios and geographical area have a large influence on gains and losses
	Battiston et al. (2019) EIOPA Report	EU (2018)	Global	Sovreign Bonds	Insurance	Sovereign	Computation of portfolio losses due to changes in sovereign bond value Two market condition hypothesis (mild, adverse)	LIMITS Database	GCAM, WITCH	Less than 1% portfolio loss under mild market conditions, down to 3% losses in adverse market conditions
Network	Battiston et al. (2017) *Nature Climate Change*	EU(2017)	Global	Loans and Bonds	Largest Banks	Energy and Utility	Stress-test with second-round effects - 100 % Catastrophic shock - Bottom-up with largest banks	None	None	DB would lose up to 30% of its equity Svenska Handelsbanken up to 7%
							Stress-test with second-round effects - IPCC Scenario shocks - Bottom-up with largest banks and different portfolio compositions	LIMITS Database	WITCH & GCAM	Most adverse case: DB would lose €2.5 billion in assets Svenska Handelsbanken up to €100 million
			Global	Loans & Bonds	All	All	Rough numbers on sectoral exposures	No	No	Potentially much higher exposures through loans (up to 281% of equity if mortgages accounted for)
	Roncoroni et al. (2019) Working Paper	Mexico (2019)	Global	Most asset classes	All	All climate-relavant sectors	Stress-test with disorderly shift to a 2°C-consistent path at several points in time	LIMITS database	WITCH & GCAM	2.5-4% of total assets
	Batteson et al. (2020) CERES Report	US (2020)	Global	Syndicated Loans	Banks	All	Cartography of US banks' syndicated loan exposure to climate-relevant assets Stess-test including secound-round effects and fire-sales	LIMITS & GREENWIN database	Whole LIMITS suite	As much as 12.5% loss in equity in case of disorderly transition in 2025

5.1.3 Microeconomic stress tests on financial institutions

Monasterolo et al. (2018) and Battiston and Monasterolo (2018) assess the financial vulnerability of particular financial institutions, respectively the two main Chinese public investment banks and the Austrian Central Bank (OeNB). The two papers resort to a similar methodology. After considering asset holdings, they measure exposures to different kinds of energy sources. Then, they link structural change from the LIMITS (2013) database to the market valuation of different asset classes[10]. To do so, they assume that the value of assets (including default probability in the case of bonds and loans) issued by energy producers depend on the relative market share change of a given energy source. Battiston and Monasterolo (2018) expand the analysis to the devaluation of government bonds, by assuming a negative linear relationship between change in the real interest rate and GDP growth. This then translates into a change in sovereign bond valuation, which depends negatively on the real interest rate. GDP growth and market share changes emerge from the stress test's shock. The latter consists in considering a jump from the LIMITS baseline to a decarbonation pathway at point in time. The relative changes in market shares and GDP between the baseline and the pathway yields devaluations and increases in default probability.
Based on these, Monasterolo et al. (2018) assume that their shock occur between 2020 and 2030. They report that reported losses, ranging from 4 to 22% of total assets, depend strongly on the underlying model used to generate the transition path. Battiston and Monasterolo (2018) take advantage of the regional disaggregation allowed for by the LIMTS database. They how that for a policy shocks in 2030, losses and gains depend on the stringency of the scenario and the region considered.

5.1.4 Mesoeconomic stress tests in financial networks

Macroeconomic stress tests go beyond the study of direct exposures, by allowing for financial contagion (Battiston and Martinez-Jaramillo, 2018) due to the direct exposures of financial actors to others. They can significantly exacerbate direct losses (Batteson and Saccardi, 2020). The seminal paper of climate stress tests is given by Battiston et al. (2017), who include second-round losses for banks due to the propagation of the first shock on the interbank market. While the upper

[10] The LIMITS scenarios were generated by several Integrated Assessment Models. The studies mentioned here focus on scenarios generated by two models: GCAM (Documentation, 2019) and WITCH (WITCH Team, 2017).

bound for losses (in the event of a 100% devaluation of utility and carbon-intensive assets) is sizeable, the authors show that more plausible shocks onto utility holdings imply small Value-at-risks (95% interval) for the biggest EU banks. They see this result as a lower bound, since only one asset class is considered (utilities), and that only losses on equity are accounted for. Roncoroni et al. (2019), studying the Mexican financial system, expand Battiston et al.'s method. They add two other effects: a fire-sale round, in which agents target specific prudential ratios and adapt their balance-sheet accordingly, and a computation of losses incurred by non-domestic stockholders. Portfolio compositions are fixed *ex ante*[11].

Battiston et al. (2017) consider all projections from the LIMITS database, derive a shock distribution, and then run a Value-at-risk analysis based on this distribution. Roncoroni et al. (2019) compute shocks from a point in time of the BAU scenario to the same point in time in a decarbonation pathway. The study reports higher losses than Battiston et al. (2017) because of the two additional rounds of effect. Finally, Batteson and Saccardi (2020) considers policy jumps along the baseline as in Roncoroni et al. (2019) but do not incorporate fire sales.

Yet, absent an encompassing macroeconomic scenario, and the modelling of macro-finance feedback loops, the picture remains incomplete (Espagne, 2018; Semeniuk et al., 2020). Stress tests have by design either a micro- or a meso-economic focus (see nonetheless Stolbova et al. (2018) for a theoretical attempt to extend the financial-network approach at the macro level). Hence the need for a full-fledged representation of transition risks including the macroeconomy.

5.1.5 Dynamic macroeconomic stress tests

The DeNederlande Bank (DNB, Vermeulen et al. (2018, 2019)) and the European Systemic Risk Board (ESRB, 2020) proposed such scenarios. These studies are aimed at studying the short-run effects of a "disruptive" transition scenario (NGFS, 2020).

[11] This is an important weakness, as this boils down to assuming that investors do not shift their exposures through time (Kalinowski and Chenet, 2020)

Table 14: Dynamic stress tests - Summary of the literature

Stress-Test Type	Authors/Years /Publication	Geographical Coverage	Assets' Coverage	Depreciated Assets' class/Metric	Exposed financial sectors	Assets' Sectors	Methodology	Reference Scenario(s)	Underlying model(s)	Findings
Dynamic	Vermeulen et al. (2019) Report	Netherlands	Global	All assets	Banks, pension funds & insurance companies	Mining & Petrochemical Utilities Basic Industry Transport	Use of a macroeconomic model, then apply structural change + macro shock results to balance-sheet data 5-year horizon	Policy shock (Increase in worldwide carbon price by US$100)	NiGEM	Shock (Total assets) Banks : 2-3% Insurers: 2-11% Pension Funds: 7-10% Due mostly to interest rate changes (Taylor Rule)
								Technology shock (Doubling of the share of low-carbon energy in final energy demand)		
								Policy + Technology shock		
								Confidence shock (Lower consumption and investment, increase of risk premium by one basis point)		
	ESRB (2020) Report	EU	Global	All assets	Banks, pension funds & insurance companies	Mining & Petrochemical Utilities Basic Industry Transport	Use of a macroeconomic model, then apply structural change + macro shock results to balance-sheet data 5-year horizon Includes retro-feedback from financial sector to the macroeconomy	Policy shock (Increase in worldwide carbon price by US$100)	NiGEM	-0.8% mark-to-market loss for banks and pension funds Some credit rationing (-2% less than baseline max) -0.8% decrease in CET1 ratios
								Technology shock (Doubling of the share of low-carbon energy in final energy demand)		Very short-run losses, compensated through increased productivity -0.5% mark-to-market losses for banks and insurances Small losses on CET1 ratios
	EIOPA (2020) Report	EU	EU	All Assets	Insurance	Oil & Gas, Power, Automotive, Cement & Steel, Coal, Aviation & shipping	Detailed mapping of expoures of the EU insurance sector, scenario analysis of changes in asset valuations due to late and sudden delayed transition	Late and sudden policy shock : rapid dwitch from baseline to IEA's 2°C or 1.5°C scenario	WEM	25% equity loss on high-carbon assets due to late and sudden transition
	Grippa & Mann (2020) IMF Working Paper	Norway	Global	Stocks	Stockholders	Oil Sector	Structural VAR linking oil sector performances to stock performance through a dividend model	None	None	5-6% asset losses on insurers, pension funds and non-money-market investment funds

Methodologically, the two studies rely on a suite of models linking a short-run transition scenarios (built from scratch) to transition risks. The scenario is first run by a macroeconomic model (NIESR's NiGEM (2016)). Its outputs will enter a disaggregated sectoral model. The outcomes of both models finally feed a financial module, that yields financial-risk metrics. Both papers also use a similar set of scenario. A policy shock consists in a one-off US$100 increase of the global carbon price. A technology shock figures an accelerated deployment of low-carbon technology. The DNB adds a "confidence shock", in which dithering climate policies lead to lower investment and consumption and an increase in risk premiums of one basis point. The two studies further differ by their geographical scope. The DNB is concerned by the Dutch financial system while the ESRB by the EU's as a whole. Finally, the ESRB improves the DNB's methodology by modelling a feedback loop from the financial sector to the broader economy.

The geographical scope seems to play a role in the magnitude of losses. Vermeulen et al. (2019) report that policy and technological shocks lead to manageable losses. However, if they were to occur at the same time, as much as 11% of Dutch financial assets could be wiped off, with banks bearing most of the brunt. Their confidence shock yields only slightly smaller losses on financial values, but much lesser impacts on macroeconomic variables. By contrast, the ESRB reports that losses remain below 1% of total EU assets. It also shows that retro-feedback effects are benign in both scenarios.

Grippa et al. (2020) adopt a different approach using a structural VAR model applied to Norway. They estimate first the response of Norwegian oil companies to decreases in output. Then, they apply their structural model to output reductions and carbon taxes consistent with Norway's NDCs. Feeding the results in an asset-pricing model, they gauge the effects on the Oslo Stock Exchange's All Share Index. They finally gauge the exposure of Norwegian financial companies. They find most asset-holders are exposed to a 5-6% hit on their balance sheets.

5.1.6 Issues with the shock approach

Overall, the stress test approach suggests that transition risks can be significant under some hypotheses. Yet, stress tests come with their own issues. As put by Borio et al. (2014), stress testing requires the application of a "plausible but severe shock" onto a given model. This severeness is not without posing some questions.

First, the magnitude of shocks can be discretionary. In the case of exposure mapping, as in Weyzig et al. (2014), scenarios are explicitly homemade projections based on rough, guesstimate shocks on direct holdings. If this provides interesting benchmarks, the plausibility of assumptions should be discussed. For macroeconomic stress tests, the magnitude of shocks questions what is *in fine* represented in corresponding scenarios.

As emphasised by Borio et al. (2014), that large and sometimes rather indeterminate shocks must be applied to the system comes with the limitations of underlying models. The latter rarely feature the amplification mechanisms typical of financial markets. "Normal" shocks on such models will never lead to a meaningful response on the part of the model. Hence that "All this shifts the burden of producing any damage from the properties of the models to the size of the shocks, which end up being 'unreasonably' large" (Borio et al., 2014, p.). The question is therefore how "unreasonable" applied shocks are. For instance, Vermeulen et al. and the ESRB's policy shock features a carbon price level more usually characteristic of the year 2030s. Applying it overnight at a 2017 calibration year represents an important policy overshoot. Network-based stress tests are less concerned by such criticism. The emphasis of network externalities makes for the amplification mechanismsBorio et al. (2014) finds missing in more traditional models (Bingler et al., 2020). However, data limitations prevents the measure of losses beyond interbank markets (Battiston and Martinez-Jaramillo, 2018). Instability-prone shadow-banking entities, for instance, van hardly be accounted for (Abad et al., 2017). Financial systems are complex, multiplex network with several layers of interactions, making the inventory of all interactions an arduous task[12]. What's more, only a reduced number of asset classes can be studied in climate stress tests (Battiston et al., 2017). All this suggests that smaller shocks than those studied may prove harmful.

Linking market valuation to market shares further limits the analysis to the energy sector. Other branches cannot be accounted for through sub-sectoral market shares. Finally, demand reductions, for instance due to energy efficiency, cannot be captured by market shares. This invites to consider alternative indicators linking greenhouse gas emission to structural changes, as proposed by Monasterolo et al. (2017).

"Jumping" from a BAU point to a 2°C-compatible scenario (Battiston and Monasterolo, 2018;

[12]See Battiston and Martinez-Jaramillo (2018) for a summary of research challenges for the network approach to financial distress in general.

Monasterolo et al., 2018; Roncoroni et al., 2019) is also problematic regarding the 2°C-compatibility of the overall path. Such "jumps" overshadow that what counts are cumulative emissions over a full path, not immediate emissions. Hence, shifting from a BAU to an early-action 2°C-compatible pathway is no longer 2°C-compatible. This leads to underestimate the shock that would be necessary to ensure 2°C-compatibility from BAU.

On the other hand, relying on a shock distribution as in Battiston et al. (2017) applied to a contemporary calibration point obscures the message. If the point of calibration represented the beginning of a mitigation policy run, including shocks that would normally occur late in IAM pathways may misestimate potential losses. As such, Battiston et al. (2017) and Batteson and Saccardi (2020) are not so informative on the financial network effects of a transition starting tomorrow. Rather, they give an idea of the losses emerging for possibly under- or overshooting policy adjustments.

There is thus room for refining some simplifying assumptions (Monasterolo et al., 2018), but also for improving the representation of transition shocks. A step in that direction would be to considered "delayed transition" scenarios only. Currently the LIMITS database only includes transitions delayed until 2030, but scenarios including lags until 2025 or 2035 could be used in stress test exercises.

5.2 Long-run approaches

Another strand of literature assesses transition risk along mitigation pathways (NGFS, 2020). Only a handful of studies develop long-run assessment of transition risks[13] (Table 15) Two distinct approaches have been developed.

[13] Some studies (CISL, 2015; Dietz et al., 2016; Bovari et al., 2018, 2020) study long-run risk, but do not separate analytically between physical and transition risks. I therefore left them aside for this review.

Table 15: Long-run assessments - Summary of the literature

Study Type	Authors/Year /Publication	Coverage - Exposure	Assets' Coverage	Depreciated Assets' class/Metric	Exposed financial sectors	Assets' Sectors	Methodology	Reference Scenario(s)	Underlying model(s)	Findings
Long-run	Mercer (2015) Report	Global	Global	Expected yearly returns decreases over 35 years (to 2050)	All	Energy sector equities Real estate Timber Agriculture	4-scenario approaches with 4 risk types (resources/policy/technology/resource)	2°C, 3°C and 4°C scenarios	Homemade investment model	Around 1% loss in returns for Oil-Gas-utilities, down to 5% decrease, mostly driven by private equity, small cap equity and emerging market equity
	HSBC (2019) Report	Global	Global	Foregone profits & equity valuation	All	All sectors in MSCI ACWI (Global Equity Index)	Use of IAM to derive macro and structural impacts onto equity price through a simple CAPM model	Homemade, based on IPCC	TIAM-UCL	2% loss on average across sectors, with significant variance
	Mercer (2019) Report	Global	Global	Expected yearly returns decreases over 35 years (to 2050)	Asset managers (Various portfolios)	Energy sector equities Real estate Timber Agriculture	4-scenario approaches with 2 risk types (Transition & Physical) Stress-test component	2°C, 3°C and 4°C scenarios	E3ME	Small losses/gains (+0,1; -0,4) depending on the porfolio at stake. Potentially much higher with unanticipated policy shocks (factor 10)
	UNEP FI (2019) Report	Global	Global	Climate VaR (ratio between discounted climate-relatec cost/profits and current market value) - Equity	Asset managers (Various portfolios)	All	Scenario allowing to compute carbon-price trajectories, then used to compute costs (tech change allows for extra profits), then plugged into a Merton model to generate effect on equity and debt, which finally lead estimates for portfolio behaviours 15 years horizon for portfolios	IPCC (SSP)	REMIND/GCAM + Carbon Delta Model	Immediate : $4.3trillion Delayed: $5,4 trillion
	Buongiorno et al. (2020) Report	UK/Global	Global	Changes in returns	Asset managers	All relevant + Real Estate & several asset classes	Three scenarios (Orderly/Disorderly/Failed Transtion) 2020-2100 Homemade financial model, macro picture based on E3ME	Orderly Transition (2020, smoothed pricing behaviour)	Homemade (ClimateMAPS) + E3ME	Small losses in return over manageable time spans, mostly on equity
								Disorderly Transition (2025, sentiment shock)		Sudden transition leads to one-off 15% return losses in 2025
	Kastner (2020) Master's Thesis (Uppsala Univerty)	Global	Global	NPV losses	Asset Managers	All	Use of a portfolio model to compute losses	Limited Decarbonation: low carbon prices (US$ 100 in 2050)	Homemade Portfolio Model	0.3% loss on Global Index Portfolio
							based on two decarbonation scenarios	Ambitious Transition (145 US$/tCO2 by 2030)		3% losses on Global Index Portfolio
NGFS Approach	Banque de France (2020) Report	France	France (+Rest Eu)	All assets + Default Probabilities	All	All relevant (Focus on Mining, Agriculture and Petroleum)	Orderly Transition (Baseline)	Smooth introduction of a carbon tax in 2020	IAMs NiGEM BdF Sectoral Model BdF Financial Model	Not displayed
							Delayed Transition	Introduction of a carbon tax in 2030, consistent with existing IPCC scenarios		Sudden transition overall more detrimental than delayed action
							Sudden Transition Scenario	Introduction of a 1.5°C-consistent carbon tax in 2025, long-run productivity shock due to technological unreadiness		Probabilities of default can increase between +10% (bars-cafés) and fivefold (petroleum) even in the lng run

5.2.1 Portfolio assessment of transition pathways

Early studies, mostly coming from the grey literature, have derived insights on how different portfolios would perform along 2°C- or even 1.5°C-compatible trajectories depending on their composition (Campiglio et al., 2019). They explore transition and physical risks altogether, but separate both analytically. Mercer (2015, 2019), a consulting agency, used successively two IAMs (GCAM then E3ME) to derive portfolio return losses due to physical and transition risks. It concluded that transition risks are quite small despite important variation across sector-specific assets. HSBC (2018), with a CAPM approach based on foregone profits, using the TIAM-UCL IAM, also displays small losses with important sectoral variations. Finally Kästner (2020) develops a complex NPV model and also concludes to small portfolio losses. Yet, she highlights the numerous limitations coming along these models. UNEP Finance Initiative (2019), by contrast, reports significant losses on index-following portfolios. To translate structural changes into financial asset revaluations, these approaches rely on the use of "transition factors" or "asset sensitivities". These are coefficients linking losses in real-economy sectors to their financial valuation. Albeit defensible given the under-theorising of the field, their use is opaque in its functioning and quite discretionary in its application. This casts doubt on the reliability of their results without further robustness checks. Finally, such studies are microeconomic in nature, because they only look at losses on representative portfolios.

5.2.2 The NGFS approach

By contrast, the NGFS aimed at offering a broader, macroeconomic perspective on transition risks in a recent study (Allen et al., 2020). Its method is similar to the DNB's and the ESRB's. But its mitigation scenarios are not built from scratch but based on existing mitigation pathways generated by various IAMs. The study runs from 2020 to 2050 and is focused on France.

Consistently with its general approach (Bertram et al., 2020), the NGFS contrasts an "orderly" scenario, in which climate policies are implemented early and gradually to two variants of a "disorderly" pathway. A "delayed-transition" scenario supposes that climate action is implemented late, in 2030, but is 2 °C-compatible. On the other hand, a "sudden-transition" variant assumes that climate policies are implemented earlier (2025) but in an adverse technological context. Both scenarios assume limited Carbon Dioxide Removal (CDR) technology availability. Originally so, the “orderly” scenario is taken as baseline while the two “disorderly” variants serve as experiments. Finally, the modelling exercise does not include a feedback from financial variables to the broader economy.

The interest of this study lies in its important number of outcomes. Overall, Allen et al. (2020) show that a conjunction of adverse technological conditions and severe climate policies may lead to larger financial disturbances in the medium-to-long-run than a simply “delayed-transition” occurrence.

The study shows that “disorderly” transition paths could lead to significant financial instability beyond 2040. However, absent some insight on the costs and losses on the baseline, assessing the disruptivity of “disorderly” paths is arduous. The authors report that such baselines do not give rise to high costs. Since the authors discuss the case of France, this may seem reasonable, as the country ”only” needs to reduce its emissions by 2% per year to reach its 2050 goals (Guivarch, 2020). However, such assumptions must be considered cautiously, since transitional efforts may be costlier for other countries.

Plus, some scenarios assumptions are surprising. In their “sudden-transition” scenarios, Allen et al. (2020) suppose that productivity gains (*i.e* the exogenous trend of a CES production function) fall to zero in 2025 and stay that way. By contrast, the ”delayed transition” scenario features a one-off productivity shock aimed at representing a disorderly transition scenario, but productivity gains are maintained. Assuming a transitory shock in the event of a delayed and disorderly transition seems reasonable. But eliminating productivity gains in the ”sudden transition” scenario for 25 years of a run out of 30 represents a huge cumulative shock with respect to baseline. The shock explicitly sets the world economy onto a lower growth path, close to a secular stagnation projection. What is more, the “sudden-transition” scenario features higher carbon taxes than its delayed-transition counterpart, in spite of earlier implementation. In fact, this projection explicitly considers carbon prices consistent with the NGFS’s 1.5 °C scenario with limited CDR (Bertram et al., 2020). This interrogates the comparability of the two “disorderly” variants.

This further questions what is measured along those paths. The authors show that most long-run costs (three-fifths) are driven by higher carbon taxes. Productivity shocks only account for one-fifth, even in the absence of productivity gains. This suggests that this study only gauges a flow effect, the decrease in value-added and turnover that is incurred by the most exposed industries. Other kinds of transition drivers (Semeniuk et al., 2020) remain to be explored, as well as the dynamic effects of structural inertia and other "lock-in" effects through stranded assets [14].

5.2.3 Other approaches

Other long-run studies have used other approaches. Bouchet and Le Guenedal (2020) use a Merton model to link carbon pricing trajectories with default probabilities in non-financial sectors. They show that carbon prices would hit corporate cash flows enough to increase default probability for directly exposed sectors (fossil fuels and utilities). Cormack et al. (2020) use a similar but more elaborated methodology to assess the financial health of EU utilities along transition paths. They show that most EU utilities would survive a 2 °C-compatible transition and even offer improved returns on equity after ditching low-carbon assets[15]. By contrast, Chevallier et al. (2021) argue that many of the largest oil, coal and gas companies would be very vulnerable to bankruptcies under stringent emission reduction targets absent a deep change in their business model. Finally, Reinders et al. (2020) find that Dutch banks could see between 3 and 30% of their Tier-1 capital could be wiped if high carbon taxes are implemented. These three studies, however, do not capture inter-industry interactions or asset devaluation effects. Nelson et al. (2014) show that due to overall lower operating costs, the low-carbon transition would in fact lead to aggregate benefits in the power and transportation sectors. This would henceforth reduce the risk of financial instability. Yet, absent a discussion on revenues in both sectors (higher or lower energy prices for instance) and of possible extra costs due to new infrastructures, results should be taken with precaution.

This literature thus offers insights on the magnitude of transition-risks. The evidence suggests that transition shocks would yield significant, but manageable losses. Uncertainties yet remain regarding the total exposure of financial institutions, and the relevant amplitude of shocks. Long-run assessments suggest that delayed and/or severe climate action can lead to important market and

[14] Pierfederici (2020) provides a useful summary of the research areas the NGFS will have to tackle, for instance a better representation of technical change, and the interactions between transition and physical risks.

[15] However, their results are somewhat ambiguous, as their simulations fail to achieve the capacity targets laid out in 2 °C-compatible scenarios for low to medium price assumptions

credit risks in the longer run. Uncertainties remain in terms of scenarios and methodology. As a result, a broader set of models and scenarios should be explored. Effects beyond that of a carbon tax and including other financial risks will also require further research.

6 Summary and discussion

The transition-risk literature shows relatively important instability potentials. The transition will leave in its wake important amounts of stranded assets. Financial markets, as of today, seem increasingly concerned about climate challenges. But they still fail to consistently price transition risks and opportunities. Finally, stress-tests and long-run transition-risks assessments,on the average, invite to caution on market and credit risks. However, many uncertainties remain, both methodological and theoretical. Stranded assets cannot be systematically linked to financial instability. The asset-pricing literature does not tell much on the long-run reaction of financial markets to transition risks. Finally, direct transition-risk assessment scenarios and methodologies, still incipient, require maturation.

6.1 Uncertainties and its mapping

The transition is fraught with uncertainties. Its precise course is not unequivocal or consensual. Hence the embrace by the traditional E3 literature of a *prospective* attitude to the low-carbon transition. By doing full justice to the radical uncertainty (Bolton and Kacperczyk, 2020b) accompanying the transition, the literature has never sought to provide one-off policy advice. Rather, its goal has been to highlight the areas of certainties and uncertainties surrounding existing projections and, as a result, open the debate more than closing it. That financial supervisors and scholars adopted such approach in the realm of climate change is meaningful. It represents a major conceptual and methodological shift away from traditional risk-assessment methodologies (Bolton et al., 2020), by explicitly rejecting an approach in terms of probabilities and statistical definition of risks.

But such approach come with methodological requirements like sensitivity and uncertainty analyses. To answer them, the transition-risk literature should broaden its scenario and model portfolios, and highlight the key parameters at stake when it comes to assess transition risks. This includes exploring less traditional, non-equilibrium modelling techniques (Bolton et al., 2020; Svartzman et al., 2020), such as stock-flow consistent and agent-based models. These have been deemed more accurate in representing real-financial interactions (Hafner et al., 2020). Such models can accommodate higher degrees of complexity than traditional models and therefore provide precious insights on future outcomes (Monasterolo et al., 2019). They could also integrate the insights from the various sub-strands I have reviewed in this article. Some work has already been proposed in that direction (Dafermos et al., 2018; Monasterolo and Raberto, 2018; Raberto et al., 2019). This would, however, hardly be a panacea from a methodological standpoint. These approaches come with their own issues. Given the relative under-formalisation of financial economics outside of equilibrium approaches, their use would entail an important work on behavioural assumptions, and increase the range of discretion in terms of functional forms and variables. Such methods, especially agent-based models, pose severe calibration issues (Naqvi and Stockhammer, 2018). Finally, sensitivity analyses would include changes in behavioural equations, extending thereof the range of uncertainties.

What's more, the literature remains mainly focused on policy risks which can be explained by their relatively easier modelling. Yet, many dimensions of technology risks are still to be explored (Pierfederici, 2020). Surprises can emerge not only from green breakthroughs, but also from disappointments in terms of technology readiness. Exploring the effects of disappointed hopes in CDR availability would be of great interest.
The asset-pricing literature does not allow to disentangle policy and technology expectations and their effects on pricing, except for a few studies (Byrd and Cooperman, 2018). Hence a need for additional work on expectation formations, and on how transition "blindness" (Silver, 2017) may lead endogenously to a "disorderly" transition. Consumer-preference risks have not been tackled by quantitative methodologies, given the frontier they represent in terms of modelling and inference. As put by Svartzman et al. (2020) the quest of a model representing all relevant inklings is bound to fail. It calls for for more qualitative approaches. Such themes have received attention from institutionalist thinkers. In a series of papers, Frank W. Geels and coauthors have proposed an approach in terms of "socio-technical" transitions. Such approach would make for the study of the co-evolution of sub-parts of human systems (Geels, 2013; Geels et al., 2017; Geels, 2019). Svartzman et al. (2020) identify such approaches as fruitful complements to modelling . Yet, if applications of this framework has been applied to transition risks (Foxon and Pearson, 2008), much work remains to be done.

6.2 “Green bubbles” and financial instability

As mentioned in Section 1, the literature has mostly focused on how brown assets could lose value, hence that this review has been organised accordingly. The flipside possibility of a “green bubble”, *i.e*, an overvaluation of green and environmentally responsible assets once the transition kicks in, due to overoptimism or overshooting investment behaviours, has been comparatively left aside.

This focus on the vulnerabilities faced by carbon-emitting companies can be explained by the sluggish dynamics of low-carbon investments, despite acceleration after the Paris Agreement (Monasterolo and de Angelis, 2020). Yet, this dynamics is apparently reversing, with the financial press and financial analysts starting to worry about a “green bubble” due to massive investments in ESG and green values since the beginning of 2021 (Nauman, 2021).

Although these concerns can seem a bit premature, would the trend prolong, it would be valuable to revisit the early ‘green bubbles” literature. Beyond pro-gas and pro-nuclear assessments by the coiner of the expression (Wimmer, 2016), a scant empirical literature has studied the behaviour of green stock values on several stock exchanges. Bohl et al. (2013) showed that the financial valuation of renewable energy companies in Germany did exhibit a certain degree of overvaluation over the 2000s, which resulted in significant downward swings after the 2008 crisis struck. (Wang et al., 2020) provides a similar assessment for China, and show that exogenous weather factors and changing micro- and macroeconomic regulations furthered boom-burst behaviours on some Chinese renewable energy indices.

The long-run consequences on the industry’s dynamics and the broader economy are still to be explored, and invite to comparison with similar technological bubbles, such as the Dotcom crisis. These studies remind us that an all-encompassing study of transition risks and vulnerability can hardly do without a “bubble-bursting” eventuality putting a break on green investments (Semeniuk et al., 2020). Such scenario would in fact be much more consistent with existing theories of financial instability and technological change (Perez, 2003; Minsky, 1986). In short, current worries from financial analysts recall that shifts to green values on financial markets, albeit positive, should not be taken as a full-blown victory. Such dynamics can bear risks of their own, which may, in worst cases, interact with all the others mapped in this review. Hence an invitation to caution, and to the design of appropriate policies.

6.3 Defining financial instability

Finally, providing a sound theoretical definition of financial instability would clarify some endeavours of the literature. In particular, it would help differentiating between different courses of events. If financial instability is understood as a situation in which financial markets do not perform well their role of fund allocation, then the acceptation is broad, and encompasses financial frictions. The key question is the extent to which such financial disturbances will translate into macroeconomic disorders which could put a brake on the transition. This calls for broadening the view of financial disturbances, both in terms of scopes and geographical occurrences. A second direction would be to agree on a set of broad metrics or indicative thresholds that may provide even a rough quantitative definition of financial instability. That the literature have not discussed this aspect is surprising given the amount of scholarship on the matter. Indeed, the literature on so-called "early-warning signals" has provided numerous metrics for the propensity of crises to occur (Barrell et al., 2010; Tymoigne, 2011; Borio, 2014). Given the high amount of such metrics, this would call for an in-depth reflection on the relative relevance of each in the context of the low-carbon transition. This would also make clearer the theoretical links that would be privileged by the literature. Jordà et al. (2015) argue in this respect that stock prices are not a very good indicator of systemic risks. History has shown that credit-making and debt are better predictors of large and macroeconomically relevant crises, suggesting that the attention should be paid to these indicators Schularick and Taylor (2012). Such view, close to traditional Minskian insights has led to some threshold proposals, like a share of private debt superior to 270% of GDP (Keen, 2017) with some applications to transition economics (Bovari et al., 2018). However, Semeniuk et al. (2020) argue that most thinking on financial instability has adopted a macroeconomic approach (with some focus on particular sectors, such as housing) ill-adapt to the multi-sectoral dynamics of the low-carbon transition. This calls for a disaggregated picture, with accompanying data challenges.

Conclusion

Should we fear transition risks ? This overview of the current literature has shown that they raise legitimate concerns. The low-carbon transition may be highly transformative, and consequent losses for financial systems, national or worldwide, could be very high. Some theoretical links are still hardly understood, and prospective works should be deepened. Uncertainties should be better mapped, by broadening the range of possible scenarios, and the use of other models. Finally, behavioural reactions to climate events and new information or cognitive frameworks is still to be fully appreciated. This calls for future and exciting research.

This methodological eclecticism creates a tension between the "transition risk" concept, that relates to a probabilistic vision of uncertainty (Knight, 1921), and the way it is approached in the literature. The latter has emphasised radical uncertainty (Bolton et al., 2020) and encouraged the use of forward-looking assessment. But such approaches are not easily convertible into risk-assessment and valuation tools. Because they do not use probabilities, they can provide intervals for possible outcomes, but no definite value. There is nonetheless an ambition throughout the literature to provide such insights to help financial institutions have more foresight and derive sound pricing and hedging strategies (Monasterolo et al., 2019; NGFS, 2020; TCFD, 2020a). This poses important questions as to the extent to which such approaches can be translated into operational approaches readily available to financiers. Battiston and Monasterolo (2020) provide in this respect an interesting attempt in this direction, by expanding their basic stress-test framework. They demonstrate that the value of exposed portfolios depends on the probability of occurrence of a given climate-policy scenario and on other parameters. As such this exercise illustrates the difficulties to do without probabilistic apparatuses when it comes to value assets. Even worse, given the forward-looking nature of transition risks, the subjectivity of such probabilities is even more pronounced than in other instances, as no substantiation by statistical models can be found. This is problematic as uncertainties inherent to the transition may be reduced to the inventory of events and the probabilities attached by the assessor. A solution would be to consider distributions for different model runs and scenarios, as the IPCC does in presenting key outcomes (Masson-Delmotte et al., 2018). However, this would give a credibility premium to the average model and the average scenario. But there is no *a priori* reason why extremes should not be accounted for.

Said plainly, forward-looking methodologies do not match current practices on financial markets. They will doubtfully enter the calculations of financial agents, who remain embedded in quantitative methodologies based on probabilistic risks (Christophers, 2017; Thomä and Chenet, 2017). Better said, there is a tension between the academic and positive interests of the transition-risk literature and its use by financial practitioners. Its spreading to financial institutions will require more than the display of results, but a familiarisation and training of financiers to that kind of methods as well as dedicated communication techniques (Harnett, 2017). Svartzman et al. (2020) goes further by defending the use of qualitative methodologies. Again, their adoption by financial institutions will require a strong educational effort, and probably an even more sweeping change of how agents rationalise their actions on financial markets.

History has shown that some constructs eventually spread out to the whole financial system and becomes usual methods used by asset holders. One can thus hope that scenario-based analysis and other transition-risk approaches eventually know the same fate as the Black-Scholes formula (with, hopefully, more positive outcomes (MacKenzie, 2003) !). However, given the current state of affairs, characterised by uncertainties and a relative *status quo* in financial thinking (Ameli et al., 2020; Christophers, 2019), it is uncertain that the adoption will come endogenously from the financial sector. This calls for a prolongation of supervisors' work beyond the provision of results, but also of porting methodologies. Exercises like the Bank of England's (2020) and the French *Autorité de Contrôle Prudentiel et de Résolution* (ACPR, 2020), which will build on a bottom-up and discursive process between regulators and financial institutions will be of chief interest.

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