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ECB economy-wide climate stress test

Methodology and results

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Abstract

Climate change is one of the greatest challenges facing humankind this century. If left unchecked, it is likely to result in more frequent and severe climatic events, with the potential to cause substantial disruption to our economies, businesses and livelihoods in the coming decades. Yet the associated risks remain poorly understood, as climate shocks differ from the financial shocks observed during previous crises. This paper describes the ECB's economy-wide climate stress test, which has been developed to assess the resilience of non-financial corporates (NFCs) and euro area banks to climate risks, under various assumptions in terms of future climate policies. This stress test comprises three main pillars: (i) climate-specific scenarios to project climate and macroeconomic conditions over the next 30 years; (ii) a comprehensive dataset that combines climate and financial information for millions of companies worldwide and approximately 1,600 consolidated euro area banks; (iii) a novel set of climate-specific models to capture the direct and indirect transmission channels of climate risk drivers for firms and banks.

The results show that there are clear benefits to acting early: the short-term costs of the transition pale in comparison to the costs of unfettered climate change in the medium to long term. Additionally, the early adoption of policies to drive the transition to a zero-carbon economy also brings benefits in terms of investing in and rolling out more efficient technologies. The results also show that, although the effects of climate risk would increase moderately, on average, until 2050 if climate change is not mitigated, they would be concentrated in certain geographical areas and sectors. When comparing the effects of transition and physical risk, the outcomes indicate that physical risk would be more prominent in the long run, especially if policies to transition towards a greener economy were not introduced. Finally, the results suggest that for corporates and banks most exposed to climate risks, the impact would potentially be very significant, particularly in the absence of further climate mitigating actions. Climate change thus represents a major source of systemic risk, particularly for banks with portfolios concentrated in certain economic sectors and specific geographical areas.

JEL codes: C53, C55, G21, G38, Q54.

Keywords: climate stress-test, transition risk, physical risk, climate scenarios.

Executive summary

Climate change is one of the most prominent challenges the world has to face this century, and governments around the globe have committed to combat it in different ways. The Paris Agreement (2015) represented a milestone in this regard given that it seeks a worldwide response aimed at “keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius”.

Policies aimed at curbing emissions and facilitating the transition to a greener economy may, however, create significant risks for the most carbon-intensive industries. Transition risk refers to the negative impact that the introduction of climate policies to reduce CO2 emissions could have on certain high-emitting firms. For example, industries that rely heavily on non-renewable or highly polluting resources, such as mining or fossil fuel extraction, could face a sharp fall in profits and higher production costs. Another possible driver of climate risk is physical risk, which refers to the economic impact stemming from the expected increase in the frequency and magnitude of natural disasters. Production plants located in areas that are exposed to natural hazards, for example close to rivers or the seashore and therefore prone to flooding, could suffer significant damage should a climate event occur. This damage could interrupt the production process in the short term and potentially lead to business failure in the longer term.

These two categories of climate risks constitute an emerging source of systemic risk and have the potential to destabilise the provision of services by financial institutions and the normal functioning of financial markets, with knock-on effects for the real economy. First, transition risk could undermine the creditworthiness of bank counterparties as well as asset prices, with, potentially, detrimental consequences for bank solvency. Second, as climate change advances, the risk of abrupt financial losses in climate risk-sensitive geographical areas would increase, thereby leading to the erosion of collateral and asset values for a large number of financial institutions.

Over the last few years, some central banks and policy institutions have started to work on the development of stress-testing methodologies or scenario analyses aimed at capturing the impact of climate risks on the financial system and the overall economy. While important steps have already been taken in this area, most of these proposals are still lacking certain elements that are crucial to fully assess the impact of climate risks on the financial system and the real economy.

The main contribution made by this paper is the development of a centralised (top-down) economy-wide climate stress test that assesses the resilience of NFCs and euro area banks to transition and physical risk, applying a range of assumptions in terms of future climate policies. The stress test presented here comprises three main pillars. First, climate-specific scenarios identify future projections of climate and macroeconomic conditions over the next 30 years. Second, a comprehensive dataset combines climate and financial information for millions of companies worldwide, and maps them to banks through granular loan and security holdings. Third, the specific transmission channels of climate risk drivers for firms and banks are captured thanks to a novel set of climate-specific models.

The ECB's economy-wide climate stress test builds on exercises performed previously by other central banks and supervisory authorities along four dimensions. First, it is top down in nature as it relies on data, assumptions and models developed by ECB staff, thereby ensuring full transparency and replicability of the framework, as well as comparability in terms of the impact for banks and the final outcomes. Second, it is a granular exercise that analyses banks' credit and market portfolios at exposure level, thus fully accounting for heterogeneous and firm-specific vulnerabilities to climate risks. Third, the scope of the exercise significantly expands on previous stress tests, as it encompasses 4 million corporates worldwide, as well as 1,600 consolidated banking groups in the euro area. The climate data to be collected to perform such a broad and granular analysis is, to the best of our knowledge, the most comprehensive set of backward and forward-looking climate and financial information available at the central bank level. Finally, the exercise analyses the interactions between transition and physical risk, encompassing both the direct and indirect (through macro scenarios) impact on firms and banks of more severe and frequent natural disasters. This makes it possible to compare the future costs and benefits of climate policy action.

The results of the ECB's economy-wide climate stress test first show that there are clear benefits in acting early. The short-term costs of the transition pale in comparison to the costs of unfettered climate change in the medium to long term. The early adoption of policies to drive the transition to a zero-carbon economy also brings benefits in terms of investing in and rolling out more efficient technologies. The results also show that, although the effects of climate risks would increase moderately, on average, until 2050 if climate change is not mitigated, they are concentrated in certain geographical areas and sectors. Additionally, the results show that if policies to transition towards a greener economy are not introduced, physical risks become increasingly higher over time: they will increase non-linearly, and due to the irreversible nature of climate change such an increase will continue over time. It is thus of foremost importance to transition early on and gradually, to mitigate the costs of both the green transition and the future impact of natural disasters.

The results also show that for corporates and banks most exposed to climate risks, the impact is potentially very significant, especially in the absence of further mitigating policies. If climate risks are not reduced, the costs to companies arising from extreme weather events would rise substantially, and significantly and negatively affect their creditworthiness. Climate change thus represents a major source of systemic risk, particularly for banks with portfolios concentrated in certain economic sectors and, more importantly, in specific geographical areas. Finally, the anticipated impact on banks in terms of losses would mostly be driven by physical risk and would potentially be severe over the next 30 years.

1 Introduction

The Paris Agreement **reached in December 2015 set the ambitious aim of limiting climate change through a global response**, and specifically aimed at "keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius".[1] However, empirical studies suggest that commitments made by governments to date are far from being sufficient. Without further action, Climate Action Tracker (2018) estimates global warming of around 3°C above pre-industrial levels by 2100, while the Intergovernmental Panel on Climate Change (IPCC) estimates that it could exceed 4°C.

Recent studies show that, although challenging, reaching the Paris Agreement targets and limiting global warming is feasible if supported by reforms to cut carbon emissions. A scenario compatible with the Paris Agreement targets would need a substantial decrease in global CO2 emissions, both with respect to current trends as well as compared to the projected CO2 decrease implied by current policies. In particular, several studies argue that global net CO2 emissions should go to zero or become even negative before 2050 in order to meet the Paris Agreement targets.[2] As a consequence, the European Commission proposed a European Green Deal in 2019 calling for "no net emissions of greenhouse gases in 2050" and for a decoupling of economic growth from the resources used.[3]

Transition risk refers to the negative impact that the introduction of climate policies to reduce CO2 emissions could have on certain high-emitting firms. Policies aimed at curbing emissions and facilitating the transition to a greener economy could create significant risks to the most carbon-intensive industries. For example, industries that heavily rely on non-renewable or highly polluting resources, such as mining or fossil fuel extraction, could face a sharp fall in profits and higher production costs.

Climate-related risks also include physical risk, which refers to the economic impact stemming from the expected increase in the frequency and magnitude of natural hazards should policies to mitigate climate change and meet the Paris Agreement targets not be introduced. Production plants located in areas that are exposed to natural hazards, for example close to rivers or the seashore and therefore prone to flooding, could suffer significant damage should a climate event occur. This damage could interrupt the production process in the short term and potentially lead to business failure in the longer term.

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1 See also the United Nations climate change webpage on the Paris Agreement.

2 Similar results and conclusions were also reached by the "In-depth analysis in support of the Commission Communication COM(2018) 773" on the long-term strategy. Similarly, the OECD report (2017) concluded that meeting the targets set in the Paris Agreement requires CO2 emissions to start decreasing if the current trend is to be reversed before 2030.

3 See Proposal on the European Climate Law reflecting the agreement between the European Parliament and Council, Council of the European Union, Brussels, 5 May 2021.

Both transition and physical risks could have a detrimental effect on financial institutions. Direct exposures to affected firms through lending or asset holdings could generate losses if defaults occurred. In addition, there could be exposures to households and firms that are indirectly affected, through supply-chain linkages or from lower demand and higher unemployment as a result of a more generalised economic downturn. Additionally, as climate change advances the risk of abrupt value losses in climate risk-sensitive geographical areas would increase, leading to the erosion of collateral and asset values for a large number of financial institutions. Insurance liabilities are particularly exposed to an increased frequency and severity of climate and weather-related events that damage property or disrupt trade.

While it is common to distinguish between transition risks and physical risks, in truth the two are intertwined. In the absence of further climate policies, businesses face higher costs from increasing physical risk. Yet policies to limit carbon emissions, such as a carbon tax, could increase the costs of raw materials and energy, or require businesses to carry out a costly and large-scale overhaul of their production processes to eliminate the use of carbon. Transition and physical risks are therefore two sides of the same coin: greater policy action might increase the impact of transition risks, but at the same time reduce physical risks in later decades. This relationship is one of the key elements captured and quantified in the ECB’s economy-wide climate stress test.

Since the financial crisis, stress tests have become a vital part of the supervisory and financial stability toolkit to assess the resilience of financial institutions to adverse conditions. In particular, economy-wide stress testing has become a powerful tool to capture the endogenous nature of systemic risk caused by the interplay between all the institutions and markets that interact in the financial system (Anderson, 2016; Anderson et al., 2018; Dees et al., 2017; Henry and Kok, 2013).

There is a growing strand of literature aimed at capturing the impact of climate risks on the financial system and the overall economy through stress tests. Even though important steps have already been taken in this area, most of the existing frameworks are still lacking certain crucial elements that are needed to fully assess the impact of climate risks on the financial system and the real economy. More details on this are provided in Section 2.2.

The main contribution made by this paper is the development of a centralised (top-down) economy-wide climate stress test to assess the resilience of NFCs and euro area banks to transition and physical risks based on a range of assumptions in terms of future climate policies. The ECB’s economy-wide climate stress test comprises three main pillars. First, climate-specific scenarios identify future projections of climate and macroeconomic conditions over the next 30 years. Second, a comprehensive dataset for millions of companies includes climate and financial information, and combines them with granular bank exposures through loan and security holdings. Third, the transmission channels of climate risks for the firms and banking sectors are captured thanks to a novel set of climate-specific models. The framework will also be extended in the future to incorporate additional portfolios and institutional investors (e.g. households and non-banks) and to allow for endogenous bank reactions to deteriorations in economic conditions through changes in their portfolio composition.

The ECB's economy-wide climate stress test builds on similar exercises performed by other central banks and supervisory authorities along four dimensions. First, it is top down in nature as it relies on data, assumptions and models developed by ECB staff, thereby ensuring full transparency and replicability of the framework, as well as comparability in terms of the impact for banks and the final outcomes. Second, it is a granular exercise that analyses banks' credit and market portfolios at exposure level. Third, the scope of the exercise significantly expands on previous stress-tests, as it encompasses 4 million corporates worldwide, as well as 1,600 consolidated banking groups throughout the euro area. The climate data to be collected to perform such a broad and granular analysis is, to the best of our knowledge, the most comprehensive set of backward and forward-looking climate and financial information available at central bank level. Finally, the exercise analyses the interactions between transition and physical risks, accounting for both the direct and indirect (through macro scenarios) impact on firms and banks of more severe and frequent natural disasters. This makes it possible to compare the future costs and benefits of climate policy action.

The results of the ECB's economy-wide climate stress test first show that there are clear benefits in acting early. The short-term costs of the transition pale in comparison to the costs of unfettered climate change in the medium to long term. The early adoption of policies to drive the transition to a zero-carbon economy also brings benefits in terms of investing in and rolling out more efficient technologies. These results underline the crucial and urgent need to transition to a greener economy, not only to ensure that the targets of the Paris Agreement are met, but also to limit the disruption to our economies, businesses and livelihoods in the long run.

The results also show that although the effects of climate risks would increase moderately on average until 2050 if climate change was not mitigated, they would be concentrated in certain geographical areas and sectors. In particular, the outcomes of the analysis show that activities in the mining and electricity and gas sectors would have to bear significant costs to reduce emissions in line with the Paris Agreement targets, with a consequent increase in their probability of default in the short to medium term in the wake of a green transition. At the same time, firms located in geographical areas that are most exposed to physical risk would suffer from a major decline in their creditworthiness if climate change was not mitigated, as a consequence of more severe and frequent natural disasters.

Additionally, if policies to transition towards a greener economy are not introduced, physical risks become increasingly higher over time: they will increase non-linearly, and due to the irreversible nature of climate change such an increase will continue over time. Projections of the probabilities of default for firms and banks over the next 30 years show that, by 2050, the impact would be the greatest under a no-transition scenario because of increasingly higher levels of damage from natural disasters. The impact would be the most severe for companies located in vulnerable geographical areas, and for banks with portfolios that are particularly concentrated in countries that are the most affected by natural disasters.

The results also show that for corporates and banks most at risk the impact would potentially be very significant, especially in the absence of further climate policies. If climate risks are not mitigated, the costs to companies of extreme weather events would rise substantially, and greatly increase their probability of default. The resulting "hot house world" would be particularly challenging for certain regions projected to become markedly more vulnerable to events such as heatwaves and wildfires in the future. Climate change thus represents a major source of systemic risk, particularly for banks with portfolios concentrated in certain economic sectors and, even more importantly, in specific geographical areas.

Finally, the anticipated impact on banks in terms of losses would mostly be driven by physical risk, and this would potentially be severe. Euro area banks would face higher expected losses if climate risks were not mitigated by an orderly transition scenario. Additionally, losses on loans would be the highest for banks located in countries with either low levels of collateral protection or high exposure to physical risk. The results also confirm that if climate change is not mitigated, the consequences of physical risk on banks' losses would increase in the long run in a non-linear fashion. Due to the irreversibility of climate change those losses would only become greater over time.

This paper is organised as follows. Section 2 gives an overview of the methodological framework. Section 3 presents the climate scenarios and their projected impact on the key indicators selected. Section 4 describes the data collection and infrastructure, and sets out certain key indicators for measuring the impact of the current transition and of physical risk on the sample. Section 5 presents the transmission channels and effects of climate risks on NFCs. Section 6 describes how transition and physical risks would transmit to banks. Section 7 outlines the next steps envisaged and possible extensions of the current framework. Section 8 contains the conclusions.

2 The methodological framework

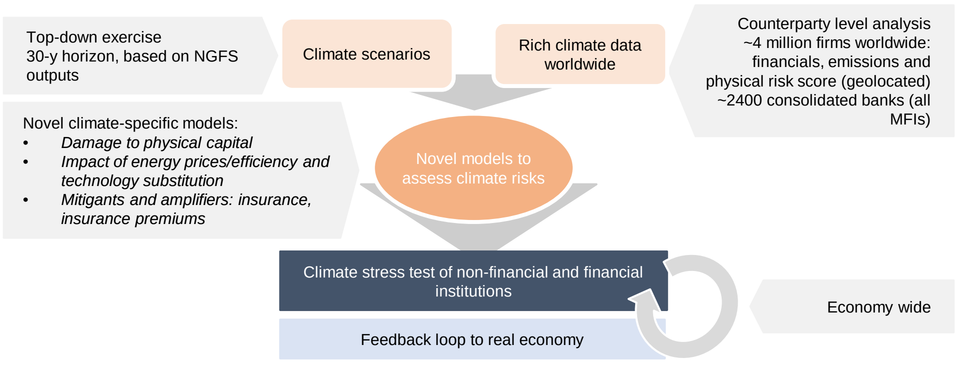
The ECB climate risk stress-testing framework offers a comprehensive methodology for evaluating the impact of alternative climate scenarios on the resilience of NFCs and banks over a time horizon of 30 years in the future. The set-up is unique and different from climate stress-test exercises performed by other central banks and supervisory authorities given that it provides a top-down, system-wide estimation of the effects of transition and physical risks (and of their interactions). The construction of a unique, rich dataset of financial and climate information for millions of corporates worldwide has made it possible to assess climate risks at a granular, counterparty level. Furthermore, the specific climate risk transmission channels for firms and banks that could not be captured in full by traditional financial models have been estimated through novel models specifically developed for this exercise.

2.1 Key distinctive features

The ECB's economy-wide climate stress test is characterised by four key innovative features: (i) it is a centralised, top-down exercise, (ii) it relies on climate-specific scenarios that allow for the interactions between transition and physical risks over a 30-year time horizon, (iii) it is a counterparty-level analysis, (iv) it assesses the implications of climate risks for firms and banks by applying a dedicated set of models that capture the specific transmission channels for transition and physical risks. As displayed in Chart 1, the exercise combines several innovative features that distinguish the ECB climate stress test from other assessments. The following paragraphs will describe each of these elements in greater detail.

Chart 1

Main elements of the ECB economy-wide climate stress test



Source: ECB.
Notes: NGFS: Network for Greening the Financial System; MFIs: monetary financial institutions.

The ECB's economy-wide climate stress-test is a pure top-down exercise, as it relies solely on internal datasets and models, and has been conducted centrally by ECB staff. As opposed to bottom-up exercises, that rely on banks' self-assessment of their exposure to climate-related risk and their readiness to address it, the proposed framework is based on data, assumptions and models that have been developed by ECB staff and that have been homogenously applied to all euro area financial institutions that are part of the sample. More precisely, the framework differs from those that: (i) adopt a bottom-up approach (see, among others, Bank of England, 2019/2021a/2021b; ACPR and Banque de France, 2020); and (ii) are applied to perform a scenario analysis rather than a pure stress-test exercise (ESRB, 2020 and ECB/ESRB, 2021).

Another key feature of the proposed framework relates to the climate scenarios developed, that allow for both transition and physical risks, as well as the interactions between the two. Most of the very few climate stress-testing exercises that have been developed so far limit their analysis to transition risk (see, among others, Vermeulen et al., 2018; ESRB, 2020; ACPR and Banque de France, 2020 - which accounts for the indirect consequences of physical risk only through macroeconomic dynamics without measuring the simultaneous impact of natural events on the economy and financial institutions). Due to the complexity and uncertainty of this issue, combined with the requisite long forecast-horizons and data limitations, relatively little has been done to assess the physical risk effects on financial stability: this is especially true for climate stress testing. A strand of literature has recently started to focus attention on the potential consequences of global warming on key macroeconomic indicators, such as inflation (Parker et al., 2018), real estate prices (Bernstein et al., 2019; Baldauf et al., 2020) and labour productivity (Zhang et al., 2018; McKinsey Global Institute, 2020), among others. Other studies assess the impact of specific natural catastrophes on more specific, financial sector-related variables, such as credit supply (Faiella et al., 2018; Cortés et al., 2017) or bank default probabilities (Klomp, 2014).

The current detailed evaluation of transition and physical risks for firms has been made possible thanks to the creation of a unique dataset that includes counterparty-level climate and financial information. ECB analytical credit datasets (AnaCredit)[4] and ECB Securities Holding Statistics - Group (SHS-G)[5] data were used to identify banks' exposures at granular level. This granularity made it possible to accurately map banks' NFC counterparties together with their carbon footprint, physical-risk exposure and financial information. The carbon footprint of firms is derived from the Urgentem[6] carbon-emission and climate risk dataset, while

4 AnaCredit is a dataset containing detailed information on individual bank loans in the euro area, harmonised across all Member States.

5 ECB Security Holding Statistics by Banking Group covers all significant banking groups under direct ECB (around 120 groups) supervision, including holdings of all subsidiaries and branches within and outside the euro area. Each institution reports granularly its portfolio holdings at individual ISIN level, including market value and nominal value held, and whether the amounts are held to maturity or in the trading book. ECB (2021).

6 Urgentem is an independent provider of emissions data, climate risk analytics and advisory services to the finance industry on carbon investment strategies.

the physical-risk scores of firms were extracted from the Four Twenty Seven[7] dataset on physical climate risks. Other data sources, such as Orbis, Bloomberg, Eikon and iBACH, were used to complement climate data with financial information.[8]

The set-up proposed captured the key transmission channels through which climate risks affect the NFC sector, and consequently the banking sector through credit and market risks. The novel models developed for this exercise simultaneously allow for the effects of transition and physical risk. It is assumed that firms would be affected differently by transition risk depending on their projected greenhouse gas (GHG) emissions, energy mix and technological innovation. For physical risk, firms were assumed to be subject to heterogeneous effects based on their geographical location, and thus vulnerability to future natural disasters. Mitigants and amplifiers were also considered, specifically in the form of insurance coverage (that mitigates the impact of physical hazards on tangible assets) and insurance risk premiums (that instead amplify firms' costs, especially in certain areas and under certain scenarios). First, the methodology made it possible to model credit risk and market risk based on granular information of bank exposures. Second, the ECB stress-testing framework was formulated so that the static balance sheet assumption adopted for banks could be adequately relaxed to allow for a feedback loop - and the corresponding second-round effects - between the banking sector and the macro economy (see Budnik et al., 2019). The set-up could also be extended to include additional institutional sectors (e.g. households and non-banks) and be applied to assess the impact of various regulatory and policy measures.[9]

2.2 Main differences between existing climate stress tests

The ECB's economy-wide climate stress test sits alongside a wide range of climate stress-testing initiatives by European and international institutions. While there are similarities, the ECB exercise aims to improve on past initiatives by introducing significant innovations in terms of data and modelling, being the only climate stress test to capture the interactions of physical and transition risks at firm level over a long time horizon. In addition, it is one of the few top-down exercises of this kind, with an unprecedent number of non-financial and financial institutions being incorporated within its stress-testing scope.

In 2018 De Nederlandsche Bank (DNB) became one of the first central banks to conduct an energy-transition-risk stress test.[10] This top-down exercise was aimed at capturing the transition-risk exposures of Dutch banks, insurers and pension funds over a horizon of five years. The DNB developed four energy transition scenarios for the purposes of this stress-test to encompass the impact of government policy, technological advances as well as a decline in consumer

7 Four Twenty Seven, an affiliate of Moody's, is a publisher and provider of data, market intelligence and analysis related to physical climate and environmental risks.

8 See Appendix A for further details of the dataset that the ECB climate risk stress-testing framework employs.

9 See Section 6 for additional information on future extensions of this methodological framework.

10 See De Nederlandsche Bank N.V., (2018).

confidence if the transition was postponed and technological breakthroughs were absent. The analysis was performed at a sectoral level, covering the majority of bond and equity holdings of Dutch banks, insurers and pension funds, as well as corporate loans (excluding commercial real estate) for the largest Dutch banks. The results of the exercise revealed that financial institutions would face sizeable, but manageable, losses in the event of a disruptive energy transition, while timely implementation of climate policies would help to avoid unnecessary losses.

The Autorité de Contrôle Prudentiel et de Résolution (ACPR) and Banque de France (BdF) recently published the results of their joint 2020 bottom-up climate pilot exercise for a group of French banking institutions and insurers.[11] The exercise assessed the implications of both physical and transition risks on credit risk, market risk and sovereign risk for nine banks and on the assets and liabilities of 15 insurance institutions over the next 30 years, drawing on the NGFS scenarios. While exposures were assessed at a sectoral level, the pilot exercise introduced important methodological innovations, such as adopting a dynamic balance-sheet assumption, allowing financial institutions to invest in and out of economic sectors based on climate risk-reward considerations. The results of the ACPR/BdF climate pilot stress-test exercise revealed an overall moderate exposure of French banks and insurers to climate risks. This was driven by the fact that half of exposures of the institutions under consideration were located in France, which was relatively less affected by physical risk than other areas, such as southern Europe. Additionally, this exercise did not allow for the simultaneous impact of specific climate events on the economy and financial institutions. In terms of transition risk, French institutions have relatively low exposures to the high-emitting sectors that would be impacted the most by a green transition.

The Bank of England (BoE) launched its Climate Biennial Exploratory Scenario (CBES) in June 2021.[12] This bottom-up climate stress test aims to capture the exposure of UK banks and insurers to both the transition and physical risks over the next 30 years. The BoE designed three climate scenarios (early action, late action and no additional action) based on the work of the NGFS. Participating banks will be expected to assess the impact of climate change on the credit risk for their banking books, while insurers will focus on changes in invested assets and insurance liabilities. This assessment will be done on a detailed counterparty-level for the largest counterparties, while the remaining portfolios will be analysed by aggregate geography and sector. Lastly, while the analysis will be performed on a static balance sheet basis, the BoE will assess how climate change will affect financial institutions' business models and investment decisions based on a detailed questionnaire.

Additionally, at the European level, the European Banking Authority (EBA) published its EU-wide pilot climate exercise in May 2021.[13] This exercise collected granular data on the exposure of 29 volunteer banks from 10 countries to

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11 See ACPR and Banque de France (2020); ACPR and Banque de France (2021); Banque de France (2020).

12 See Bank of England (2019); Bank of England (2021a); and Bank of England (2021b).

13 See EBA (2021).

corporates other than small and medium-sized enterprises (SMEs) and sought to identify and quantify their climate exposures. In addition to the climate exposure mapping, the EBA carried out a scenario analysis based on a joint EBA/ECB tool to explore the sensitivity of these exposures to climate-related shocks. This tool was applied to the same scenarios and follows the same probability of default (PD) modelling methodologies that are described later in this paper, albeit to a considerably smaller sample of non-financial and banking institutions. The results of the EBA scenario analysis point to 29 banks exhibiting higher levels of expected loss under the NGFS hot-house-world scenario than would be the case with a disorderly or orderly transition.

The joint ECB/ESRB Project Team on climate risk monitoring published a report in July 2021 that aimed to measure climate risks for the European financial system and also performed long-term forward-looking climate risk assessments for banks, insurers and investment funds.[14] The mapping of climate exposures in the ECB/ESRB report closely mirrors the data work undertaken for the ECB's economy-wide climate stress test in terms of both their counterparty-level approach and their geospatial granularity (address level for physical risk) and scope (1.5 million firms). While the stress test for the banking sector built on the preliminary results of the ECB framework described in this paper, those for the insurance and investment fund sectors also pointed to the benefits associated with an orderly transition. Lastly, the report highlighted the necessity of granular, forward-looking stress-test methodologies to more accurately capture financial stability risk from climate change. At the same time, it pinpointed the main challenges to this, such as the limited availability of reported data points that led to important data gaps and the absence of approaches that could capture second-round effects and prospective non-linearities.

Baudino and Svoronos (2021) also highlight the numerous challenges around climate stress testing as compared to traditional solvency stress tests.[15] In particular, they find that the main difficulties pertain to data availability, capturing financial risks over long horizons, modelling physical risk and developing models that can convert climate scenarios into financial variables. The ECB's economy-wide stress test has made significant advancements in tackling these challenges largely thanks to the creation of an unprecedent database that combines climate and financial information for millions of firms worldwide. This made it possible to formulate a novel modelling framework that captures the impact of all key physical and transition risk drivers for firms' profitability, leverage and probability of default as well as banks' credit and market risk profiles.

[14] See ECB and ESRB (2021).

[15] See Baudino, P., Svoronov, J-P (2021).

3 Scenarios

Stress tests of the banking system investigate how bank liquidity and capital would be affected under a number of severe – but plausible – scenarios of potential future events. These hypothetical scenarios describe situations that are expected to have a negative impact on banks' businesses and balance sheets, such as a recession or a financial market crash.

Climate stress tests have a similar objective: to test the resilience of banks and NFCs in a range of climate scenarios. These different scenarios combine plausible representations of future climatic conditions with estimates of the macroeconomic impact of policies designed to limit the extent of climate change. For example, a climate scenario could include a reduction in CO2 emissions that would be compatible with meeting the temperature targets in the Paris Agreement by 2100 as well as paths for technological development, adoption rates for renewable sources of energy and energy prices. A climate scenario could also assume that policies to mitigate climate change are not introduced, thus leading to an increase in CO2 emissions and global temperatures, accompanied by an escalation in the frequency and magnitude of natural disasters.

The NGFS has designed a set of climate scenarios that are increasingly being taken as a reference for analysing climate risks to the economy and financial system. Since different policy actions might lead to different levels of investments and emission reductions, the NGFS framework differentiates between the key alternative climate scenarios that could materialise depending on the extent to which the requisite measures are adopted in a timely and effective manner (or not). Based on that, the transition will be orderly or disorderly and the levels and interactions between transition and physical risks will differ.[16] [17] According to NGFS estimates, an orderly transition would limit the economic losses from transition risk to around 4% of GDP by the end of the century. By contrast, failure to adopt the requisite measures (i.e. a hot house world) would lead to an impact from physical risk of around 25% of GDP by 2100.[18]

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16 See NGFS (2020b).

17 Transition risks materialise when the abrupt implementation of climate policy measures aimed at reducing carbon emissions affects specific sectors of the economy depending on their carbon footprint. The expected increase in the magnitude and frequency of natural catastrophes over time has an economic impact on sectors and individuals that is captured by the concept of physical risk.

18 These estimates do not usually account for all sources of physical risk. Thus, damage in a hot house world would probably be larger than what the models suggest, particularly in regions with lower resilience and capacity for adaptation.

3.1 Scenario narrative

The ECB's economy-wide climate stress test applies three main scenarios which differ from one another in their associated levels of transition risk and physical risk. Importantly, the proposed scenarios are based on the NGFS Phase I scenarios, both in terms of narrative and quantitative figures (see NGFS, 2020b).

The best-case scenario in terms of potential economic impact is referred to as the orderly transition scenario. Under this scenario, climate policy measures are well calibrated and implemented in a timely and effective manner, thus the costs stemming from transition and physical risks are comparatively limited.[19] From a climate perspective, the scenario entails meeting the Paris Agreement targets of "well below 2 degrees Celsius" by the end of the century. The proposed methodological framework takes this case as the baseline scenario which serves as a reference for comparing the effects of alternative adverse scenarios.

By contrast, in the hot house world scenario no regulation or policy aimed at limiting climate change is introduced, thus leading to extremely high physical risks. Under this scenario the costs associated with the transition are very limited (as the transition does not occur) but those related to natural catastrophes are extremely high. Under these circumstances, global warming would not remain limited, global temperatures would rise by at least 3 degrees Celsius above pre-industrial levels until 2100, and the Paris Agreement targets would not be met.

In between these two extreme climate scenarios, there is a disorderly transition scenario that assumes delayed implementation of the requisite climate policy measures. Due to delayed implementation, under the disorderly transition scenario policy action is introduced in an abrupt way, hence transition risks and their associated costs are significant. Additionally, as global warming starts being mitigated only from 2030, a disorderly transition scenario also implies the build-up of greater physical risk than would be the case with an orderly transition. Chart 2 provides a representation of how to interpret and compare the proposed scenarios in terms of physical and transition-risk levels, as well as their expected economic impact.

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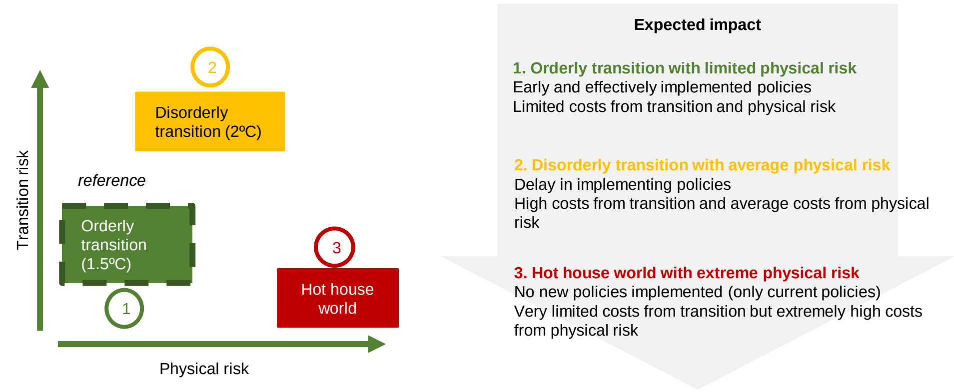
[19] This scenario would also be consistent with reaching the goals established by the European Green New Deal by 2050 (see European Commission, 2021).

Chart 2

Representation of the three scenarios in terms of physical and transition-risk levels



Source: ECB.
Note: The colours represent the expected impact in terms of global warming (green for meeting Paris Agreement targets with 1.5°C increase in temperature compared to pre-industrial levels; yellow for meeting the Paris Agreement targets with 2°C increase in temperature compared to pre-industrial levels; red for not meeting the Paris Agreement targets). The scenarios are organised in the graph based on the combination of transition and physical risks.

3.1.1 Time horizon

The selected time horizon is 30 years, which is considered to be a good compromise between the importance of assessing the long-term impact of climate risks and the need to keep prediction intervals within reasonable limits. Having a sufficiently long time horizon makes it possible to identify the reaction and dynamic adjustments made by firms and financial institutions over time to evolving environmental conditions (physical risks) and policy actions (transition risks). At the same time, it is important to adequately calibrate the length of the time horizon in order to limit the degree of uncertainty that surrounds point forecasts.

To allow for evolving transition risk, firms are presumed to adapt over time to time-varying policy conditions through adjustments to their carbon footprint. More precisely, NFCs may react to changes in taxes applied to Scope 1, Scope 2 or Scope 3 emissions by modifying their CO2 emissions through changes to their business models and/or adjustments to their production processes. To this end, the changes in firms' emissions is derived on the basis of a sector-country time path that also takes into account the initial emission levels of each firm[20].

Capturing the long-term nature of physical risks requires a sufficiently long forecast horizon. Although scientific evidence consistently points towards an increase in the magnitude and frequency of natural catastrophes should governments and policy makers not react appropriately, the long-term nature of such phenomena could prevent the correct quantification of their consequences in the short to medium term. For this reason, we assessed the trade-off between the impact of transition and physical risks in the medium to long term by assuming the

[20] See Annex A for a more details on the model used to project firm-level emission pathways

composition of banks’ exposures would remain constant over the 30-year time horizon considered in this exercise (static balance sheet assumption).

The proposed stress-testing set-up makes it possible to project the changes in the key indicators selected over the specified forecast horizon for each of the three climate scenarios. That type of exercise can be particularly informative about how the climate and macroeconomic effects under the alternative adverse scenarios differ from one another and how they compare with those expected to materialise under the orderly transition scenario (i.e. the baseline scenario). The subsections below present the projected paths of selected aggregates under the three scenarios in the case of Europe.

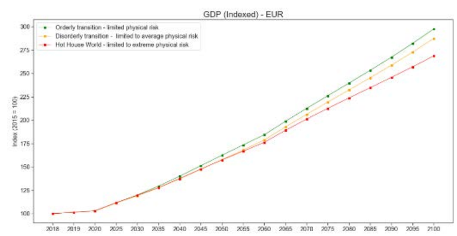
3.2 Macroeconomic and climate projections

3.2.1 Real GDP

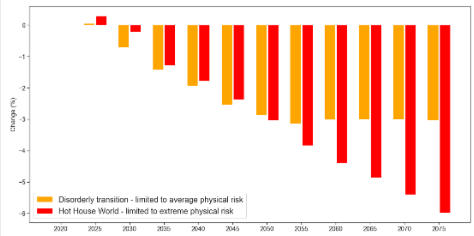
Projected levels of real GDP under the adverse scenarios fall below that of the orderly transition scenario, and such differences become wider over the forecast horizon. Chart 3 shows that real GDP could be expected to grow under all scenarios over the next decades, however the pace at which it is expected to increase would vary across scenarios, with such wedges being particularly significant in the medium to long term. Not surprisingly, from 2045/50 onwards the most adverse scenario from a macroeconomic (impact) perspective would be the hot house world scenario, while the most beneficial would be orderly transition already from 2030.

Chart 3
Projected paths for real GDP

Indexed, 2005 = 100



Percentage differences as compared with the orderly transition scenario



Source: ECB calculation based on NGFS climate scenarios (2020b).

Transition costs incurred would already affect the macro economy in the very short term, whereas damage from natural catastrophes would be expected to have a significant impact on real GDP at a longer horizon. For this reason, in the very short term real GDP would increase more in the hot house world scenario as compared with the baseline scenario.[21] However, in the medium to long term the macroeconomic costs associated with physical risk would become more significant than those related to transition risk. Finally, the higher transition costs associated with a disorderly transition would imply a larger negative impact on GDP, even when compared to the hot house world scenario: this situation however reverses after 2045, when the increased frequency and severity of natural catastrophes starts to prevail, with increasingly negative effects on GDP until the end of the century.

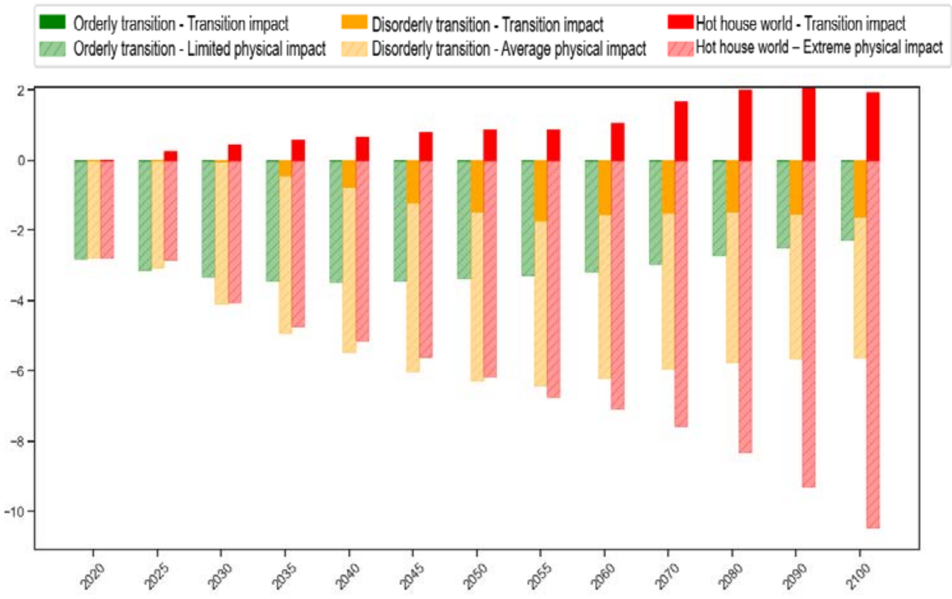
The impact of physical risk on GDP prevails over the transition costs under all scenarios and throughout the projection horizon. Chart 4 shows that the impact from transition risk is limited to no more than 2% of European GDP in the event of a disorderly transition; more frequent and severe natural disasters could, in contrast, lead to a decrease in GDP of 10% by 2100 should policies to mitigate climate change not be introduced in a hot house world scenario. Finally, in the hot house world scenario the lack of transition policies would have a positive impact on GDP: however, that benefit would be limited to no more than 2% in 2090 in the event of an orderly transition scenario and be more than offset by the increase in damage from physical risk.

Chart 4

Decomposition of real GDP between transition and physical impact

GDP impact over time relative to the orderly transition scenario without physical risk

(percentages)



Source: ECB calculation based on NGFS climate scenarios (2020b).
Notes: The filled bars represent the impact on GDP of transition costs, while the dashed bars represent the impact on GDP of damage from physical risk. The filled and dashed bars are cumulative where the effects are negative: in the hot house world scenario, where the impact from transition risk brings a benefit and increases GDP, the physical risk damage is equal to the dashed and the filled portion of the bars. In the absence of a reference scenario under the NGFS scenarios (2020b), all GDP effects are calculated against the orderly transition scenario without physical risk, this explains why the transition costs under this scenario are zero.

[21] It should be remembered that the hot house world scenario is associated with negligible or inexistent transition risk since it is assumed that no policy action will be taken.

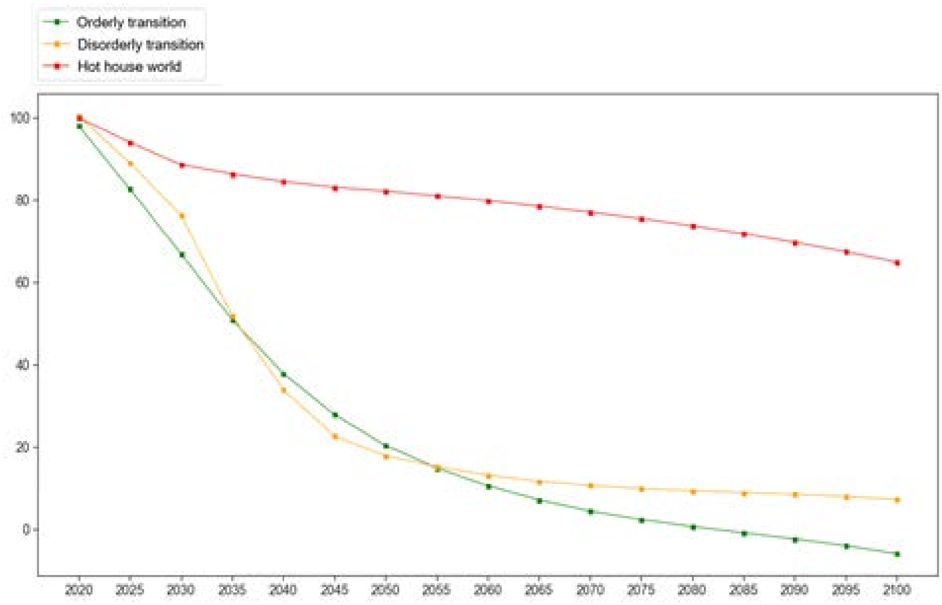
3.2.2 GHG emissions

Projected levels of carbon emissions under the hot house world scenario are well above those under the baseline scenario over the entire forecast horizon. Chart 5 represents the projected path of indexed GHG net emissions under the three scenarios (orderly transition, disorderly transition and hot house world). While the wedge between the carbon emissions under the hot house world scenario and those under the orderly transition scenario is very wide over the entire horizon, the same does not hold true for the difference between disorderly transition and the baseline scenario due to differentiated access to carbon dioxide removal (CDR) technologies between the two cases over time.[22]

Chart 5

Projected GHG emission paths for Europe

(indexed, 2005 = 100)



Source: ECB calculation based on NGFS climate scenarios (2020b).

The difference between the projected paths of gross and net carbon emissions derives from different assumptions of the future availability of CDR technologies. Chart 6 plots the projected path of gross and net GHG emissions under the three different scenarios. Not surprisingly, the assumptions as to the existence and level of sophistication of these technologies have a non-negligible impact on the projected path of emissions under all the different scenarios. In particular, the assumption that CDR technologies will be limited over the next few years suggests that gross GHG emissions would have to reduce further in order to meet the Paris temperature targets given that it would be less likely that they could be removed from the atmosphere. For the purposes of this exercise, we assumed

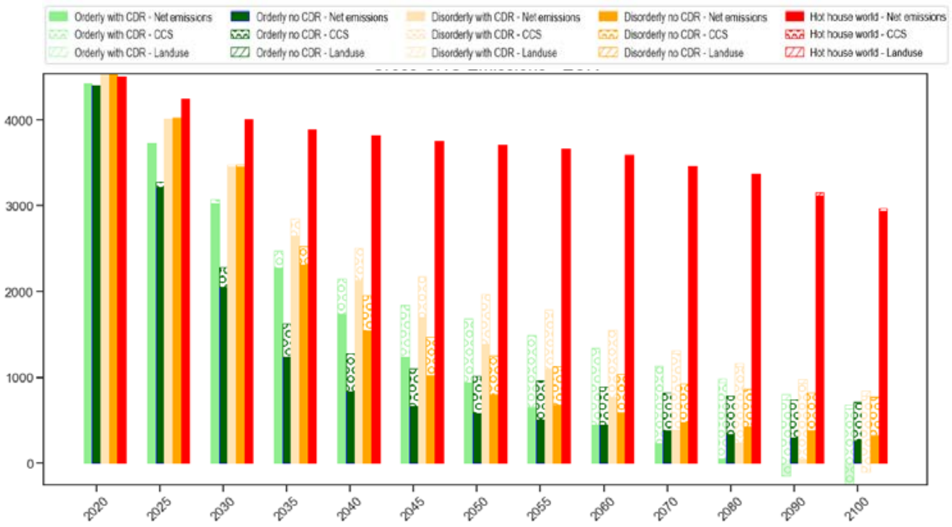
22 Due to more limited access to CDR technologies, the pace at which net GHG emissions would decrease between 2030 and 2045 would be comparatively more abrupt to ensure that the corresponding temperature targets are reached.

fully available CDR technologies under the orderly transition scenario, and only limited CDR technologies under the disorderly transition scenario.

Chart 6

Gross versus net GHG emissions

(Mt/CO2 per year)



Source: ECB calculation based on NGFS climate scenarios (2020b).
Note: CCS: carbon capture and storage.

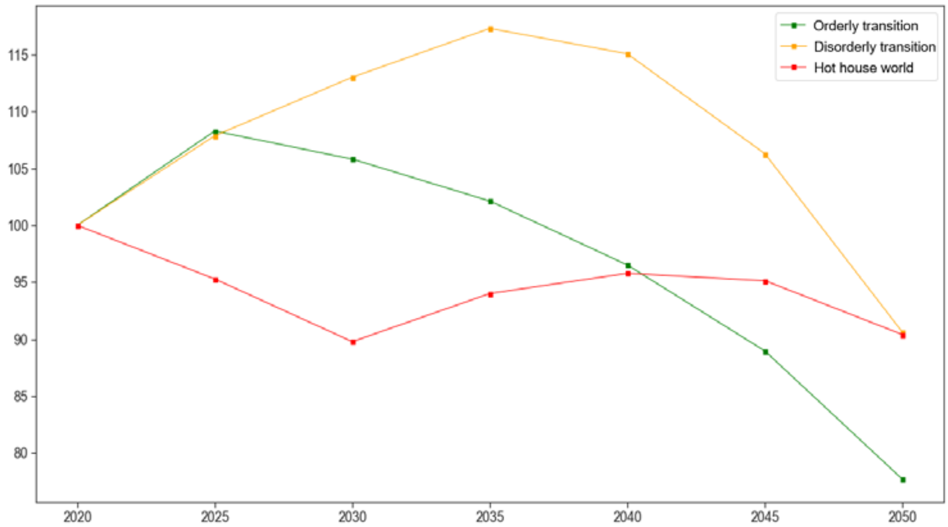
3.2.3 Energy prices and consumption

From the supply side, green energy would be produced relatively more efficiently under the orderly transition scenario, which would allow energy prices to swiftly take a downward trend. That would translate into energy prices under the baseline scenario eventually falling below those associated with the hot house world scenario. By contrast, a delayed and abrupt adoption of green technologies would translate into projected energy prices under the disorderly transition case being comparatively higher over most of the forecast horizon (Chart 7).

Chart 7

Projected energy price paths

(indexed, 2015 = 100)



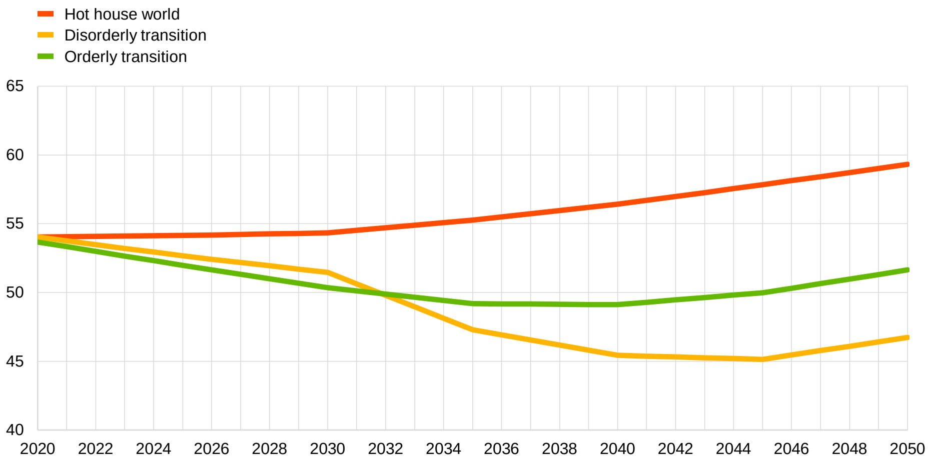
Source: ECB calculations based on NGFS reference scenarios (2020b).

A timely and efficient use of green technologies would not only exert downward pressure on energy prices through lower energy production costs but also through lower energy consumption. Chart 8 clearly shows that energy consumption under the hot house world scenario would evolve to rise above the levels corresponding to the reference scenario over the entire forecast horizon. Additionally, the delayed and abrupt way in which green technologies are incorporated in the production process under the disorderly transition scenario is reflected into a pronounced and sudden fall in energy prices around 2030.

Chart 8

Projected energy consumption paths

(exajoule)



Source: ECB calculations based on NGFS reference scenarios (2020b).

For the purpose of the ECB climate stress test, the NGFS climate scenarios are enhanced on three dimensions: granularity, combination of physical and transition risks, and energy mix. First, while the NGFS scenarios project future carbon emissions and damage from physical risk at aggregate regional level, the ECB climate stress test combines aggregate projections with firm-specific information to transpose these projections at NFC level. Second, while the NGFS scenarios model the effects of transition and physical risk separately at GDP level, the set of three scenarios presented above combines the two risks, making it possible to examine the trade-offs between a transition and no transition to a greener economy. Third, the NGFS scenarios do not have a sufficient level of granularity to make it possible to predict the future energy efficiency of firms based on current energy mix and necessary investments: this stress-test exercise also overcomes this limitation by distinguishing between different energy mixes by country and subsequently projecting firm-level energy consumption.

4 Data

The framework of the ECB climate stress test is based on a unique and highly granular dataset that combines financial and climate risk information for NFCs with data about bank exposures to NFCs. European firm-level financial data are enriched with firms’ data on physical and transition risks, and subsequently integrated with data on euro area bank exposures to these firms through loan and security holdings. The combination of financial and climate information for European companies makes it possible to conduct a granular assessment of the impact of climate risk on banks’ principal balance sheet items. Combining this analysis with individual banks’ exposures makes it possible to transform climate effects on companies into financial effects on the euro area banking system. To the best of our knowledge, this set of information is unique and has never been collected and examined by a regulatory or supervisory authority in order to perform a climate stress test. Such data richness adds to the typical advantages of a top-down economy-wide stress test, notably in terms of the homogeneity of models used, the consistency of data, the transparency of methodologies, and the comparability and replicability of results.

4.1 Data sources and integration procedure

The data used for the climate stress test integrates four main streams of information and combines regulatory and private sources. The first stream of data comprises firm-level financial information derived mainly from Orbis and complemented with other sources, such as Eikon, Bloomberg and iBACH. The second stream of data relates to firms’ climate information, i.e. the physical-risk scores obtained from Four Twenty Seven and firm-level carbon emissions data obtained from Urgentem. Subsequently, firm financial and climate information is combined with information on firms’ individual loan exposures to euro area banks, extracted from AnaCredit, and on the corporate bond holdings of banks derived from SHS-G.[23]

Data on physical and transition risks is derived from private data sources that measure firms’ exposures to future natural hazards and their carbon footprint. Four Twenty Seven data was used to calculate forward-looking physical-risk scores for firms, also distinguishing between different types of extreme weather events (physical hazards)[24]. Risk scores capture the frequency and severity of future extreme weather events and are derived at address level. Transition risk is measured by firms’ carbon footprint using both a backward and forward-looking perspective. Urgentem offers a rich dataset on firm-level historical emissions, which includes relative and absolute Scope 1, Scope 2 and Scope 3 greenhouse gas

[23] See Appendix A for further details of the dataset that the ECB climate risk stress-testing framework employs.

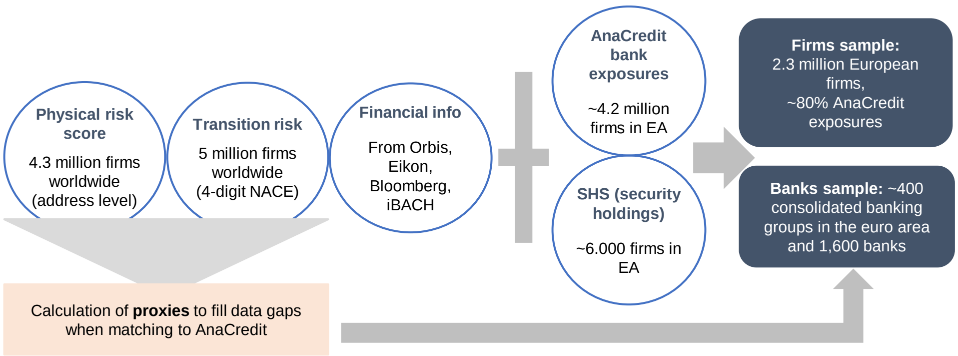
[24] Namely, flooding, wildfire, sea-level rise, water stress, heat stress, earthquakes and hurricanes. Further details are available in Appendix A.

emissions for a wide range of publicly listed and private companies. Additionally, based on the NGFS scenarios, the dataset makes it possible to project the future emissions of those companies and allow for firm-specific emission-reduction targets.

The granularity of the dataset is additionally enriched by combining firm-level financial and climate information with data on euro area banks' individual exposures to these firms. Chart 9 shows the data integration procedure in detail. First, firms were geolocated at address level and were subsequently assigned a physical-risk score based on their location. A spatial extrapolation approach[25] was used for firms with missing address information and were assigned proxies based on their postal code/nomenclature of territorial units for statistics 3 (NUTS3)[26] level. Second, firms were matched with their four-digit statistical classification of economic activities in the European Community (NACE) sectoral classification and different identifier. Firms not disclosing information on their carbon footprint were assigned inferred emissions data based on their NACE subsector of activity. Finally, using RIAD code and ISIN code identifiers firms were mapped to bank-level individual exposures derived from the AnaCredit and SHS-G databases. This procedure resulted in approximately 2.3 million European firms being matched with full financial and climate risk information. The final sample of bank exposures covered around 80% of total AnaCredit exposures held by approximately 1,600 euro area banks.

Chart 9

Overview of the data integration procedure



Source: ECB.
Notes: Data are from 2018. The banks sample only accounts for banks which reported non-zero exposures in the AnaCredit database in December 2018.

The sample coverage of euro area bank exposures to NFCs is significantly high, and homogeneous across banking systems. Chart 10 presents the portion of AnaCredit exposures covered by the dataset for this climate stress test, broken down by country. The coverage was high in all countries, ranging from 60% (in France) to almost 100% (in Estonia). On average, approximately 80% of euro area exposures to NFCs was represented in the climate stress-test sample.

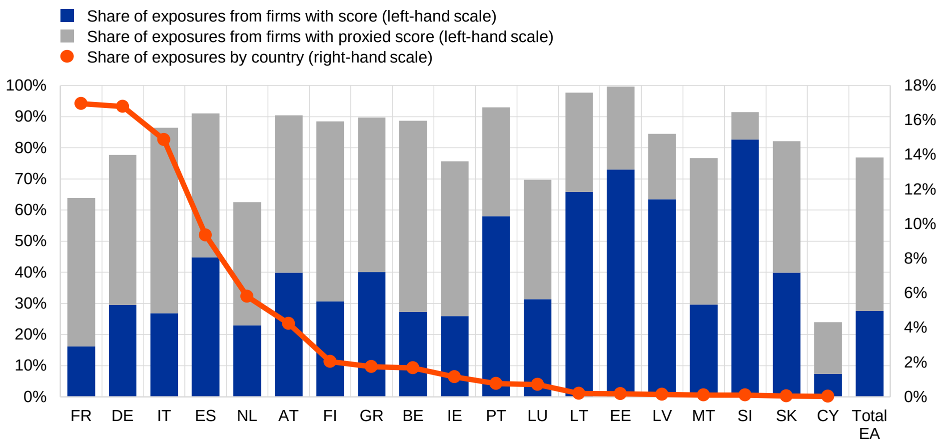
[25] The regional proxies were computed following the spatial extrapolation approach set out in the Data Supplement of ECB/ESRB (2021)

[26] The NUTS classification (nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK for statistical purposes, NUTS3 relating to small regions for specific diagnoses. For further information see "Eurostat: Your key to European statistics".

Chart 10

Sample coverage

(percentages)



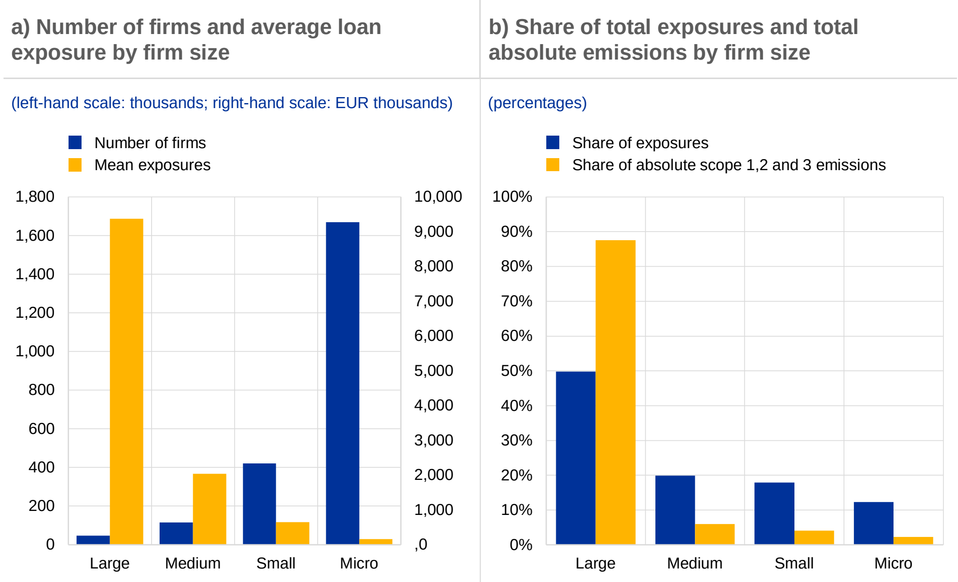
Source: ECB calculations based on AnaCredit and Four Twenty Seven data (2018).
Note: The chart presents the share of exposures of the 2.3 million firms used in the ECB climate stress test as a proportion of the total sum of exposures based on the data available in AnaCredit as at December 2018 per euro area creditor country.

4.2 Breakdown of European firms' exposures to climate risk

The majority of firms in the sample are micro firms, although the largest exposures for euro area banks in terms of amount are to large firms. Panel a in Chart 11 presents the total number of firms per size together with their average loan exposures, while panel b in Chart 11 plots the share of total exposures and emissions per firm size. Although large firms represent an extremely small portion of the sample in terms of number of companies, they clearly represent the highest share of exposures for euro area banks. Additionally, large companies seem to be the biggest polluters given that they contribute almost 90% of the overall emissions as against 50% in terms of their total exposures. Two important considerations should be raised here for interpreting this data. First, large firms typically rely on a larger supply chain, and thus produce more Scope 3 emissions (both downstream and upstream) than smaller companies. Second, large companies are typically more inclined to report their emissions than small companies (for which most data are estimated), thus their emissions suffer less from inference errors. To conclude, given that large companies produce the greatest emissions, and represent the largest share of loans, they could be seen as the biggest source of transition risk for the banking sector.

Chart 11

Firm-level transmission of financial and climate risks



Source: ECB calculations based on AnaCredit, Orbis and Urgentem data (2018).
Notes: Total absolute emissions refers to total absolute Scope 1, 2 and 3 emissions. Firms are categorised as large, medium, small and micro based on the size of their total assets. The thresholds for this categorisation are based on the European Commission's definition of SMEs.

Differences in emissions across firms of different size likewise persist when looking at emission intensities (relative to revenues) rather than levels. Chart 12 depicts the average absolute and relative emissions per firm size[27]. Comparing the emission intensities of firms, rather than levels, corrects for possible discrepancies when evaluating firms' brownness given that this metric also allows for firms' scale of economic activities. The differences in average emission intensities are less pronounced across companies: nonetheless, micro firms are almost half as carbon intense as large firms, emitting around 600 as compared to 1,100 t/CO2e per euro in revenues.

Furthermore, Chart 12 shows that Scope 3 emissions make up by far the highest share of emissions, especially for large companies. This points to the need to improve reporting standards for companies around Scope 3 emissions as they are a major source of transition risk.

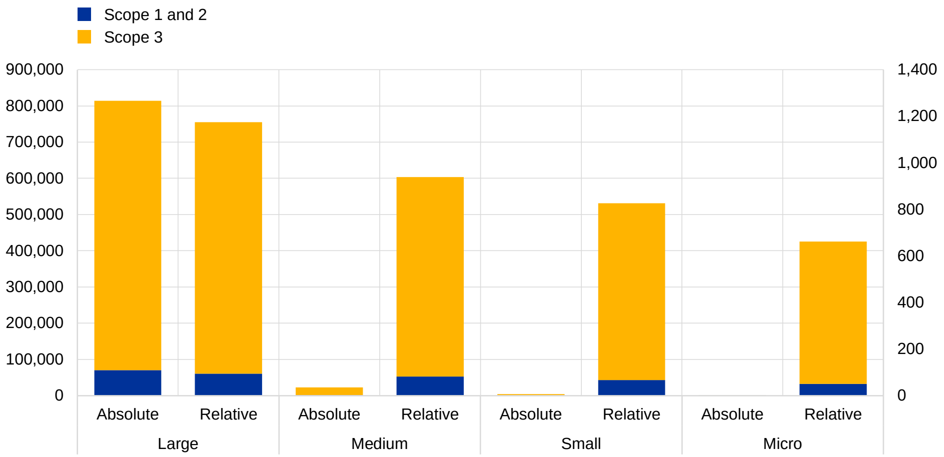
[27] The thresholds for firm size categorisation are based on the European Commission's definition of SMEs.

Chart 12

Emissions by firm size

Average emission intensities by firm size (right-hand side) and average emission levels by firm size (left-hand side)

(left-hand scale: t/CO2; right-hand scale: t/CO2 per EUR)



Source: ECB calculations based on AnaCredit, Orbis and Urgentem data (2018).
Notes: Firms are categorised as large, medium, small and micro based on the size of their total assets. The thresholds for this categorisation are based on the European Commission's definition of SMEs.

The distribution of scope 1, scope 2 and scope 3 emissions is notably heterogeneous across European sectors. Chart 13 plots the average relative scope 1, 2 and 3 emissions by sector in Panel a, and the total share of exposures and absolute scope 1, 2 and 3 emissions by sector in Panel b. The most emission-intense sectors are mining, followed by electricity and gas and agriculture. On the other hand, the biggest contributors to overall absolute emissions are manufacturing, electricity and gas, as well as transport and wholesale and retail activities.

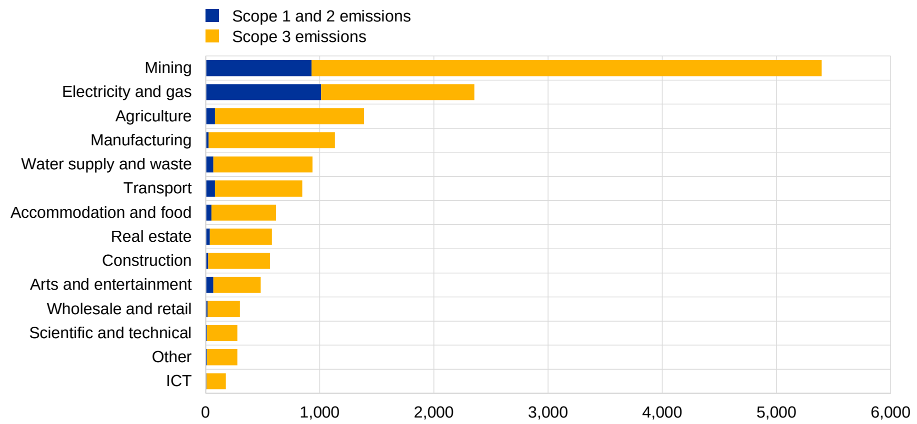
Bank loans are well diversified across sectors, however, of the highest emitters, manufacturing and wholesale and retail represent more than 30% of banks' portfolios. The share of total exposures by sector is presented in the upmost right column of panel b in Chart 13. Manufacturing and wholesale and retail together receive one-third of total euro area bank loans: this rises to 40% when banks' exposures to transport and electricity and gas are included.

Chart 13

Emissions by sector

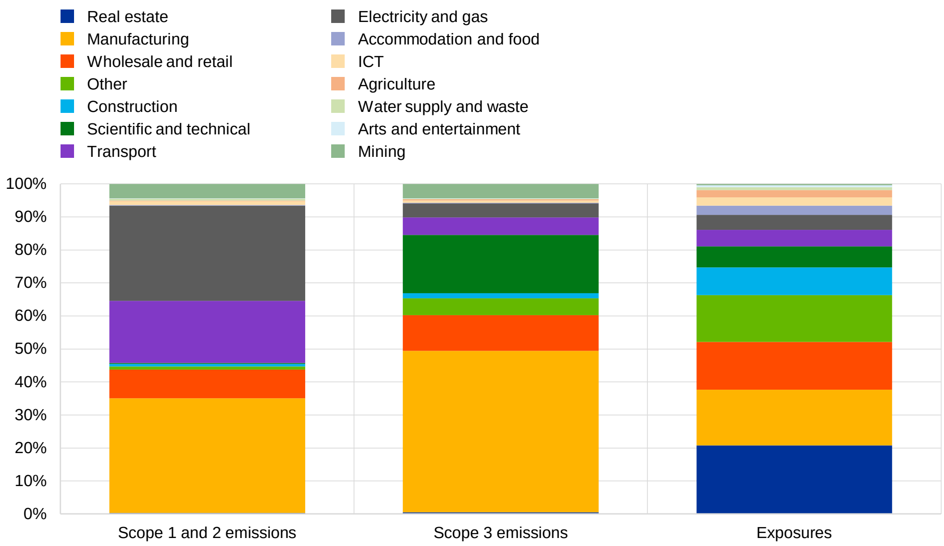
a) Average emission intensities

(t/CO2 per EUR)



b) Total share of exposures and absolute emissions

(percentages)

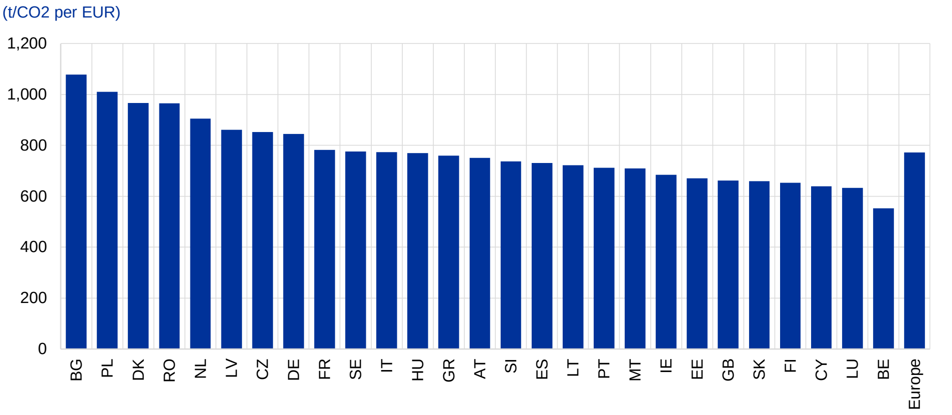


Source: ECB calculations based on Urgentem data (2018).
Notes: Level 1 NACE sectors are shown.

At the country-level, the average differences in emissions are less pronounced. Chart 14 presents the differences in average relative emissions per country. Across countries, there seems to be a low level of heterogeneity in the distribution of emission intensities. However, a few countries have above-European average emission intensities, predominantly emerging economies from eastern Europe such as Bulgaria, Poland, Romania, Latvia and Czech Republic.

Chart 14

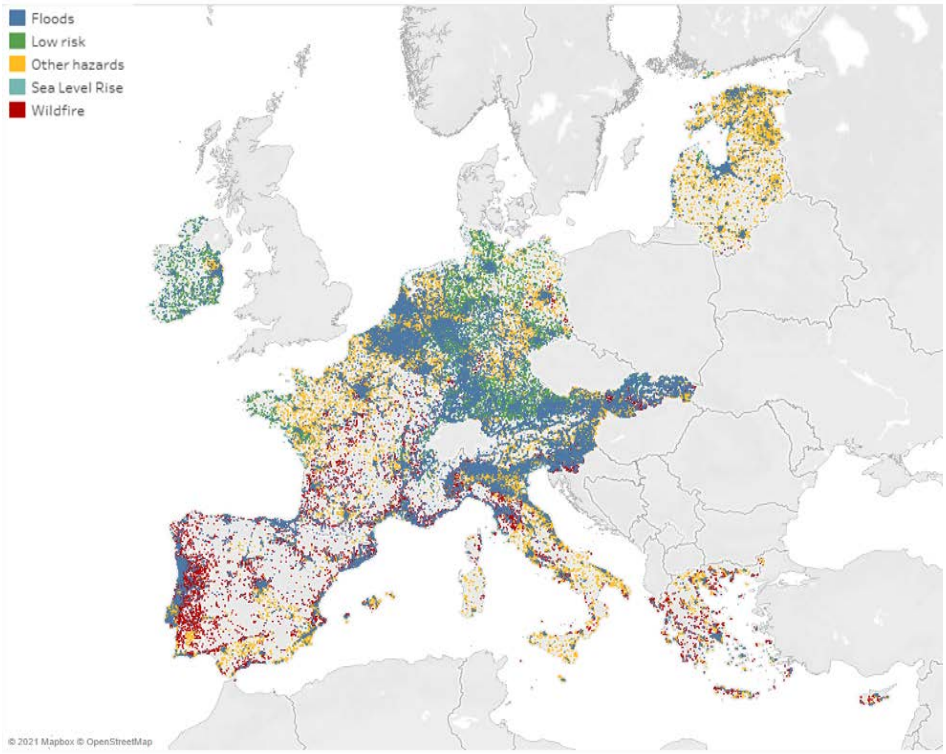
Average emission intensity by country



Source: ECB calculations based on Urgentem data (2018).

Chart 15

Physical risk: intensity and sources across European regions



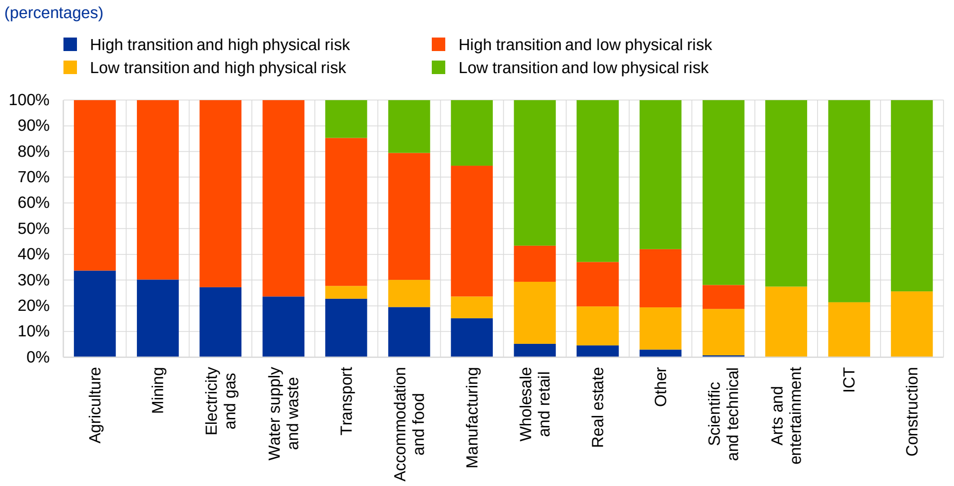
Source: ECB calculations based on Four Twenty Seven data (2018).
Notes: Physical-risk scores are forward-looking and reflect the intensity and magnitude of natural catastrophes over a 30-year horizon. The data – which are provided at address level – have been aggregated and averaged at NUTS3 level for the purpose of this chart. Of the seven risk categories available, only three are included in the framework for the ECB climate stress test, namely wildfire, flooding and sea level rise. This is due to the fact that the other categories are assumed to affect the economy as a whole, while the selected categories can have an impact at a more granular level, i.e. on individual firms (heat stress, water shortage, hurricanes and earthquakes will have large-scale effects, while wildfire will only affect the specific area in which a firm is located).

In terms of physical risk, the exposures to extreme weather events and natural catastrophes varies greatly across countries and types of hazards. Chart 15 presents the most predominant source of physical risk across European countries. Regions located in southern Europe are expected to suffer relatively more from wildfires: this is mainly based on the projected increased frequency and intensity of wildfires affecting countries located closer to the Equator, as well as the vast portion of those regions that are being affected. Countries located in eastern and central Europe are expected to increasingly suffer from flooding risk.

Firms exposed to high transition and physical risks are concentrated in specific sectors. Chart 16 presents the share of firms vulnerable[28] to transition and/or physical risks per sector. Firms exposed to high transition risk are concentrated in resource-intensive sectors, such as agriculture, mining, electricity and gas, and water supply and waste. While transition risk is prevalent in some sectors, vulnerability to high physical risk seems to be spread homogeneously across sectors, and this confirms its location-specific nature.

Chart 16

Share of firms subject to climate risk by sector



Source: ECB calculations based on Four Twenty Seven and Urgentem data (2018).
Notes: Firms are categorised as vulnerable to high transition risk if their relative emissions fall into the 70th percentile of Scope 1, 2 and 3 relative emissions for the entire sample. Firms are vulnerable to high physical risk if their probability of suffering from a wildfire or a river or coastal flood in a given year is over 1%. Level 1 NACE sectors are shown.

When focusing on tail risks for the corporate sector, the data shows that firms vulnerable to high transition or physical risk are concentrated in different countries. Chart 17 compares the share of firms subject to high physical and transition risks as well as the total bank exposures to these firms per country. The diagonal line indicates that a country has as many firms subject to high physical risk as to high transition risk. Chart 17 shows that while European countries are similarly exposed to transition risk when looking at tail firms (previous sections highlighted that this is true on average), there are a few countries that show exceptional vulnerability to high physical risk. North and central Europe countries have a share of high emitting firms of between 20% and 50%; however, their share of exposures to high physical risk firms remains very limited and, in most cases, around 5%. In contrast, firms exposed to high physical risk are predominantly concentrated in the

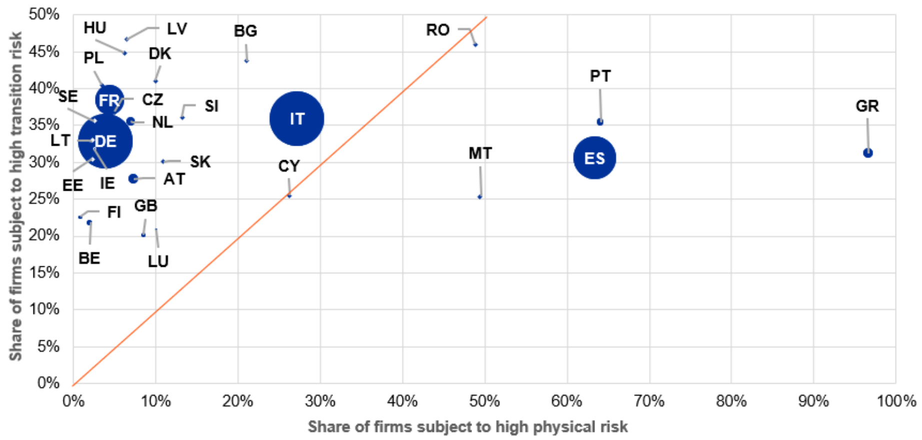
[28] Firms are categorised as vulnerable to high transition risk if their relative emissions fall into the 70th percentile of Scope 1, 2 and 3 relative emissions for the entire sample. Firms are vulnerable to high physical risk if their probability of suffering from a wildfire or a river or coastal flood in a given year is over 1%

south of Europe: here, firms exposed to high physical risk represent between 25% and almost 100% of all the firms in those countries, with Italy and Spain also having a substantial share of total exposures to (physical) risk for the European sample of firms.

Chart 17

Share of firms exposed to physical versus transition risk by country

(percentages)



Sources: ECB calculations based on AnaCredit, Urgentem, and Four Twenty Seven data (2018).
Notes: Firms are subject to high transition risk if their emission intensities fall within the 70th percentile of Scope 1, 2 and 3 relative emissions for the entire sample. Firms are subject to high physical risk if their probability of suffering from a wildfire or a river or coastal flood in a given year is over 1%. The size of the bubbles depicts the exposures at risk, and is proportional to the absolute loan exposure to high-transition and/or high-physical-risk firms in the country of origin as compared with the total exposures of euro area banks in the sample (across countries). In order to facilitate the visualization, the x-axis is not drawn to scale.

4.3 Breakdown of euro area bank exposures to climate risk

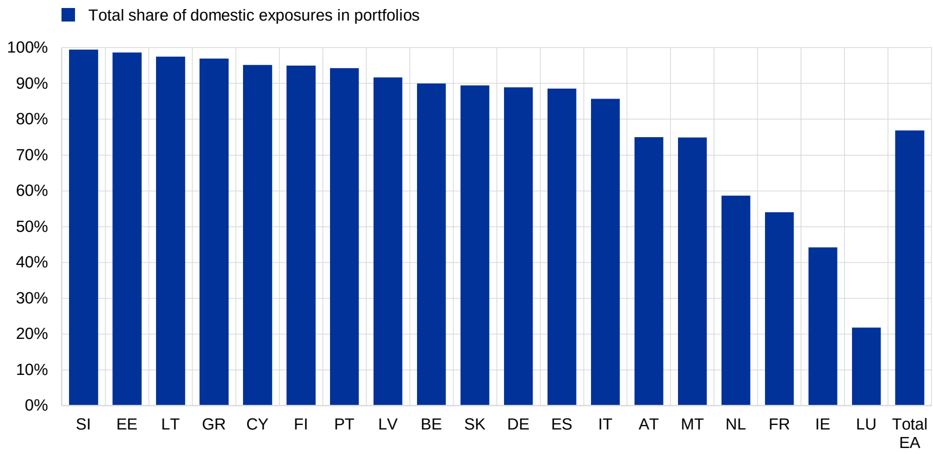
The ECB framework stress tests around 1,600 banks, covering up to 80% of the bank loans held in the euro area. In this regard, climate risk affects banks mainly through their loan exposures to firms which are subject to increased physical and transition risks. In the following sections, an overview of the composition of the bank sample is given, both in terms of number, type and location of banks, as well as their portfolios and loan exposures to climate-related risks.

Across countries, banks have a strong home bias, giving loans predominantly to domestic rather than foreign firms. Chart 18 shows the share of exposures held by domestic firms for each country. In all countries, with the exception of Ireland and Luxemburg, domestic firms make up at least 50% of bank portfolios and at euro area level 80% of banks' exposures are to domestic firms. The composition of bank portfolios in terms of domestic versus foreign firms determines the extent to which the country-level climate risk of the firms presented in Chapter 4.2. translates into country-level climate risk for banks. Based on Chart 18 it can be seen that France, Ireland and Luxemburg will be the most influenced by climate risk sourcing from firms located abroad.

Chart 18

Share of loans lent to domestic firms by creditor country

(percentages)



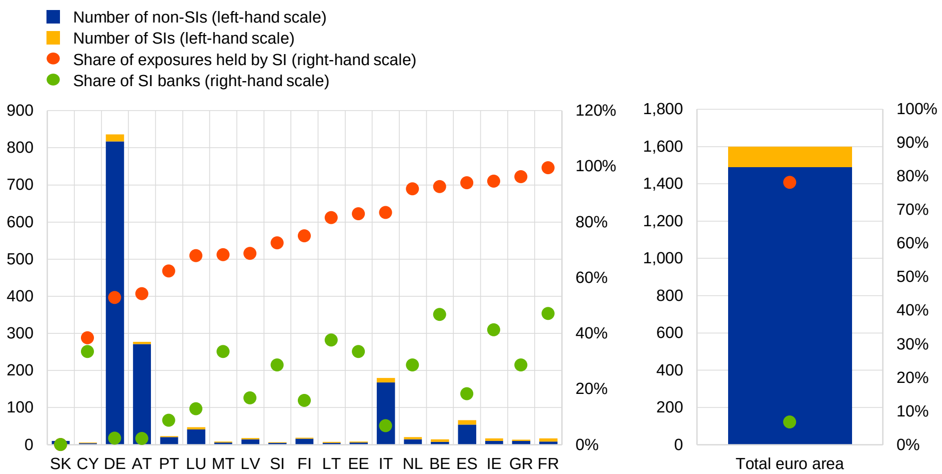
Source: ECB calculations based on AnaCredit and Orbis data (2018).

Although most banks in the sample are less significant institutions (LSIs), the majority of exposures are held by significant institutions (SIs). Chart 19 presents the number of banks and the share of SIs in the sample by country, as well as the share of total exposures held by SI banks. Across euro area countries SIs make up less than 10% of total banks in the sample, however, they hold approximately 80% of the total exposures. When looking at geographical differences, the chart confirms that some banking sectors are extremely concentrated (as in France and Belgium), while others have a larger share of exposures held by smaller banks (as in Austria and Germany).

Chart 19

Composition of the euro area banking system

(left-hand scale: number of firms; right-hand scale: percentages)



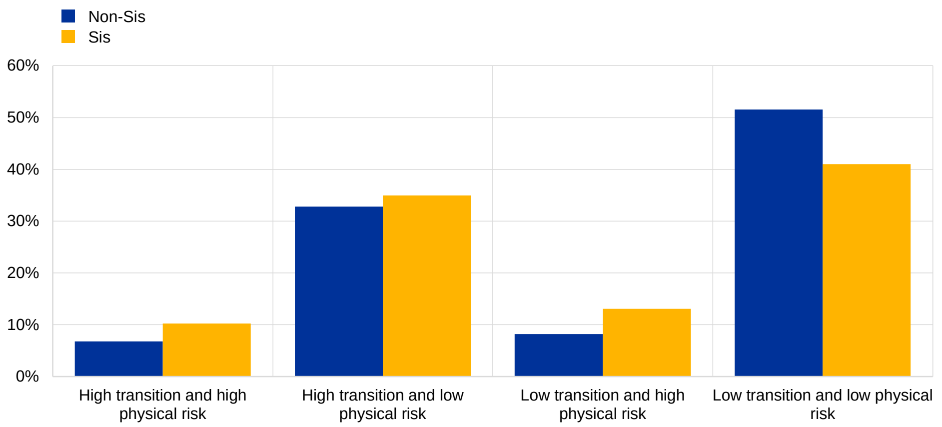
Source: ECB calculations based on AnaCredit data (2018).
Note: Banks are classified as significant institutions (SIs) based on the definition given in the Single Supervisory Mechanism (SSM) Regulation and SSM Framework Regulation. Euro area creditor countries are presented.

Large and significant institutions (SIs) are slightly more exposed to climate risk. Chart 20 shows the share of bank loans granted to firms exposed to high or low transition and physical risks for each bank type. In total, SIs have double the share of exposures to high transition and high physical risk firms as compared with less significant institutions (LSIs) (10% versus 5%), and also have a larger share of exposures to high transition (but low physical) risk firms. In total, SIs hold more than 50% more exposures to firms that are highly vulnerable to climate risk.

Chart 20

Share of bank loans exposed to climate risk per bank type

(percentages)



Sources: ECB calculations based on AnaCredit, Urgentem, and Four Twenty Seven data (2018).
Notes: Exposures are categorised as high transition risk if a firm's absolute emissions fall into the 70th percentile of Scope 1, 2 and 3 absolute emissions for the entire sample. Exposures are categorised as high physical risk if a firm's probability of suffering from a wildfire or a river or coastal flood in a given year is over 1%. Banks are classified as significant institutions (SIs) based on the definition set out in the SSM Regulation and SSM Framework Regulation.

While most countries have similar average exposures to transition risk, banks' exposures to physical risk greatly depend on their location. Chart 21 compares the share of banks' loan exposures to transition (panel a) and physical risk (panel b) by creditor country. Most countries have similar shares of exposures to high, medium and low emitters, these shares also being comparable with the average euro area results. However, banks located in south European countries, such as Greece, Cyprus, Portugal, Spain and Malta, are significantly more exposed to firms that are subject to high physical risk, not only in comparison with other countries, but also when compared with the euro area average.

Chart 21

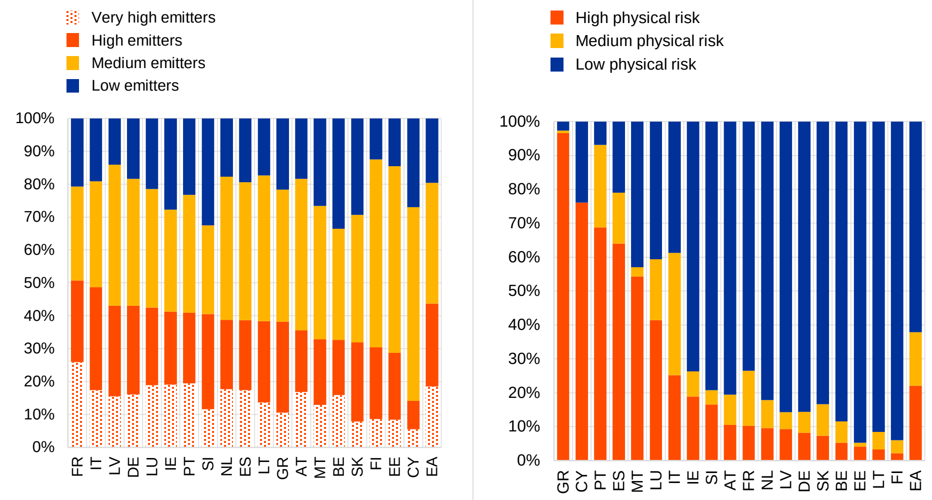
Share of bank exposures exposed to climate risk per country

a) Share of bank loans exposed to transition risk

(percentages)

b) Share of bank loans exposed to physical risk

(percentages)

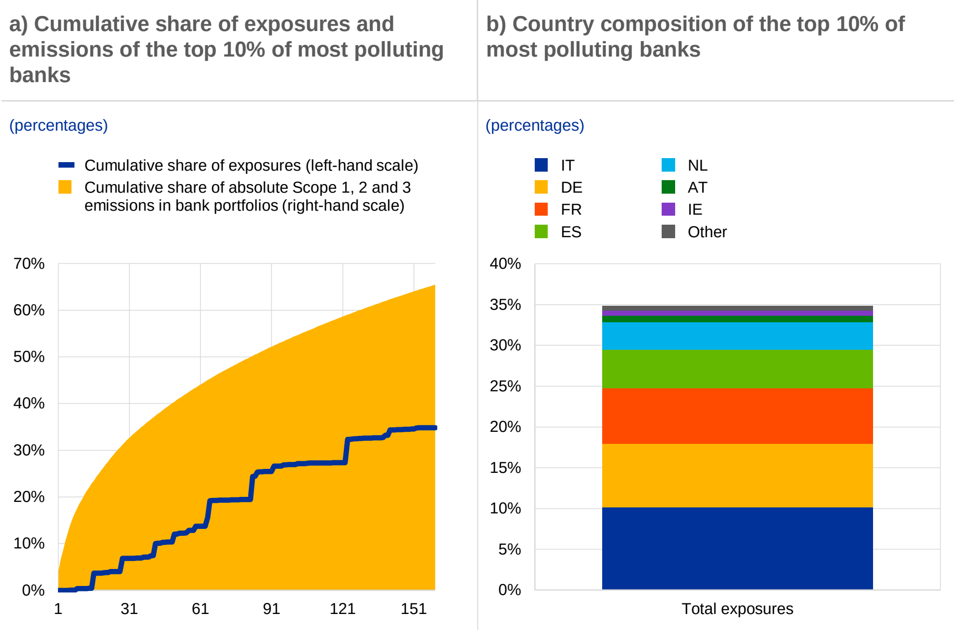


Sources: ECB calculations based on AnaCredit, Urgentem, and Four Twenty Seven data (2018).
Notes: Exposures are categorized as (very) high emitters if a firm's relative emissions are above the 70th (90th) percentile; exposures are categorised as low emitters if a firm's relative emissions are below the 30th percentile. Emission intensities include Scope 1, 2 and 3. Exposures are categorised as high physical risk if a firm's probability of suffering from a wildfire or a river or coastal flood in a given year is over 1%, exposures are categorised as low physical risk if a firm's probability of suffering from a wildfire or a river or coastal flood in a given year is less than 0.1%. Exposures are classified based on euro area creditor countries.

Although banks' exposures to transition risk are homogeneous overall across countries, tail transition risk is concentrated in specific banks and countries: the top 10% most polluting portfolios finance up to 65% of total emissions. Panel a in Chart 22 shows that the 10% most polluting portfolios correspond to 30% of the overall exposures in the euro area and finance almost 65% of total scope 1, scope 2 and scope 3 emissions in absolute terms. Among them, 65 credit portfolios, representing approximately 4% of the sample in terms of number of banks, account for 20% the total exposures and finance around 45% of all emissions. Looking at the geographical composition of these portfolios (panel b in Chart 22), one-third are located in Italy, followed by almost 50% for both Germany and France.

Chart 22

Share of exposures subject to high transition risk



Source: ECB calculations based on Four Twenty Seven and AnaCredit data (2018).
Notes: Absolute Scope 1,2 and 3 O2t emissions are presented.

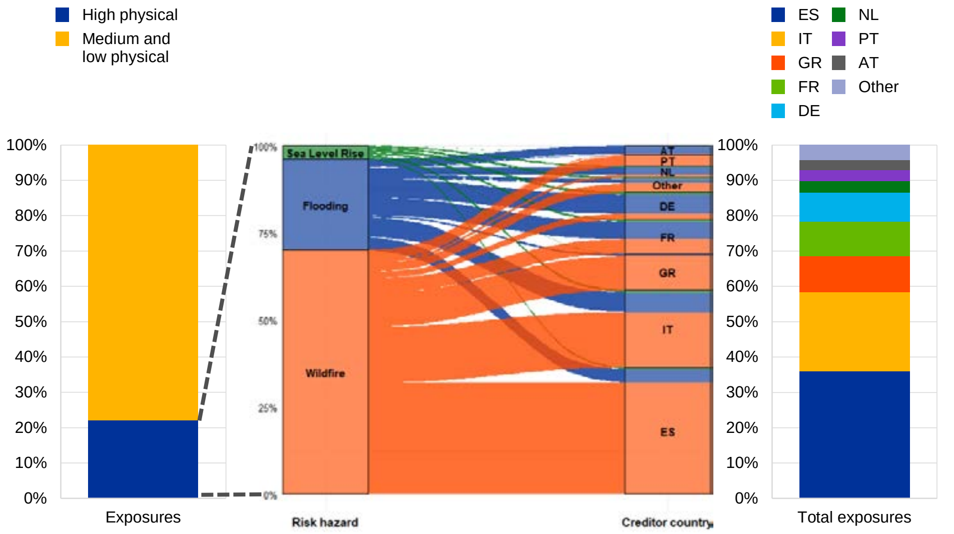
Physical risk is also extremely concentrated in specific areas: 22% of euro area bank exposures are affected by high physical risk, mostly driven by wildfires and affecting southern European countries. The middle panel in Chart 23 classifies these 22% high risk exposures according to the main type of physical risk which the firms holding these exposures are subject to. Most exposures belong to firms who are exposed to only one type of hazard event. More than half of these exposures are held by firms subject to increased risk of wildfires, whereas the other bulk relates to firms relatively prone to suffering from floods. Only a small fraction of the sample is highly exposed to sea level rises.

Chart 23

Share of exposures subject to high physical risk

Share of high physical risk exposures (left-hand side) and country composition of high physical risk exposures (right-hand side)

(percentages)



Source: ECB calculations based on Four Twenty Seven and AnaCredit data (2018).
Notes: Absolute Scope 1,2 and 3 t/CO2 emissions are presented. For the purposes of our analysis, exposures are categorised as high physical risk for firms in the sample for which the probability of suffering from a wildfire or a river or coastal flood in a given year is over 1%.

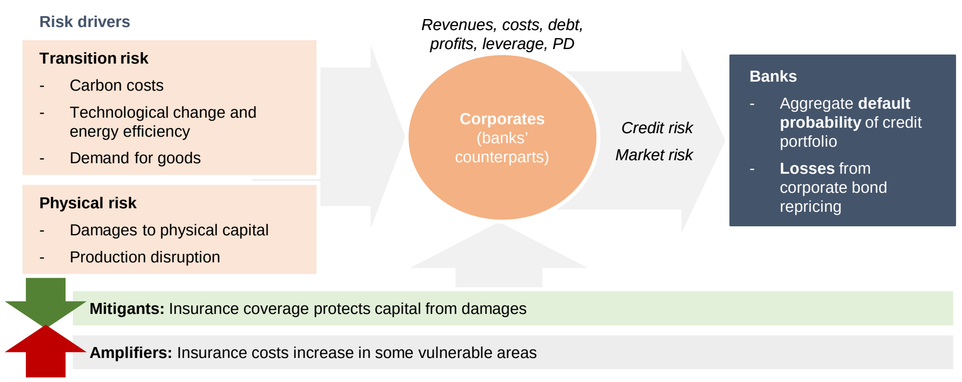
5 Transmission to firms

The climate stress-test assesses the impact of climate-related risks on the profitability and solvency of NFCs. Based on granular information on individual firms' carbon footprint and vulnerability to physical risk, the first part of the stress test evaluates their resilience to transition and physical risks, finally estimating how their possible default is differently affected through time and under different scenario assumptions.

The modelling framework translates climate risk drivers into the main balance sheet indicators for NFCs, also allowing for the role of mitigants and amplifiers. To account for the impact of transition risk, the models include carbon costs, technological change and energy efficiency, and how these are projected to change over time in the different climate scenarios. The transmission of physical risk is based on the quantification of future damage to physical capital due to climate-related natural catastrophes, as well as on their potentially disruptive effects for firms' production. On the one hand, the role of mitigants is reflected in the role played by corporates' insurance coverage, which may protect physical capital from damage; on the other hand, the impact of climate risks may be amplified due to increasingly high insurance costs, especially in certain vulnerable areas and particularly in the hot house world scenario. A schematic view of the modelling framework is represented in Chart 24.

Chart 24

Schematic overview of climate risk transmission to firms through credit risk



Source: ECB.

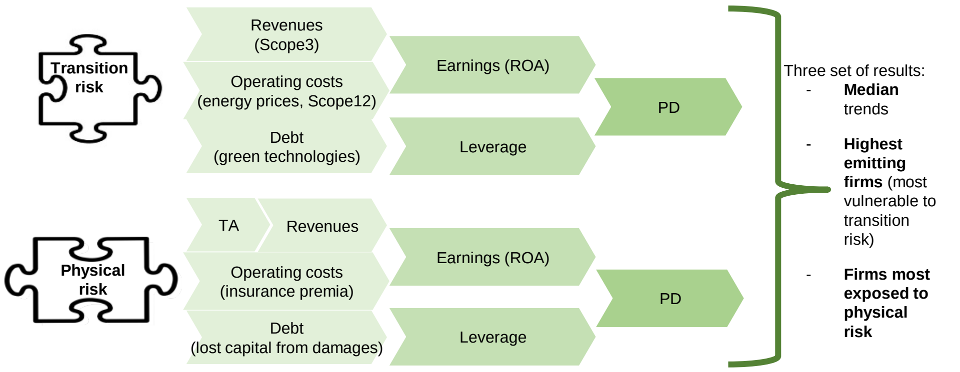
Chapter 6 will describe how default probabilities for NFCs translate into credit and market risk impacts on the banking sector, while the current chapter focuses solely on transmission to corporates. The subsequent sections will describe the methodology applied to derive corporates' balance-sheet information, and will also present the results for different sets of European firms: more details on the analytical framework, equation estimations and projections are given in Appendix B.

5.1 Impact of climate risk on NFC financials

The methodology seeks to evaluate how transition and physical risks affect the probability of default (PD) of individual firms through changes in their profitability and leverage. The main findings are shown and discussed for different subsamples of the dataset: the median European firm, the highest emitting firms (i.e., those firms that are relatively more affected by transition risk), and the firms that are most exposed to physical risk. Chart 25 displays the cascade for the estimated and projected equations that are derived for NFCs.

Chart 25

Schematic overview of climate risk transmission to firms through credit risk



Source: ECB.
Note: Although the effects of transition and physical risk on firms' fundamentals are represented separately here for clarity, all the equations are estimated jointly.

The effects that transition risk has on the main components of firm profitability (i.e., revenues and operating costs) and leverage are both supply and demand driven. On the supply side, changes in production costs are driven by carbon prices that affect firms' operating expenses proportionally to their specific Scope 1 emissions. In this framework, an increase in carbon prices is assumed to reach all firms in the economy in a form of a flat carbon tax on their Scope 1 (direct) emissions. The impact of 'direct' carbon taxes on costs depends to a large extent on the carbon price path carved by the climate policy across the scenarios, The climate policy mix also affect the energy costs of firms, which increases as a function of their Scope 2 emissions, which are used as a proxy for energy consumption. Energy costs are also influenced by the impact of the green transition on country-level energy mixes and the movement in prices induced by technological developments. In other words, we expect that the potential introduction of a carbon tax would increase the costs for firms, especially if they operate in polluting sectors. However, in a transition scenario this cost increase may be offset by a greener, more efficient and cheaper energy mix in subsequent years as well as the adoption of carbon removal technologies.

On the demand side, the effects of the transition are captured via modelling the impact of a carbon price on sales of carbon-intensive goods. More specifically, the increase in carbon prices is assumed to be a flat carbon tax on direct emissions of a Pigouvian nature, raising the cost of purchasing goods whose consumption emits greenhouse gases into the atmosphere. Firms' revenues may decline as a result, with the decrease being a function of the intensity of their Scope 3 emissions.

Finally, leverage may also increase under the transition scenario given that firms would have to invest to replace their existing production processes and switch to technologies that are friendlier to the environment. For the economy to reach the 2050 goals under the two transition scenarios firms must reduce their carbon footprint. For this decrease to be achieved it is assumed that firms must invest in the adoption of more sustainable production technologies (e.g. carbon removal) that will allow them to cut their carbon footprint. Firms may be required to raise additional capital to finance these investments, thus rising their leverage profile.

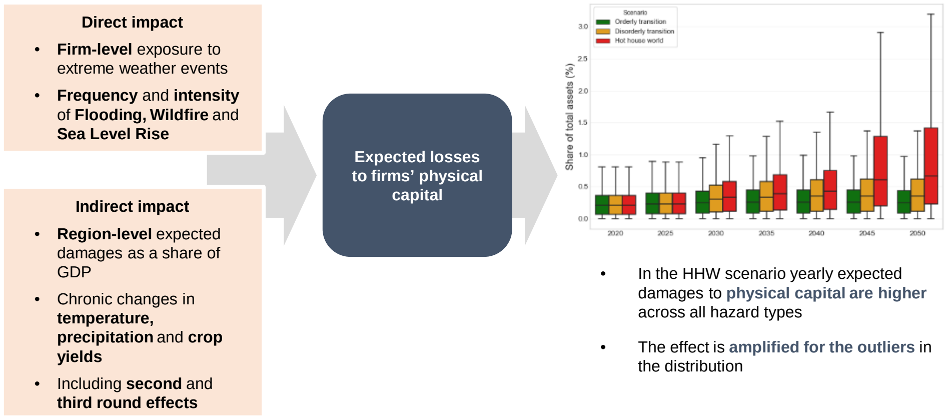
Physical risks directly affect firm revenues and operating expenses. Insurance premiums and maintenance costs would increase in line with the magnitude and frequency of natural disasters, thereby leading to higher operating costs. Natural catastrophes generate physical capital losses, which might eventually require additional investments, exerting upward pressure on leverage. At the same time, revenues would decrease as the physical capital losses would result in a decline in production capacity.

5.2 Calculation of expected losses from physical risk

The calculation of expected losses from physical risk combines direct impact on firms' exposure to extreme weather events with indirect impact, such as the expected damage at the regional level as a share of GDP. The modelling framework incorporates these direct and indirect effects to compute the expected losses to firms' physical capital, which leads to two key findings. First, damage across all hazard types would be higher in a disorderly transition as compared with an orderly transition scenario, while the hot house world (HHW) scenario would give the highest results. Second, these effects are amplified for tail-risk firms in the no transition scenario, thus confirming that physical risk has the potential to drive financial instability. Chart 26 presents a schematic overview of the calculation of expected losses from physical risk.

Chart 26

Schematic overview of the calculation of expected losses from physical risk



Source: ECB calculations based on NGFS scenarios (2020b) and Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).

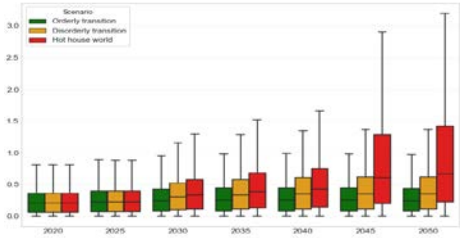
Wildfires are the hazard that affect the widest geographical area in our sample European firms, when compared to floods and sea level rise. Chart 27 displays three boxplots for the projected path of expected losses from wildfires, floods, and sea level rises, respectively. For each source of physical risk, damage is plotted for the three climate scenarios. Damage to physical capital is reported as a share of total assets and is shown to be higher under a hot house world scenario for all types of natural disasters. However, it is worth noting that these effects are significantly amplified by outlier firms in the sample, especially in the long run, if climate mitigating policies are not introduced. That means that, even if these extreme events are expected to affect a relatively low number of firms, the transmission channel to the rest of the economy (through financial exposures) might greatly amplify the aggregate impact on the system. Floods also have significant potential to destroy physical capital at a level higher than sea level rises given the highly localised nature of the latter. Contrary to floods, wildfires are more spread events affecting a wider geographical area within Europe.

Chart 27

Expected losses by hazard type: highly exposed firms – damage from natural hazards

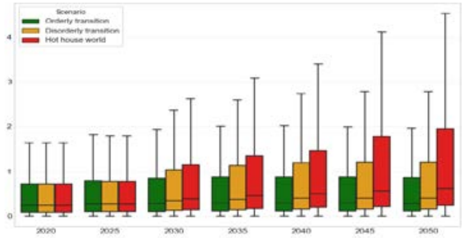
a) Wildfires

(share of total assets)



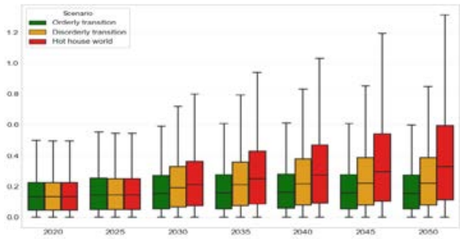
b) Floods

(share of total assets)



c) Sea level rise

(share of total assets)



Source: ECB calculations based on NGFS scenarios (2020b) and Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).

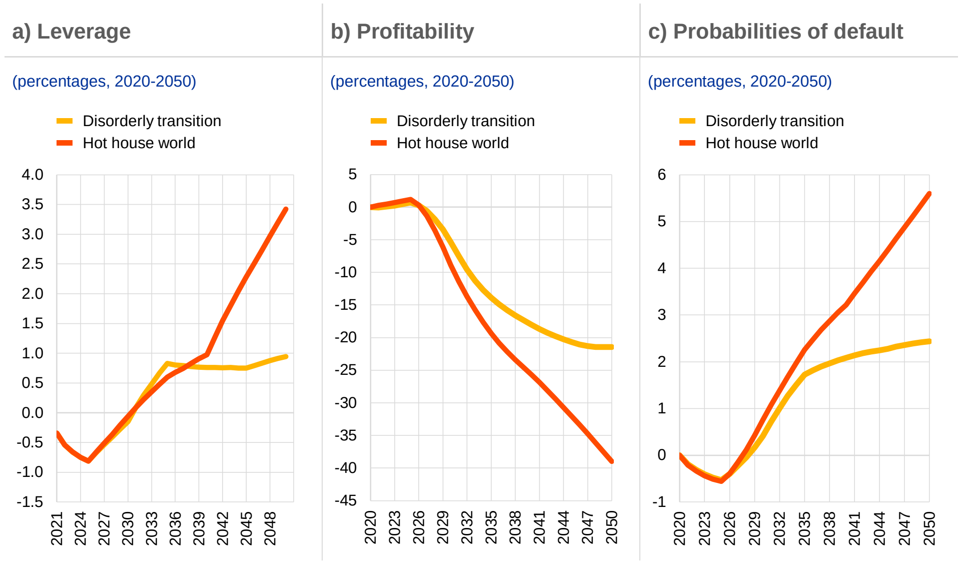
5.3 Impact on the median European firm

Overall, the median European firm is less indebted, more profitable and has a lower probability of default at the end of the horizon under the orderly transition scenario as compared with the two adverse scenarios. Under the hot house world scenario, leverage would strongly increase, especially in the second half of the time horizon, due to significant amounts of lost capital from the increased magnitude and frequency of natural disasters. Additionally, under the same scenario profitability would deteriorate substantially by up to 40% as compared with an orderly transition, due to production disruptions. As a result, if no policy action is taken to mitigate climate change default probabilities could be up to 6% higher in 2050 as compared with the orderly transition scenario. Chart 28 also shows that an orderly transition is clearly preferable to a disorderly or delayed transition, as the latter would result in higher leverage, lower probability and higher PD compared to the orderly scenario.

The short-term costs of an orderly transition are more than offset by the long-term benefits of policy action to mitigate climate change. Chart 28 shows that firms' default probabilities are slightly higher under the orderly transition scenario as compared with a disorderly or no-transition scenario: this reflects the costs that firms would have to face to comply with green policies, in particular driven by carbon taxes and technological substitution. However, these costs are more than offset in the medium to long run by the benefits of reduced physical risk and a more efficient and cheaper energy mix.

Chart 28

Projected results for the median European firm



Source: ECB calculations based on NGFS scenarios (2020b), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).
Note: All charts display median percentage changes under the disorderly transition and hot house world scenarios relative to baseline (orderly transition).

Leverage dynamics are primarily driven by implementation of the requisite investment projects in green technologies and by the debt that is incurred to cover physical damage. Leverage dynamics are affected in two ways. First, a under the transition scenarios we assume that firms at the onset of transition take out debt to invest in green technologies that will allow them to achieve the necessary emission reductions. Under the orderly transition scenario this change takes place in the 2020s, while under the disorderly scenario it occurs in the 2030s. Second, leverage increases gradually as physical damage accumulates, thus adding pressure to firms' debt levels. This effect is more pronounced under the hot house world scenario and becomes significant in the second half of the projection horizon.

The leverage change over time indicates that the investments needed to replace technologies with climate-friendly options are affordable for the median firm, and cheaper than the costs of sustaining increasingly higher damage from physical risk. For the median firm, leverage is less than 1% higher under the orderly transition scenario than under the hot house world scenario at the peak of the transition: this implies that the costs of technological substitutions would be limited as compared with the overall debt levels of a company. However, leverage becomes approximately 3.5% lower with orderly transition as compared with the hot house world in 2050, thus signalling that the long-term impact from physical risk on firms' leverage is expected to be more substantial than the impact from transition risk.

The effects of transition and physical risks on profitability also point to the benefits of early policy action, and show potentially significant impacts under the adverse scenarios, mainly driven by shocks to revenues and operating costs. It is only in the first few years that the profitability of the median firm is slightly higher in the hot house world than under the orderly transition scenario, but the effect is reversed shortly thereafter and by 2050 profitability is expected to drop by 40% compared with orderly transition if no policy action is taken. This improvement in firms' profitability under the orderly transition scenario is partly due to the efficiency gains from the green transition, and partly to the benefits of less damage from physical risk. This dynamic is visible also when looking at the disorderly transition scenario, which also shows a fall in profits as compared with orderly transition and is driven by a less efficient energy mix. However, and differently from the hot house world, under a disorderly transition scenario the relative difference in profits compared with orderly transition stabilises at the end of the period given that the transition would have been achieved even here and because of the limited effects from physical risk compared with the hot house world.

The projected PDs combine the results for leverage and profitability and show that the potential impact of no climate action could be detrimental for firms' creditworthiness in the long run. The median firm would have a slightly higher PD (~0.5%) with orderly transition during the policy implementation phase (the first 10 years of the time horizon) as compared with the hot house world, but this effect would be quickly reversed, leading to PDs becoming approximately 5.5% higher by 2050 in the hot house world as compared to orderly transition. The orderly transition scenario also shows clear benefits in terms of PDs as compared with a disorderly transition scenario under which they would increase by 2050 by approximately 2.5% as compared with an orderly transition.

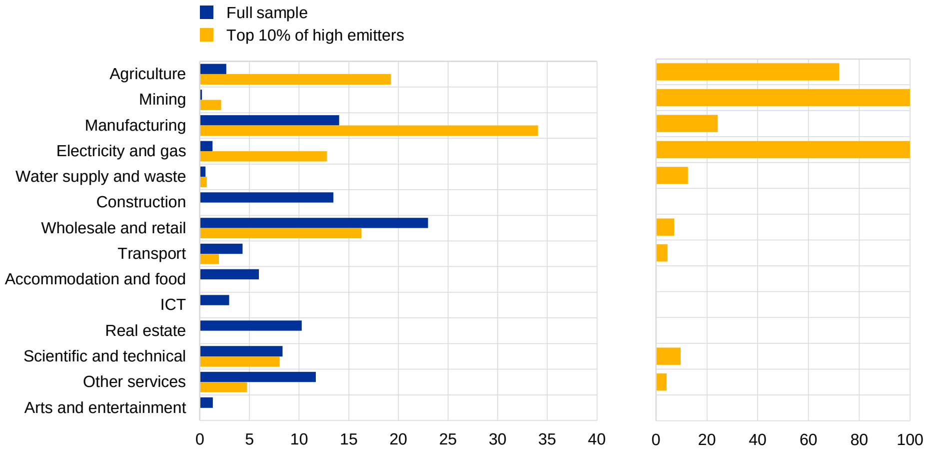
5.4 Impact on the highest emitting firms

The sectoral breakdown of high-emitting firms as compared with the entirety of the sample reveals a higher concentration of transition risk in specific sectors. High emitting firms are defined in our framework as the top 10% of firms with the highest intensity of emissions. In Chart 29 (left panel), comparison of the sectoral breakdown for the entire sample with the high emitters shows that transition risk is heavily concentrated in agriculture, mining, manufacturing and electricity and gas, which together account for almost 70% of the high-emitting firms for all that they constitute just 18% of the entire sample. The right panel in Chart 29 presents the percentage of firms in each sector that are high-emitters. For example, it shows that while mining firms represent a small percentage of the total sample, every single mining firm part of the high emitters subsample.

Chart 29

Sectoral breakdown comparison between the full sample and top 10% of high emitters

Breakdown of the percentage of firms by sector between the full percentage of firms within the sector that belong to the sample and the top 10% of high emitters (left panel) and percentage of the firms that belong to the top 10% of high emitters within sector (right panel)



Source: ECB calculations based on NGFS scenarios (2020b), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).

The impact of climate risks on the highest emitting firms is greater than for median firms, and is reflected in higher leverage and more pronounced differences across scenarios. Chart 30 presents the median results across high-emitting firms. What differentiates high-emitting firms from the rest of the sample is the need to raise substantially more debt during the transition phase to replace technologies with eco-friendly options.

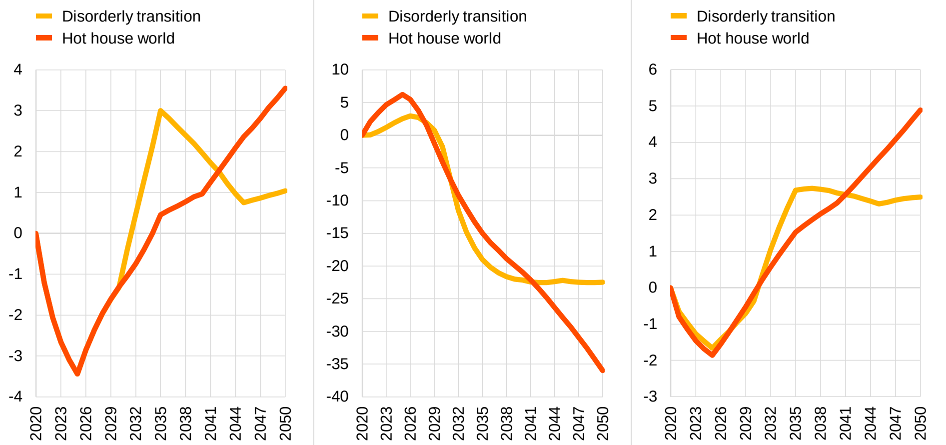
Chart 30

Projected results for carbon-intensive European firms

All charts display median percentage changes under the disorderly transition and hot house world scenarios relative to the baseline (orderly transition)

a) Leverage | b) Profitability | c) Probability of default

(percentages, 2020-2050) | (percentages, 2020-2050) | (percentages, 2020-2050)



Source: ECB calculations based on NGFS scenarios (2020b), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).
Note: For the purposes of this chart, carbon-intensive firm is taken to mean the median of the top 10% of the most carbon-intensive firms.

The leverage dynamic is more prominent than for median firms and reflects the need for high-emitting companies to raise more capital to replace their technologies and reduce emissions. This leads to a higher debt increase in the short to medium term, with both an orderly and disorderly transition. For example, high-emitting companies have to raise over 3% more debt to achieve orderly transition to a green economy, as compared with a 1% increase for median firms. The figures are similar in the case of a delayed transition. However, despite a more costly transition for this set of companies, the hot house world scenario still underperforms in the long run: by 2040 leverage in the hot house world would be higher than under the other two scenarios, with the trend increasing, thus highlighting once again the relevance of physical risk in the long run as compared with transition costs.

The profitability of high-emitting firms is also significantly impacted in the short run in the case of transition; the latter would, however, have strong long-term benefits. High emitting firms would be more affected than median firms at the beginning of the period in the case of an orderly transition given the effect of the carbon tax, which affects both revenues and operating costs. However, the profitability path also shows the importance and significance of energy efficiency gains over the time horizon, combined with benefits of reduced physical risk. By 2050, profitability is projected to be 22.5% and 35% lower under the disorderly and hot house world scenarios as compared with orderly transition.

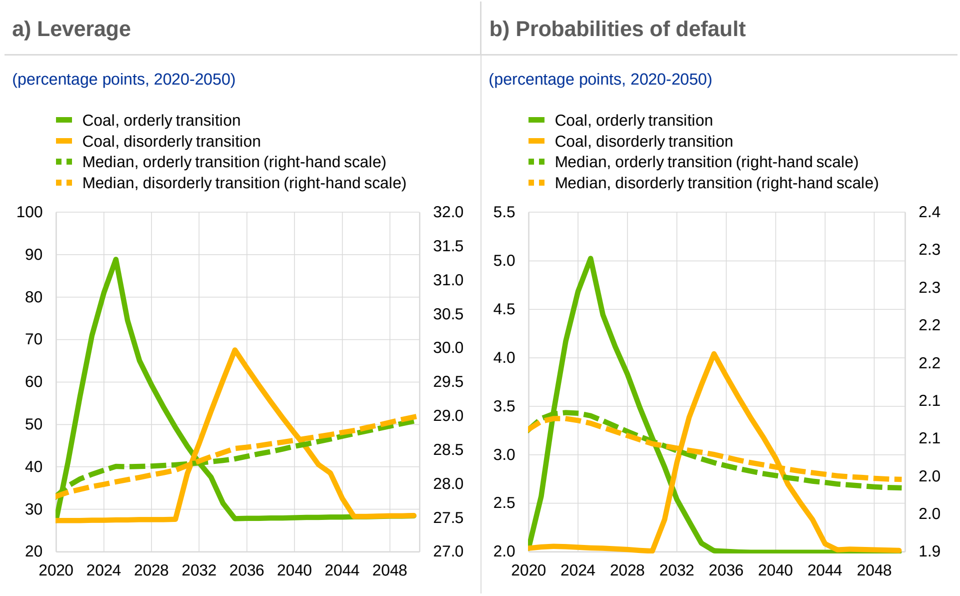
The increase in PDs with orderly transition at the beginning of the period is higher for high-emitting than for median firms, although it is still offset by the

long-term benefits of climate mitigating actions. The transition costs for high-emitting firms would lead to an increase in their PDs of 2% with respect to a no policy action scenario in the short term, as compared to an increase of 0.5% for median firms. A higher increase in default probabilities would also be the case under the disorderly transition scenario, again as compared to median firms. By 2040, however, PDs in the hot house world would be higher than under the other scenarios, and by as much as 5% as compared with orderly transition.[29]

The highest emitting sector is mining, in particular coal mining: in this case the increase in leverage and probability of default is extreme and would likely lead either to the default of such businesses or to their complete reconversion to different sectors. Compared to the rest of the economy, the emissions intensity of coal mining is several orders of magnitude higher even than the next most polluting sector. In terms of Scope 3 emissions, the mining of coal produces upward of 20,000 tonnes of carbon dioxide per million dollars of revenue whereas all other sectors of the economy fall below 3,000 tonnes for the same statistic. Comparing the results for coal-mining firms (NACE B05) with the results for the remainder of firms also shows that coal mining is a strong outlier, especially in terms of the increase in their leverage and PD during the transition. Chart 31 shows the leverage and PD for coal-mining firms for the orderly and disorderly transition scenarios.

Chart 31

Projected results for coal mining activities (NACE B05) as compared with the median firm



Source: ECB calculations based on NGFS scenarios (2020b), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).

The transition of coal-mining firms to a greener economy would require them to triple their debt and raise their leverage from 27% to 70% or 90% under the orderly and disorderly transition scenarios, respectively. At the same time, this

[29] Please note that high-emitting firms are subject to less physical risk than the median firm: this explains the relatively lower increase in PDs by 2050 in the hot house world as compared to orderly transition (a 5% increase for high-emitting firms, as compared with a 5.5% increase for median firms).

would drive their PDs up to 5% and 4% respectively, which would represent a 150% and 100% increase respectively as compared with their current values. These two results combined point to the challenge for coal-mining firms to transition and reduce emissions in line with Paris Agreement targets. The acute impact on leverage and PDs of coal mining firms is mainly driven by the need to reduce their very high Scope 3 emissions. To achieve this reduction coal-mining firms would need to invest very large sums in carbon removal technologies that offset the burning of the coal that they extract or invest in changing their business model towards another sector of activity.

Coal mining firms are shown to be faced with great survival or reconversion challenges in the case of a transition scenario, however the current framework should be refined in the near future to better capture sector-specific dynamics. The current exercise does not take into account the reduced demand for coal in the future in the case of a green transition, and the framework modelled here does not distinguish the reactions by economic sector – although it is based on firm-specific information. Although this exercise and its application already show the higher level of leverage and default probabilities a transition would entail for this sector, thus posing a survival at risk, a more refined methodology is needed to better identify winning and losing economic sectors, how they could be affected by differentiated demand shocks and consequently how they could adapt differently to changing policy conditions.

5.5 Impact on firms highly exposed to physical risk

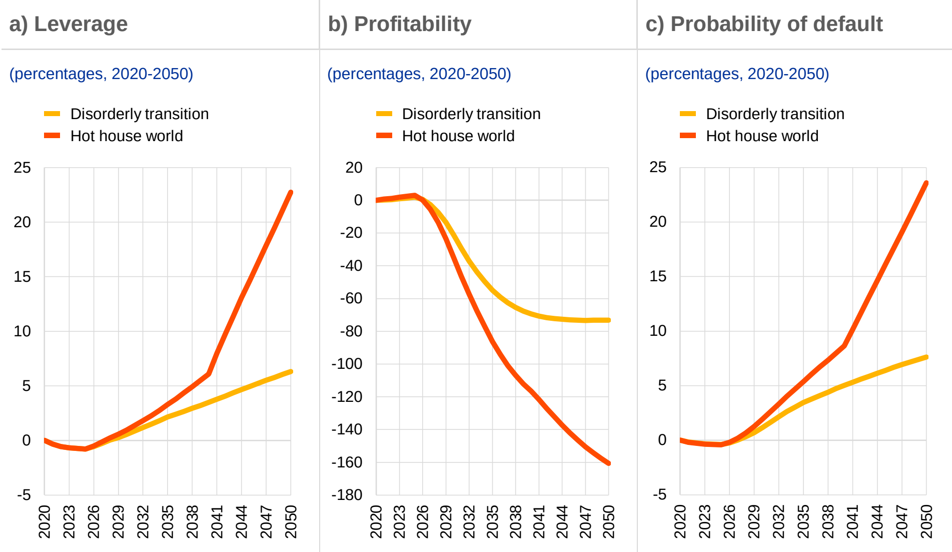
The firms that are most vulnerable to physical risk would benefit strongly from a timely and orderly transition given that the consequences of more frequent and severe natural disasters if no policy action was taken would significantly affect their financial performance. The set of firms most vulnerable to physical risk in this study includes the 10% of firms that are most exposed to physical damage over the 30-year projection horizon.[30] Chart 32 shows the change over time for leverage, profitability, and default probabilities for the set of high-physical risk firms with respect to the orderly transition scenario. Although these charts show high costs for an orderly transition in the short run, such costs pale in comparison with the costs of unfettered climate change in the medium and long run.

[30] The calculation of physical damage is described in Section 5.2.

Chart 32

Projected results for firms most vulnerable to physical risk

All charts display median percentage changes under the disorderly transition and hot house world scenarios relative to the baseline (orderly transition)



Source: ECB calculations based on NGFS scenarios (2020), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).
Notes: In defining the high-physical-risk firms, we took the 10% of the firms with the highest expected damage over the course of the entire period. Here, we show the median of that sample.

Firms highly exposed to physical risk would suffer from a strong increase in leverage over the medium-to-long run, due to increased damages from natural catastrophes should climate change not be mitigated. By 2050, leverage is projected to be 22.5% higher in the hot house world as compared to orderly transition. For both the median firm and carbon-intensive firms this figure is about 3.5%, which is indicative of the devastating impact of physical risk on the firms most vulnerable to it. This effect is mainly driven by damage to physical capital, while transition risk in this case plays a very minor role.

High-physical-risk firms would also experience the largest drop in profitability as compared with other firm samples in the event that no policy action is taken. Barring a slight increase in profitability in the hot house world over the first few years, profitability drops very significantly under the same scenario and is projected to be 1.6 times lower by 2050 than with orderly transition. The profitability dynamics are mainly driven by significant increases in operating costs, as firms would have to pay a premium in order to maintain the same insurance coverage. At the same time, as firms suffer from increasingly more severe and frequent natural disasters, they would lose parts of their physical assets and thus experience disruptions in their production chain, leading to a decline in revenues.

The probability of default of high-physical risk firms is projected to increase by 2050 by almost 25% under the hot house world scenario, a figure that is five times larger than what is observed for median and high-emitting firms. The increase in projected PDs over the forecast horizon under the disorderly transition scenario is also significantly higher than that observed for median and high-emitting firms under the same assumptions: this suggests that physical risk prevails over transition risk in the long run, especially under the hot house world scenario, and may pose serious financial stability concerns. Finally, given the irreversibility of climate change, should policies to mitigate it not be introduced, the long-term consequences of physical risk are expected to keep increasing over time even beyond the time horizon considered in this study.

5.6 Cross-country and sectoral differences

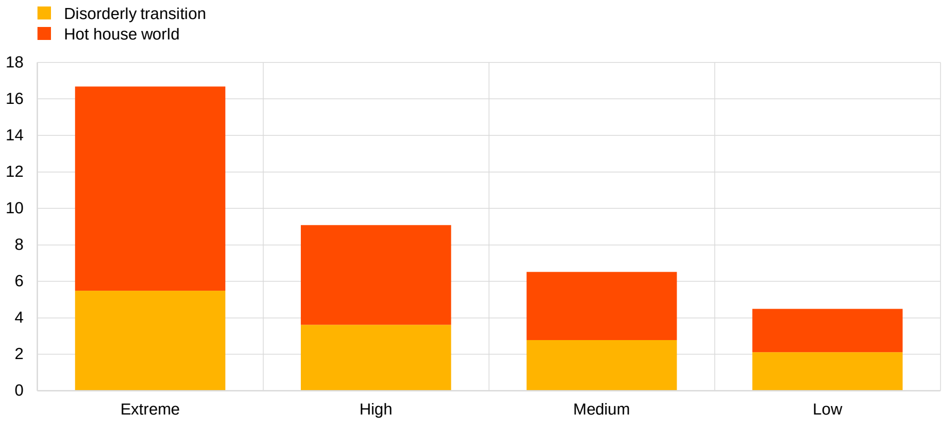
The possible financial stability implications of climate risks are mainly driven by physical risk in the long run in the event of no climate policy action and are concentrated in certain geographical areas. The comparison between the changes in the probability of default under different scenarios and for different sets of firms has shown that physical risk, if not mitigated, would have the strongest long-term negative effects. Additionally, the frequency and severity of adverse climate events is uneven across Europe, with southern European countries particularly affected by water stress, heat-stress and wildfires, and middle-to-north European countries mostly affected by flood risk. In Chart 33, regions are clustered into four categories based on their level of physical risk. When looking at the average probabilities of default by the end of the stress-test horizon relative to the orderly transition, it becomes evident that the expected effects of physical risk can range from quite low (~4% higher PDs in a hot house world as compared with orderly transition) to extremely disruptive (over 16%).

Chart 33

Probabilities of default relative to the orderly transition scenario

Median percentage changes under the disorderly transition and hot house world scenarios relative to the baseline (orderly transition)

(percentages, 2050)



Source: ECB calculations based on NGFS scenarios (2020), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).
Notes: Countries are clustered in four regional clusters groups based on their level of physical risk.under the hot house world scenario. These figures are based on the average for the entire sample for each regional cluster.

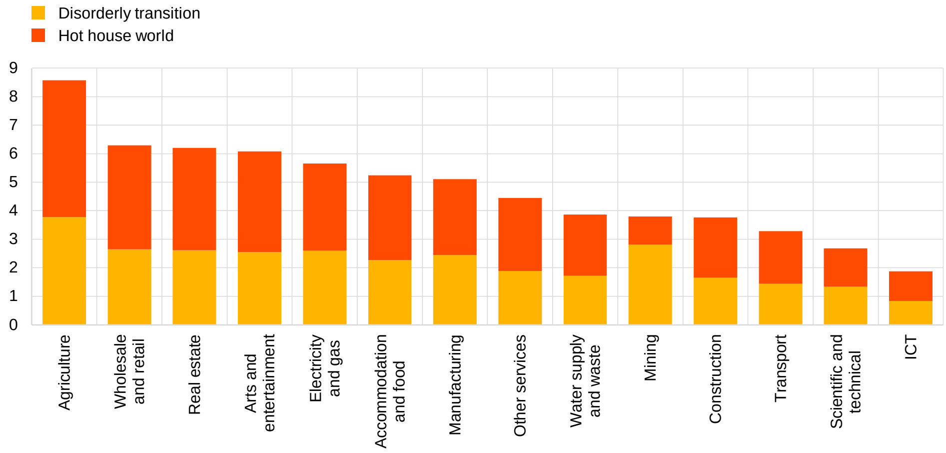
The variation in the end-of-horizon probabilities of default is larger between regions (Chart 33) than between sectors (Chart 34). Specifically, while there are regions where the average PD differentials in the hot house world scenario as compared with the orderly transition range from around 4% to 17%, the variation between sectors is much smaller, ranging from 2% in information and communication to 8.5% in agriculture. This is largely because physical risk is regionally concentrated while transition risk is mostly sector-based, and the former has a more disruptive effect than the latter, especially when looking to the end of the stress-test horizon.

Chart 34

Probabilities of default relative to the orderly transition scenario by sector

Median percentage changes under the disorderly transition and hot house world scenarios relative to the baseline (orderly transition)

(percentages, 2050)



Source: ECB calculations based on NGFS scenarios (2020), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).
Note: These figures are based on the median for the entire sample for each country.

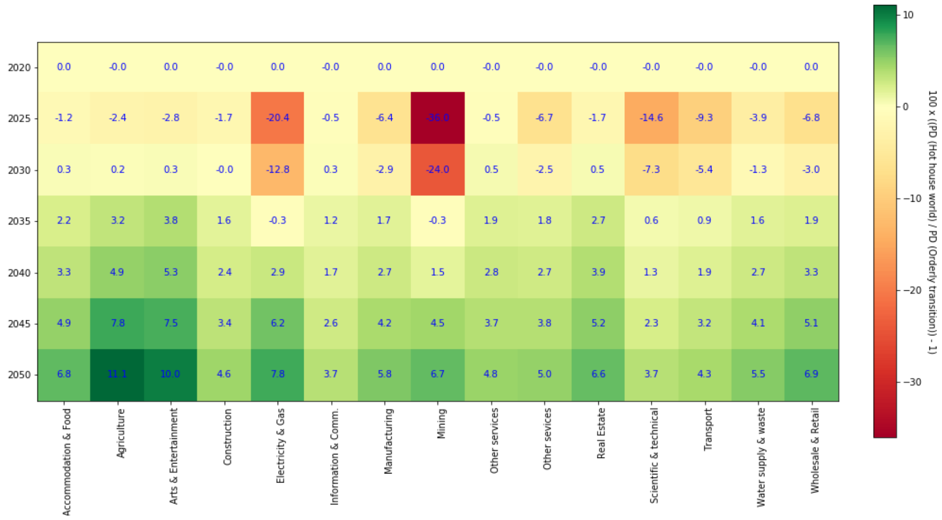
When looking at sectoral differences over time, the results indicate that mining and electricity and gas would suffer the most from transition to a green economy, whereas agriculture would benefit the most from reduced physical risk in the long run. Chart 35 shows the differences in PDs under the hot house world scenario as compared with orderly transition, broken down by year and sector, thus making it possible to compare the changes over time of PDs at the peak of the orderly transition in 2025 with the same PDs at the end of the horizon, when physical damage would have increased in a hot house world. Negative values thus indicate the costs of transition in the short run, while positive values indicate the benefits of a green transition under a no-policy action scenario. Firms in the mining, electricity and gas sectors are most at risk because of high transition costs, while firms in the agriculture sector benefit the most from averting the physical damage that would occur in a hot house world. Overall, the impact of transition scenarios on firm financials is highly heterogeneous across sectors: however, while some firms are hit harder by transition costs than others, all sectors ultimately benefit from making the transition.

Chart 35

Changes in sectoral default probabilities[31]

Changes relative to 2020 values, calculated for a hot house world scenario relative to an orderly transition scenario

(percentage difference between 2020 and 2050)



Source: ECB calculations based on NGFS scenarios (2020), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).

5.7 Benefits of a green transition

Overall, the medium-to-long-term benefits of a green transition outweigh the short-term costs, especially for the firms most vulnerable to physical risks. Chart 36 presents the percentage differences in PDs with respect to the start point (2020), across the three scenarios covered by this analysis and for two different sets of firms: the median firm across the entire sample, and the median firm across the 10% of firms exposed to highest physical risk. The chart shows that, for both categories, an orderly transition to a greener economy is the most preferable choice in terms of creditworthiness and default probabilities.

The results also show that, on average, orderly transition to a greener economy brings benefits in terms of default probabilities that are reduced from the current values. When focusing on the median firm in Chart 36, the results show that default probabilities for orderly transition slightly increase in the first 10 years: however, this trend reverses, and by 2050 falls by 4% as compared with 2020. A similar result, although delayed and of a smaller magnitude, can be observed in the case of a disorderly transition. The hot house world scenario would instead see an increase in firm-level PDs over the next 30 years for both sets of firms, due to

31 The arts and entertainment sector appears to be one of the sectors that would benefit the most from an orderly transition. However, this is because the sector has almost no emissions and thus is not affected by transition risk: as a consequence, the PD change under the orderly transition scenario would decrease, thus enlarging the difference between it and the PD under the hot house world scenario (which is driven by physical risk).

increased damage from physical risk in the long run should climate change not be mitigated.

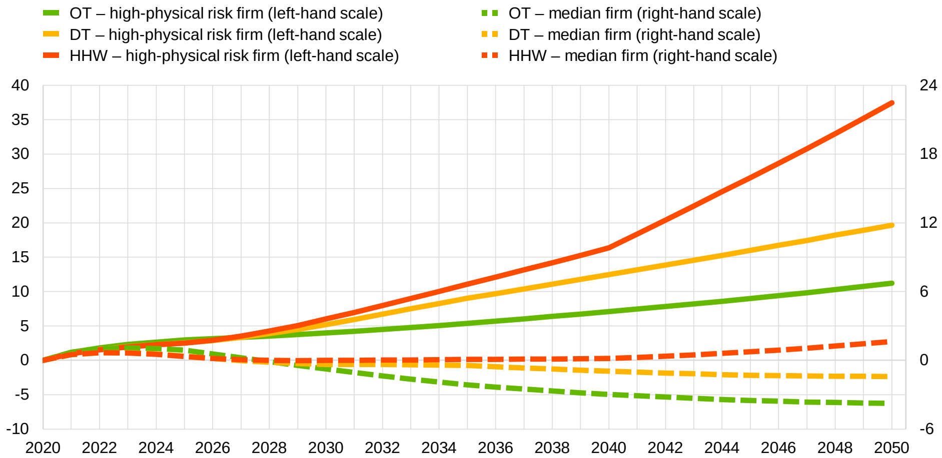
Finally, the disruptive potential of a lack of transition in the medium to long term is significant for firms that are highly exposed to physical risk. For this set of firms the results show extremely small short-term costs for transitioning, but at the same time significant medium-to-long term costs from inaction. Specifically, the probability of default for high-physical risk firms rises by 11%, 20% and 37.5% in 2050 for the orderly transition, disorderly transition and hot house world scenarios respectively. This clearly indicates that the impact on these high-risk firms could potentially be very pervasive, leading to possible financial stability risks for banks highly exposed to those firms through loans or security holdings.

Chart 36

Changes in firms' default probabilities for median and high-risk firms

Changes relative to the start period for the median portfolio, and for the top 10% of firms suffering from highest physical risk

(percentages, 2020-2050)



Source: ECB calculations based on NGFS scenarios (2020), Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).
Notes: For the carbon-intensive firm, we have used the median of the top 10% of the most carbon-intensive firms. In defining the high-physical risk firms, we are showing the median of the 10% of firms with the highest expected damage over the course of the entire period.

6 Transmission to banks

The second part of the ECB stress-testing exercise evaluates the impact of climate risk on the euro area banking system through the credit and market-risk channels. Based on granular information on loan exposures to NFCs and corporate bond holdings of euro area banks, the impact of transition and physical risk on firms is translated into the creditworthiness of banks' credit and corporate bond portfolios under the three climate change scenarios considered in this study.

6.1 Credit risk channel

To quantify the impact on banks' credit risk, the changes in the probability of default (PDs) and loss given default (LGDs) of banks' loan books is derived under different climate scenarios. Furthermore, the analysis combines the projections on PDs and LGDs to estimate the expected losses on banks' corporate credit portfolios at the end of the time horizon (2050). The main findings are presented for the median euro area bank, and by clusters of banks to better capture tail risks in the banking sector.

The results show, across all the different subsamples of banks considered, that there is clear evidence of the benefits of an orderly transition as compared with the other adverse scenarios. The short-term costs of a green transition are more than compensated for by the long-term benefits, while physical risk tends to prevail in the medium to long run if climate policies are not implemented: based on this assumption, the impact on the corporate loan book of the banks most exposed to physical risk could be very significant.

6.1.1 Default probabilities

The proposed approach translates firm-level default probabilities to banks' loan book probabilities of default based on the portfolio composition of banks. For each bank, the probability of default of a specific loan exposure to an NFC is weighted by its relative exposure size within the total portfolio. A bank's overall PD is therefore calculated using the exposure-weighted average of corporate-level PDs.

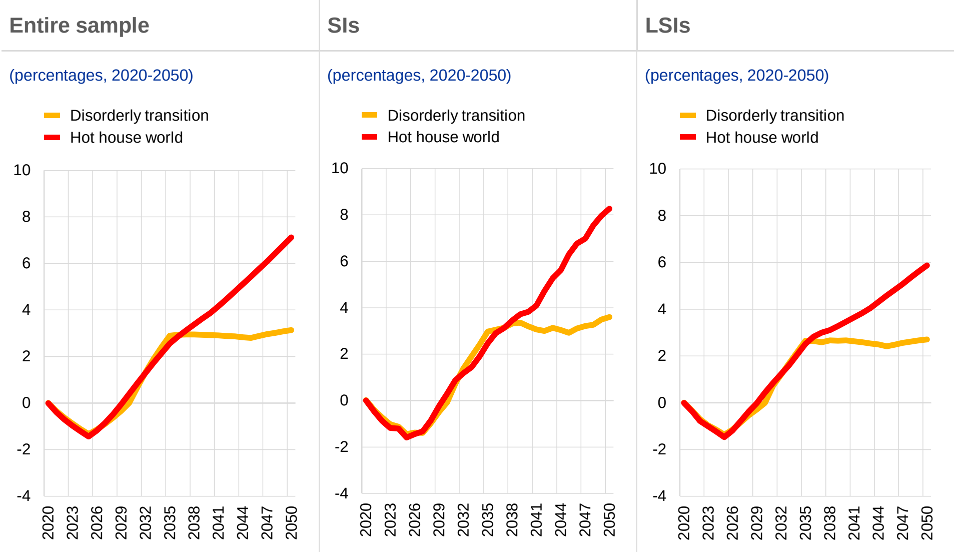
In the short-run banks would suffer from the costs of a green transition; however, this effect is reversed in the medium to long run, thus pointing to the economic benefit of an orderly transition. The first figure in Chart 37 presents the median percentage deviations of probabilities of default under the hot house world and delayed transition scenarios relative to orderly transition (baseline scenario) for euro area banks. Banks would benefit until the beginning of 2030 if the economy does not or delays transition, with a PD that is up to 1.5% lower than under the orderly transition scenario. This effect is, however, more than reversed in the medium to long run. By 2050, median loan portfolio PDs would have increased by 7% in a hot house world relative to the baseline: if the irreversible nature of physical risk is not mitigated, that increasing trend is expected to continue at least at the same pace even beyond 2050. Under a delayed-transition scenario, the relative higher PDs peak in 2035 at around 1% to 2% due to the assumption that firms would finance their transition through an increase in their debt. This financial burden on firms would translate into banks' portfolios. As observed for firms, the impact in the case of a disorderly transition is limited as compared with the impact under the hot-house world scenario, and stabilises at around 3% (as compared with the baseline) in the second half of the projection horizon.

Significant banks are more severely affected under a scenario without transition, resulting in a 2% higher increase in their median PDs under the hot house world scenario by 2050 relative to other banks. The last two figures of Chart 37 present the median percentage deviations in loan portfolio PDs for euro area significant institutions (SI) and non-SIs. Under a hot house world scenario, SIs would experience a more negative impact from physical risk, given that they would be more strongly exposed to firms vulnerable to extreme weather events. If, therefore, climate risks are not mitigated, SIs would experience an increase in median PDs significantly higher than the median increase of the other banks in the sample.

Chart 37

Probabilities of default: percentage changes relative to the baseline scenario

All the charts display the median percentage changes under the disorderly transition and hot house world scenarios relative to the baseline (orderly transition)



Source: ECB calculations based on NGFS scenarios (2020), AnaCredit, Orbis, iBACH, Urgentem and Four Twenty Seven data (2018).
Notes: Banks are classified as significant institutions (SI) based on the definition set out in the SSM Regulation and SSM Framework Regulation. Median bank refers to the median probability of default per year and scenario of the respective sample.

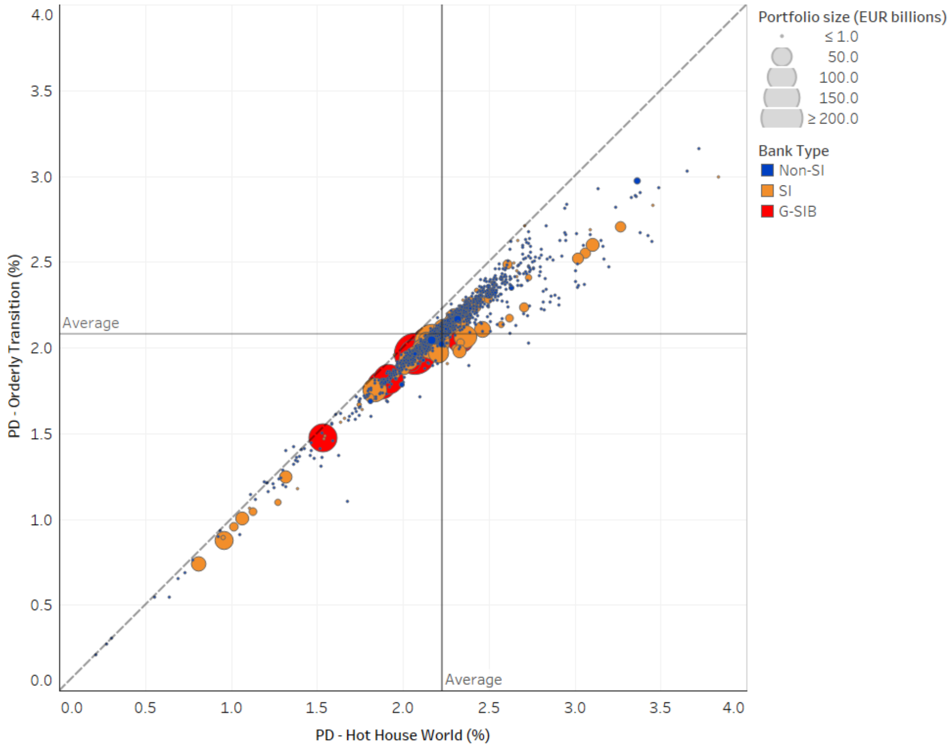
Bank-level results indicate that in 2050 nearly all banks would benefit from an orderly transition as compared with the hot house world scenario. Chart 38 compares the corporate loan portfolio PDs under the orderly transition scenario (y-axis) with the hot house world scenario (x-axis). Banks located below the diagonal line would have their PDs relatively higher under a hot house world scenario, which is the case for all but a few small banks. In terms of PD levels, on average bank-level PDs under the orderly transition scenario would be approximately 2.1% by 2050, while in the hot house world the average PD would be around 2.3%, which represents an increase of 7% (consistently with what is shown in Chart 37).

Chart 38

Probabilities of default by 2050: orderly transition versus the hot house world

y-axis: Orderly transition; x-axis: Hot house world

(percentages)



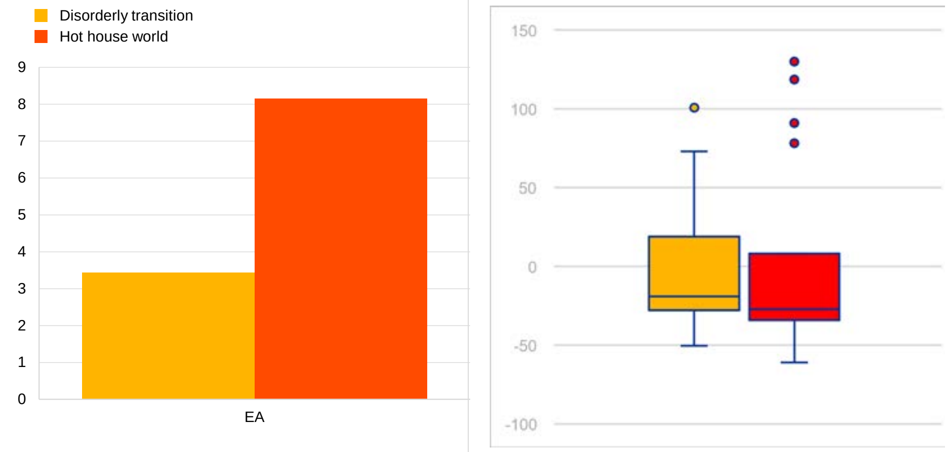
Source: ECB calculations based on NGFS scenarios (2020), AnaCredit, Orbis, Urgentem and Four Twenty Seven data (2018).
Notes: Banks are classified as global systemically important banks (G-SIBs) if, based on various systemic criteria, their failure would trigger a wide financial crisis and threaten the global economy. Banks are classified as significant institutions (SI) based on the definition set out in the SSM Regulation and SSM Framework Regulation. The bigger the size of the bubbles in the chart, the higher the loan exposures to NFCs. Blue bubbles refer to LSIs, yellow bubbles to SIs and red bubbles to G-SIBs.

A hot house world scenario would have a higher and non-linear impact on banks' corporate credit books, with particularly severe effects in some geographical areas. The increase in loan portfolio PDs of an average Euro area bank by 2050, represented in Panel a of Chart 39, would be more than two times higher in a hot house world compared to a disorderly transition scenario, relative to the orderly transition scenario. Panel b illustrates the country-level deviations from the Euro area average in the case of a disorderly transition and of a hot house world scenario, again relative to the orderly transition scenario. Some countries would experience a disproportionally larger deterioration in banks' loan portfolio PDs compared to the rest. This heterogeneous impact would be particularly evident in a hot house world scenario, thus highlighting the non-linear and location-specific nature of physical risk in the medium-to-long run.

Chart 39

Distribution of probabilities of default by 2050

a) Euro area average percentage changes under the disorderly transition and hot house world scenarios relative to the baseline (orderly transition)	b) Distribution of country-level deviations from the Euro area average
(percentages)	(percentages)



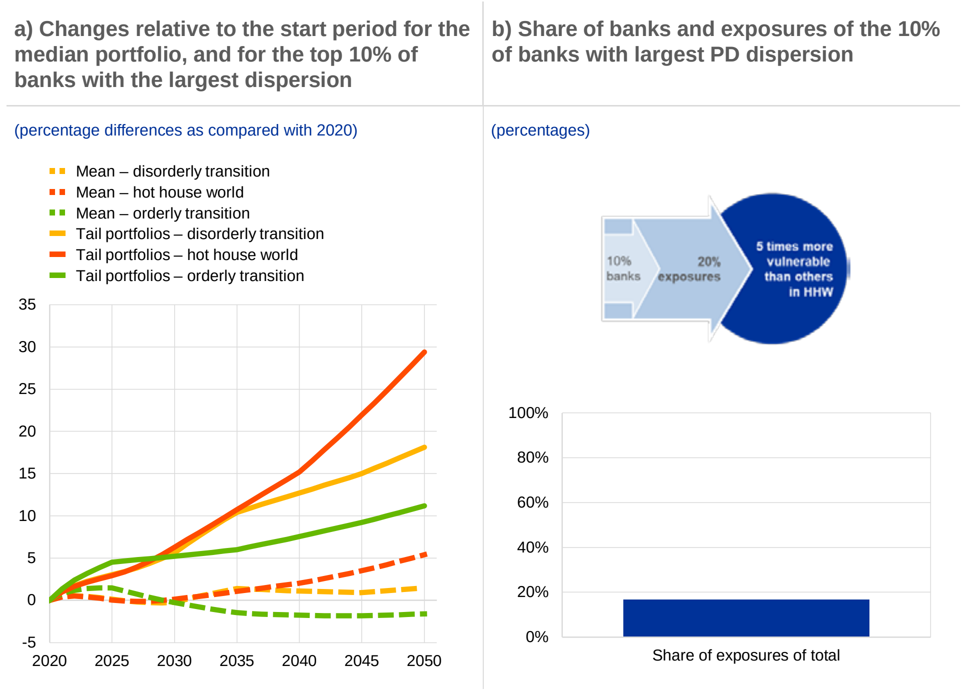
Source: ECB calculations based on NGFS scenarios (2020), AnaCredit, Orbis, Urgentem and Four Twenty Seven data (2018).
Notes: Average refers to the average change in the probability of default of banks' credit portfolios between the respective scenario and the baseline in 2050 and across euro area banks.

If policies to transition towards a greener economy are not introduced, physical risks become increasingly higher over time, with the potential to become very significant. Chart 40 presents the average percentage change in median loan portfolio PDs relative to 2020 values for the top 10% of banks in terms of PD dispersion, and compares it with the same values for the median results across all banks in the sample. In the hot house world, the average increase in PDs by 2050 relative to 2020 would be around five times higher for tail banks as compared with the total sample average, with PDs rising to 30% by 2050. Tail banks would also experience a long-term increase in average PDs under the transition scenarios: this is substantially different from the mean results for the entire sample, for which Chart 40 shows a clear benefit in terms of PD reduction in the event of early and effective climate policies for achieving a green transition.

Tail-risk banks that experience the largest long-term increase in their PDs as compared with 2020 values are domiciled in countries more vulnerable to physical risk. Panel b in Chart 40 presents the share of exposures representing the 10% tail-risk banks. Overall, these banks account for around almost 20% of the total sample exposures, thus pointing to a higher-than-average size.

Chart 40

Projected probabilities of default of banks' corporate loan books



Source: ECB calculations based on NGFS scenarios (2020), AnaCredit, Orbis, Urgentem and Four Twenty Seven data (2018).

6.1.2 Loss given default

The impact of climate change on the loss given default (LGD) of banks' corporate loan portfolios is modelled through a micro and a macro channel. The micro channel captures the deterioration in value of physical collateral due to damage caused by physical risk. The macro channel takes into account the changes in LGD due to macrofinancial shocks focusing in particular on changes in GDP stemming from both transition and physical risks as prescribed by the scenarios[32]. The total change in LGDs for each bank loan is derived by taking the sum of the impact of both channels.

The share of loans protected by collateral is extremely heterogeneous across countries, although it is approximately 50% on average, of which most is represented by physical collateral. Figure 41 presents the share of loans protected by physical and non-physical collateral at country level. Countries with the largest amount of collateral in absolute terms correspond to those that also have the largest exposures, namely Germany, Italy, Spain and France. Among them, the level of protection based on physical rather than non-physical collateral is extremely heterogeneous, with Germany having a much higher share of physical collateral compared with the other three countries. When focusing on relative rather than absolute collateral coverage, the Netherlands, Portugal, Lithuania and Cyprus

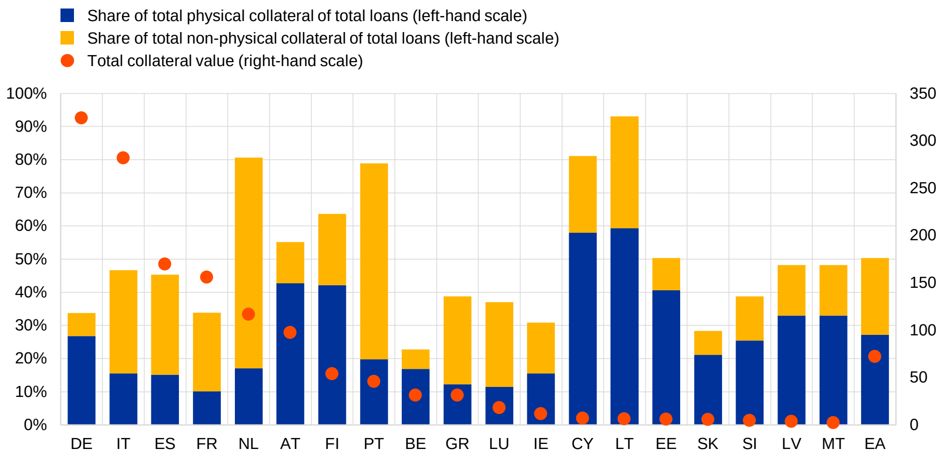
[32] The LGD shocks via the macro channel have been calculated applying the methodology described in ECB/ESRB (2020). The same methodology was applied and described in EBA (2021).

display the highest values, although with very different levels of physical and non-physical collateral.

Chart 41

Share of loans protected by physical and non-physical collateral

(left-hand scale: share of physical and non-physical collateral; percentages; right-hand scale: total collateral value; EUR billions)



Source: ECB calculations based on AnaCredit, Orbis, Urgentem and Four Twenty Seven data (2018).
Notes: Euro area creditor countries are shown. EA corresponds to euro area averages.

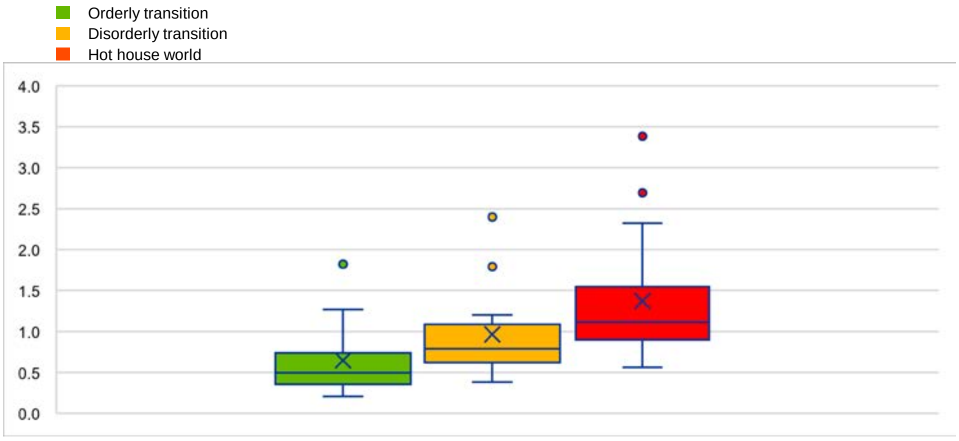
The impact on corporate-credit-portfolio LGDs is mainly driven by damage to physical collateral over the 30-year time horizon. Chart 42 shows the country-level distribution of the increase in portfolio LGDs between 2020 and 2050. Due to the impact of the damage to physical collateral, banks would experience the greatest average increase of their portfolio LGDs in a hot house world. Furthermore, a hot house world would cause bank portfolio LGDs to be more dispersed, thereby affecting bank portfolios in some countries disproportionally worse than in others, highlighting the non-linear nature of physical risk. The fact that higher level of damages to physical collateral seems to dominate, is illustrated by the share of physical collateral protection having similar levels across both vulnerable and non-vulnerable countries to physical risk.

Chart 42

Distribution of the increase in portfolio LGDs due to physical damage and transition shocks

Difference between 2050 and 2020 LGDs

(percentage points)



Source: ECB calculations based on NGFS scenarios (2020), AnaCredit, Orbis, Urgentem and Four Twenty Seven data (2018).
Notes: Portfolio LGDs are the average of loan-level LGDs weighted by their exposure amount.

6.1.3 Expected losses

The climate-stressed PDs and LGDs of banks' corporate loan portfolios are combined to derive the expected losses for banks. For each climate scenario and bank, the expected losses of NFC counterparties are derived by multiplying the loan amount with their scenario-specific LGD and PD. Applying the static-balance-sheet framework, the exposure-at-default amount by 2050 is assumed to be the notional outstanding for each loan in 2020. Finally, for each bank portfolio and scenario, the total losses are derived by adding up the loan-specific expected losses of their counterparties.

The expected losses of bank credit portfolios are minimal in the event of an orderly transition towards a greener economy. Chart 43 shows expected losses in the euro area banking system relative to the baseline by 2050, calculated using the climate-related stressed PDs and LGDs as described in previous sections. Euro area banks would face higher expected losses of around 8% in a hot house world relative to an orderly transition.

The impact on expected losses from climate change is mainly driven by physical risk which diverges the most between scenarios. Panel b in Chart 43 shows that banks domiciled in some countries would experience a much more pronounced increase in expected losses under the hot-house-world scenario relative to the baseline as compared to the Euro area average. This divergence suggests that the strongest driver for their expected losses is physical risk, which pushes the levels of both PDs and LGDs higher than for countries less prone to physical hazards. Expected losses under the hot house world scenario exhibit a non-linear increase, as the impact of physical risk hits banks in some countries disproportionately stronger.

Chart 43

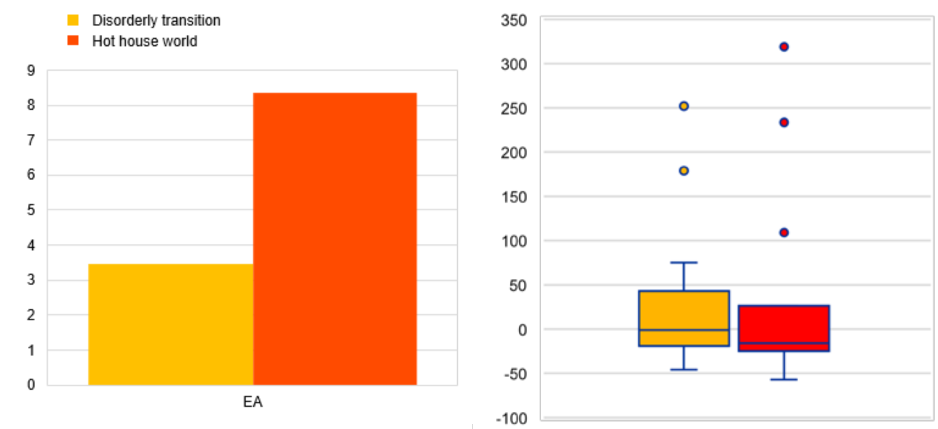
Distribution of expected losses by 2050

a) Total Euro area percentage changes under the disorderly transition and hot house world scenarios relative to the baseline (orderly transition)

(percentages)

b) Distribution of country-level deviations from the Euro area average

(percentages)



Source: ECB calculations based on NGFS scenarios (2020), AnaCredit, Orbis, Urgentem and Four Twenty Seven data (2018).
Notes: Total refers to the total change in bank-level expected losses between the respective scenario and the baseline between 2020 and 2050 and across euro area banks.

6.2 Overview of the market-risk channel

The impact of climate change on banks' corporate bond portfolios is captured through the sensitivity of the price of securities to movements in market-risk factors due to climate risks. Under the EBA stress test framework, banks perform a revaluation of financial securities by observing the variation in a portfolio's fair value in response to a change in financial market factors. A similar approach is followed in this climate stress test by using an internal ECB pricing tool that captures linear and non-linear changes in the prices of debt instruments in the event of market risk shocks.[33] These sensitivities are obtained at international securities identification number (ISIN) level by observing price dynamics in the corporate bonds market over time.

The challenge is to construct market-risk shocks driven by climate change dynamics that could be used to reprice corporate bonds. Using the aforementioned tool, repricing of corporate bonds is relatively simple as long as the market-risk factors are provided. The NGFS scenario output, however, does not provide the requisite variables given that it does not generate projections of financial

[33] See Giglio, C., Shaw, F., et al (2021)

market variables. This is partially resolved in the Phase II release of June 2021[34] which includes shocks to certain asset classes, such as equities and long term interest rates, but it still fails to account for credit spreads.

To overcome this challenge, an internal ECB model has been developed to approximate the shock on credit spreads from transition and physical risks under the three climate scenarios. First, an internal ECB model has been employed to estimate the sensitivity of excess bond premia to the PD of the security's issuer and to a variety of corporate bond characteristics, such as maturity and currency. This model uses daily data provided by Iboxx on bonds issued by NFCs.

Second, the climate-adjusted PDs of corporate bond issuers, as derived in Chapter 5, have been used and implemented in the market risk module. Once the sensitivity of excess bond premia on PDs has been estimated, it is combined with the issuer PD over the time horizon under each scenario. In contrast to loans, the impact of climate risk on corporate bonds is instantaneous - similar to the market-risk approach of standard EBA stress tests. Thus, the difference between the start-point PDs (in 2020) and the maximum value throughout the 30-year time horizon is selected for each scenario to obtain the relative change in excess bond premia.

Shocks to excess bond premia and subsequent changes in the fair value of corporate bond portfolios are estimated for a subset of banks. In particular, the dataset built for this climate stress test made it possible to reprice all ISINs issued by NFCs for the 78 significant institutions reported in the SHS-G dataset. The total market value of these securities amounts to approximately EUR 80 billion.

The impact of market risk is somewhat limited as compared with the credit-risk channel, however it follows similar dynamics in terms of scenario comparison and country differences. Chart 44 shows that losses in the fair value of the corporate bond portfolio are almost always higher in the hot house world scenario than with an orderly transition. Furthermore, Chart 45 shows that the increase in market losses in a hot house world is more severe than in a scenario with orderly transition, relative to the baseline. At the same time, market losses seem to be homogeneous across banks. However, given the small size of the corporate bond portfolio (EUR 80 billion) relative to banks' total assets (EUR 30 trillion), the market-risk impact is rather limited, particularly when compared with the credit-risk channel.

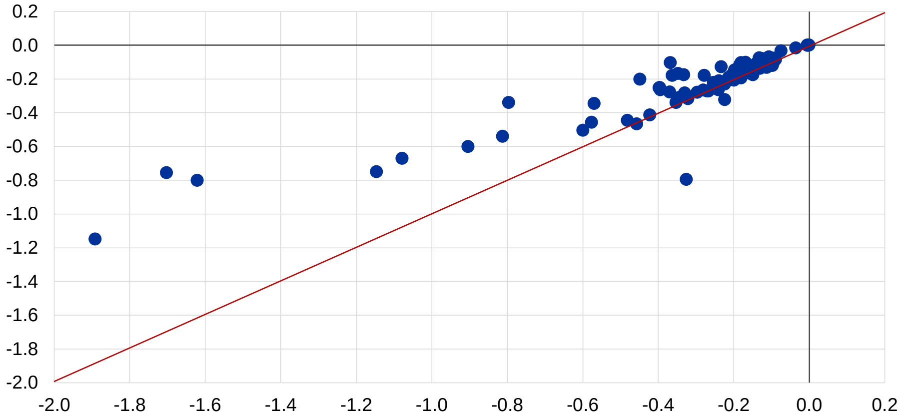
[34] See NGFS (2021).

Chart 44

Market losses for banks' corporate bond portfolio

Portfolio losses per bank in 2050

(percentages, y-axis: orderly transition, x-axis: hot house world)



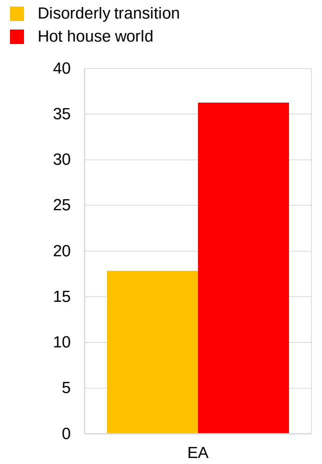
Sources: ECB calculations based on Iboxx, SHS-G data (2018).

Chart 45

Distribution of market losses between 2020 and 2050 relative to the baseline

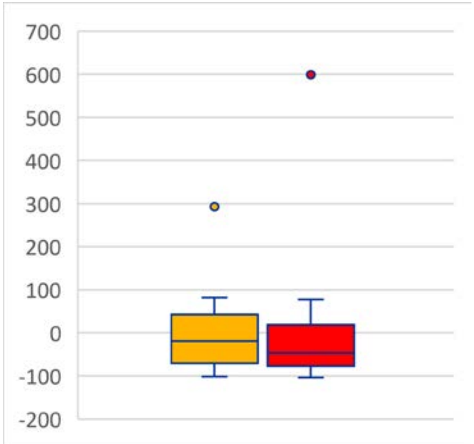
a) Euro area average under the disorderly transition and hot house world scenarios relative to the baseline (orderly transition)

(percentages)



b) Distribution of country-level deviations from the Euro average

(percentages)



Sources: ECB calculations based on Iboxx, SHS-G data (2018).
Notes: Average refers to the average change in bank-level expected losses between the respective scenario and the baseline between 2020 and 2050, and across euro area banks.

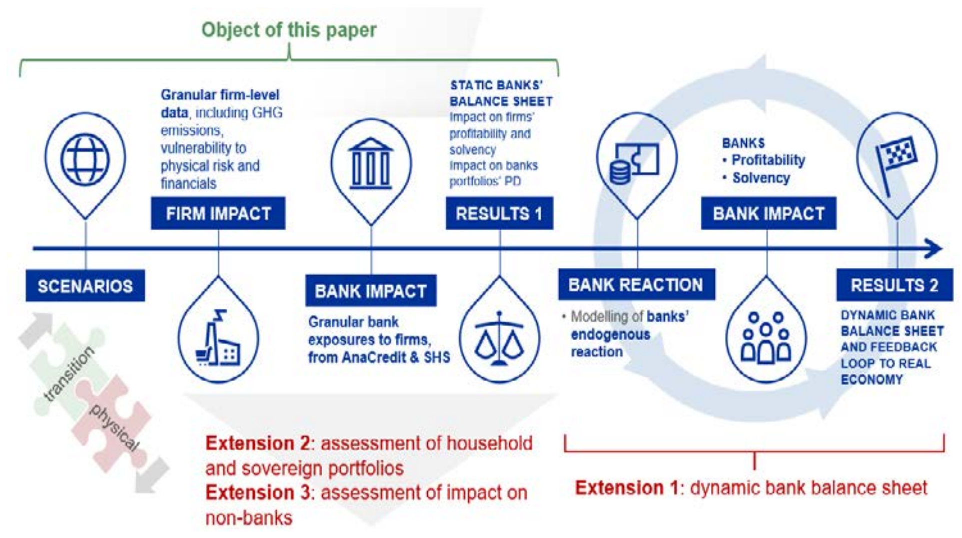
7 Future extensions

7.1 ECB roadmap on climate stress testing

This paper presents the first step of the ECB roadmap towards a comprehensive climate stress-testing framework. The exercise presented here assesses the impact of climate risks on banks based on their granular loan and security exposures to NFCs: however, the underlying assumption is that banks' exposures and their composition remain fixed over the entire timeframe. Additionally, some banks' portfolios are excluded from the analysis due to lack of sufficient data or of sufficient granularity. Finally, although banks constitute a big portion of the euro area financial sector, other intermediaries play an important role, not only in terms of provision of financial services to customers but also in terms of climate risk mitigation and/or amplification. Thus, the ECB roadmap in this field aims to relax these assumptions and extend the analysis to additional portfolios and financial institutions. Chart 46 summarises the main steps of the current exercise as well as the planned extensions of the methodological framework.

Chart 46

Schematic overview of the ECB roadmap on climate stress-testing



Source: ECB.

7.2 Update with NGFS Phase II scenarios, and ongoing applications

The current framework as described in this paper will be updated with the new NGFS scenarios, published in June 2021.[35] With respect to the scenarios considered in this paper, the new scenarios combine the outputs of the NGFS

[35] See NGFS (2021).

Integrated Assessment Models with the National Institute Global Econometric Model (NiGEM) to enrich the macroeconomic dynamics. As a result, the new scenarios have distinct innovative features that will enhance the stress-testing framework, in particular (although not limited to): a higher level of geographical and sectoral granularity, a richer set of macroeconomic output variables, the combination of physical and transition risks, and the inclusion of more physical-risk hazards. The new results updated with the new scenarios will also serve as the basis for the future extensions described in the next sections.

The climate stress-test methodology and results will be used to inform the 2022 supervisory climate stress test, and the climate stress test of the Eurosystem balance sheet. ECB Banking supervision has announced a thematic stress test on climate risks for 2022 to deep-dive into banks' internal stress-test practices and raise awareness of climate risk. The exercise described in this paper will be used as a basis for developing appropriate climate scenarios and supporting the supervisory bottom-up analysis. Additional consultations are ongoing within the ECB for applying the methods employed in this economy-wide climate stress test to feed the climate stress test for the Eurosystem balance sheet. The Eurosystem balance sheet climate stress test is part of the climate action plan devised following the ECB's Strategy Review and is expected to be completed in the first quarter of 2022[36].

7.3 Dynamic balance sheet and feedback loop to the real economy

The assumption that banks' balance sheets are static will be relaxed in order to account for second-round effects and establish a feedback loop between banks and the real economy. Allowing for banks to react to climate-induced shocks that affect their profitability and capitalisation ensures a more accurate evaluation of climate risks for the overall economy. An adverse climate scenario could result in deterioration of bank profitability and capitalisation. This, in turn, could be perceived by investors as a sign of the declining creditworthiness of those banks. The wholesale funding costs of banks affected would likely rise, further reducing bank profitability. Such effects could lead to a contraction in lending to households and firms, ultimately affecting output growth and overall macroeconomic conditions. These second-round macroeconomic effects of climate risks would then feed back into the banking sector, thereby resulting in an amplified aggregate effect on the overall economic system (Chart 30). This mechanism is already incorporated into the ECB macroprudential stress test toolbox (see Budnik et al., 2019) and will be adapted and applied to the second climate stress test stage.

The current feedback loop will be enriched with a further layer of bank exposure classifications, based not only on a firm's sector but also on its carbon footprint and exposure to physical risk. For example, firms with a higher

[36] For more information please refer to the ECB action plan to include climate change considerations in its monetary policy strategy published in June 2021

carbon footprint would suffer more mark-to-market losses and/or would require different provisioning under the three scenarios assumed in this study: consequently, the banks mostly exposed to these firms would experience a higher reduction in profitability and would contribute more to a further deterioration of the macroeconomic conditions. The same mechanism applies to those banks most exposed to counterparties subject to climate-related risks.

7.4 Extension to other financial intermediaries and portfolios

The methodological set-up could be extended to incorporate the effects of transition and physical risks on banks' retail portfolios. Such effects could be modelled by capturing the relationship between macroeconomic variables and households' default probabilities. The reason for developing such a modelling approach is twofold. First, granular data on banks' loans to the household sector are not available, nor is data on the specific geographic location of the underlying physical collateral.[37] Second, the creditworthiness of households can be approximated as a function of aggregate country-specific conditions (e.g., unemployment rate, income, house prices). On the basis of this, default probabilities and LGDs for households could be derived at the country level.

The climate stress-test exercise proposed in this note will be extended to asset managers. Financial securities on asset manager portfolios are exposed to both transition and physical risks. In addition, the transmission channels are similar to those affecting banks' security holdings. Therefore, asset managers could be stress tested alongside banks by using the same asset-specific paths in combination with granular data on funds' assets. The main limitation in this case is, again, the level of data granularity. Contrary to the case of banks, data on holdings by institutional investors is only available at the sectoral level.

The methodology could also be extended to the insurance sector, which could prove to be particularly exposed to physical risk. Increased physical risk might lead to an increase in insurance risk premiums given the greater magnitude and frequency of extreme weather events. A higher probability of natural catastrophes, and the greater economic losses consequent on their greater magnitude could raise insurance costs or limit insurance coverage (increasing the so-called insurance-protection gap). First, higher risk premiums would affect consumers. Second, those premiums would exert a downward pressure on firms' profitability, thereby leading to an increase in their probability of default. Additionally, higher underwriting risk because of more severe disasters if climate change is not mitigated would also put insurance companies at risk of financial instability. Finally, an amplification mechanism could be triggered, with further negative consequences for the banking sector through the credit and market-risk channels.

Additional areas of work would include improving the modelling of firms' adaptation and adding contagion mechanisms across financial institutions.

[37] AnaCredit does not provide any information on loans to households.

The current framework assumes that all firms will be able to transition to greener production processes and any differences on adaptation capacity between firms are based on higher or lower costs of adopting green technologies. In reality firms in different sectors exhibit high heterogeneity in adaptation capacities. One area for future research could therefore be to look at how firms might change their business models through technological innovation, the different technological breakthroughs required by each sector to successfully decarbonise, while also introducing sector or firm-specific supply and demand shocks. Finally, the current framework considers banks, or other financial intermediaries, in isolation, while the financial sector is actually based on a dense network of relationships with direct and indirect common exposures. Future work might include enriching the current framework with contagion dynamics that could amplify the impact of climate risks even further.

8 Conclusion

The ECB's economy-wide climate stress test was developed to assess the resilience of NFCs and euro area banks to transition and physical risk under climate policy scenarios. The stress test presented here comprises three main pillars. First, climate-specific scenarios identify future projections of climate and macroeconomic conditions over the next 30 years. Second, a comprehensive dataset for millions of companies collects climate and financial information and combines them with granular bank exposures through loans and security holdings. Third, the specific transmission channels for climate risk drivers for firms and banks are captured thanks to novel climate-specific models.

The stress test described in this paper improves on similar exercises performed by other central banks and supervisory authorities along four dimensions. First, its top-down, centralised nature ensures full transparency and replicability of the framework, as well as comparability in terms of the impact and final outcomes for banks. Second, the granularity of the exercise makes it possible to account fully for the heterogeneity and uniqueness of climate risks, not only across regions and sectors but also within them. Third, the exercise assesses climate risks for four million corporates worldwide and 1,600 consolidated banking groups across the entire euro area. This has been made possible thanks to an extended climate data collection exercise that, to the best of our knowledge, has provided the most comprehensive set of backward and forward-looking climate and financial information available at central bank level. Finally, the interactions between transition and physical risks have made it possible to compare the future costs and benefits of climate policy action.

The results of the ECB's economy-wide climate stress test first show that there are clear benefits to acting early. The short-term costs of transition pale in comparison with the costs of unfettered climate change in the medium to long term. The early adoption of policies to drive the transition to a zero-carbon economy would also bring benefits in terms of investing in and rolling out more efficient technologies. These results underline the crucial and urgent need to transition to a greener economy, not only to ensure that the targets of the Paris Agreement are met but also to limit the long-run disruption to economies, businesses and livelihoods.

The results also show that although the effects of climate risks increase moderately, on average, until 2050 if climate change is not mitigated, they are concentrated in certain geographical areas and sectors. In particular, the outcomes of the analysis show that activities relating to the mining and electricity and gas sectors would have to bear significant costs to reduce emissions in line with the Paris Agreement targets, with a subsequent increase in their probability of default in the short to medium term in the event of a green transition. At the same time, firms located in geographical areas that are most exposed to physical risk would face a considerable decline in their creditworthiness as a consequence of more severe and frequent natural disasters if climate change is not mitigated.

Additionally, the outcomes of the stress test highlight that if policies to transition towards a greener economy are not introduced, physical risks become increasingly higher over time; they increase in a non-linear fashion, and due to the irreversible nature of climate change such an increase will continue over time. The projections of firms' and banks' default probabilities for the next 30 years show that, by 2050, the greatest impact would occur under a no-transition scenario due to increasingly high levels of damage from natural disasters. Such effects would be greater for companies located in vulnerable geographical areas and for banks with portfolios particularly concentrated in those countries most affected by natural hazards. It is thus of foremost importance to transition early on and gradually, to mitigate the costs of both the green transition and the future impact of natural disasters.

The results also show that for corporates and banks most at risk the impact is potentially very significant, especially in the absence of further climate policies. If climate risks are not mitigated, the costs to companies arising from extreme weather events could rise substantially, and greatly increase their probability of default. The resulting "hot house world" will be particularly challenging for certain regions projected to become markedly more vulnerable to events such as heatwaves and wildfires in the future. Climate change thus represents a major source of systemic risk, particularly for banks with portfolios concentrated in certain economic sectors and, even more importantly, in specific geographical areas.

Finally, the impact on banks' expected losses is mostly driven by physical risk and is potentially severe. Euro area banks face higher expected losses if climate risks are not mitigated under an orderly transition scenario. Additionally, the highest expected losses on loans are faced by banks located in countries with either low levels of collateral protection or high exposure to physical risk. These results also confirm that in the absence of climate policies banks' expected losses would continue to increase non-linearly over time due to climate change's irreversible nature.

The climate stress-test methodology and results of this paper will be used to inform the 2022 supervisory climate stress test, and the climate stress test of the Eurosystem balance sheet. Banking supervision has announced a thematic stress test on climate risks for 2022, in order to deep-dive into banks' internal stress test practices and raise awareness on climate risk. The exercise described in this paper will be used as a basis to develop appropriate climate scenarios and support the supervisory bottom-up analysis. Additional consultations are ongoing within the ECB on applying the methods employed in this economy-wide climate stress test to feed the climate stress test of the Eurosystem balance sheet, which is expected to be completed in the first quarter of 2022.

The current framework will be updated and extended to further improve the robustness and completeness of further exercises. First, the methodology and results described here will be updated to incorporate the new NGFS scenarios, published in June 2021. Second, the static balance sheet assumption will be relaxed to allow for second-round effects and a feedback loop between banks and the real economy arising from dynamic reactions by banks to changes in their counterparties' creditworthiness. Third, the methodological set-up could also be extended to incorporate the effects of transition and physical risks on banks’ retail portfolios and expanded to assess the effects on other financial intermediaries, such as asset managers and insurance companies.

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Appendix A: data sources

Although top-down in nature, the stress-test methodology described above makes it possible to conduct a granular, counterparty-level analysis of climate risks thanks to a unique collection of data. The modelling framework relies on detailed information on: (i) banks' exposures (loans and bond holdings) to NFCs; (ii) the CO2 emissions of each individual counterparty in banks' portfolios; (iii) the projected physical-risk exposure of every single counterparty in banks' portfolios at address level; (iv) the balance-sheet information of banks' NFC counterparties. The combination of these four factors provides a unique set of information that, to the best of our knowledge, has never been collected and examined by a regulatory authority to perform a climate stress test. Such data richness adds to the typical advantages of a top-down and macroprudential stress test, mainly in terms of the homogeneity of models used, the consistency of data, transparency and the comparability and replicability of results.

The analysis proposed in this paper relies on several data sources, including both regulatory datasets and data obtained from private providers. As already anticipated in previous sections, AnaCredit, supervisory reporting and ECB SHS-G data help identify banks' exposures at a highly granular level. This counterparty-level information makes it possible to map precisely banks' counterparties to their carbon footprint and physical risk exposures by merging regulatory data with Urgentem carbon emission data and Four Twenty Seven climate risk data. Granularity is essential to capture climate-related risks given that their impact can be extremely heterogeneous across sectoral and geographical dimensions.

This data collection will become the first large dataset to bring together firm-level information on financial accounts and exposure to climate risk. More precisely, this dataset combines three sets of information on each non-financial corporation to which a bank is exposed to: a) its balance-sheet information, b) geographical location, c) carbon footprint and exposure to physical risk. The financial details for each firm are mainly derived from Orbis, and complemented by other sources, such as Bloomberg, iBACH and Eikon. Information on CO2 emissions and physical risks were obtained from private data providers. Overall, this comprehensive dataset maps a large set of firms against their resilience to transition and physical risks, and thus makes it possible to assess the potential impact of climate-related phenomena on each sector and geographical location.

Complementing this firm-level information with banks' exposures makes it possible to translate firms' risk into bank resilience. Banks' exposures to individual counterparties are obtained from AnaCredit (loans to NFCs) and SHS-G (securities and equity): this mapping is thus useful to assess the impact of firms' reaction to climate change at bank level, based on their direct exposures to such change.

Urgentem data for transition risk

Urgentem is a provider of transparent emissions data and climate risk analytics to the finance industry. Urgentem offers a unique dataset that covers greenhouse gas (GHG) emissions data for more than 15,000 companies globally over the last 10 years. These historical emissions include Scope 1, Scope 2 and all 15 categories of Scope 3 (value chain) emissions.[38] One great advantage of Urgentem as compared with other data providers is that it covers granular Scope 3 emissions, which are of utmost importance for deriving the carbon footprint of a firm, encompassing all the CO2e emitted throughout the value chain. To put the importance of Scope 3 emissions into perspective, it should be noted that they represent more than 85% of the world's overall footprint. However, Scope 3 emissions are difficult to measure and are rarely reported by firms: for this reason, Urgentem has developed a statistically robust inference model to estimate Scope 3 information if a corporation fails to report this data. To ensure transparency, the dataset makes it possible to distinguish whether the emissions have been reported by the firm itself or estimated using the Urgentem inference model. Second, Urgentem offers long time series (ten years) of companies' emissions with consistency across all relevant data points. Finally, Urgentem ensures a very high quality of data given that it relies on sophisticated, multi-stage data-cleaning and validation processes and outlier treatment, complemented by bilateral undertakings with the companies themselves to validate the results.

In addition to the 5,000 observations collected from public sources every year, Urgentem can use its inference model to estimate the emissions of any company (listed or unlisted) based on that firm's revenues and sector of activity. Five thousand companies were chosen by Urgentem as being representative of the universe of the biggest equity indices (e.g. MSCI World, FTSE 1000, Stoxx 600): for them, Urgentem regularly collects emissions data under corporate undertakings and public sources, including but not limited to: annual reports, financial statements and sustainability reports. The 'inferred' emissions are derived from a model used on 30,000 publicly listed companies every year, and there is scope for its application to a wider set of firms, even unlisted. Finally, it should be noted that the inference model does not project emissions into the future but provides an estimate of the 10-year time series for emissions.

Urgentem has developed a methodology for expanding the inference of emissions data beyond listed companies to encompass estimated Scope 1, 2 and 3 emissions data for unlisted companies. In close collaboration with Urgentem, we applied this methodology to infer values for more than 4 million private companies. The methodology is in-line with the listed universe methodology used by Urgentem, where companies' emissions are inferred based on an industry-specific statistical model. The model is calibrated using disclosed emissions data from a large sample of public companies. An additional step, involving the introduction of

[38] See Annex C for a more detailed discussion on the definition of the emissions Scopes and issues around emissions reporting

International Standard Industrial Classifications (ISICs) into the model, has been taken to adapt the model for unlisted firms.

Urgentem has developed a model that can estimate the future emissions of both public and private companies until the year 2100. The methodology uses both disclosed and modelled corporate emissions data and takes into account emission reduction targets disclosed by companies. In addition, it is calibrated to consider the future GHG emission trends indicated by the various climate scenarios developed by NGFS. Under the methodology, projected future emissions are affected by both regional and global emissions pathways under the climate scenarios adopted, allowing for company-specific GHG emissions profiles and reduction ambitions. The model accounts for the effects of negative emissions as an outcome of carbon dioxide removal (CDR) technologies and from land-use changes (LUCs) within each scenario. Urgentem can thus generate Scope 1, 2 and 3 GHG emissions estimates for the universe of listed and unlisted companies considered in the stress test, calibrated to the entire suite of NGFS climate scenarios.

Four Twenty Seven data for physical risk

Four Twenty Seven specialises in providing data solutions to assess the vulnerability of firms to physical risk based on their geographical location. Using satellite data as well as information on weather patterns, Four Twenty Seven data report the exposure of each firm to different natural catastrophes. The first great advantage of this dataset is that it models the probability distribution for the occurrence of 6 different extreme weather events. Second, these probability distributions are derived for very granular geographical areas, i.e. at address level. The third, unique feature of this dataset is its forward-looking nature. Using different IPCC models that project extreme weather patterns, Four Twenty Seven has designed vulnerability scores that reflect firms' exposure to physical risk until 2040.[39]

Data provided by Four Twenty Seven also translates physical risk into financial risk for a set of 2,500 large publicly listed corporations. Four Twenty Seven has managed to map the location of all physical assets (e.g. offices, branches, warehouses, production plants, middlemen, etc.) across the value chain of each firm, and has stressed them against extreme weather events. Aggregating this data, the result is an integrated vulnerability score encompassing a firm's entire spectrum of operations. It should be noted that this is a common issue for physical risk assessment, as larger firms have operations in many different locations across the world and it is very challenging to be entirely familiar with them all.

[39] More information on the Four Twenty Seven indicators and their matching with AnaCredit can be found in the Data Supplement of ECB/ESRB (2021)

Regulatory data to map banks’ exposures

The ECB’s analytical credit datasets, or AnaCredit, are a collection of data containing detailed information on individual bank loans in the euro area, harmonised across all Member States. The dataset contains granular loan-by-loan data and covers credit, debtor and credit risk information. In terms of scope, information must be provided for all agents residing in euro area countries, while for other EU countries such reporting is voluntary. The credits covered by the dataset consist of conventional lending products (derivatives and off-balance sheet items are excluded) and comprise only credits extended to legal entities (i.e. credit to households is excluded).

The Securities Holding Statistics - Group Module (SHS-G), contains information collected by euro area national central banks on the financial securities holdings of individual banking groups in the euro area. The dataset lists ISIN-level information on securities held by each banking group and focuses mainly on equities and debt securities.

Financial information on banks’ counterparties

Financial information on non-financial companies in the dataset are obtained by Bloomberg, Eikon, Orbis and iBACH. The set of financial information comprises of several key variables from firms’ balance sheet, income statement and capital structure. These data sources are also used to obtain the address of firms’ facilities. More information on the variables relevant for the analysis can be found in Appendix B.

Bloomberg and Eikon are used for publicly listed companies, while Orbis and iBACH complement the collection with information on private companies. Orbis is a database containing financial and business information on 116 million global public and private companies. iBACH is a database of aggregated and harmonized accounting data of non-financial incorporated enterprises managed by the European Committee of Central Balance-Sheet Data Offices (ECCBSO), an informal body of experts from National Central Banks and National Statistical Institutes of Europe.

Several steps are taken to ensure the accuracy and consistency of financial information and to fill data gaps. First, data are cleaned off basic reporting mistakes and internal inconsistencies of balance sheet information. Second, data items are winsorized. Lastly, to fill gaps for missing variables, NACE sector multiples with respect to firm size are used as proxies. Firms with missing information in either size or revenues are dropped from the sample.

Appendix B: analytical steps

Estimation stage

In the following equations the subscript or superscript *i* denotes the firm, *t* denotes the time (year), and *s* denotes the scenario. Naturally, the scenarios are irrelevant at the estimation stage and only come into play in the projections stage.

- Total assets (estimated in log)

$$TA_s^{i,t} = \alpha + \beta_1 TA_s^{i,t-1} + \sum_j \beta_j macro_{j,s}^t + \sum_k \beta_k dummy_k^i + \epsilon_s^{i,t} \quad (1)$$

where we include the logarithm of GDP and the inflation rate as macroeconomic control variables together with size, region, and sector dummies.

- Revenues (estimated in log)

$$Revenues_s^{i,t} = \alpha + \beta_1 \; Revenues_s^{i,t-1} + \beta_2 \; TA_s^{i,t} + \beta_3 VAT^t + \beta_4 t + \; \beta_5 sector^i + \epsilon_s^{i,t} \quad (2)$$

Revenues capture demand-side dynamics that may impact firms from climate policies. In this setup an increase in carbon price is assumed to affect both producers and consumers of emissions. Climate policies would tax or make more expensive the consumption of carbon intensive goods (e.g. diesel cars) thus indirectly raising the true price of the product. To capture the potential impact of this indirect price increase we estimate the relationship of revenues with VAT, an indirect tax.

- Operating expenses (estimated in log)

$$OpEx_s^{i,t} = \; \alpha + \beta_1 OpEx_s^{i,t-1} + \; \beta_2 TA_s^{i,t} + \; \beta_3 t + \; \beta_4 sector^i + \; \epsilon_s^i \quad (3)$$

Operating expenses capture supply-side dynamics. Annual changes in carbon prices and energy prices are captured in the production costs of firms.

- Earnings

Earnings are modelled as operating earnings: revenues minus expenses.

$$Earnings_s^{i,t} = Revenues_s^{i,t} - OpEx_s^{i,t} \quad (4)$$

- Leverage

We define leverage as firms' share of total debt to total assets

$$Leverage_s^{i,t} = \frac{Total\ debt_s^{i,t}}{Total\ assets_s^{i,t}} \quad (5)$$

- Profitability

$$Profitability_s^{i,t} = \frac{Earnings_s^{i,t}}{Total\ assets_s^{i,t}} \quad (6)$$

- Default probabilities

$$PD_s^{i,t} = \alpha + \beta_1 leverage_s^{i,t} + \beta_2 \mathrm{Profitability}_s^{i,t} + \beta_3 log(GDP_s^t) + \beta_4 log(GDP_s^t)^2 + \beta_5 age^{i,t} + \epsilon_s^{i,t} \quad (7)$$

The model estimates the relationship of annual probabilities of default with corporate profitability and leverage as well as other macro and firm-level variables. The age of each firm is expressed in years since its creation and is capped at 50 years. Observations on annual PDs were obtained from Moody's Credit Edge product.

Physical risk for firms

First, increased exposure of firms to natural catastrophe events increases the cost of insurance (8), feeding directly into operational expenses. A change in operating expenses is estimated to have a linear relationship with the increase in expected losses of insured assets (9).

$$L_{t,c} = \frac{Damages_{t,c}}{TA_t \cdot Insured\ TA_c} \quad (8)$$

$$\Delta C_t^i = (L_{t,j} * \left(1 + \left(\frac{Score_{2050}^i - Score_{2050}^{mean(c,a)}}{Score_{2050}^{mean(c,a)}}\right)\right) * Phys.capital_t^i \quad (9)$$

Second, physical risk is assumed to impact firms' physical capital stock, as this depreciates by extreme weather events. Leveraging on the estimation of physical damages from the NGFS scenario we calibrate a damage function that predicts the total damage from physical risk at country level. Using Four Twenty Seven's probability distributions for hazard events occurring at a firm's geographical location combined with indicators on the intensity of hazard events, it is possible to calculate expected annual damages to capital. Further heterogeneity on the physical risk impact is introduced by calibrating the expected damage to capture locational differences in the intensity of natural hazards conditional on that hazard occurring.

$$L_{t,c} = \frac{Damages_{t,c}}{GDP_{t,c}} \tag{10}$$

$$Intensity = (L_{t,c} * \left(1 + \left(\frac{Score^{i}_{2050} - Score^{mean(j,a)}_{2050}}{Score^{mean(j,a)}_{2050}}\right)\right) * Phys.capital^{i}_{t} \tag{11}$$

$$\begin{aligned} &Expected\ relative\ damage\ size\ (E) \\ &\quad = E\left[frequency_{j}\right] * \ (L_{t,c} * (1 + (\frac{Score^{i}_{2050} - Score^{mean(j,a)}_{2050}}{Score^{mean(j,a)}_{2050}})) \\ &\quad * Phys.capital^{i}_{t}) \end{aligned} \tag{12}$$

Projection stage

Each estimated equation is projected iteratively for each forecasted year, but may receive additional inputs each forecast step, before projection into the next year. The following are the steps followed at the projection stage:

1. Two versions of Total Assets (TA) are projected each year.
   (a) One version follows the projection of equation (1) without physical damage and does not include any other exogenous effects.
   (b) The second version also projects equation (1) but includes the physical damage to its TA incurred directly by the firm concerned. This physical damage lowers the level of physical capital of the firm concerned. This reduced version of TA is used in the projections of firm revenues as it is a hit on the firm's production capacity although these assets continue to contribute to the firm's costs. At the same time, we assume that fixed costs associated with the impaired physical assets are already booked by the firm for that period. Hence, version (a) is used to project operating costs, but version (b) is used to project revenues.

$$TA^{i,t}_{s}(damaged) = \widehat{TA^{i,t}_{s}} + E * tangible\ share^{i,t}_{s} \tag{13}$$

2. Revenues are projected using the impaired TA given that the impaired physical assets at time t cannot contribute to that year's production.

$$\begin{aligned} Revenues^{i,t}_{s} = \alpha + \beta_1 Revenues^{i,t-1}_{s} + \beta_2\, TA^{i,t}_{s}(damaged) + \beta_3 \text{adjusted}_{VAT^{t}} + \beta_4 t \\ + \beta_5 sector^{i} + \epsilon^{i,t}_{s} \end{aligned} \tag{14}$$

3. An adjusted VAT rate can be used in the framework to capture an indirect price shock on high emitting products. The shock is calibrated to increase the VAT rate progressively based on the firm's Scope 3 emission intensity – focusing on

the ‘use of goods sold’ Scope 3 category. Specifically, the goods produced by the bottom 10% of emitters receive a 0 percentage point change, while the top 10% of emitters receive the maximum VAT change. The maximum shock on the VAT is capped at 5% with a linear relationship determining the VAT rate increase for firms in between the bottom and top 10% of emissions. This shock is introduced only as a gradual increase in the OT scenario and a sudden increase in the DT scenario in 2020 and 2030 respectively.

4. Operating expenses are projected for year t as follows:

$$OpEx_s^{i,t} = \widehat{OpEx}_s^{i,t} + \Delta cost(carbon\ cost)_s^{i,t} + \Delta cost(energy\ cost)_s^{i,t} + insurance\ premia_s^{i,t} * tangible\ share_s^{i,t} \quad (15)$$

where

$$\Delta cost(carbon\ cost)_s^{i,t} = carbon\ tax_s^{i,t} * Scope1_s^{i,t} - carbon\ tax_s^{i,t-1} * Scope1_s^{i,t-1} \quad (16)$$

and

$$\Delta cost(energy\ cost)_s^{i,t} = energy\ price_s^{i,t} * energy\ consumption_s^{i,t} - energy\ price_s^{i,t-1} * energy\ consumption_s^{i,t-1} \quad (17)$$

where energy consumption is a function of the scenario, the energy mix and the level of the firm’s Scope 2 emissions. More information on the energy mix can be found in the relevant segment (‘Energy Mix’).

5. To project leverage, we need to project a firm’s total debt, which requires several steps to be followed.

   (a) In our framework, corporates are assumed to maintain the same capital structure over time, meaning that assets, liabilities and equity all grow at the same rate. Based on this, we project the growth of liabilities based on the growth of total assets.

   (b) We distinguish between three main contributing effects to changes to total debt:

      (i) First, we assumed that over time, a trend effect applies to debt which increases it at the same rate as total assets;

      (ii) Second, debt increases as firms have to raise funds to invest in greener technologies in order to meet their emission targets. The amount that they have to raise depends on the decrease in emissions they have to achieve to reach the 2050 target and a replacement cost that is calibrated based on IMF (2019)

$$\text{Investment} = \Delta(\text{Total Emissions})(\text{t/CO2}) * \text{replacement cost}\left(\frac{\$}{\text{t/CO2}}\right);$$

This replacement cost is further calibrated to differ across the Orderly and Disorderly scenarios according to the cost of CDR and other green technologies projected by the NGFS. For the Hot house world scenario, firms are not assumed to invest in green technologies as the transition to a green economy does not take place and emissions are reduced thanks to policies and technology already in place before the start of the scenario horizon.

(iii) Third, debt increases as firms need to raise funds to cover the incoming physical damage that impairs some of their physical assets. Firms are assumed to raise debt to recover only their uninsured damages assets as insurance scheme pays for the value of protected assets. Information on the share of insured damages is obtained from publicly available data by the European Commission and EIOPA on catastrophe insurance.

The combination of those effects allows us to project leverage as follows:

$$Leverage_s^{i,t} = \frac{TotalDebt_s^{i,t} + Investment_s^{i,t} + Uninsured\ Physical\ Damages_s^{i,t}}{Total\ Assets_s^{i,t}}$$

Estimation results

Table 1

Estimations of Total Assets

VARIABLES	(1) Ln (TA)	(2) Ln (TA)	(3) Ln (TA)	(4) Ln (TA)	(5) Ln (TA)
L. ln (TA)	0.978*** (0.000387)	0.903*** (0.000926)	0.903*** (0.000935)	0.905*** (0.000936)	0.981*** (0.00205)
L2. Ln (TA)					-0.0570*** (0.00194)
Ln (GDP)	0.0100*** (0.000491)	0.00909*** (0.000477)	0.00963*** (0.000489)	0.00952*** (0.000857)	0.00562*** (0.000837)
Inflation rate	0.00349*** (0.000233)	0.00152*** (0.000228)	0.00156*** (0.000232)	0.00144*** (0.000256)	0.000227 (0.000281)
Constant	0.221*** (0.0156)	2.197*** (0.0268)	2.145*** (0.0276)	2.125*** (0.0342)	1.764*** (0.0348)
Observations	161,233	161,233	159,062	157,698	126,599
R squared	0.991	0.991	0.991	0.991	0.992
Number of ID	30,657	30,657	30,551	30,297	26,208
Size dummies		Yes	Yes	Yes	Yes
Sector dummies			Yes	Yes	Yes
Region dummies				Yes	Yes

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 2

Estimations of Revenues

VARIABLES	(1) Ln (revenues)	(2) Ln (revenues)	(3) Ln (revenues)	(4) Ln (revenues)
L. ln (revenues)	0.839*** (0.00113)	0.839*** (0.00112)	0.802*** (0.00125)	0.854*** (0.00232)
L2. ln (revenues)				-0.0207*** (0.00202)
VAT rate	-0.00120*** (0.000191)	-0.00120*** (0.000190)	-0.00160*** (0.000187)	-0.00114*** (0.000180)
Constant	0.312*** (0.0126)	10.49*** (0.493)	11.22*** (0.497)	-4.742*** (0.613)
Observations	145,246	145,246	143,176	115,902
R squared	0.982	0.982	0.982	0.984
Number of ID	27,447	27,447	27,349	23,946
Time dummies		Yes	Yes	Yes
Sector dummies			Yes	Yes

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 3

Estimations of Operating Expenses

VARIABLES	(1) Ln (oper exp)	(2) Ln (oper exp)	(3) Ln (oper exp)	(4) Ln (oper exp)
L. ln (oper exp)	0.863***	0.862***	0.823***	0.832***
	(0.00103)	(0.00103)	(0.00117)	(0.00228)
L2. ln (oper exp)				0.0146***
				(0.00202)
Ln (TA)	0.123***	0.124***	0.169***	0.149***
	(0.00109)	(0.00109)	(0.00125)	(0.00130)
Constant	0.258***	12.06***	12.79***	-1.682***
	(0.0124)	(0.516)	(0.519)	(0.643)
Observations	145,246	145,246	143,176	115,978
R squared	0.982	0.982	0.982	0.983
Number of ID	27,447	27,447	27,349	23,975
Time dummies		Yes	Yes	Yes
Sector dummies			Yes	Yes

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 4

Estimation of Probabilities of default

VARIABLES	(1) PD
Leverage	0.0454***
	(0.000859)
Profitability	-0.0533***
	(0.00165)
Ln GDP	-0.00693*
	(0.00382)
Ln GDP sq	0.000113*
	(6.79e-05)
Age	-0.000140***
	(5.89e-06)
Constant	0.105*
	(0.0537)
Observations	155,134
Number of ID	28,167
R squared	0.119

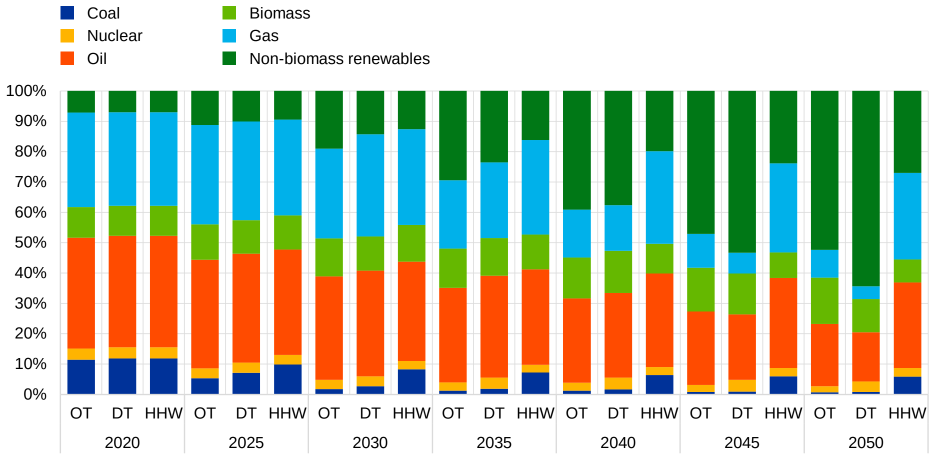
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Energy mix

The scenarios provided by the NGFS contain detailed projections on Europe-wide consumption of different inputs used in the generation of electricity. The following chart shows these projections. Under the hot house world scenario, the proportion of fossil fuels, such as coal, gas, and oil, in the energy mix decrease only slightly. In the transition scenarios these polluting inputs are gradually replaced by greener alternatives, such as biomass, although this occurs at different speeds depending on whether the transition is orderly or disorderly.

Chart 47

Energy mix under the various scenarios

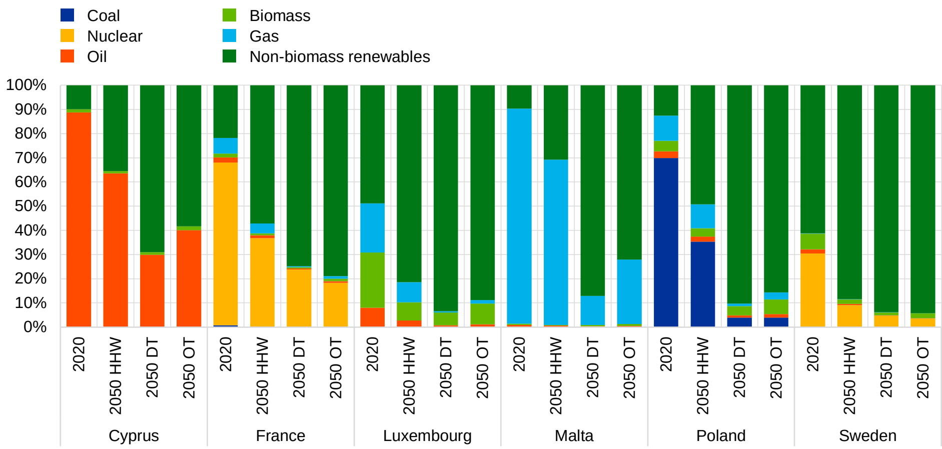


Source: ECB calculation based on NGFS climate scenarios (2020b).

To further improve the granularity of our projections, we obtained data from Eurostat on the current (2020) energy mix for each EU27 country. We then used the predicted year-on-year change for each fuel in the NGFS projections to produce a country-level energy mix projection. The following chart shows both the starting point in 2020 and the scenario-dependent end point in 2050 for a selection of countries. This energy mix projection is used to calculate the cost of changes in energy consumption based on the projected energy prices from each energy source.

Chart 48

Country-level energy mix projections



Source: ECB calculation based on NGFS climate scenarios (2020b) and current energy mix from Ember, Eurostat.
Notes: Projection based on current country energy mix and NGFS energy mix scenarios for Europe.

Loss given default

Loss given defaults (LGDs) are not reported in AnaCredit. Hence, loan-level LGDs are approximated by looking at the collateral value relative to the notional value of the loan. This is predicated on the assumption that in the event of a default a bank can only recover the collateral assigned to the loan and that it will be paid the full collateral value.

Appendix C: Carbon emissions reporting

Under the Greenhouse Gas Protocol companies' emissions are broken down into direct and indirect greenhouse-gas (GHG) emissions. Direct GHG emissions are emissions from sources that are owned or controlled by the company, while indirect GHG emissions are a consequence of the activities of the company but occur at sources owned or controlled by another company.

Based on this distinction, companies' emissions are divided into Scope 1, Scope 2 and Scope 3, the first one being direct emissions and the latter two being indirect emissions. Scope 1 relates to direct GHG emissions deriving from, for example, combustion in owned or controlled boilers, furnaces, vehicles, or emissions from chemical production in owned or controlled process equipment.[40] Scope 2 emissions consist of electricity indirect GHG emissions, and account for GHG emissions from the generation of purchased electricity consumed by the company.[41] Scope 2 emissions are considered to be indirect since they physically occur at the facility where electricity is generated. Scope 3 emissions include all other indirect GHG emissions, and can be optionally reported. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Some examples of Scope 3 activities are the extraction and production of purchased materials, transportation of purchased fuels, or use of sold products and services.

Together the three scopes provide a comprehensive accounting framework for managing and reducing direct and indirect emissions. Chart 49 provides an overview of the relationship between the scopes and the activities that generate direct and indirect emissions along a company's value chain, and gives some examples of activities typically associated with direct and indirect GHG emissions.

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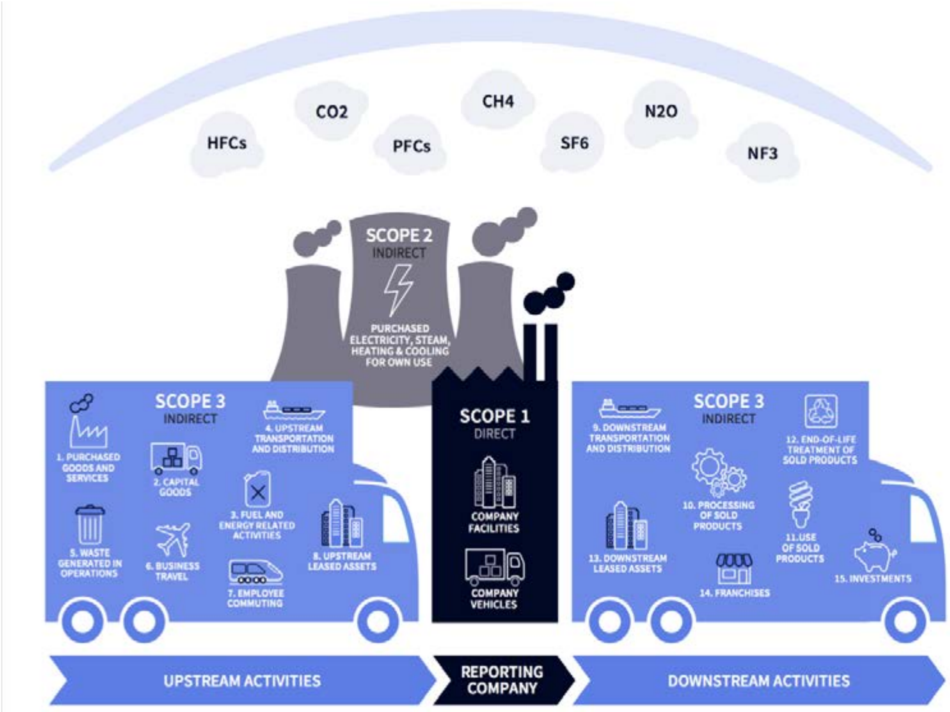
40 Direct CO_2 emissions from the combustion of biomass, as well as GHG emissions not covered by the Kyoto Protocol (e.g. chlorofluorocarbons (CFCs), nitrogen oxides (NOx), etc.) are not included in Scope 1 but must be reported separately.

41 Purchased electricity is defined as electricity that is purchased or otherwise brought into the organisational boundary of the company.

Chart 49
Illustration of Scope 1, Scope 2 and Scope 3 emissions



Source: Urgentem based on the Greenhouse Protocol.

There is the concern that accounting for indirect emissions may lead to double counting when two different companies include the same emissions in their respective inventories. Potential double counting may also depend on how consistently companies with shared ownership or trading programme administrators choose the same approach to set the organisational boundaries. Under the Greenhouse Protocol, whether or not double counting matters depends on how the reported information is used. In general, for GHG risk management and voluntary reporting, double counting is less important. However, double counting needs to be avoided when compiling national (country) inventories under the Kyoto Protocol' in general, however, these are compiled via a top-down exercise using national economic data rather than through aggregation of bottom-up company data.

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