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Climate Risks in Financial Assets

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Abstract

This note reviews the empirical evidence available in the academic literature about the impact of climate-related risks on financial assets. It addresses three main questions: does climate change already affect financial asset returns? What is the potential impact of future climate-related costs on financial asset prices? Do financial markets adequately price in these costs? We find compelling evidence that climate-related events such as hurricanes and droughts – i.e. physical risks – already have a negative impact on both equity and debt instruments through lower payoffs and higher non-performing loans. We also find early evidence that transition costs impact on some financial assets more than others. Evidence on the effects of future climate costs on financial assets indicates that the financial risks associated with them are financially significant, even with conservative estimation methodologies. The magnitude of these risks critically depends on the extent to which investors currently price them in and on potential second-round effects. Several empirical studies point to a lack of awareness about future climate costs by investors, which support the concerns that financial markets currently do not adequately price in climate financial risks.

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1 Introduction

"Climate-related risks are a source of financial risk": the opening sentence of the first comprehensive report by the Central Banks and Supervisors Network for Greening the Financial System (NGFS 2019a) sounds like a wake-up call for the financial community. This warning, supported by more than 40 central banks and supervisors from all around the globe, must be taken seriously by financial investors. At the same time, central banks and financial supervisors frequently point to uncertainties around the magnitude and timing of climate change's impacts on financial assets as a reason for inaction. As a result, changes to their practice has been largely incremental.

Against this background, we review the empirical evidence on the link between climate risks and financial asset prices available to date in the academic literature. We address three main questions: is there empirical evidence that climate change already affects financial asset prices? What is the potential impact of future climate-related costs on financial assets? Do financial markets adequately price in these costs? We focus our survey on the impact of physical and transition costs on equity and debt instruments – i.e. on stocks, bonds, and loans, respectively. We also provide recommendations to bridge the knowledge gaps that we identify in our findings.

We find compelling evidence that the physical costs associated with climate-related events such as hurricanes and droughts have already a negative impact on both equity and debt instruments. They significantly decrease the payoffs of equities and increase the proportion of non-performing loans. As the occurrence of such events is projected to rise substantially with climate change, their impact on financial assets will also grow. Since the transition to a low-carbon economy is yet to happen, empirical evidence of the impact of transition costs on financial assets are scarcer, but the examples available indicate that transition costs have already reduced equity returns and increased default probabilities for some firms.

Turning to the effect of future physical and transition costs on financial assets, conservative stress tests for transition risks – i.e. without second round effects and without sudden revisions of investors' expectations – estimate that portfolios constituted of both equity and debt instruments could lose up to 10% of their value within 5 years. This loss could materialize within one year if investors suddenly revise their expectations to reflect future transition costs. For scenarios in which no transition happens – i.e. scenarios with maximum physical costs – a sudden revision of investors' expectations to account for future physical costs could generate losses up to 40% of the value of a diversified portfolio. In addition, second-round effects through investors' cross-exposure to each other are likely to significantly amplify losses.

Our review of the literature highlights that the impact of climate change on future financial asset performance crucially depends on whether physical and transition costs are already reflected in current asset prices. Empirical evidence on this issue is limited, but we find compelling evidence that points to a lack of awareness about future climate costs by investors. This strongly suggests that financial prices do not currently adequately reflect future climate costs. This concurs with the conclusion by the NGFS that “there is a strong risk that climate-related financial risks are not fully reflected in asset valuations.” (NGFS 2019a, p. 4)

Against this background, we urge both investors and financial regulators to systematically assess the climate risk exposure of their portfolio and of financial institutions that they supervise, respectively. For that, we believe that stress tests are the best way to evaluate shorter-term financial risks associated with climate change. The evidence presented in this study highlights that two key ingredients should be included in the design of such stress tests: first, the impact of swift revisions in investors’ expectations regarding future physical and transition costs, and second, the consequences of second-round effects on financial markets. Both features have a significant influence on the size of potential losses due to climate change, and both are likely to happen. Further research on the extent to which future climate costs are already priced in by financial markets, as well as a better understanding of second-round effects on financial markets, is also critical in this context.

This note is structured as follow: the next section describes the channels through which climate-related costs become financial costs and thus impact financial asset valuations. Section 3 reviews the evidence on the impact of climate-related costs on assets that have already been observed empirically. Section 4 collects the results from the available studies on the assessment of the impact of future physical and transitions costs on financial asset valuations. Section 5 presents the evidence on whether current financial markets adequately reflect future climate-related costs. Section 6 concludes and summarizes our recommendations.

2 From climate-related costs to a change in asset prices

This section describes the channels by which climate-related costs impact on equity and debt instruments’ market value. In short, the market price of a financial asset is equal to the present value of its expected future payoffs plus a risk premium. Any change in expected payoffs due to climate change will then result in an adjustment of asset prices on financial markets. To better understand how climate change can impact market prices, we thus first outline how climate-related physical and transition costs influence equity and debt instruments’ payoffs. We then focus on how climate change can lead to a revision of market participants' expectations about these payoffs. Finally, we emphasize that the market price revaluations triggered by climate change are likely to be amplified by financial markets.

2.1 CLIMATE-RELATED COSTS AND ASSET PAYOFFS

The market price of a financial asset is largely determined by its future payoffs – i.e. its future income flows. For equity instruments, payoffs are equivalent to the cash flows generated by the firm issuing the equity. For debt instruments, they are the interests paid by the borrower, as well as the final repayment of the principal. If the issuer of equity falls into bankruptcy or a debt instrument defaults, the payoffs are, for equity instruments, the liquidation value of the assets owned by the issuer, and, for debt instruments, the value of the assets posted as collateral by the issuer.

Climate-related costs are not different from any other financial costs: they decrease the income flow of the issuer of a financial instrument. This has two consequences: first, they impact the payoffs of equity instruments, by reducing the cash flows generated by the issuer. Second, they can impair the financial soundness of an issuer, which can trigger its default. Moreover, climate-related costs also impact payoffs by reducing the liquidation value of the assets owned by the issuer, in the case of equity instruments, and by decreasing the value of the assets posted as collateral by the issuer, in the case of debt instruments.

In this section, we describe in more detail the concrete channels by which climate-related costs affect the income flow of equity and debt instrument's issuers, as well as the value of the assets that they own.

Physical costs

Physical costs correspond to the economic and financial losses caused by climate-related hazards. Such hazards are divided into two categories: acute hazards and chronic hazards. Climate-related hazards are considered acute when they arise from extreme climate events such as droughts, floods and storms; they are chronic when they arise from progressive shifts in climate patterns such as increasing temperatures, sea-level rise and changes in precipitation. Costs from acute and chronic hazards comprise both their direct impacts (like e.g. damages to property or disruptions of firms' operations) and their indirect impacts (like e.g. disruptions in the supply chain or lower aggregate demand from affected markets).

Physical costs can negatively impact on asset payoffs through several channels such as reduced revenue from decreased production capacity (e.g. due to supply chain interruptions and worker absenteeism) and lower sales (e.g. due to demand shocks and transport difficulties), as well as increased operating costs (e.g. due to the need to source inputs from alternative more expensive supplies) and increased capital costs (e.g. due to damage to facilities). Physical costs can also reduce the value of issuers' assets both through direct damages e.g. to houses and factories during extreme weather events, but also through write-offs of assets situated in high-risk locations.

Transition costs

Transition costs can be defined as the costs of economic dislocation and financial losses associated with the process of adjusting toward a low-carbon economy. Three sources of transition costs are usually considered as relevant for the financial sector: changes in policy (e.g. higher carbon prices or limits on carbon emissions), changes in technology (e.g. low-carbon technologies becoming more competitive than carbon-intensive ones) and changes in market preferences (e.g. households switching toward greener consumption due to environmental concerns). All three types of change will require financial efforts for firms to adapt their business models to new economic conditions.

At the same time, not all firms will be equally impacted; winners and losers will emerge both at the sectoral and at the firm level. The availability of low-carbon alternatives to a sector and the preparedness of individual firms within a sector are key factors to consider in that context.

Transition costs can affect payoffs in several ways, including, for example, research and development expenditures in new and alternative technologies, costs to adopt and deploy new practices and processes, reduced demand for carbon-intensive products and services, as well as increased production costs due to changing input prices (e.g. for energy and water) and output requirements (e.g. for carbon emissions and waste treatment).

The transition to a low-carbon economy can also significantly affect the value of equity and debt issuers' assets: potential re-pricing of stranded fossil fuel assets is a case in point. Changes in real estate valuation due e.g. to stricter energy efficiency standards provide further illustration.

2.2 EXPECTATIONS ABOUT CLIMATE-RELATED COSTS

When the payoffs of an asset are not known in advance, the investors must rely on their forecasts to assess them and value financial assets. Expectations about future payoffs thus play a pivotal role in determining the market price of financial assets. Expected cash-flows, expected probabilities of default and expected values of liquidated assets and of collateral underpin all financial asset prices. On financial markets, asset price movements are thus highly dependent on the evolution of investors' expectations. A revision of these expectations can lead to sharp price movements. The asset price drop that happens in these cases constitutes a financial risk for investors.

We can distinguish two types of expectations revisions: a change in expectations that result from exogeneous events or an endogenous change in expectations. We describe these two different types in the case of climate change in the subsections below.

Climate-related shocks

In efficient financial markets, asset prices reflect market participants' forecasts of future cash-flows. Climate-related costs are part of that. The occurrence of an unexpected climate event might lead investors to update and revise their expectations about future climate costs and consequently about future payoffs. This translates into a change in asset price.

Acute climate hazards, like for example a flood, a storm or a drought, are very likely to trigger such asset price movements. A firm using agricultural products in its production might, for example, see the costs of its inputs significantly increase after a drought. If this firm is not able to pass these higher costs to its customers through higher prices, such an event will lower its profits over several quarters. If the drought is unexpected, then financial analysts will revise down their cash flow forecasts of this firm, and the price of its equity will fall accordingly.

The realization of transition risks can have similar effects. The introduction of policy measures such as a carbon tax by a country, for example, will impact the cash flows of local firms using carbon-intensive inputs. Financial analysts will integrate this fact in their payoffs forecasts when it becomes clear that the government will introduce such a policy and revalue assets accordingly. A technological breakthrough is another case of transition risk realization. New technologies to produce renewable energy, for example, can substantially modify the cost that firms within a sector are facing. As renewable energy becomes less costly, the firms using it as input will see their production costs decrease and their profits relatively increase compared to other firms. This will translate into a change in the relative asset prices between these firms.

Physical and transition risks may also lead investors to revise their assessment of uncertainty around future payoffs. If this uncertainty increases, investors will ask for a larger risk premium. This also translates into a fall in asset prices.

Note that a climate-related shock can potentially trigger a significant and rapid change in asset prices. Indeed, when such a shock happens, investors revise their expectation for the entire stream of future payoffs, incorporating all the costs that this firm will face in the future. Changes in costs that occur over relatively long periods of time are immediately integrated and cumulated in investors' expectations. A sharp drop in asset prices triggered by physical or policy events could amount to a 'climate Minsky moment' a scenario in which markets may be destabilized by the magnitude of losses. (Carney 2018).

Endogenous expectation revisions

Investors might also revise down their expectations about future payoffs endogenously. This is the case, e.g., when they switch to new forecasting models, revise the parameters of their current models or rely on newly available data to calibrate them. The introduction of new sources of costs into a forecasting model is a case in point for such endogenous expectation revision. This case is particularly relevant for climate-related costs. Indeed, for long these costs have been ignored or understated by financial analysts. Standard financial forecasting models were simply not integrating them. The situation is changing as the awareness of climate-related costs grows in the society. Models that integrate climate-related costs in asset valuation are now available (see, e.g., Monnin 2018) and an increasing number of investors are starting to use them.

A key question for financial risk is whether climate-related risks are sufficiently reflected in current financial markets. If they are not, then there is a risk that investors would significantly revise down their payoffs expectations once they start integrating them in their forecast. This could trigger a large downward revaluation of asset prices and thus constitute are risk for the financial sector.

2.3 AMPLIFICATION MECHANISMS ON FINANCIAL MARKETS

As described in the previous section, a revision of investors' expectation about climate-related costs can potentially lead to a downfall in asset prices. Such downward movements can then be exacerbated by the structure of financial markets itself and the way they are currently functioning. There are several channels by which an asset price downfall can be amplified (herding behavior, speculation, financial frictions, etc.). In this section, we highlight two of these mechanisms that we consider as particularly relevant in the case of climate risks.

Considering amplification mechanisms on financial markets is important because even if the direct financial risks posed by climate change might seem manageable at first sight, the asset price revaluations that they can trigger can be much larger than the initial shock. The last financial crisis illustrates this well: apparently small initial losses on the U.S. subprime mortgage market generated effects that threatened the stability of the global financial system.

Network effects

In the case of climate-related costs, an important distinction must be made between direct and indirect effects, both at the economic and the financial level. At the economic level, initial losses due to climate-related events in one sector percolate in the entire economy. Firms are not only affected by the consequences of climate change on their own activities but also by its effects on their supply chains or on their customers. Cahen-Fourot et al. (2019), for example, show that a cap on fossil fuel production would strand assets in the mining sector, but also trigger waves of asset stranding in other sectors – like, e.g., electricity and gas, coke and refined petroleum products, basic metals and transportation – through the input-output structure of the economy.

At the financial level, financial institutions that are exposed to climate risky assets will directly be impacted by a decrease in the price of these assets. But financial institutions that are not directly exposed to them might also suffer losses though their exposure to other financial institutions. Battiston et al. (2017), for example, show that the indirect exposure of European banks to climate-policy-relevant sectors is as large as their direct exposure.

Balance sheet effects

Losses in asset value can also translate into a larger decline in asset prices through balance sheet readjustments and fire-sales (see, e.g., Krishnamurthy 2010 or Shleifer and Vishny 2011). In such a case, a decline in the price of some assets deteriorates the balance sheet of investors. This might cause them to liquidate other assets, which lowers their prices and deteriorates balance sheets further. Although we are not aware the phenomenon has been considered in the literature with regards to climate related risks, such a vicious cycle induced by sell-offs may amplify the losses due to a climate event and affect assets and institutions that were not initially exposed to the shock, as well as trigger financial losses that are, overall, far larger than the direct losses due to climate risks.

3 Climate-related costs and asset prices: the evidence so far

While climate change is already influencing the economy, most of its financial effects are still ahead of us. Nonetheless, initial empirical evidence on its impact on asset prices is already starting to emerge. In this chapter, we point to economic effects, which are already empirically perceptible and relevant for asset prices: the impact of physical and transition costs on firms' profits and stock returns; and on borrowers' financial soundness. We focus our review on economy-wide studies.

3.1 Impact on firms' cash flows and stock returns

There is empirical evidence that physical and transition costs already impact on firms' cash flows, which is a key determinant of their stock performance. The next subsections present the empirical evidence of these impact on both cash flows and stock returns.

Physical costs

Droughts are a case in point for the impact of climate-related physical costs that have already reduced firms' cash flows. Hong et al. (2019) use a sample of weather data from 31 countries in the period 1985 to 2014 to show that dryer weather conditions are associated with lower profitability in the food industry. Higher temperatures are a further case in point. Addoum et al. (2019) and Hugon and Law (2019) show that, in the U.S., extremely hot summer temperatures negatively impact firms' earnings in some specific sectors. Addoum et al. (2019) find that profits are affected mainly through the consumer demand and labor productivity channels, while the crop yield channel is not an important determinant. Both studies also highlight that certain sectors or individual firms are benefiting from extreme temperature conditions, like warm autumns.

Kruttli et al. (2019) show that hurricanes, which are becoming more intense due to changes in the climate, impact stock prices in the US. They study the evolution of stock returns after hurricanes in the U.S. from 2002 to 2017 and find that within the 120 trading days after the landfall of hurricanes, the stock returns for firms operating in disaster regions are significantly lower than the returns of other firms.

Bansal et al. (2016) and Balvers et al. (2017) finds that stock returns are impacted by temperature shocks. Both studies analyze the U.S. stock market over a very long sample – 62 years for the former and 80 years for the latter. Bansal et al. (2016) also find similar evidence in a sample covering 39 countries over 42 years.

Transition costs

Evidence on transition costs are scarce as the transition to a low-carbon economy is yet to happen. Bernardini, et al. (2019) however provide some insights on how such a transition can impact firms' profits within a specific sector. For that they study the case of European electric utilities and show that, following the progressive introduction of economic incentives by the European Union to stimulate investment in renewable energy – i.e. a policy shock – the profit of electric utilities companies using non-renewable energy as input fell sharply whereas it stayed constant for companies using renewable energy as input. The negative impact on profits is transmitted to shareholders via lower stock prices.

3.2 IMPACT ON BORROWERS' FINANCIAL SOUNDNESS

Climate-related costs impose a burden on borrowers, which can lower their ability to service their debt. Some early evidence of this impact is already available for both physical and transition costs.

Physical costs

Physical damages from extreme weather events associated with climate change already affect the ability of debtors to service their loans. Noth and Schüwer (2018) study the impact of weather-related events on the performance of about 6’000 banks in the U.S. over a period from 1994 to 2012. They find that banks operating in regions hit by weather-related disasters observe higher non-performing loans and higher foreclosure ratios than other banks during the two years following an event. This significantly increases the failure probabilities of these banks. This effect holds when controlling for bank characteristics that are typically associated with bank failures, such as bank equity ratios or non-performing assets ratios. Klomp (2014) finds similar results for a sample off banks in 160 countries over the period from 1997 to 2010 that weather-related events impair the financial soundness of debtors.

Transition costs

Transition costs also impacts borrowers’ financial soundness. The measures taken by Chinese authorities to foster the transition to a low-carbon economy provide a useful case-study to highlight the impact of policy-triggered transition risks on debt instruments. Huang et al. (2019), for example, show that after the implementation of the Clean Air Action launched by the Chinese government in 2013, default rates of high-polluting firms rose by around 50%. In the same context, Cui et al. (2018) highlight that Chinese banks with a higher green credit ratio – i.e. banks that are less exposed to loans to polluting firms – experience lower non-performing loans.

4 Future Climate-related costs and asset prices: what lies in front of us?

In this chapter, we review the main estimates available in the literature for the *future* impact of physical and transition costs on financial assets. We first discuss the key initial choices that must be made in choosing the estimation methodology, we then look at the different methodological options available in each steps of the empirical estimations, and finally proceed to present and discuss the available estimates.

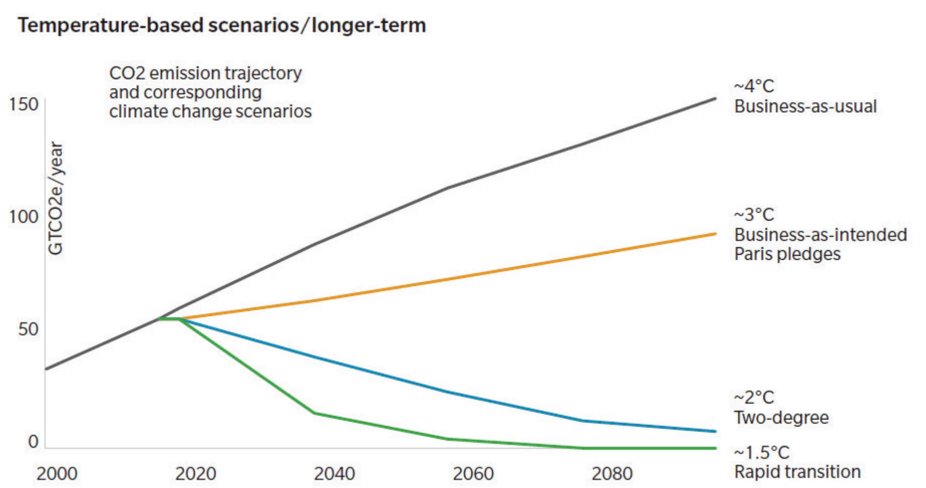
4.1 Key choices for an estimation methodology

Before estimating the future impact of physical and transition costs on financial asset prices, two important choices must be made: 1) which climate change scenarios will be used and 2) which type of scenarios do we want to analyze – long-term scenarios or stress-test scenarios?

Climate change scenarios

A necessary step in the process of investigating the future financial impact of climate-related factors is to develop assumptions on what the future might look like. These visions of the future take the form of scenarios considered both possible and relevant. In the field we are reviewing, and following the tradition of Integrated Assessment Modelling, a critical variable defining scenarios is the long-term increase in global temperatures with respect to pre-industrial averages. Common scenarios, especially in the studies focusing on transition risks, are the ones imposing a limit of 1.5°C and 2°C to temperature increase, as stated in the Paris Agreement (UNFCCC 2016). Other commonly used scenarios are those defined by policy commitments, such as the Nationally Defined Contributions (NDCs), and those which assume no transition. Figure 1 illustrates the four most common types of scenarios.

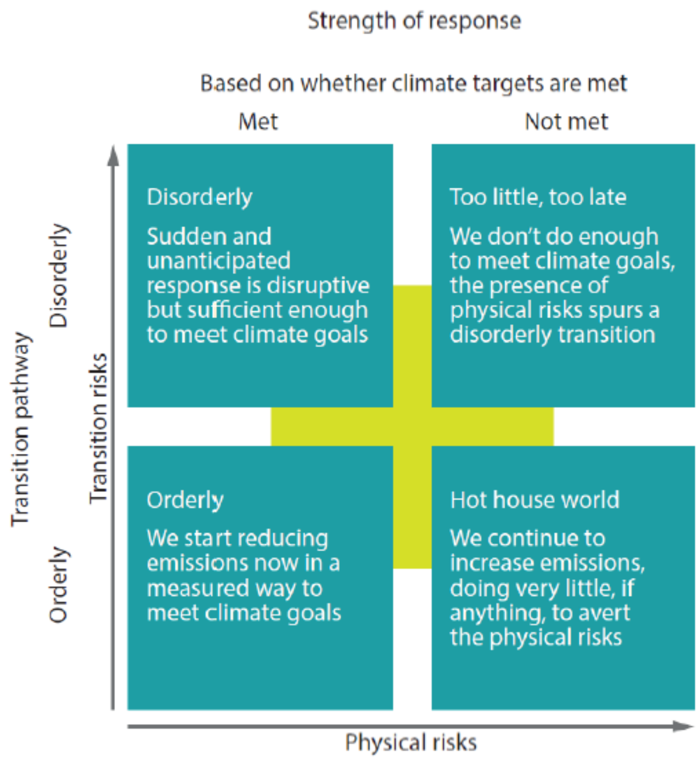
FIGURE 1: COMMON CLIMATE TRANSITION SCENARIOS



Source: Colas et al. (2019)

In addition, considerations around the shape of the transition have become increasingly important, as a specific target (e.g. 2°C) could be obtained through both a gradual non-disruptive transformation and an abrupt transition with systemic disruptions. The NGFS, for example, recommends using four different scenarios organized 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 2019b, p. 30). This classification generates four types of scenarios (see Figure 2): 1) an orderly transition that achieves climate goals, 2) a disorderly transition that achieves climate goals, 3) a disorderly transition that happens too late to meet the climate goals ("too little, too late") and 4) a business-as-usual scenario with no disorderly transition but in which climate goals are not met ("hot house world").

FIGURE 2: NGFS HIGH-LEVEL FRAMEWORK FOR SCENARIO ANALYSIS



Source: NGFS (2019b)

The UK Prudential Regulatory Authority (PRA) has defined three stress test scenarios for its insurance sector (PRA 2019): i) a rapid policy action set to hit in 2022, achieving the 2°C goal through a disorderly process (a 'climate Minsky moment'); ii) an orderly transition, putting the global economy on a path to reach carbon neutrality by 2050 and keeping temperature increases well below 2°C and iii) the absence of all transition efforts. Some other studies also distinguish between an immediate and a delayed transition policy action, with the latter being more likely to create socioeconomic disruptions, as well as stronger climate impacts. HSBC (2019), for instance, distinguishes between a 2020 and a 2030 Policy Action scenario.

The choice of the specific scenarios to investigate depends on the scope of the research. For instance, studies focusing on transition risks might only look at 2°C, possibly distinguishing between different policy implementation timing or different technological development trajectories. On the other hand, studies focusing on physical impacts might limit their analysis only to emission pathways creating an increase of temperatures of 4°C or beyond. Studies can also include both transition and physical risks, typically involving a trade-off between the two (see Figure 3). Mercer (2019) and UNEP FI (2019) are examples of studies combining both physical and transition risks.

FIGURE 3: CLIMATE SCENARIOS AND RISK IMPLICATIONS

	Green scenario			Brown scenario
Scenario	Rapid Transition	Two-degree	Business-as-intended	Business-as-usual
Corrective transition response	Very strong	Strong	Substantial	Limited
Change in temperature vs. pre-industrial era (2100)	1.5°C	2°C	3°C	4°C

← MORE TRANSITION RISK

- Controlled yet aggressive change
- Short-term impact but reduced long-term impact
- Lowest economic damage

MORE PHYSICAL RISK →

- Accelerating changes in earth system impacts
- Impacts continue to increase over time
- Economic damages increase

Source: Colas et al. (2019)

Long-term studies vs. stress tests

Studies looking at the financial impacts of climate-related risks can be distinguished depending on whether they focus on long-term scenarios or on shock scenarios. Studies adopting a long-term perspective typically analyze the effects of different emission pathways and related temperature targets on macro- or company-level variables, with the aim of understanding whether certain portfolios would offer higher or lower average returns over the next 15, 30 or 100 years. The development of carbon-reducing technologies and the introduction of carbon prices is typically gradual and the results of the imposed emission/temperature targets, as determined by some macroeconomic and climate models. This is the case, among others, in Mercer (2019), UNEP FI (2019), HSBC (2019) and Dietz et al. (2016).

A different approach consists in imposing certain climate- or transition-related shocks to the system to see how financial variables would react in the short-term (usually one year, or slightly more). This approach is like the stress testing exercises routinely adopted to evaluate the solidity of financial institutions to tail risk (i.e. in the case of unlikely but plausible events), and consistent with the methodology typical of DSGE macroeconomic models. For instance, Vermeulen et al. (2018, 2019) look at four distinct transition scenarios characterized by a policy shock (the introduction of a global carbon price of USD 100 per ton of CO_2 emissions) or a technology shock (a doubling of the share of renewable energy in the energy mix in the coming five years), as well as both or none of the measures. CISL (2015) studies instead how different forward-looking 'market sentiments', i.e. expectations of financial markets about future transition patterns, affect current macroeconomic and financial variables. In other cases, stress test exercises directly impose specific financial impacts. Battiston et al. (2017) propose two different approaches to their stress test: First, they assume a 100% devaluation of the financial assets in the fossil industry (and successively in other sectors, namely utilities, energy-intensive industry, housing and transport) to estimate upper-bound losses to financial institutions. In a second test, they calculate shock distributions to the market share of three sub-sectors (fossil-fuels in the primary energy market, fossil-fuels in the secondary energy market, and renewables in the secondary energy market) and assume the changes in market shares to correspond to changes in equity before estimating banks' losses. PRA (2019) details specific impacts on the financial assets of different industries, building on the available evidence in the literature.

4.2 OPTIONS WITHIN THE DIFFERENT ESTIMATION STEPS

Once the basic choices about the scenario to study and the type of studies – long-term vs. stress tests – have been made, several specific methodological options are possible to estimate physical and transition costs. We present these options below along the different steps that characterize most methodologies (see Monnin 2018).

Economic impacts

To evaluate the impact of different scenarios on financial assets, one first needs to understand what the impact of these scenarios would be on economic variables. Broadly speaking, two main approaches are possible at this stage.

First, a 'top-down' approach can be adopted, 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. These economic estimates are then translated into financial variables using additional modelling and valuation techniques (see next section). Mercer (2019), for instance, uses a macroeconometric model (E3ME) to obtain the sectoral GDP impacts of their scenarios of interest. 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. Vermeulen et al. (2018, 2019) use a macroeconometric model (NiGEM) to derive the impacts of their scenarios on both macroeconomic variables (GDP, inflation, etc.) and global stock prices. It then diversifies the impacts across industries by calculating their 'transition vulnerability factors' according to their level of embodied carbon emissions.

Second, one can use instead a 'bottom-up' approach, focusing directly on the company or asset 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 modelling structures are likely to have a strong impact on the results. Most models used 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 macroeconometric functions and 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 cost.

As discussed in UNEP FI (2019), the scope of the analysis, can differ quite dramatically, including a combination of some or all of the following elements: i) direct impacts on firms/sectors (in the form of direct climate-induced disruption of operations or policies imposing additional carbon costs); ii) impacts on the supply chain (in the form of climate-induced disruptions to suppliers or trade routes, or higher costs due to carbon prices being passed down the value chain from suppliers); iii) impacts on downstream markets (in the form of changes in the demand for specific goods and services); impacts on the macroeconomic environment (in the form of changes of aggregate economic activity, inflation or exchange rate).

In addition to the potential transition costs, some studies include the positive benefits of technological opportunities arising from the development of new industries (HSBC, 2019; UNEP FI, 2019). It should be noted that all studies using companies' portfolios take very specific circumstances as their base and so can only deliver partial analysis, unlikely to be representative of the reaction of the whole financial sector.

Financial impacts

The economic impacts, however calculated, need to be translated into financial impacts. Methodologies in this step 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. 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 valueadded. In addition, they employ their own survey data to estimate the corporate loan exposures of the largest Dutch banks.

The approaches to evaluating the financial impact typically involve only first-round effects, i.e. they evaluate the sensitivity of firms/assets to certain scenario-induced economic trends, without considering further dynamic interactions. Battiston et al. (2017), on the other hand, introduce in their analysis a second-round effect, determined by exposure of financial institutions among themselves. These second-round effects are in some cases larger than the direct effects and might trigger wider systemic implications.

Exposure

Once the impact of future scenarios on different sectors/firms/assets has been evaluated, one can proceed to aggregate these impacts at a wider level, namely into portfolio holdings. In the literature, these can take the form of actual portfolios or just representative ones. UNEP FI (2019) considers two representative asset holdings: a 'market portfolio' composed of 30,000 companies equally weighted and a 'top 1,200 companies portfolio' closely mimicking the MSCI World Index. HSBC (2019) uses the MSCI ACWI (All Countries World Index). Mercer (2019) uses a representative growth portfolio made of a large variety of asset classes. In a similar fashion, CISL (2015) analyses four distinct portfolios representing the typical investment strategies of insurance companies ('High Fixed Income') and pension funds ('Aggressive', 'Balanced' and 'Conservative'). These include sovereign bonds, corporate bonds, and equities from both developed and emerging economies, as well as other types of asset classes.

Battiston et al. (2017) take instead the actual financial exposures of specific financial institutions. They analyze the exposure of about 80'000 disclosed equity holdings in the US and the EU to transition risk, using data from the Bureau van Dijk Orbis database. They also analyze bank loan portfolios, although a large part of their sectoral composition – and thus of the risk they are exposed to – must be inferred for a lack of data. Vermeulen et al. (2018, 2019) construct a database of the majority of the equity and bond exposures of Dutch financial institutions (that includes banks, pension funds and insurance companies), making use of the national bank's Securities Holdings Statistics. The method of looking at the financial exposure of investors to sectors/companies/assets likely to be affected by physical or transition risks has been adopted by several other works (see for instance: ESRB, 2016 and Giuzio et al., 2019), although without an explicit modulization of how the price or returns of financial assets would be affected.

Measure of impact

The results of the procedures discussed above can be presented in several forms, using several measures. Mercer (2019) uses the annualized value of the impact of climate scenarios on the portfolio return. UNEP FI (2019), as well as Dietz et al. (2016), Spedding et al. (2013), and – for their distributed shocks model – Battiston et al. (2017) calculate a 'Climate Value at Risk' (VaR), which is the present value of the costs or profits caused by each considered scenario, divided by the current market value of the company. Climate-related costs and profits reflect physical risks, transition risks and technological opportunities. CISL (2015) report the 5-year performance of the portfolios they have analyzed, for three different scenarios.

Another way of showcasing the scenario performance of asset classes or portfolios is to report the change in the net present value (NPV) of their profits (HSBC, 2019) or the change in stocks' share prices (Ralite and Thomä, 2019) in comparison to those in a baseline scenario. Vermeulen et al. (2018, 2019) and Battiston et al. (2017), in the case of their upper-bound estimates, report the asset loss feared in the respective scenarios. The latter show banks' equity losses as a percentage of total equity holdings. Vermeulen et al. (2018, 2019) report losses relative to the total assets of each sector ("total stressed assets"). In their study, they disaggregate reported equity changes into three sources of losses: changes in the risk-free interest rate; exposure to carbon intensive industries; and exposure to other industries.

4.3 AVAILABLE ESTIMATES

Table 1 summarizes the results of the main studies looking at the financial impact of climate-related risks. The next subsections present our analysis of these results.

Long-term studies

The long-term studies currently available give a homogeneous picture of the impact of physical and transition risks on financial assets: the impact is marginal in the long-term and it does not differ substantially between transition scenarios. These results must however be interpreted with a pinch of salt: the models underlying them are usually long-term macro-models in which financial markets play a smoothing role – i.e. investors do integrate climate change into their expectations and they constantly and progressively reallocate their asset portfolios. Such models do not give a good picture of what can happen on financial markets between now and the forecast horizon. For example, they are not conceived to simulate disorderly and abrupt transition paths, or to estimate the impact of the drastic changes in expectations, which could happen if investors currently do not integrate future climate costs, but suddenly revise their forecasts about them.

TABLE 1: ESTIMATIONS OF CLIMATE COSTS ON ASSET PRICES

Authors (Model used)	Type of Risk (Type of analysis)	Portfolio/ Exposure	Measure	Asset class	Time horizon	Scenarios		
						2°C	3°C	4°C
Mercer, 2019 (E3ME)	**Physical & Transition** (Long-term)	Represen-tative growth portfolio	Impact of scenario on portfolio return (year average)	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**
UNEP FI, 2019 (REMIND)	**Physical & Transition** (Long-term)	Market Portfolio of 30,000 firms	Company Climate VaR*	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 relative to BAU	Equity	2050	-2%		
						2°C	**2.5°C**	
Dietz et al., 2016 (DICE)	**Physical & Transition** (Long-term)	Global stock of financial assets	Climate VaR (mean)	Equity and bonds	2100	-1,18%	-1,77%	
						2°C	**No action**	
CISL. 2015 (GEM)	**Transition** (Stress test)	High fixed income	Portfolio performance	Equity, bonds, and other assets	5 years	-3%	-4%	
		Conservative				9%	-26%	
		Balanced				17%	-30%	
		Aggressive				25%	-45%	

*refers to the ratio between present-value climate-related costs/profits and current market value.

Table 1 continued: Estimations of climate costs on asset prices

Authors (Model used)	Type of Risk (Type of analysis)	Portfolio/ Exposure	Measure	Asset class	Time horizon	Scenarios			
						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%
		…Insurers				-8,12%	-2,08%	-10,83%	-2,68%
		…pension funds				-6,73%	-2,99%	-10,16%	-6,65%
						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, loans (first round)	shock occurs in 2017	2.55%	3.79%	13.18%	15.09%
				Ditto (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**
				Ditto (first round)		0.26%	0.41%	0.19%	0.06%
				Ditto (first and second round)		0.63%	0.96%	0.47%	0.13%

*reported with standard deviations

Stress test studies

Stress tests give a better picture of the risks that financial asset could be facing due to climate change in the short to medium term. Stress test scenarios are relatively severe but still plausible. Vermeulen et al. (2018, 2019) provide, in our view, the most sophisticated estimation of transition risks currently available. They show that, in the case of a transition triggered by both a policy and a technological shock, the portfolios held by Dutch insurers and pension funds, which include equities, bonds and loan instruments, could lose up to 10% of their value within 5 years. Note that his estimation does not consider neither possible second-round effects on financial markets, nor sharp expectations revisions by investors. The Value-at-Risk methodologies used by Dietz et al. (2016) also allows us to get an idea of stress test scenarios. They estimate that, with one percent probability, equity and bond market together could lose 17% of their value within 80 years if no transition happens and about 9% if the transition materializes.

The results presented above, together with others, can then be used to inform the definition of 'climate stress tests' that financial regulators can ask financial institutions to run in order to test their solidity to climate-related financial risks. One example is the new climate stress that the UK Prudential Regulatory Authority has asked insurance companies to run. The details of the stress test are shown in Table 2, where the first scenario describes a rapid and disorderly policy action with shock parameters set to hit in 2022; the second scenario describes an orderly transition, putting the global economy on a path to reach carbon neutrality in 2050; and the third scenario assumes no transition and a temperature increase of 4°C by 2100. Although these scenarios include different timeframes, the stress tests considered by the PRA simulate an instantaneous shock on the investment and liabilities. Note that the assumptions that the PRA uses in these scenarios have been put together for exploratory purposes and to ensure that firms complete the return on the same basis. The PRA underlines that "*this set of assumptions are developed for illustrative purposes only.*" (PRA 2019, p. 32). The Bank of England will run a more comprehensive stress test of the UK financial system's resilience to physical and transition risks in 2021 (see Bank of England 2019). This stress test aims at developing scenarios that are consistent with a range of possible climate pathways and integrate these pathways with macroeconomics and financial models. This exercise should provide parameters that are both more analytically grounded and coherent.

TABLE 2: PRA ILLUSTRATIVE STRESS TEST SCENARIOS

		Transition risks			Physical risks		
		Rapid and disorderly transition	Orderly transition	No Transition	Rapid and disorderly transition	Orderly transition	No Transition
Fuel extraction	Coal	-45%	-40%			-5%	-20%
	Oil	-42%	-38%				
	Gas	-25%	-15%				
Power generation	Coal	-65%	-55%			-5%	-20%
	Oil	-35%	-30%				
	Gas	-20%	-15%				
	Renewables (inc. nuclear)	10%	20%				
Transport	Automotive non EV	-30%	-10%			-5%	-10%
	Automotive EV	15%	50%				
	Marine (inc. ports)	-15%	-10%				
	Aviation (inc. airports)	-21%	-18%				
Energy intensive industries	Manufacturing heaviliy reliant on fossil fuels	-35%	-25%		-5%	-10%	-20%
	Other manufacturing	-15%	-10%		-5%	-10%	-20%
Agriculture and Food Security	Agriculture and food security sector	-65%	-50%		-5%	-10%	-20%
	Transporting/trading/supplying food	-15%	-10%			-5%	-10%
Real Estate Assets	Global Average	-10%				-15%	-30%
	North America	-10%				-15%	-30%
	Europe	-5%				-8%	-15%
	Asia and Pacific	-20%				-30%	-60%
Water utilities					-5%	-10%	-20%
Other sectors						-2%	-5%

Expectation revision and second round effects

The estimations mentioned above rely on the hypotheses that investors fully integrate climate change costs in their expectation for asset payoffs and that financial market will operate smoothly without amplifying asset price movements, through e.g. second round-effects (see Section 2.4). However, some studies do try to estimate the impact of sharp expectation revisions and of second-round effects. Their results show a significant impact on financial asset prices.

CISL (2015) estimate the impact of a sudden revision of investors' expectations about the impact of climate change on asset payoffs. Such a situation could happen when investors do not fully integrate climate costs in their forecasts, which seems to be currently the case (see Section 5) and then suddenly correct this omission. CISL estimate that such a change in investors' expectations could lead to a 40% correction within one year in the value of a balanced portfolio if investors integrate the consequences of a no transition scenario. This figure decreases to 10% in the case of a transition to a 2°C world.

Second-round effects seem also to be an important amplifying factor of climate change impact on financial markets. Battiston et al. (2017) assess how an initial transition shock would propagate in the banking sector through the cross-exposures of banks with each other. They find that such second-round effects could more than double the impact of the initial shock.

5 Do financial markets adequately price-in climate risks?

Climate-related physical and transition costs do already have an impact on financial asset prices – as documented in Chapter 3. To what extent future climate-related costs – – as outlined in Chapter 4 will result in corrections on financial markets depends on the degree to which they are already reflected in current asset prices. This chapter reviews the available empirical evidence that allows to answer this question.

Empirically, there are several ways to shed light on the question of whether climate-related financial risks are already priced-in in current markets. First, in efficient markets, if investors already integrate future climate costs in their valuations, then current information about such costs cannot be used to forecast future asset returns. Second, if analysts correctly understand the impact of climate events on asset payoffs, they should revise their payoff forecasts once such an event materializes. Third, if investors price in climate risks, then assets exposed to these risks should trade with a higher risk premium. In the next subsections, we review the empirical evidence corroborating or contradicting these tests.

5.1 PREDICTABILITY OF ASSET RETURNS

In efficient markets, investors use all available information to best forecast future payoffs and then price assets accordingly. In such a case, no information can be used to forecast asset returns. In other terms, if some piece of information is found to *ex ante* forecast the return of an asset, then it can be concluded that investors do not use this piece of information to forecast future asset payoffs – i.e. investors overlook this piece of information. In the context of climate-related costs, if information related to climate change is found to forecast future asset returns, that means that the impact of climate change on future payoffs is not adequately used by financial market participants – i.e. the impact of climate change is not priced-in.

There is some evidence that climate-related information can be used to forecast future asset returns. Hong et al. (2019), for example, find that, for a sample of 31 countries from 1985 to 2014, the trend in droughts in a country forecasts the stock returns for companies in the food industry. They conclude that "this return predictability is consistent with food stock prices underreacting to climate change risks." Kumar et al. (2019) find that firms' sensitivity to temperature anomalies forecast their stock returns. They measure firm's sensitivity by the impact of temperature anomalies in one period on its stock return in the same period and show that this measure is then able to predict firm's future stock returns. They conclude that "these findings are consistent with stock markets underreacting to firms' climate sensitivity."

5.2 FORECAST REVISIONS

Some climate-related events influence firms' profits (see Section 3.1). For example, extreme temperatures negatively impact firms' earnings in some specific sectors (Addoum et al., 2019, and Hugon and Law, 2019). If this impact is well understood by analysts, then the occurrence of such an event will lead them to revise down their earnings expectations for the firms that have been affected.

Addoum et al. (2019) test this hypothesis by looking at changes in analysts' forecasts for earnings before and after the occurrence of 8'584 extreme temperature events in the U.S. These events have been previously identified as relevant for firms' earnings. They find 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. (2015) provide a counterexample of analysts' forecasts revision after receiving news on transition risks. For that, they analyse the stock market reaction after the publication of a 2009 paper in *Nature*, which concluded that only a fraction of the world's existing oil, gas, and coal reserves could be emitted if global warming by 2050 were not to exceed 2 °C above pre-industrial levels. Griffin et al. find that this article prompted an average and permanent stock price drop of 1.5% to 2% for the largest U.S. oil and gas firms within three trading days. This result hints that investors revised their payoff forecast downward after becoming aware of possible stranded assets in the oil and gas sector. The small magnitude of the reaction contrasts however with the predictions of some analysts and commentators of a substantial decline in the shareholder value of fossil fuel companies from a carbon bubble.

5.3 CLIMATE RISK PREMIUM

Basic financial theory states that if an asset is riskier than another, then investors must be compensated with a premium to hold it. This also applies to climate risks: if an asset is exposed to higher physical and transition risks than others, then it should deliver higher returns to investors to compensate for their risk-taking. We survey evidence of such a risk premium in equities and bank loans.

Equities

Görgen et al. (2019) and Bernardini et al. (2019) find that stocks that are more exposed to transition risk deliver lower returns than others, which is inconsistent with a risk premium. Görgen et al. (2019) use a sample of about 1’600 globally listed firms over a period ranging from 2010 to 2017 and find that firms, which are more exposed to their measure of transition risk, underperform relative to other firms. Bernardini et al. (2019) focus on European electricity utilities. Their data show that firms, which were hit by a transition shock in the second part of their sample period (2013-2017), did not display higher returns on equity before the shock (2008-2012), which is a sign that the transition shock was not priced in.

Bank loans

If a firm is exposed to higher climate risks than others, then banks should also reflect this fact by charging a higher spread on loans to it. Delis et al. (2019) test this hypothesis in the context of stranded asset risk. For that, they compare the loan rate charged by banks to fossil fuel firms – along their climate policy exposure – to non-fossil fuel firms. They find that before 2015 banks did not price climate policy exposure of fossil fuel firms. After 2015, however, the risk starts to be priced, especially for firms holding more fossil fuel reserves. However, the economic significance of this risk premium is rather small and is very unlikely to match the potential losses from stranded assets.

Huang et al. (2019) find similar results: they show that after the implementation of the Clean Air Action by the Chinese authorities – i.e. after the materialization of a policy shock – Chinese banks increased the loan spread by 5.5% to high-polluting firms. Even if this increase corresponds to a higher risk premium, its size does not match the large increase in default rate observed for polluting firms after the policy shock. In short, both studies indicate that banks have started pricing climate-related risks, but not sufficiently.

6 Conclusions and recommendations

Our review of the literature highlights evidence that climate-related events do already have an impact on the performance of financial assets. Hurricanes and droughts, for example, have a negative impact on both equity and debt instruments – leading in some cases to a significant decrease in the payoffs of equities and increase in the proportion of non-performing loans. As the occurrence of such events is projected to rise substantially with climate change, their impacts on financial assets will also grow.

Forecasting the impact of future physical and transition costs comprises very long-term projections as well as shorter-term assessments. We believe that shorter-term stress tests are the best way to capture the current risks to which investors are exposed. The losses estimated with the stress tests that are available in the literature are economically significant, even with conservative methodologies. We found that expectation revisions and second round effects are likely to substantially increase initial financial losses due to climate-related events.

Whether investors currently adequately price in future physical and transition costs is crucial. The answer to this question conditions the size of potential financial losses. Empirical evidence is limited but we find convincing evidence that points to a lack of awareness about future climate costs by investors and that financial prices do not currently adequately reflect them. This concurs with the conclusion by the NGFS that “there is a strong risk that climate-related financial risks are not fully reflected in asset valuations.” (NGFS 2019a, p. 4)

Against this background, we recommend investors to systematically assess the climate risks in their portfolios with a particular emphasis on the use of stress tests. In the conception of the stress test scenarios, two key dimensions should be included: first, the impact of a swift revision of market participants’ expectations about future physical and transition risks should be assessed, as there are strong signals that financial markets currently do not adequately price in these costs. Furthermore, second-round financial effects should be considered in the models, as they have the potential to significantly amplify initial losses. Financial investors should also be supported by regulatory steps, such as obligatory disclosure by issuers of financial instruments of the climate financial risks, to which their underlying business is exposed. Disclosure initiatives such as the TCFD go in the right direction for that but they might fall short if they are not very widely adopted by issuers and if investors do not use the information that they provide.

Climate financial risk is also a challenge for central banks and financial regulators in charge of micro- and macro-supervisions (Campiglio et al. 2018). Here again, we urge financial authorities to use climate stress tests to assess the exposure of single financial institutions and of the financial system as a whole. When defining standard methodologies for stress tests to be performed by supervised institutions, special attention should be given to the development of relevant scenarios, such as those recently proposed by the NGFS (2019a). As for investors, we again emphasize the importance to integrate potential swift revisions of market expectations and second-round effects in the design of stress tests. When the exposure of financial institutions and of the financial system to climate risks is found to be significant, options are available to regulators to reduce it, like, e.g., systemic capital buffers (see, e.g., D'Orazio et al. 2019).

As emphasized several times in this note, whether climate risks are adequately reflected in current financial asset prices is a fundamental question. The size of future potential losses crucially depends on the answer to this question. Current academic literature offers anecdotal evidence on this matter and outlines pathways for further research on this this issue.

Finally, available empirical evidence on second round effects points to a substantial amplification of initial losses due to climate-related events, highlighting the need to include them into the design of stress tests. The methodologies to do so are in their infancy. Developing them further is critical.

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