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Climate-related risks in financial assets

Emanuele Campiglio[1,2] | **Louis Daumas**[3,4] | **Pierre Monnin**[5] | **Adrian von Jagow**[6]

[1]University of Bologna, Department of Economics, Bologna, Italy

[2]RFF-CMCC European Institute on Economics and the Environment (EIEE), Milano, Italy

[3]CIRED, Nogent-sur-Marne, France

[4]Ecole des Ponts ParisTech, Champs-sur-Marne, France

[5]Council on Economic Policies, Zurich, Switzerland

[6]Vienna University of Economics and Business, Institute for Ecological Economics, Vienna, Austria

Correspondence
Adrian von Jagow, Vienna University of Economics and Business, Institute for Ecological Economics, Vienna, Austria.
Email: adrian.jagow@wu.ac.at

Abstract

The financial risks and potential systemic impacts induced by climate change and the transition to a low-carbon economy have become a central issue for both financial investors and their regulators. In this article, we develop a critical review of the empirical and theoretical literature concerning the impact of climate-related risks on the price of financial assets. We first present the theoretical links between asset pricing and climate-related risks and develop a theory of how climate risk drivers transmit costs to firms and lead to asset price changes. We then discuss studies looking at past climate-related events, which show that both climate physical impacts and transition dynamics can trigger a revaluation of financial assets through multiple direct and indirect channels. Finally, we review the emerging literature that uses forward-looking methodologies to estimate future climate-related asset price changes, which suggests that climate financial risks can indeed have significant implications on financial stability.

KEYWORDS

asset pricing, climate change, climate-related financial risks, financial stability, low-carbon transition

1 INTRODUCTION

Recent years have seen an expansion of the debate on the links between climate change and the financial system. Both private actors (e.g., firms, banks, asset managers, financial service providers) and public institutions (e.g., central banks, financial supervisors) have been trying to understand how economic and financial stability might be affected by (i) physical climate change impacts and (ii) the transition to a carbon-free economy. The main concern is that a combination of climate-related drivers (e.g., an abrupt introduction of mitigation policies following an extreme physical event) could cause economic costs to firms, which could then be transmitted to financial institutions via defaults and drops in market capitalization. If the drop in financial asset prices is large enough, it could lead to a financial crisis with systemic economic and social ramifications; a concept referred to as a 'Green Swan' (Bolton et al., 2020) or a 'Climate Minsky moment' (Carney, 2015).

While this conceptualization provides important insights into the exploration of possible futures, it is still not clear how likely a Green Swan scenario would actually be. In particular, under which conditions should we really expect a significant drop in the price of financial assets as a consequence of climate-related drivers? The answer to this question depends not only on the realization (or not) of specific future events, but also on the degree to which the realization of climate-related risk is already accounted for in current asset prices.

The aim of this article is to develop a critical review of the existing literature investigating the links between climate change, the low-carbon transition and the price of financial assets. Previous reviews of related bodies of literature have focused on the state of environmental risk management at financial firms and supervisors (Breitenstein et al., 2021), the theory of including climate-related risks in macroeconomic models (Giglio et al., 2021), and specific asset classes such as equity (Venturini, 2022).

Our contribution covers equity, bonds, loans and real estate markets. We structure the literature further by distinguishing two main areas of analysis. First, we discuss the literature studying how real past physical and transition risk drivers have affected the prices in the stock, bond, loan and real estate markets, i.e. the backward-looking literature. Second, we examine the literature that uses possible scenarios of climate-related risk drivers to estimate future asset price revaluations, i.e. the forward-looking literature. Our review is preceded by an investigation into the conceptual links between climate-related risks, economic costs and asset pricing.

We find that investors do react to climate-related risks, leading to changes in asset prices, in the cost of capital for firms and in various assessments of financial risk. However, financial markets likely underprice these risks. Forward-looking methodologies, which include both stress tests and scenarios-led models, also find that climate-related risks can substantially impact financial asset prices. While this improves our understanding of the impact of climate-related risk drivers on financial assets, more research is needed to pinpoint the drivers of financial instability.

The remainder of the article is structured as follows. Section 2 introduces the conceptual foundations on which the literature builds. Section 3 reviews the backward-looking literature on climate-related risks and asset pricing. Section 4 explores the methodologies using forward-looking scenarios. Section 5 discusses current research gaps. Section 6 concludes.

2 | CLIMATE-RELATED RISKS AND ASSET PRICES

This section briefly presents the main asset pricing model categories currently used by financial market participants and discusses their accuracy in assessing climate-related risks. We introduce key concepts in the pricing of climate-related risks and distill four transmission channels through which climate-related risks could cause economic losses and changes in asset prices. We highlight how climate-related risks could be destabilizing for financial markets.

2.1 | The pricing of financial assets

2.1.1 | When does the price of a financial asset change?

According to standard asset pricing theory, the market price of a financial asset is equal to the expected net present value (NPV) of its expected future payoffs – that is, its future income flows (Cochrane, 2001). For equity instruments, payoffs are equivalent to the dividends paid by the firm issuing the equity. For debt instruments, they are the interests and the repayment of the principal by the borrower. Additionally, investors ask for a premium to compensate for the risk they take on (Pástor & Veronesi, 2013).

The price of a financial asset therefore largely depends on financial investors' expectations about payoffs and risk exposure. A revision of these expectations can lead to sharp price movements. We can distinguish (i) changes in expectations resulting from exogenous events; and (ii) endogenous expectations revisions. Exogenous changes are due to sudden unexpected events, either at the systemic level (e.g., the Covid-19 pandemic or an economic recession) or at a company level (e.g., the announcement of weak quarterly profits, a risky lawsuit or a sudden price increase of key production inputs), which are able to modify the near—or longer-term profit prospects. Endogenous reassessments are due to a change in the forecasting model or the parameters they are fed (e.g., new risk drivers are identified and their relationship to financial assets are better understood).

Additionally, the price of a financial asset can change with investors' risk perception. Changes in expected default probabilities, as well as in the expected values of liquidated assets or collateral, determine the amount of risk taken by investors. Higher financial risk would decrease financial asset prices or force the issuers of the asset to provide higher returns for investors as a compensation for the additional risk.

The nature of the financial instrument and the markets on which they are traded determine how their prices react to financial risks. Equity prices, which are valued in the very short term, will react almost immediately to emerging risks. Loans are not valued on such a short-term basis. Rather than revalued, their riskiness determines the future loan conditions for the same borrower. Bonds operate similarly if they are issued at fixed rates. They may also be issued at floating rates, with interest payments determined by underlying indices, altering their fundamental value in relation to the index. However, bonds are also traded on secondary markets and thus their yield can fluctuate more immediately based on new information.

2.1.2 | Asset pricing models

The asset pricing models, which have been mostly used in the context of climate risks, can be divided into two broad classes: models based on arbitrage mechanisms and models based on firms' fundamentals and risk exposures. They differ in their approaches to measuring mispricing. Arbitrage models identify mispricing by comparing the price of two assets generating similar expected financial return profiles (e.g., the Black-Scholes option pricing model; see Black & Scholes, 1973). Models based on firms' fundamentals and risk exposures assess mispricing by comparing the price of an asset with its theoretical fundamental value given its expected risk-return profile. This profile can be based on (i) macroeconomic factors (e.g., the Consumption-based Capital Asset Pricing Model (CAPM), see Breeden, 1979); (ii) firm-specific risk factors at the market level (e.g. the Fama-French model, see Fama & French, 1993; and the Carhart model, see Carhart, 1997) or (iii) firm-specific risk factors at the individual level (e.g., asset variance in the CAPM). Arbitrage and fundamental models both have their advantages and drawbacks: arbitrage models, based on comparing asset prices between themselves, cannot identify mispricing if markets are globally mispriced. Fundamental models, based on the estimation of a theoretical asset price, give imprecise assessments that are highly dependent on the assumptions underpinning the model.

Models based on fundamentals and risk exposures are however better suited to address climate-related risks for at least two reasons. First, since they are based on estimated future flows (income, cost) and risks, they can integrate projected values for these flows and risks in different climate scenarios. They therefore do not rely on past data. Previous research has stressed that the use of past data cannot capture the effects of climate change, a phenomenon for which economic consequences have not been fully observed yet (Dunz et al., 2021; Svartzman et al., 2021). Second, they provide an assessment of the alignment of overall financial prices with the value they could take under different climate scenarios. This is particularly useful to spot a general misalignment of financial prices – for example, when financial actors globally underestimate a risk factor, which could be the case for climate-related risks. Models based on arbitrage mechanisms, on the other hand, are less likely to identify such cases because they compare market prices relative to each other and thus would miss an overall misalignment of all prices. Models based on fundamentals and risk exposures have been mobilized in some of the studies that will be surveyed in Section 3 (Alessi et al., 2021; Monasterolo & de Angelis, 2020). Note, however, that asset pricing models are not applicable to some types of assets, such as loans (Ehlers et al., 2021) or real estate. Some papers may also deploy alternative identification strategies to understand the impact of a climate-related event on asset prices, like difference-in-differences approaches around a key event (e.g., Nguyen et al., 2020).

2.2 | Climate-related risks and asset prices

We now turn to the climate-specific aspects of asset pricing. Climate change and the low-carbon transition can modify financial asset prices via multiple channels. Figure 1 visually presents the main transmission channels (see Semieniuk et al., 2021 for more details on transition risk drivers and Clapp et al., 2017; Lepousez et al., 2017; TCFD, 2017 for details on physical risk drivers).

We can identify the types of climate-related risks. Since Carney (2015), the literature distinguishes between transition, physical and liability risks:

- *Transition risks* stem from the transition to a low-carbon economy. They include risks created by mitigation and adaptation policy, emerging clean technologies and behavioral changes of consumers and investors (TCFD, 2017).
- *Physical risks* emerge from a changing climate (i.e., a long-term shift in the mean and variance of temperatures and magnitude of weather events). Climate change redraws risk patterns for

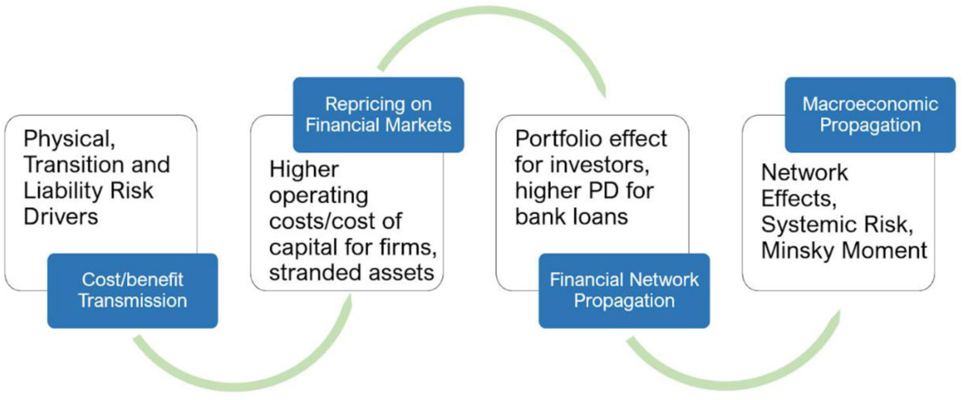


FIGURE 1 The journey from climate-related impacts to asset price changes [Colour figure can be viewed at wileyonlinelibrary.com]

assets, which can be either acute (e.g., from extreme weather events) or chronic (e.g., from sea-level rise). Physical changes do not only threaten built capital stocks and flows, such as output, but also labor productivity (Kjellstrom et al., 2009; Zander et al., 2015).
- *Liability risks* stem from the possibility of costly climate change litigation against polluting industries or inert governments and financial institutions (alternatively, they are referred to as litigation risks). While the importance of liability risks for asset prices remains under-researched, the Sabin Center for Climate Change Law (2022) documents that there have already been made a number of claims in the US, many against state and federal institutions, as well as the fossil fuel industry. Setzer and Higham (2021) find that climate change litigation is being brought before courts in an increasing number of countries.

Second, these drivers can affect the current or prospective profits of firms. We jointly consider physical, transition and liability risks to underline the conceptual similarity and complex interaction between them.[1]

While the three risk types have distinct drivers, their economic effects on the exposed firms share four main transmission channels:

- *Assets*: A climate-related event destroys capital assets, prohibits their use or makes them unprofitable to be used. For example, a carbon tax could trigger asset stranding or make previously productive capital uncompetitive (transition risk). Lower mean precipitation could, e.g., decrease the productivity of agricultural land (physical risk). The firm must prematurely write off its assets.
- *Investment*: A climate-related event forces a firm to update its infrastructure or production process. For example, a new clean technology standard (transition risk) or higher mean temperatures (physical risk) force upgrades to the infrastructure. The capital expenditure (CapEx) of the firm increases.
- *Production network*: A climate-related event creates costs by changing demand patterns, disrupting supply chains, or making it impossible to serve markets. A carbon border adjustment mechanism could reduce the demand for high-carbon imported inputs (transition risk). An extreme weather event could disrupt a trading route (physical risk). Climate-related litigation

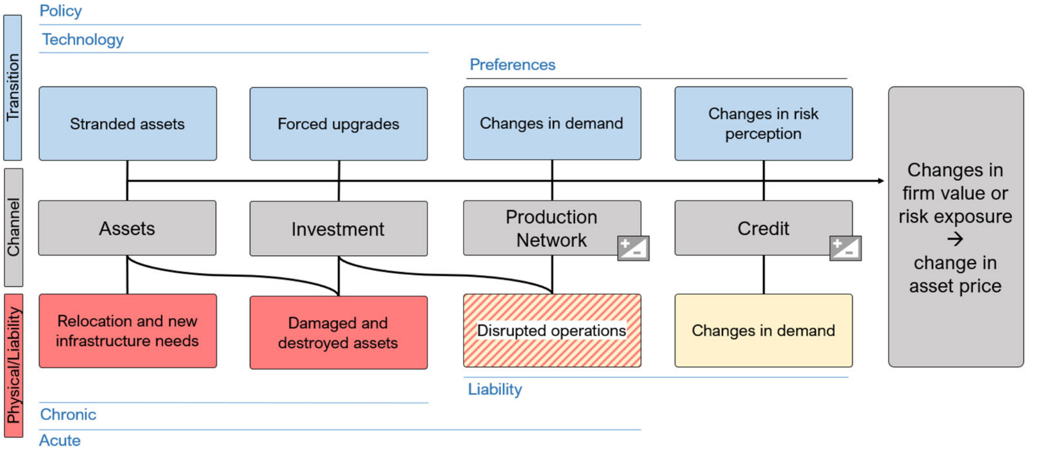


FIGURE 2 Four common transmission channels for impacts from physical (red), transition (blue) and liability (yellow) risks. Channels, which can transmit positive as well as negative changes, are marked (+/−) [Colour figure can be viewed at wileyonlinelibrary.com]

could reduce the willingness to do business with a firm (liability risks). Costs materialize as revenue losses or increased operating expenditure to keep up supply chains.

- *Credit*: A climate-related event leads to a reaction by capital markets, upon which a firm relies. A changed risk profile due to the exposure to transition, physical or liability risks could increase its interest rates for debt capital or insurance premia. If the firm's value decreases, so does its leverage for debt capital.

Figure 2 summarizes how transition, physical, and liability risk drivers can be jointly considered as impacting firms through four transmission channels. Some of these channels can act positively or or negatively on companies, as the low-carbon transition may also create value for some firms. While some regions may be affected by increased risk of drought, others may witness opposite trends (Hong et al., 2019).

From a methodological standpoint, climate factors are introduced both as macroeconomic factors that impact the market of a specific asset and as a source of risk to which specific firms are exposed. To assess whether climate-related risks are priced in, researchers are working around three lines. Some of them estimate the impact of climate events on firms' fundamentals (gains and losses, productivity, etc.) and then check whether market prices reflect these impacts (Hong et al., 2019). Others compare the risk premium[2] of assets exposed to climate-related risks with those that are not (or less) exposed to them, to see whether market participants price the difference in risk exposure (Alessi et al., 2021; Wen et al., 2020). Finally, researchers also check whether market prices react to news on climate risks, as should efficient markets do (Byrd & Cooperman, 2018; Faccini et al., 2021).

Third, the change in actual or expected company profit prospects will change the price of their financial assets. We can distinguish two types:

- *Exogenous shocks* from materializing climate-related risks affect a company's ability to service debt obligations or share profits with equity owners, leading to revaluations of their financial contracts. Additionally, new information on a firm's exposure to climate-related risks can lead

to reassessments of the risk premium asked by investors. The fundamental uncertainty over the course of climate-related impacts, both over physical climate change (Deser et al., 2012; Shepherd, 2014) and the policy response (Fried et al., 2019), could manifest as a higher risk premium.
- *'Endogenous' reassessments* by investors can change their perception of a firm's exposure to climate-related risks. For example, a change in the model used for forecasting revenues could lead to a reassessment of the firm's value and thus of the value of its assets. Methodologies incorporating climate-related risks are increasingly used and developed by investors (Monnin, 2018).

Networks in financial markets can amplify initial direct losses incurred due to assets' vulnerability to climate-related risks (e.g., a value drop of fossil fuel companies' securities), resulting in financial instability. Indeed, financial markets are deeply interconnected, multi-layered webs of debt and credit relationships. As such, adverse network externalities have been found to play an important role in spreading financial risks that had originally affected only one counterparty, with possible systemic implications if many actors are concerned (Acemoglu et al., 2015; Gai & Kapadia, 2010). In the context of climate-related risks, studies have shown that initial, seemingly innocuous shocks can have far-reaching consequences if network externalities are accounted for, even for agents not concerned by the initial shock (Battiston et al., 2012; Krause & Giansante, 2012). These models have mostly focused on contagion within the interbank market, whereby balance sheet shocks due to climate-related risks increase counterparty risk and propagate losses amongst banks by diminishing the value of their claims (Battiston et al., 2017). Subsequent papers have added relationships between banks and investment funds, as well as fire-sale dynamics (Roncoroni et al., 2021). Of course, these papers do not exhaust the range of possible mechanisms,[3] which also encompass default cascades (Allen & Gale, 2000), liquidity crunches (Gai et al., 2011) or bearish herd behavior (Kiyotaki & Moore, 2002). On the latter, an emerging literature has emphasized the role of "climate sentiment" in shaping climate risk dynamics. On theoretical grounds, Dunz et al. (2021) and Battiston et al. (2021) have insisted on the importance of investors' non-rational expectations in driving transition outcomes and risk exposures. On the empirical side, an emerging literature has intended to measure "climate sentiments" through textual analysis from newspapers (Ardia et al., 2020; Engle et al., 2020) and Twitter (Baylis, 2020; Santi, 2021). It has notably shown that investors' perception of climate-related risks greatly hinged on the occurrence of physical risks events (Choi et al., 2020), with short-lived and small effects on asset prices (Pástor et al., 2021). Brière and Ramelli (2021) show that arbitrage activity in the form of inflows into green exchange-traded funds (ETFs) can be used to capture investor demand for green investments and that these sentiments do not reflect fundamental changes in the underlying securities. All these interlinks could play out in case of climate-related shock, calling for more work in exploring all possible ramifications (Battiston & Martinez-Jaramillo, 2018).

Increased attention to climate financial risk in the absence of information about climate-related impacts could trigger a system-wide reassessment of losses from climate change exacerbated by herd behavior (Jaffe, 2020; Palao & Pardo, 2017). Materializing climate-related risks could trigger a steep fall of prices across all asset classes and tighten financial conditions, a phenomenon referred to as 'climate Minsky moment' (Carney, 2018). Such moments, referring to theories on investor behavior developed by Hyman Minsky (1970), are defined as a time of reckoning among market participants after a period of stable growth and prosperity. Market confidence, the theory goes, encourages investors to shed their risk aversion (Bellofiore & Halevi, 2011) and enter increasingly speculative investments with borrowed money (Henningsson, 2019).

Nikolaidi (2017) describes a third scenario for a 'climate Minsky moment'. In the case that mitigation policy is effective, a "green bubble" could emerge as a result of investors' exaggerated confidence. Semieniuk et al. (2021) discuss the possibility of a credit bubble in sunrise industries (i.e., those that stand to gain from the structural change accompanying the low-carbon transition) in this context. They find that the current literature on financial risks from the low-carbon transition is largely silent on a green bubble and instead emphasizes the financial instability concerns from overinvestment in sunset industries (i.e., those that stand to lose). The authors observe that this is an inversion of the prevailing Schumpeterian view that sunrise sectors are (more) likely to cause overinvestment and financial losses. A possible explanation for this inversion may be that the cause of the low-carbon transition is not only driven by opportunity and a price advantage within the sunrise industries, but also by opportunity cost and political will.

The emergence of clean technologies could also fuel asset bubbles or 'manias.' Previous technological transitions, such as the emergence of the internet, have been associated with such asset bubbles. In the case of the low-carbon transition, financial markets have shown great appetite for products with a green label. Aramonte and Zabai (2021) describe the recent growth in investor interest in environmental finance as a potential source of finance instability. According to the data analyzed by the authors, magnitudes of the current growth of investments with ESG (i.e., considering environmental, social and governance criteria) labels (especially in mutual funds and ETFs) are comparable to the growth of mortgage-backed securities in the time before the Great Financial Crisis. The fundamental social change associated with this asset boom is akin to a transition risk driver in the sense we defined above. However, the current asset boom and the potential asset price deflation that could follow are endogenous processes to financial markets. This endogeneity makes a potential green asset bubble slightly different from the other kinds of climate-related risks we survey here. Given this and the small number of publications on "green bubble" risk, we do not focus on this literature in the review below.

3 | BACKWARD-LOOKING METHODOLOGIES

After having discussed the general conceptual framework of this literature, we now study the empirical evidence offered by backward-looking studies. We try to address two fundamental questions. (i) Do climate-related risks influence asset prices? And (ii) are climate-related risks *efficiently* priced-in on asset markets? We turn to each of these questions separately

3.1 | Do climate-related risks influence asset prices?

To approach this question, we review the literature focusing on the observable links between climate-related risk drivers and asset prices.[4] A significant and diversified body of work exists by now, studying different types of assets with different methodological approaches, and obtaining sometimes opposite results. We digest this heterogeneity by identifying key dimensions to categorize available studies.

A first differentiation can be drawn by distinguishing the contributions investigating the effects of climate-related risks on 'negatively exposed' assets, and those studying instead 'positively exposed' assets:

- *Negatively exposed assets* are those assets that are assumed to be the losers of a low-carbon transition (e.g., assets from fossil fuel corporations and firms with high carbon intensity) or affected by physical climate change (e.g. bonds from municipalities with inundated areas from sea-level rise or equity of firms with production facilities close to disaster zones).
- *Positively exposed assets* on the other hand are assumed to be beneficiaries of a low-carbon transition (e.g., assets from renewable energy producers and firms with low carbon intensity).

3.1.1 | Negatively exposed assets

We report the findings of the literature focusing on negatively exposed assets in Panel 1 and in Tables A1 (physical risk drivers) and A2 (transition risk drivers) in the appendix. Given the wealth of different approaches in the literature, we identify three key dimensions to categorize the contributions: (i) type of asset; (ii) measure of impact; and (iii) direction of the effects.

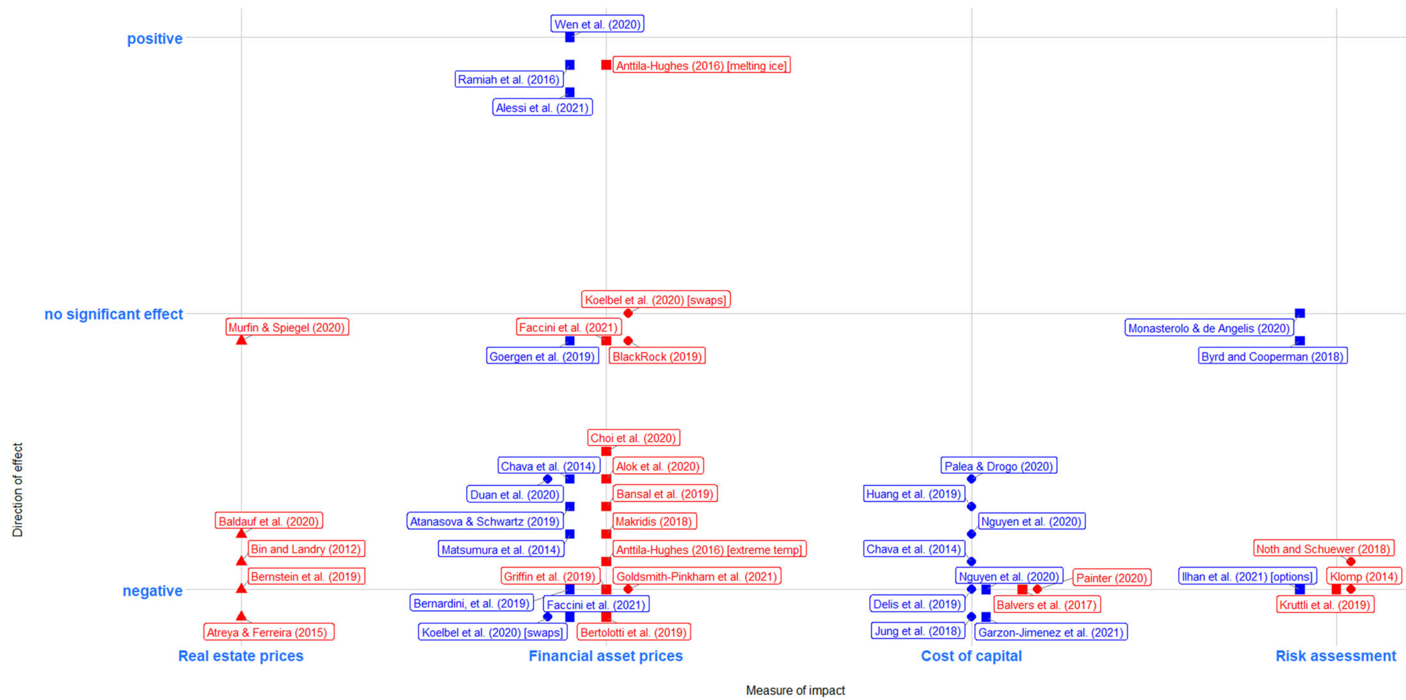
First, we distinguish between different types of assets being studied: equity, bonds, loans and real estate. We identify them in Panel 1 by using different symbols. Second, we distinguish four main types of impact measure, that is the indicator used to compute the extent to which asset prices are affected by the climate-related risk drivers (the columns of Panel 1):

- *Financial asset prices* refers to changes in the price of stocks and derivatives, as well as the valuation of bonds.
- *Real estate prices* refers to changes in real estate prices affected by climate impacts. While real estate is not a financial asset per se, it is frequently used as collateral for loans, which in turn appear on the balance sheet of listed financial institutions or are traded within mortgage-backed securities.
- *Cost of capital* refers to changes in the cost of equity or the cost of debt firms face. The category encompasses measures for the cost of equity, loan rates/spreads and issuance cost for debt instruments.
- *Risk assessment* refers to a change in financial risk as measured by financial risk metrics. This category encompasses papers that use the following measures of impact: tail risk, capital adequacy ratio (CAR), implied volatility, rate of non-performing loans and distance-to-default.

Third, where multiple contributions look at the same asset class using broadly similar impact measures, we differentiate them according to the results they obtain: negative effects (that is a drop in the asset price or an increase in the cost of capital), no effects or positive effects (lower, middle and upper row, respectively, in Panel 1). Finally, we also distinguish transition (blue) and physical (orange) risk drivers by color.

Based on our analysis of the literature, summarized in panel 1, we can establish some conclusions:

- The effects of physical and transition risk drivers across all four measures of impact are predominantly negative. Yet, some positive effects are detected in studies focusing on financial asset prices.
- Positive effects for negatively exposed assets are only documented as far as equity price changes are concerned. Three out of the four papers finding positive asset price reactions focus on transition risks. In particular, investors that learn about a firm's environmental impact from mandatory disclosures (Alessi et al., 2021) and their eligibility for carbon pricing schemes



PANEL 1 Backward-looking literature studying changes in the price of assets negatively exposed to physical (red) and transition (blue) risk drivers. Symbols denote impacts on stocks and options (■); bonds and loans (●); and real estate (▲). More details on the papers cited here can be found in Tables A1 and A2 in the Appendix [Colour figure can be viewed at wileyonlinelibrary.com]

(Wen et al., 2020) seem to ask a risk premium from issuers. This increment is now referred to as a "carbon premium" in the literature (Alessi et al., 2021; Bolton & Kacperczyk, 2021). Anttila-Hughes (2016) finds that extreme temperature events depress asset prices of fossil-fuel producing energy firms in the ten days period after the event. However, news of collapsing polar ice sheets have positive effects. He attributes this to the possibly reduced cost of energy firms' access to polar resources.

- Real estate prices are predominantly negatively affected by physical risk drivers. Exposure to sea-level rise (Bernstein et al., 2019), as well as a location in flood plains or the path of a hurricane is penalized with lower prices (Atreya & Ferreira, 2015; Bin & Landry, 2013). Murfin and Spiegel (2020), however, find no price effect for houses that have shorter inundation times in the event of a flood when controlling for other house specific factors.
- Lenders seem to price in possible climate-related risks when making lending decisions and setting interest rates, although the magnitude of effects overall is low. In the literature, firms exposed to physical and transition risks face higher cost of capital, evidenced in higher interest rates for loans (Chava, 2014; Huang et al., 2019) and fewer positive lending decisions (Nguyen et al., 2020). Cost of equity is also affected (Garzón-Jiménez & Zorio-Grima, 2021; Nguyen et al., 2020).

3.1.2 | Positively exposed assets

We also review the related literature studying assets that may benefit from a low-carbon transition, i.e. *positively exposed assets* (for an overview, see Table A3 in the Appendix). Such positive exposure may come in the form of compliance with the EU-ETS (the European Union's emission trading scheme) (Ravina, 2020; Ravina & Kaffel, 2020), relatively lower emissions (Bernardini et al., 2021; Cheema-Fox et al., 2019; Monasterolo & de Angelis, 2020; Soh et al., 2017) and renewable energy and cleantech firms (Kempa et al., 2021; Noailly et al., 2021). Almost all papers in this category focus on transition risks, with most contributions studying price effects on stocks (Bernardini et al., 2021; Cheema-Fox et al., 2019; Ramelli et al., 2019; Ravina & Kaffel, 2020; Soh et al., 2017) and bonds (Ravina, 2020). One paper investigates the effect of environmental policy stringency on the cost of debt for non-renewable energy firms (Kempa et al., 2021); another on the probability to receive venture capital funding when climate sentiments are high (Noailly et al., 2021). Two contributions study the effect of transition risk drivers on the value given by financial risk metrics, that is, the rate of non-performing loans at banks (Cui et al., 2018) and the systemic risk associated with equity (Monasterolo & de Angelis, 2020), respectively. Anttila-Hughes (2016) is the only paper investigating assets that may be positively exposed to physical climate risks: stocks of energy firms show positive abnormal returns in response to news of collapsing polar ice sheets.

All but one paper in this category (Bernardini et al., 2021) find that transition risk drivers have positive effects on asset prices and decrease riskiness or the cost of capital of positively exposed firms. This is a similar result to the predominantly negative effects we document for negatively exposed assets above. However, it follows a different logic. The fact that physical and transition risk drivers may create costs for negatively exposed firms does not imply that other, non-exposed firms would benefit economically. Thus, such positive price effects may be the result of capital shifting out of assets exposed to climate-related risks and into non-exposed assets.

Returning to the question asked at the outset of this section, we conclude that climate-related risks do influence asset prices. This influence is mostly negative for negatively exposed assets, that is, firms' (equity) value decreases, the perceived risks associated with their assets increase, or firms face higher cost of capital; and positive for positively exposed assets. The heterogeneity in the methodologies employed by authors to understand the differentiated impact of climate-related risk drivers on asset prices means that results (and especially their magnitude) are not easily comparable. In our review, we cannot do enough justice to this circumstance, which is why we have limited our visualization to the extent that it only reports the direction of the effect, not the magnitude. That being said, results are usually robust to a wide range of robustness checks (e.g., Delis et al., 2019), and to the precise specification of asset pricing models. Across papers, results are for instance broadly consistent across Fama-French five-factor models (Bolton & Kacperczyk, 2021) and a Fama-French three-factor model (Bernardini et al., 2021). Finally, within papers, authors tend to estimate carbon risks based on several asset pricing models, showing qualitatively similar results (Bernardini et al., 2021; Görgen et al., 2019).

3.2 | Are climate-related risks efficiently priced?

The discussion above has shown that financial markets tend to increasingly account for climate-related risks, although the magnitude of detected effects varies across asset classes, locations, and sectors. It remains to assess whether these estimates correspond to an "efficient" pricing of climate-related risks, that is, whether movements in asset prices signal an adequate hedge against physical and transition risks.

Most papers limit themselves to the display of effects, without discussing efficiency. Yet, some authors, based on theoretical discussions (Griffin et al., 2015) or the low magnitude of detected effects (Delis et al., 2019), provide informal appreciations of whether pricing is adequate, and often conclude that it is not the case.

Proving efficient pricing rigorously would require discussing whether the Efficient Market Hypothesis (EMH) holds in the context of climate-related risks. However, such an endeavor faces a "joint hypothesis" issue, a circularity implying that the measure of abnormal returns requires that the asset pricing model at hand operates at equilibrium, and therefore that measured prices are equilibrium prices. Whether pricing is efficient or not is therefore an impossible question to answer. For instance, whether the size of a risk premium is indeed the right one cannot be said with certainty. Qualitative insights, however, have been provided by some papers. They test whether the conditions for the EMH hold in presence of climate-related risks. These conditions can be summarized as follows:

- *Predictability of returns*: Information about climate-related impacts, including indicative data such as temperatures or policy proposals, from one period should not be able to forecast returns in the next period, because investors make use of forecasts in their decisions.
- *Forecast revisions*: Investors should revise expected payoffs once new climate-related information becomes first available, because they can interpret the economic and financial costs of such an event.
- *Climate risk premium*: Assets exposed to climate-related risks should trade with a premium.

Exercises of this type have so far mostly been carried out in the context of physical risks, with the exception of the work of Bolton and Kacperczyk (2021b). They show a mixed picture, with a greater number of papers pointing to an underreaction of markets to climate-related risks (see Table 1). Another strand of the literature, based on portfolio analysis, has consistently shown that there exists a significant green premium or "greenium", allowing portfolios long on low-carbon

TABLE 1 Summary of the literature review on efficient pricing of climate-related risks

Authors	Hypothesis	Conclusion
Predictability of returns		
Hong et al. (2019)	A higher incidence of droughts caused by climate change will reduce profits of food producers.	The authors find that a trend ranking can be used to forecast profit growth and stock returns of food companies. This return predictability is consistent with food stock prices underreacting to climate change risks.
Kumar et al. (2019)	A firms' sensitivity to abnormally high temperatures can be used to forecast stock returns.	Firms with lower sensitivity yield higher returns, but effects fade quickly. The authors conclude that stock markets underreact to climate sensitivity.
Forecast revisions		
Schlenker and Taylor (2019)	Prices of affected assets will not change after observable climate-related events. Or, if previously not priced in, investors will revise their expectations once risks materialize.	Investors' expectations are closely oriented along climate data. Hedging markets against temperature-related risks operate efficiently.
Addoum et al. (2020)	Analysts' forecasts for earnings change after the occurrence of 8′584 extreme temperature events in the U.S, which were identified as relevant for firms' earnings.	There is no evidence that analysts adjust their earnings forecasts after the firms they cover have experienced an extreme temperature event, which suggest that analysts do not fully integrate the impact of climate change in their expectations.
Griffin et al. (2019)	The equity price volatility firms complacent to Extreme High Surface Temperature (EHST) events is expected to increase. Further, investors recognize climate change as a driver of EHST events only after 2013, and assume they are random up until 2003.	Investors underprice physical risks because the authors observe negative excess equity returns to EHST events.
Climate risk premium		
Bolton and Kacperczyk (2021a)	Stock returns are not affected by corporate carbon emissions.	Higher carbon emissions at the firm level are associated with higher stock returns in all sectors and on all continents, despite the fact that they should face very different levels of transition risk in principle.

assets and short on high-carbon ones to quasi-systematically beat the market (e.g., Cheema-Fox et al., 2019; Ravina & Kaffel, 2020). Such results stand in sharp contrast with the EMH. Finally, it must be noted that the EMH has come under significant fire after the Great Financial Crisis, with a large literature rebutting it as theoretically flawed (Crotty, 2008). In the more precise context of climate-related risks, lengthy scholarship has also expressed doubts as to the validity of the EMH from behavioral and institutionalist standpoints (Ameli et al., 2020; Thomä & Chenet, 2017).

All in all, the literature tends to tilt towards the opinion that climate-related risks are inefficiently priced and financial markets underreact to them. As more climate-related risks materialize, financial markets may suffer, to a certain extent, from climate-related risks, as they seem so far not priced-in to their full extent. The question, in turn, is that of the magnitude of these potential financial disturbances, which cannot be answered based on backward-looking studies alone. Rather, this requires the use of forward-looking methodologies, to which we turn in the next section.

4 | FORWARD-LOOKING METHODOLOGIES

Forward-looking methodologies aim to include the impact of uncertain, but conceivable climate-related events in their foresight. We use the term ‘methodology’ here broadly to refer to models, analyses and estimation techniques.

Projecting how climate-related events may result in financial asset price changes requires models to make assumptions about future climate change; which climate mitigation policies will be implemented; the channels through which climate-related events impact firms and their business operations; and how these impacts translate into asset price changes and financial market dynamics.

While methodologies share important characteristics, they also differ considerably within each of these categories. In the following, we organize our discussion of the differences as follows. We first discuss two key choices that methodologies face: that of the forward-looking scenario and of the time horizon. We then turn to four other steps in the estimation, responsible for most of the heterogeneity in reported asset price changes: The exposure of an asset to climate-related risk drivers; the translation of economic costs to financial costs; the extent to which financial markets mitigate or amplify initial costs; and the measure of impact.

4.1 | Key choices for forward-looking methodologies

4.1.1 | Constructing forward-looking scenarios

A necessary step in the process of investigating the future financial impact of climate-related risks is to develop assumptions on what the future might look like. These visions of the future take the form of scenarios, which are usually not guided by probabilities (an exception is Battiston & Monasterolo, 2021). This is because there is uncertainty over feedback effects and tipping points in the climate system. Policy paths in democracies are also plagued with uncertainty (Chenet et al., 2019).

Scenarios are an established means to deal with this uncertainty. They “should have a clear, plausible, qualitative narrative but also be data-driven” (NGFS, 2019, p. 22). In the field we are reviewing and following the tradition of Integrated Assessment Modeling (IAM), a critical variable defining scenarios is the long-term increase in global temperatures with respect to pre-industrial averages. It makes sense to group scenarios[5] by the degree of expected warming, which co-determines the stringency of climate policy and thus of transition risks:

- **Policy action scenarios** that limit the warming over the next half-century or so to 1.5–2°C are associated with the strictest transition measures, while physical impacts appear more manageable. In these scenarios, the shape of the transition determines the shocks to economic activity: a target temperature rise of below 2°C could materialize either through a gradual transition of the economy or through an abrupt transformation leaving some key industries behind.
- **Extrapolating scenarios** are oriented along the temperature path associated with current emission levels. Taking the Paris Accord's nationally defined contributions (NDCs) as a baseline, temperatures in 2100 are likely to exceed the 2°C target by several decimal points (Robiou Du Pont & Meinshausen, 2018). Current emission pathways assessed in the UNEP Emissions Gap Report show that a warming of 3°C is most likely (Edo et al., 2019). These scenarios are thus associated with both transition risks, which in some scenarios are directly derived from NDCs, and physical risks.
- **No-policy action scenarios** take current emissions or even an increase in fossil fuel use as given and put global warming by the end of the century at anywhere from 4°C to more than 8°C. They are associated with virtually no transition risks. Physical climate risks are most pronounced in these scenarios.

In addition, considerations around the shape of the transition have become increasingly important, as a specific target could be obtained through both a gradual non-disruptive transformation and an abrupt transition with systemic disruptions. The Network for Greening the Financial System (NGFS), for example, recommends organizing scenarios along two dimensions: first according to whether climate targets are met or not, and second whether the transition happens in an orderly manner or not (NGFS, 2019). This classification generates four scenario categories. (i) An orderly transition that achieves climate goals (that is, stays below 1.5 or 2°C of warming); (ii) a disorderly transition that achieves climate goals, (iii) a disorderly transition that happens too late to meet the climate goals ("too little, too late") and (iv) a "hot-house-world" scenario without a disorderly transition but in which climate goals are not met. The NGFS has since developed six individual scenarios, two in each category with the exception of the "hot-house-world" category. They are partly based on current signals from governments to decarbonize and are supposed to provide financial institutions with a common starting point for an analysis of impacts to their measures of interest (NGFS, 2021). Some methodologies apply the NGFS suggestions (Allen et al., 2020) or congruent scenarios that follow the logic of "orderly", "disorderly" and "no transition" (Bongiorno et al., 2020). However, other institutions have simultaneously developed their own scenarios, e.g., focusing on the differences between technological and policy-induced transition risks (ESRB, 2021; Vermeulen et al., 2018).

The choice of which specific scenario to investigate also depends on the scope of the research. For instance, studies focusing on transition risks might only look at a 2°C-scenario. On the other hand, studies focusing on physical risk drivers might limit their analysis only to emission pathways creating an increase of temperatures of more than 2°C. Studies can also include both transition and physical risks, typically involving a trade-off between the two. Mercer (2019) and UNEP FI (2019) are examples of studies combining both physical and transition risks.

4.1.2 | Time horizons: long-term forecasts versus stress tests

The speed and modalities of implementation of mitigation policies are crucial, as they determine the magnitude of both transition and physical risks. The forward-looking literature offers two possibilities to project the speed of change: current portfolios are either stressed with events that are expected to materialize in the future; or the development of portfolios is extrapolated into a point in time in the future when climate-related risks are expected to fully materialize. We thus distinguish methodologies by their focus on either long-term scenarios or on short-term stress tests.

- *Stress tests* impose physical or transitional shocks on individual institutions and their portfolios or on the financial system as a whole. They are short-term and instantaneous in nature but are sometimes used to shock future projected developments of a portfolio. This approach resembles the stress test exercises routinely administered by financial market regulators (for an introduction into stress testing for banks see Dent et al., 2016). Shock scenarios aim at creating unusual stress and so focus on "tail risks", referring to the tails of probability distributions.
- *Long-term scenarios* incorporate transition and/or physical effects of probable emission pathways and analyze their effects on macro—or company-level variables over the next 30–100 years. Given the high uncertainty around the stringency of climate policy and the development of carbon-sequestering technologies, some of the scenarios also aim to comprise tail risks.

4.2 | Options within different estimation steps

Once the basic choices about the scenario and the time horizon of studies have been made, several specific methodological options are possible when estimating physical and transition costs. These include:

1. *Determining the exposure of an asset*. Methodologies must determine the degree to which a company and its assets are exposed to climate-related risks to be able to estimate the costs of the shock.
2. *Determining the financial costs of the economic shock*. The economic impacts, however calculated, need to be translated into financial impacts. Methodologies in this step strongly differ across studies.
3. *Including financial and non-financial market dynamics*. Methodologies can consider how financial networks amplify initial financial effects.
4. *Choosing the measure of impact*. Methodologies can present the financial impacts of the scenarios or stress tests using several measures.

We present these options below along the different steps that characterize most methodologies.

4.2.1 | Determine the exposure of an asset

Different companies and assets are treated unequally by climate change and climate policy. The pricing of climate-related risks must consider this heterogeneity by assessing the exposure of assets to climate-related risks and the firm's sensitivity, that is, the ability to respond and adapt to the exposure. Hubert et al. (2018) define exposure as "the presence of the system of interest in a place and setting that could be adversely affected by a hazard." This presupposes detailed knowledge of a company's assets and business model and how they might be exposed to climate-related risks.

Such knowledge includes spatial information on the exact geographic locations of a company's facilities, as well as expected climate impacts. These should be combined with the sectoral disaggregation of financial portfolios to account both for common traits of industries and the heterogeneous spatial exposure of companies of the same sector. In the case of transition risks, companies of the same sector may operate in different jurisdictions, subjecting them to different policies. Finally, additional analysis should include information on market power, which could affect the pricing of products. Such an approach would highlight that not all companies have the same scope of action when exposed to a shock.

In practice and among methodologies, approaches vary significantly in the granularity and breadth of exposure analysis. On transition risks, some use impacts on (sectoral) value-added, calculated for several mitigation scenarios, to determine the potential financial losses (Mercer, 2019). Others create a factor from empirical information that links the average CO2 intensity of an industry's production to asset returns in 56 industries (Vermeulen et al., 2019). HSBC (2019) uses an Integrated Assessment Model (TIAM-Grantham) to derive a set of trajectories for sectoral activity, emissions, energy use and carbon prices, which are then transformed into changes in company-level revenues and costs through additional bottom-up models. On physical risks, Four Twenty Seven and Deutsche Asset Management (2017) map facilities and their exposure to flood plains. Using this information, they find that firms with spatial diversity fare better against acute climate risks. Others use spatial data on asset locations and on climate change impacts (up until 2100) not only to determine exposure to direct physical risks but also relevant second-order financial effects (BlackRock, 2019). Where data is sparse, employing qualitative empirical research, such as interviews, can help determine the exposure of loan portfolios (Vermeulen et al., 2019). Another time-intensive way to determine loans' exposure is to identify corporate loans to fossil fuel producing firms, factoring in non-fossil fuel dependent business activities (Weyzig et al., 2014).

Such approaches are characterized by a 'top-down' approach, which involves using a macroeconomic model to translate physical impacts and transition costs into effects on GDP, inflation and interest rates, prices of intermediate and consumption goods (energy commodities, in particular), changes in trade patterns, and others. Where data availability allows, methodologies build exposure analyses 'bottom up', from the asset, firm or sectoral level.

This is the case, for instance, of UNEP FI (2019), which uses a number of models to evaluate both the physical and transition impacts on the costs and revenues of companies. Trucost (2019) uses different carbon price scenarios to calculate the company-level carbon costs and the resulting 'earnings at risk', before aggregating the impacts at the portfolio level. The underlying methodological approaches and modeling structures are likely to have a strong impact on the results. Most models assume some form of maximization, usually in the form of an intertemporal optimization of a welfare function, to determine carbon price trajectories and other macroeconomic variables, given certain emission scenarios. Others, most notably E3ME, are governed by macro-econometric functions and are demand- rather than supply-driven, meaning that transition-related investments are treated as a positive increase in expenditure (and hence GDP) rather than a utility-reducing costs.

Disaggregated information about exposure is important to show that some assets or loans of a company may be more at risk than others. In the past, it has been difficult to obtain project-specific data to estimate loan or bond exposure to climate-related risks and, to a lesser degree, that of equity. Disclosures of climate-related risks, as recommended by the Taskforce on Climate-related Financial Disclosures (TCFD, 2017) can help to fill this information gap. But they might be insufficient if they are not widely adopted by issuers and if investors do not use the information that they provide. The EU taxonomy for sustainable activities ("EU Green Taxonomy" for short; European Commission, 2020), which defines screening criteria for sustainable economic activities, will be used to make the contents of sustainable finance products more transparent. Financial institutions will have clear guidelines as to what they can label a "sustainable" product. This could further incentivize them to improve the screening of an asset's exposure to transition risks. However, it should be pointed out that an asset's degree of alignment with the EU Green Taxonomy does not correspond directly to its exposure to climate-related risks (Monasterolo, 2020).

4.2.2 | Determine the financial costs of the economic shock

The economic impacts, however calculated, need to be translated into financial impacts. Given the many assumptions necessary for this step, the methods strongly differ across studies. Dietz et al. (2016), for instance, after using the DICE model to calculate the GDP impacts of different mitigation scenarios, assume corporate earnings to be a constant share of GDP in the long-run, and the value of financial assets to be a function of discounted cash flows. In Mercer (2019), a heatmap of sensitivities of different industries and asset classes is developed, to transform sectoral GDP impacts into returns for different asset classes, disaggregated by industry. In UNEP FI (2019) the present value of the projected costs and opportunities from transition and physical impacts are compared to the current market valuation of the enterprise to calculate the Climate Value at Risk of the company. Ralite and Thomä (2019) use a sensitivity factor based on the correlation between GDP growth and share prices found in the stress tests of the European Systemic Risk Board (ESRB) to turn GDP impacts into stock price changes. Allen et al. (2020) use a dividend discount model (DDM), which translates their results at the level of sectoral value-added into dividends and thus stock value. Vermeulen et al. (2018, 2019) assign sector-specific transition vulnerability factors and prospected equity returns to assets and securities in 56 industries (using NACE categories). The vulnerability factors are based on the amount of carbon emissions used to generate value-added. In addition, they employ their own survey data to estimate the corporate loan exposures of the largest Dutch banks.

4.2.3 | Include financial network dynamics

Financial networks play an important role in spreading financial risks that had originally affected only one counterparty (Bateson & Saccardi, 2020; Battiston et al., 2017; Mandel et al., 2021; Roncoroni et al., 2021). The direct financial risks posed by climate change might seem manageable at first sight, but the asset price revaluations that they can trigger can be much larger than the initial shock. Some methodologies thus consider amplification mechanisms and propagation in financial markets. These amplifications are conceptualized as network effects, "contagion" (Roncoroni et al., 2021) or "second round effects" (Battiston et al., 2017).

Models of loss contagion among banks have been explored widely in the aftermath of the Great Financial Crisis of 2007. This literature, which focuses on the role of interbank markets (Georg, 2013; Krause & Giansante, 2012) has been a starting point to consider the role of networks in transmitting climate-related shocks (Bateson & Saccardi, 2020; Roncoroni et al., 2021). However, there are also multiple indirect network effects that can amplify initial shocks. First, rapid revaluations of certain assets can translate into a broad decline of asset prices through balance sheet readjustments and fire-sales (see, e.g., Krishnamurthy, 2010 or Shleifer & Vishny, 2011). In such a case, a decline in the price of some assets deteriorates the balance sheet of investors, causing them to liquidate other assets, which in turn lowers prices and deteriorates balance sheets even further. Recently, such fire-sale dynamics have been added as "third-round effects" to models of financial contagion in the case of climate-related risks (Roncoroni et al., 2021). Second, a related channel of contagion could be activated by the sudden revision of expectations. Herding behavior (Kiyotaki & Moore, 2002) and speculation may exacerbate climate-related risks due to a lack of information on the change in fundamentals (Jaffe, 2020; Palao & Pardo, 2017). Herding would be problematic, if there was evidence that investors base their expectations on similar observable events. An emerging literature has emphasized the role of "climate sentiments", that is, investors' expectations of future profitability and thus investment preferences under climate change, in shaping climate risk dynamics (Dunz et al., 2021). For example, "Climate sentiments" run high during times of attention-grabbing events such as UN Conferences of the Parties (COP) and have a larger effect on stock prices during those times (Santi, 2021). Finally, there are a range of possible mechanisms, which have not been explored in the climate risk case. These include default cascades (Allen & Gale, 2000) and liquidity crunches (Gai et al., 2011).

In the literature we review, most methodologies limit themselves to evaluating first-round effects, i.e. the asset price changes in direct response to a scenario-induced economic shock. Exceptions are Battiston et al. (2017), who introduce network effects in the form of a liquidity shock through a model of interbank lending markets and Roncoroni et al. (2021). The latter extend the interbank model with third-round effects from fire sales and fourth-round effects from losses that go beyond banks' ability to absorb the shock and consequently affect external creditors. Such network effects are in some cases larger than the direct effects and might trigger wider systemic implications.

4.2.4 | Include non-financial market dynamics

Just as asset price changes can cascade through financial networks, climate-related costs to one firm can also spread to other firms through supply chains or to customers through selling markets. Cahen-Fourot et al. (2021) construct a model from Input-Output tables to show that a policy shock initially affecting few industries can have material consequences along their supply chain. A cap on fossil fuel production would strand assets in the extractive sector and lead to idle assets in electricity and gas, basic metals, coke and refined petroleum products, transportation, etc. A key finding from their analysis is that even if a sector is not directly affected by a risk, it may not be a sound alternative to move financial capital into. A similar approach is used by Godin and Hadji-Lazaro (2020) in the case of South Africa, with comparable qualitative results.

4.2.5 | Choose the measure of impact

To interpret the results from methodologies, the measure of impact must be considered, i.e., how asset price changes are reported. Sometimes, typical indicators of financial risk are reinterpreted for climate-related risks. UNEP FI (2019), as well as Dietz et al. (2016) and – for their distributed shocks model – Battiston et al. (2017) calculate a 'Climate Value at Risk' (VaR). However, its precise definition differs across methodologies. Mercer (2019) uses the annualized value of the impact of climate scenarios on the portfolio return. Barker et al. (2015) analyze the impact of carbon taxation on profit-before-tax of companies listed in the MSCI World index (a global weighted index of around 1500 companies) and assume it serves as a proxy for the potential loss of future market (and thus equity) value. Similarly, HSBC (2019) reports the change in the NPV of the profits within an MSCI World index. CISL (2015) reports the 5-year performance of the portfolios they have analyzed, for three different scenarios.

Another way of displaying the scenario performance of asset classes or portfolios is to report the earnings at risk (Trucost, 2019) or the change in stocks' share prices in comparison to those in a baseline scenario.

Battiston et al. (2017) specify equity losses of banks as a percentage of their total equity holdings. Vermeulen et al. (2019) state losses relative to the total assets of each sector (what they refer to as "total stressed assets"). Equity changes can have three sources: changes to the risk-free interest rate; exposure to carbon-reliant industries; and exposure to other industries. BlackRock (2019), looking at corporate mortgage backed securities, reports the increase in expected default rates on these instruments. Trucost (2019b) uses scenario-led methodologies to test the impact of climate-related risks on credit or corporate bond ratings. Finally, some methodologies opt for reporting risk scores or ratings for assets, portfolios or even sovereigns. The CRIS methodology, put forward by Lepousez et al. (2017), uses detailed information on physical hazards and asset exposure to derive scoreboards for individual assets. These include (for a corporate bond) information on the hazards that the business activity is most exposed to and the locations that are most at risk. They report an overall score on a scale from 0 to 99 instead of a monetary measure. We do not showcase them in Table 2.

4.3 | Reported asset price changes

In this section, we present the academic and industry contributions that have already tried to estimate the impact of climate-related risks on asset prices. We review the main estimates available in the literature for the *future* impact of physical and transition costs on financial assets as opposed to historical events, which we covered in Section 2.

Table 2 summarizes the results. We report (1) the types of risk under consideration, (2) the portfolio or index that is exposed to the risks, (3) the measure of impact, (4) the asset classes considered and (5) the time horizon of the scenario analysis or, if applicable, the assumed year of the stress test. To group scenarios, we refer to the relative temperature increase over pre-industrial levels by the end of the century that is assumed in the scenario. Where this information is not readily available, we refer to the names given by the authors.

Looking at the results, stress tests tend to expose more extreme asset price or earnings changes. Especially in harsher scenarios, stress tests give estimates at the upper end of the spectrum. Ralite and Thomä (2019) report a negative change in share prices of up to 60% under their "too late and too sudden" scenario. Similarly, Trucost (2019) estimate that earnings at risk in a hypothetical scenario can be as high as 140% in the case of utilities (although they show how heterogeneously this risk is distributed within the industry). Equally grim is the outlook on utilities under a stringent transition scenario by Barker et al. (2015), estimating a profit loss of up to 76.5%. Battiston et al. (2017) report high increases in equity loss if second-round losses via the interbank lending markets

TABLE 2 Estimates for asset price changes from selected literature (continues over 4 pages)

Study (Model)	Type of Risk (Type of Analysis)	Portfolio/Exposure	Measure	Asset class	Time horizon	Scenarios		
						3-4°C	**1.5°–2°C**	
Barker et al., 2015 (not specified)	Transition (Stress test)	MSCI World Index (Utilities)	Profit before tax	equity	2020	−15.3%	−76.5%	
		MSCI World Index (Basic materials)				−4.2%	−19.4%	
		MSCI World Index (Energy)				−2.8%	−11.8%	
		MSCI World Index (Industrials)				−1.5%	−7.2%	
						2°C	**2-2.5°C**	**No mitigation**
CISL, 2015 (GEM)	Transition (Stress test)	High fixed income	5-year portfolio performance	Equity, bonds, and other assets	5 years	−3%	4%	−4%
		Conservative				9%	12%	−26%
		Balanced				17%	16%	−30%
		Aggressive				25%	25%	−45%
						2°C	**2.5°C**	
Dietz et al., 2016 (DICE)	Physical and transition (Long term)	Stock of global financial asset	Climate VaR (impact of scenarios on present value of assets) –mean	Equity and bonds	2100	−1,18%	−1,77%	

(Continues)

TABLE 2 (Continued)

Study (Model)	Type of Risk (Type of Analysis)	Portfolio/Exposure	Measure	Asset class	Time horizon	Scenarios 3-4°C	1.5°–2°C		
						Fossil-Fuel	Fossil-Fuel + Utilities	F-F + Util. + Energy-intensive	F-F + Util. + E-intens. + Housing????+ Transp.
Battiston et al., 2017 (DebtRank)	Transition (Stress test: reported sectors 100% devalued)	Eurozone Banks	total relative equity loss	equity, bonds and loans, after first round	shock occurs in 2017	2.55%	3.79%	13.18%	15.09%
				after first and second round		6.08%*	9.75%*	27.91%*	30.24%*
	Transition (Stress test: with shock distributions)		VaR (5%)			**Fossil-Fuel Primary**	**F-F Primary + F-F Secondary**	**F-F P + Renew. Secondary**	**Renew. Secondary**
				first round		0.26%	0.41%	0.19%	0.06%
				first and second round		0.63%	0.96%	0.47%	0.13%
						Policy shock	**Tech. Shock**	**Double shock**	**Confidence shock**
Vermeulen et al., 2018 (NiGEM)	Transition (Stress test)	Dutch banks	Asset loss	Equity, bonds, loans	5 years	2,17%	1,14%	2,73%	1,67%

(Continues)

TABLE 2 (Continued)

Study (Model)	Type of Risk (Type of Analysis)	Portfolio/Exposure	Measure	Asset class	Time horizon	Scenarios			
						3-4°C	**1.5°–2°C**		
		Dutch insurers				8,12%	2,08%	10,83%	2,68%
		Dutch pension funds				6,73%	2,99%	10,16%	6,65%
						Disorderly			
Monasterolo et al., 2018	Transition (Stress-test)	Chinese Development Banks	Portfolio value	Syndicated Loans		4.2%–22% loss			
							*reported with standard deviations		
Mercer, 2019 (E3ME)	Physical & Transition (Long-term)	Representative growth portfolio	Impact of scenario on portfolio return (per year average)			2°C	3°C	4°C	
				Total portfolio	2030	0,11%	−0,02%	−0,07%	
					2050	−0,05%	−0,09%	−0,14%	
					2100	−0,07%	−0,12%	−0,18%	
				Equity (developed)	2100	−0,10%	0,10%	−0,20%	
				Equity (emerging)		−0,20%	−0,30%	−0,40%	
				Growth bonds		0,00%	0,00%	−0,10%	
						1.5°C	**2°C**	**3°C**	

(Continues)

TABLE 2 (Continued)

Study (Model)	Type of Risk (Type of Analysis)	Portfolio/Exposure	Measure	Asset class	Time horizon	Scenarios 3-4°C	1.5°–2°C	
UNEP FI, 2019 (REMIND)	Physical & Transition (Long-term)	Market Portfolio of 30,000 companies	Company Climate VaR (ratio between present-value climate-related costs/profits and current market value)	Equity	15 years	−4,56%	−3,36%	−1,84%
		1200 Top companies				0,05%	−0,46%	−0,80%
						2°C		
HSBC, 2019 (TIAM-Grantham)	Transition (Long term)	MSCI ACWI (All countries World Index)	Change in profits (NPV) relative to No Policy scenario	Equity	2050	−2%		
						Smooth Transition	**Too late, too sudden**	
Ralite & Thomä, 2019 (Discounted Cash Flow)	Transition (Stress test)		change in share prices compared to baseline	equity	shock occurs in 2025	−20–50%	−30–60%	
						4°C		
BlackRock, 2019 (RHG-NEMS)	Physical (Long term)	(Bloomberg Barclays Aggregate Index)	Default rate on CMBS	Commercial Mortgage Backed Securities	2060–2080	+ 0.6%		
						2°C		

(Continues)

TABLE 2 (Continued)

Study (Model)	Type of Risk (Type of Analysis)	Portfolio/Exposure	Measure	Asset class	Time horizon	Scenarios			
						3-4°C	**1.5°–2°C**		
Trucost, 2019 (not specified)	Transition (Stress test)	Utilities	Earnings at Risk	Equity	2030	~140%			
		Materials				~100%			
		Energy				~55%			
		Industrials				~12%			
						2°C (Ref-Pol450)	**2°C (Ref-Pol500)**		
Battiston & Monas-terolo, 2019 WITCH/GCA	Transition (Stress-test)	OeNB	Portfolio value	Sovereign bonds	Shock	−0.13% −+0.12%	−0.36% −+0.08%		
						2°C (Ref-Pol450, mild market condi-tion)	**2°C (Ref-Pol450, adverse market condi-tion)**	**2°C (RefPol500, mild market condition)**	**2°C (RefPol500, adverse market condition)**
Battiston et al., 2019 (CLI-MAFIN)	Transition (Stress-test)	EU/EEA Insurance companies	Portfolio value	Sovereign Bonds	Shock	up to 0.6% loss	up to 2.6% loss	up to 0.4% loss	~1.8% loss
						2°C, Orderly	**2°C, Disor-derly**	**Failed Transition**	

(Continues)

TABLE 2 (Continued)

Study (Model)	Type of Risk (Type of Analysis)	Portfolio/Exposure	Measure	Asset class	Time horizon	Scenarios 3-4°C	1.5°–2°C	
Bongiorno et al., 2020 (ClimateMAPS)	Physical & Transition (Long-run)	Global	Median equity market returns	Equity	around 2025	Small losses	−18%	no losses
					2060	−15%	−25%	−50%
						Delayed Transition	**Sudden Transition**	
Allen et al., 2020 (NiGEM)	Transition (Long-run)	France, Europe, ROW	Equity price	Equity	expectations change today about 2050	−2% to −8%	−5% to −20%	
						2°C (Fossil Fuel + Util.)	**2°C (+other sectors)**	
Bateson and Saccardi (2020)	Transition (Stress-test)	US Banks	Portfolio value	Syndicated loans	Initial shock	−3% loss	−18% loss	
					After 2nd round	−8% loss		
						Policy shock	**Techno shock**	
ESRB (2021)	Transition (Stress-test)	Banks, pension funds	Mark to-market losses	All assets	5 years	−0.8%	−0.5%	
						Disorderly		

(Continues)

TABLE 2 (Continued)

Study (Model)	Type of Risk (Type of Analysis)	Portfolio/Exposure	Measure	Asset class	Time horizon	Scenarios 3-4°C	Scenarios 1.5°–2°C
EIOPA (2020)	Transition (Stress-test)	EU Insurers	Portfolio value	Equity	Shock	−25%	
						Disorderly	
Grippa et al. (2020)	Transition (Stress-test)	All financial actors (Norway)	Mark to-market losses	Equity	2020-2040	−5% to −6%	
						Disorderly (RefPol-500)	
Roncoroni et al., 2021 (GCAM)	Transition (Stress-test)	Mexican Banks & Investment Funds	Relative equity loss	All	Shock	2.5-4% ot total asset value	

are considered. The stress test of the Dutch financial sector by Vermeulen et al. (2019) exemplifies that the co-occurrence of two shocks, i.e. technology and policy, can significantly exacerbate transition risks for financial actors. Long-term studies focusing on profitability of portfolios, such as HSBC (2019) and Mercer (2019), report relatively minor losses. Research using VaR as a measure of future impacts on asset prices report relatively high values, see the results by Dietz et al. (2016) and UNEP FI (2019). The latter also shows that a global, broadly invested portfolio will likely suffer more from both transition and physical risk scenarios than the top 1200 companies.

5 | RESEARCH GAPS

Despite a leap in the breadth and depth of the literature on climate-related risks in asset prices, some research challenges remain. First, more must be done to better understand how climate events can trigger abrupt price corrections on financial markets. Second, a recent push to improve the available climate-related data raises issues for financial market participants and supervisors. Third, there are implications for the forward-looking methodologies, which must adapt to the changing data landscape.

5.1 | Potential risks to financial stability

From extreme weather events to more stringent climate policies and litigation costs, climate-related risk drivers abound. Empirical evidence tends to indicate that such climate risks are not fully priced in by market participants, a fact which is often highlighted by policy-makers, including central bankers and financial supervisors. This opens the door to potential sharp price corrections as investors revise their expectations.

Our review of the backward-looking literature showed that additional climate-related information overwhelmingly leads to changes in asset prices, which are predominantly negative. As we have discussed at the outset of this paper, the sudden revision of expectations about the ability of assets to generate a return or about the financial risks they face, may have consequences for financial stability. A better understanding of what could trigger such expectations revisions is key to anticipate episodes of financial instability. However, there is currently no framework that offers an explanation to when such a 'Climate Minsky moment' (Carney, 2018) would occur. Future research will thus have to investigate what determines tipping points in the financial system.

Furthermore, little is known about how initial climate shocks on asset prices propagate and are amplified by financial markets. Some pioneering work has already been done with financial network models to assess such propagation and amplification mechanisms. They usually show that indirect exposures to climate-related risks are material. Some banks can be severely affected by them, even if they seem to have no exposure at first sight (see, e.g., Roncoroni et al., 2021). Similarly, both physical and transition-related shocks can propagate along the economic value chain, affecting economic actors well beyond those that are directly hit (see, e.g., Cahen-Fourot et al., 2021). Such network effects are usually absent from forward-looking methodologies.

Another potential source of financial instability could come from the creation of a green bubble, i.e. the overinvestment in low-carbon technologies and the heightened interest in financial assets labeled as "green" or "ESG", which has thus far seen very little empirical analysis (Semieniuk et al., 2021). Given that sources of renewable energy now undercut certain fossil fuels in the cost of power generation (IRENA, 2021), the risk of a green bubble may also rise, requiring more research to understand under which conditions it could emerge and burst.

5.2 | Climate-related disclosures and financial supervisors

There is currently a push to develop common frameworks under which to report climate-related disclosures. The guidelines set by the Task Force on Climate-Related Financial Disclosure (TCFD, 2017) are becoming the international standard for that. Such initiatives are supported by financial supervisors, who increasingly tend to support mandatory disclosure guidelines for firms. Parallel to that, policy-makers are also engaged in defining economic activities, which support the transition to a low-carbon economy and are thus eligible for green investment labels. The most notable examples of such taxonomies are China's *Green Bond Endorsed Project Catalogue* issued in 2015 and the EU's *Taxonomy for sustainable activities* issued in 2021.

Such initiatives are welcome: more data will improve the assessment of climate financial risks. However, further research should aim to understand which data best reflect firms' and households' exposure to climate-related risks. Transition risks are a case in point: exposure to transition risks greatly depends on a firm's current and future actions and investments to ensure its transition to low-carbon technologies. There is no consensus on what forward-looking indicators to use to capture such plans. Current emissions, one of the main indicators used to assess transition risks, are limited in this context.

Collecting the right information to assess climate-related risks is further complicated by the fact that financial supervisors need such data from a diverse range of economic actors. Small and medium enterprises (SMEs) represent a bottleneck in this respect. Knowledge about their activities is needed to assess a banks' exposure to climate-related risks, but SME's capacity to deliver the complex data required for climate risk assessments is limited. Future research should Identify appropriate indicators that balance complexity and robustness.

5.3 | Dealing with uncertainty in forward-looking methodologies

Financial firms are looking for better toolkits to assess their exposure to climate-related risk (see for instance the survey of Gibbs et al., 2020). We identify two areas for further developing forward-looking methodologies to meet this demand: dealing with uncertainty and reflecting financial market dynamics.

Despite ever-greater efforts by climate science to understand the complex interactions in the climate system, the unprecedented nature of climate change means that fundamental uncertainty about future impacts will remain. Using multiple plausible scenarios and employing inter-model comparison exercises (i.e. running a number of different models using the same set of scenarios) are established means to deal with this uncertainty. As new knowledge about climate impacts and their assigned probabilities constantly emerges, scenarios should be updated frequently to reflect this change in what is deemed plausible. Methodologies should be flexible enough to quickly adapt to updated scenarios.

Second, as highlighted above, the propagation of climate-related risks through financial and non-financial networks remains understudied. A distinction must be made between the effects of gradual changes to economic processes and shock scenarios. Treating the financial system as a force that shapes the macro-economy, through changing expectations about the realization of climate risk, could help understand better the drivers of systemic risks.

6 | CONCLUSIONS

In this paper, we review the literature studying the pricing of climate-related financial risks. We summarize the current theoretical perspective on climate-related risks (encompassing physical, transition and liability risks) and discuss how they enter asset pricing frameworks. We offer a novel perspective on how climate-related risks materialize as economic costs for firms through four distinct channels and how these economic costs translate into financial asset price changes.

We structure the backward-looking literature (i.e., literature using historical-empirical data), distinguishing two types of assets (*negatively* and *positively exposed assets*) and four different measures of impact (*financial asset prices, real estate prices, cost of capital* and *risk assessment*). We show that new information about climate-related risk drivers predominantly leads to negative effects across the four measures of impact. Only in the categories of risk assessment and financial asset prices, there seems to be some ambiguity in findings. When an asset is positively exposed to transition risks (as, for example, in the case of renewable energy firms), most papers in our review find that transition risk drivers have positive effects on the asset prices, or that they reduce the risk exposure or cost of capital of the firms. We conclude that climate-related risks do influence asset prices and that results are usually robust to a wide range of alternative specifications of asset pricing models. At the same time, the results suggest that climate-related risks are not fully priced. We find mixed evidence on whether risks are priced efficiently.

Given the current turn towards forward-looking methodologies, we also review the literature focusing on the asset price impact of long-term climate and transition scenarios and stress tests. This literature is mostly guided by considerations around tail risk and plausibility rather than probability. We highlight the heterogeneity of the methodological choices to make in this context, including scenarios, the relevant time horizon, the method to determine the exposure of an asset to climate-related risks, the translation of economic costs to financial costs, and others. Model components, which study the amplification or mitigation of initial effects through financial networks, are only sparingly applied.

This heterogeneity in approaches and scope of forward-looking methodologies makes it difficult to compare results. Most methodologies focusing on transition risks test at least one climate mitigation scenario (in which the anthropogenic mean temperature increase stays below two degrees). Some choose instead to juxtapose a “smooth” and a “sudden” transition path. Methodologies focusing on the impact of physical climate risks employ at least one scenario, where the two-degree-target is overshot. The losses estimated both by the stress test and the long-term approaches are economically significant, but stress tests with their focus on tail risks report starker estimates. Network effects and co-occurrence of risk are likely to substantially increase initial financial losses.

Stress tests seem to be the avenue that most financial regulators and private actors opt for today. Given the remaining uncertainty over the exact consequences financial actors need to expect from both climate change and climate policy, stress testing is a promising way to periodically receive information about financial reactions to plausible scenarios. Regulators and central banks should continue to build their expertise in climate stress testing. Their emphasis should be in detecting systemic risks and including the analysis of the potential of propagation of initial shocks through production and financial networks.

Finally, while regular stress tests can keep regulators and financial actors informed about worst-case scenarios, long-term scenario analysis can improve their understanding of alternative climate futures under fundamental uncertainty. Their use and scope should be increased and refined, rather than concentrated around a few scenarios that seem most likely at a particular point in time. The impact of physical climate risk drivers should be considered in combination with transition and liability risks, as the future will most likely hold a mix of the three.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Louis Daumas https://orcid.org/0000-0003-3239-8538
Adrian von Jagow https://orcid.org/0000-0002-1622-555X

ENDNOTES

[1] These interactions are non-trivial. To name but two examples, higher transition risks from stricter climate policies are likely to limit physical risks in the future. Higher physical risks from unmitigated climate change on the other hand will spur litigation against governments and firms responsible for inaction. For a thorough discussion about the possible interactions of risk drivers, see Basel Committee on Banking Supervision (2021).

[2] When explicit asset pricing models are used, climate-related risks are included as a risk factor after being estimated through common methodologies (e.g., Fama & MacBeth, 1973).

[3] See Battiston and Martinez-Jaramillo (2018) for a review of existing models.

[4] While scientists increasingly use attribution science to link 'natural' catastrophes to man-made climate change, epistemological difficulties persist (Eckstein et al., 2020, p. 10). Some weather phenomena have increased in frequency, intensity and duration concurrently with a warming atmosphere (Committee on Extreme Weather Events et al., 2016). This section reviews the financial impacts of all event types, which could be attributed to climate change in principle, regardless of whether the authors use attribution science to create a causal link between a physical event and climate change.

[5] Labeling the scenarios is a delicate matter, as it can involve value statements. Most contributions, like ours, use labels to make scenarios easily recognizable. Hausfather and Peters (2020) point out, however, that referring to the "no-policy-action scenarios" as "business-as-usual (BAU) scenarios" overestimates the likelihood of such a scenario.

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APPENDIX

TABLE A1 Backward-looking literature studying assets negatively exposed to physical climate risk drivers

Authors	Asset class	Climate risk driver	Measure of impact	Effect on measure	Results
Bin and Landry (2013)	Real Estate	Disaster	(real) asset price	Negative	−5.7 to −8.8% on prices for houses in an affected area after hurricanes materialize. Other houses trade with a risk premium of 6.0–20.2% if located in a potential flood zone
Bernstein et al. (2019)	Real Estate	Sea-level rise (SLR)	(real) asset price	Negative	−7% discount relative to similar but unaffected properties
Murfin and Spiegel (2020)	Real Estate	Sea-level rise	(real) asset price	No significant effect	No price effect
Atreya and Ferreira (2015)	Real Estate	Disaster	(real) asset price	Negative	Houses in inundated areas trade with a markdown of 36–48% after the flood
Baldauf et al. (2020)	Real Estate	Sea-level rise	(real) asset price	Negative (lower pricies in “believer” neighborhoods than “denier” neighborhoods)	Houses located in “denier” neighborhoods cost around 7% more than those in “believer” neighborhoods
BlackRock (2019)	Bonds (Municipal)	Hurricanes	asset price	No significant effect	No price effect of heightened exposure of municipal bonds to storm risk
Kölbel et al. (2020)	Credit-default swaps	Custom climate risk measure based on language algorithm	asset price	No significant effect	For physical risks, there is no statistically significant impact on CDS spreads
Makridis (2018)	Stocks (all sectors)	extreme temperatures	asset price	Negative	−0.1 percentage point decline in stock returns for one standard deviation increase in monthly degrees at extreme temperature (below 15 degrees or above 84°F)
Anttila-Hughes (2016)	Stocks (energy)	News (extreme temperatures)	asset price	Negative	−1% (temperature records) and + 3% (melted ice shelves) return over 10 days
Anttila-Hughes (2016)	Stocks (energy)	News (Melting polar ice)	asset price	Positive	+3% return over 10 days after the news
Bansal et al. (2019)	Stocks (all sectors)	extreme temperatures	asset price	Negative	A one standard deviation increase in the long-run temperature leads to a 3% decline in equity valuations

(Continues)

TABLE A1 (Continued)

Authors	Asset class	Climate risk driver	Measure of impact	Effect on measure	Results
Griffin et al. (2019)	Stocks (all sectors)	extreme temperatures	asset price	Negative	Cumulative excess returns of −0.42%, more negative for costlier (−1.38%) and longer (−0.68%) Extreme High Surface Temperature (EHST) events. No effects for extreme cold temperatures
Bertolotti et al. (2019)	Stocks (electric utilities)	Disaster	asset price	Negative	−1.5% stock prices and +6 percentage points implied volatility for firms affected by the hurricane
Choi et al. (2020)	Stocks (all sectors)	extreme temperatures	asset price	Negative	−48 bps in the long-short emission-minus-clean portfolio
Alok et al. (2020)	Stocks (all sectors)	Disaster	asset price	Negative	Post-disaster, portfolio weights of stocks linked to disaster zones decrease for all funds regardless of location, but far more for funds close to the disaster zone
Faccini et al. (2021)	Stocks (U.S. common stocks)	News	asset price	No significant effect	No price effects detected
Goldsmith-Pinkham et al. (2021)	Bonds (Municipal)	Sea-level rise	asset price	Negative	A one standard deviation increase in SLR exposure leads to a 2–5% reduction in the present value of a municipal bonds or an increase of 1% to 3% in the volatility of local government cash flows
Painter (2020)	Bonds (Municipal)	Sea-level rise	cost of capital	Negative	U.S. counties exposed to physical risk face higher costs of refinancing: A one percent increase in climate-related risk increases the annualized issuance costs by 23.4 basis points for long-term maturity bonds
Balvers et al. (2017)	Stocks (all sectors)	extreme temperatures	cost of capital	Negative	The cost of equity capital rises by 0.22% due to the additional burden of climate-related risks, corresponding to a present value loss of 7.92%
Klomp (2014)	Loans (Commercial banks global)	Disaster	risk	Negative	Banks' distance-to-default decreases when home country is hit by a large-scale disaster. Disasters also lead to a credit-crunch, especially in emerging economies
Noth and Schüwer (2018)	Loans (Commercial banks US)	Disaster	risk	Negative	More non-performing loans and higher foreclosure ratios in the years following an event
Kruttli et al. (2019)	Stocks (all sectors)	Disaster	risk	Negative (higher implied volatility)	+5–10 percentage points implied volatility for firms affected by the hurricane

TABLE A2 Backward-looking literature studying assets negatively exposed to transition risk drivers

Authors	Asset class	Climate risk driver	Measure of impact	Effect on measure	Results
Kölbel et al. (2020)	Credit-default swaps	Custom climate risk measure based on language algorithm	asset price	Negative	Transition risks increase CDS spreads especially after the Paris Agreement. Transition exposed CDS experiences reduction in the range of 71–119 bps after the paris agreement
Chava (2014)	Stocks (S&P 500 & Russell 2000)	Custom Environmental Concern Measures	asset price	Negative	7% carbon premium on stocks
Bernardini et al. (2021)	Profits [stocks, if listed] (Utility sector)	Policy shock	asset price	Negative	Falling profits of high carbon firms. Lower profits also resulted in falling stock prices
Ramiah et al. (2016)	Stocks (all sectors)	Policy shock	asset price	Positive	Environmental regulations increase volatility and can generate abnormal returns in the range of 30–40%. Even if most of the news items refer to stricter regulation, most abnormal returns are positive.
Görgen et al. (2019)	Stocks (all sectors)	Custom Brown-Green-Score (BGS)	asset price	No significant effect	The Brown-minus-Green portfolio has a statistically insignificant negative risk premium of −0.097% per month
Faccini et al. (2021)	Stocks (U.S. common stocks)	News	asset price	Negative	There is only evidence that news about US climate policy is priced, and more pronounced after 2012. The spread's alpha ranges between 0.46% and 0.96% for decile portfolios.
Alessi et al. (2021)	Stocks (all sectors)	Custom score	asset price	Positive	Markets attach a negative risk premium to greener portfolio (disclosing environmental performance and with lower emissions). This means dirty stocks trade with a premium. Markets attach a risk factor if quality of disclosure is accounted for alongside emission performances
Wen et al. (2020)	Stocks (included in Shenzhen Pilot ETS)	Policy shock	asset price	Positive	The stock returns of companies participating in the Shenzhen ETS pilot experience positive returns after the start of the pilot, indicating a carbon premium. The authors theorize that this is because of the higher carbon exposures of companies trading under the ETS

(Continues)

TABLE A2 (Continued)

Authors	Asset class	Climate risk driver	Measure of impact	Effect on measure	Results
Duan et al. (2020)	Bonds (all sectors US)	Carbon intensity	asset price	Negative	Presence of significant carbon alphas on bonds (average +16 basis points), attributed to investor's underreaction
Noailly et al. (2021)	Stocks	News index	asset price	Negative	Four basis points drop in excess stock returns for firms with one-SD above mean CO2 emissions, following a one-SD increase in EnvP news index
Matsumura et al. (2014)	Stocks (S&P 500)	Carbon emissions	asset price (firm value)	Negative	Median +$2.3bn of market capitalization for firms disclosing carbon emissions. For each additional thousand metric tons of carbon emissions, firm value decreases by $212,000
Atanasova and Schwartz (2019)	Stocks (Fossil fuel firms)	Growth of undeveloped oil reserves	asset price (Tobin's Q)	Negative	A 1%-increase in investment in undeveloped proven reserves decreases Tobin's Q by .00002
Chava (2014)	Loans (S&P 500 & Russell 2000)	Custom Environmental Concern Measures	cost of capital	Negative	20% higher loan rates for environmentally hazardous firms (25 bps)
Nguyen et al. (2020)	Stocks (all sectors Australia)	Policy shock	cost of capital	Negative	Higher cost of capital (+2.5–3 basis points cost of equity) for polluting firms after the ratification of the Kyoto Protocol. Emitters' implied cost of equity increases by 2.5% post-ratification
Nguyen et al. (2020)	Loans (all sectors Australia)	Policy shock	cost of capital	Negative	Higher cost of capital (+5–6 basis points cost of debt) for polluting firms after the ratification of the Kyoto Protocol. Relative to non-emitters, this is an increase in the interest rate spread of 5.4% post-ratification
Jung et al. (2018)	Loans & Bonds (all sectors Australia)	Carbon emissions	cost of capital	Negative	+38–62 basis points in cost of debt for one standard deviation in scope 1 emissions
Huang et al. (2019)	Loans	Policy shock	cost of capital	Negative	Loan spread to high-polluting firms increases by 5.5% (i.e., a higher risk premium after the policy shock); default rates of these firms rose by around 50%
Delis et al. (2019)	Loans	Policy shock	cost of capital	Negative	Fossil fuel firms experience rising credit cost by 16 basis points

(Continues)

TABLE A2 (Continued)

Authors	Asset class	Climate risk driver	Measure of impact	Effect on measure	Results
Palea and Drogo (2020)	Loans and bonds (Non-financial sectors Eurozone)	Carbon-intensity/Policy shock	cost of capital	Negative	A 1-point increase in carbon itensity (Scope 1 & 2) increases cost of debt by 5%. After the Paris Agreement, while high emitters' cost of debt was not affected (because it was already priced), low emitting industries saw their cost of debt increase
Garzón-Jiménez and Zorio-Grima (2021)	Stocks (all sectors Emerging Markets)	Carbon emissions	cost of capital	Negative	A 1%-increase in scope 1 and 2 emissions increases cost of equity by 0.03 units
Ilhan et al. (2021)	Options (S&P 500)	Carbon intensity	risk	Negative	Downward tail risk increase (very) sligtly with industry's carbon intensity
Byrd and Cooperman (2018)	Stocks (Coal)	News	risk	No significant effect	0.05%–3.24% (mean 1.2%) CAR upon positive news; no significant reaction to negative news
Monasterolo and de Angelis (2020)	Stocks	Policy shock	risk	No significant effect	Carbon-intensive assets are not yet penalized

TABLE A3 Backward-looking literature studying assets **positively** exposed to transition risk drivers

Authors	Asset class	Climate risk driver	Measure of impact	Effect on measure	Results
Ravina and Kaffel (2020)	Stocks (all sectors Europe)	Policy shock	Positive	asset price	Higher returns (0.2%-—0.34%) on EU-ETS compliant portfolios (i.e not paying a carbon price)
Bernardini et al. (2021)	Profits [stocks, if listed] (Utility sector)	Policy shock	No significant effect	asset price	No effects for low carbon firms.
Ramelli et al. (2019)	Stocks	News	Positive	asset price	Transition-proof companies experienced positive abnormal returns of 62 basis points ten days after the election of Donald Trump and 101 basis points after the nomination of Scott Pruitt as head of EPA.
Ravina (2020)	Bonds (all sectors Europe)	Policy shock	Positive	asset price	Higher returns (0.03-—0.13%) on EU-ETS compliant portfolios (i.e not paying a carbon price)
Soh et al. (2017)	Stocks (all sectors US)	Carbon intensity	Positive	asset price	Low-carbon portfolios outperform high-carbon one (Abnormal returns of 3.5%–5.4%)

(Continues)

TABLE A3 (Continued)

Authors	Asset class	Climate risk driver	Measure of impact	Effect on measure	Results
Cheema-Fox et al. (2019)	Stocks (all sectors US and Europe)	Carbon emissions	Positive	asset price	+2% annual alpha on decarbonised porfolios
Noailly et al. (2021)	Equity of cleantech firms	News index	Positive	cost of capital	A higher EnvP news index is associated with cleantech startups receiving venture capital funding at a greater probability
Kempa et al. (2021)	Loans (renewable energy firms)	Policy shock	Positive	cost of capital	A one standard deviation increase in the OECD Environmental Policy stringency Index decreases the costs of debt of renewable energy firms by 19% relative to those of non-renewable energy firms. Environmental policies are likely to have an risk-reducing effect. This results in a lower risk premium on renewables of .15–.4 basis points
Cui et al. (2018)	Loans (Banks China)	Policy shock	Positive	risk	Banks with a higher green credit ratio experience a lower rate of non-performing loans
Monasterolo and de Angelis (2020)	Stocks	Policy shock	Positive	risk	The systemic risk associated with low-carbon indices drops after the announcement of the Paris Agreement. The relative weight of low-carbon indices in an optimal portfolio increases after the announcement