Climate-related risk and financial stability

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by
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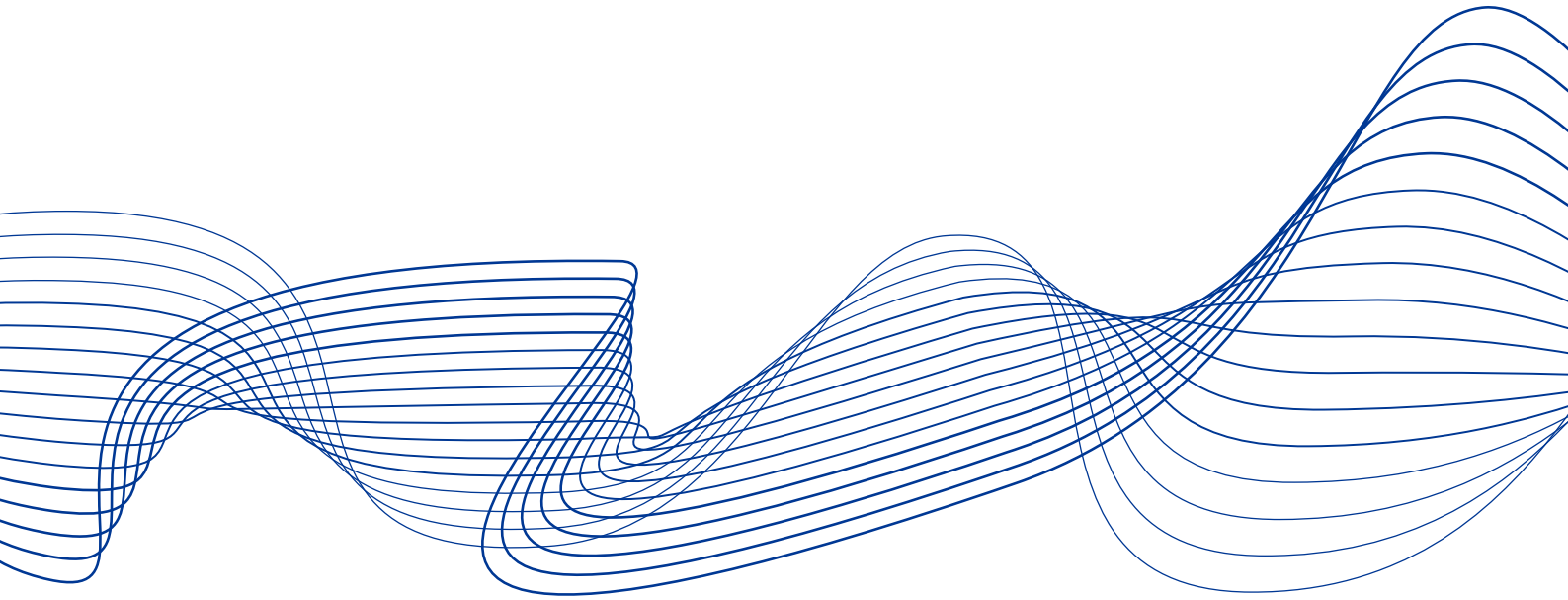

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Executive Summary

The impacts of climate change on financial stability hinge on both the distribution of financial exposures and the evolution of prospective financial system losses. A first challenge to accurately sizing impacts in this respect is exposure *granularity* – fine resolution measurement is required to trace out heterogeneous and novel physical and transition risk impacts across geographies, sectors and firms.[1] A second challenge is the unprecedented nature, including long-dated *horizon,* of climate risk – necessitating innovation in forward-looking modelling to identify prospective financial losses. This report tackles both challenges, unveiling an analysis of a broadened set of climate change drivers over long-dated financial risk horizons, with the aim of providing a more encompassing and robust quantification of financial stability risks in the European Union to underpin targeted and effective policy action.

A granular mapping of financial exposures to climate change drivers suggests uneven vulnerability across EU regions, sectors and financial institutions. A mapping of the physical risks of climate change requires geolocated hazards to be linked to economic and financial risk exposures. An analogous mapping of the transition risks of climate change requires an encompassing view of exposures to carbon emissions across the entire value chain, including downstream emissions, as financial markets continue to rapidly green. While subject to measurement uncertainty, three forms of risk concentration emerge from this granular mapping.

- **Exposures to physical climate hazards are concentrated at the regional level, with potential stranding risks.** A matching of physical risk drivers to 1.5 million euro area firms at the address level shows that riverine floods are the most economically relevant widespread climate risk driver in the EU over the next two decades. Wildfires, heat stress and water stress could have a strong impact on some regions, possibly compounded by further stresses such as rising sea levels in the second half of this century. Ultimately, a coalescing of such natural hazards could impact up to 30% of euro area bank corporate exposures. Systemic amplifiers leading to potential stranding could follow from two sources. A first is interactions with existing financial vulnerabilities, noting that exposures appear to be more relevant for weakly capitalised and/or less profitable banks. A second and perhaps even more concerning systemic amplifier relates to protection gaps. On the one hand, physical collateral, backing the majority of collateralised exposures, may itself be compromised by climate hazards, thereby subject to “wrong way risk”. On the other hand, insurance might not represent a buffer, particularly in a systemic shock with widespread impacts on affordability or coverage, given that only 35% of economically relevant climate losses on average are estimated to be currently insured in the EU.

- **Exposures to emissions-intensive firms are concentrated not only across but also within economic sectors, leaving parts of the financial system vulnerable to potentially destabilising financial market corrections.** A matching of all scopes of firm greenhouse gas (GHG) emissions to over 1.5 million euro area firms suggests that exposures to high-emitting

[1] A detailed gap analysis, framing the focus of this report, is contained in: ESRB (2020), “**Positively green: Measuring climate change risks to financial stability**”.

firms represent 14% of collective euro area banking sector balance sheets – mainly concentrated in the manufacturing, electricity, transportation and construction sectors. Exposures vary greatly not only across economic sectors, but also within them – losses related to the highest emitting firms could constitute an estimated 10% of bank balance sheets in the event of credit rating downgrades associated with a rapidly rising carbon price to Paris-aligned levels. In the case of investment funds, portfolio greening needs are even greater – with over 55% of investments tilted towards high-emitting firms and an estimated alignment with the EU Taxonomy at only 1% of assets. As for insurers, while direct holdings are contained, they could be amplified by investment fund cross-holdings of around 30%. Such impacts could be particularly pronounced should financial markets abruptly reprice the financial risk associated with climate change – against a backdrop of rapid market growth of green finance and environmental, social and governance (ESG) investing despite still limited disclosures, standards and taxonomies.

- **Exposures to climate risk drivers are also concentrated in specific European financial intermediaries.** With regard to physical risk, 70% of banking system credit exposures to firms subject to high or increasing physical risk hazards over the next decades are concentrated in the portfolios of only 25 banks. For transition risk, many EU investment funds may be subject to increased scrutiny noting that, on average, only 11% of portfolios can currently be considered as green.

Long-term scenario analysis for EU banks, insurers and investment funds suggests credit or market risk losses from an insufficiently timely or effective climate transition. Three climate scenarios drawn from the Network for Greening the Financial System (NGFS) are explored, examining both physical and transition risk drivers as well as assumptions on climate technologies: a reference *orderly* scenario of timely policy adjustment complemented by effective carbon dioxide removal technologies, against a destabilising *disorderly transition* and a *hot house world* physical risk-laden outcome. The scenarios are translated into actionable form by leveraging the granular risk mapping and transposing macroeconomic model outputs to 55 economic sectors and numerous regions. The scenarios are then run through stress test models for banks, insurers and investment funds. A consistent finding is that credit and market risk could cumulate from a failure to effectively counteract global warming. Notwithstanding uncertainties around methodologies analysing such long-dated horizons, scenarios indicate that physical risk losses – particularly for high-emitting firms – would become dominant in around 15 years in the event of an insufficiently orderly climate transition, with falls of up to 20% in global GDP by the end of the century should mitigation prove to be insufficient or ineffective.

- EU **banking sector** credit risk losses under adverse climate scenarios could amount to 1.60-1.75% of corporate risk-weighted assets in a 30-year timeframe. Such a magnitude is around half that of adverse scenarios used in conventional macroeconomic stress test exercises (albeit with a far shorter horizon). A *hot house world* scenario leads to more financial system losses than a *disorderly transition* scenario – both in the sectoral concentration of bank losses (with electricity and real estate together accounting for over half of the total impact) and in the broader distribution of bank level losses.

- EU **insurance sector** market risk revaluation losses could be material in key climate-sensitive sectors for corporate equity and, to a lesser extent, corporate bond investments over the next

15 years under a *disorderly transition* scenario. While average impacts are quite modest, amounting to about 5 percentage points above a reference orderly adjustment scenario, modelling using sector-level production plans and technologies suggests particularly large losses of 15% for equity holdings in oil, gas and vehicles.

- Market risk losses could also be relevant for EU **investment funds**. Adverse scenarios suggest a direct aggregate asset write-down of 1.2% in holdings of equity and corporate bonds in the next 15 years, which together make up over 60% of around €8 trillion in investment fund assets. At the same time, the overwhelming majority of losses among the fund universe are driven by investments in energy producers and could be amplified in case of fire sales. At the fund level, higher emitting investment portfolios could see losses of up to 14%.

Notwithstanding notable progress in measuring and modelling climate related risk, much still remains to be done. The sufficiency of reported data – including commonly agreed physical risk metrics, as well as forward-looking and downstream emissions aspects – remains a key issue, illustrated by the need for recourse to estimates of private data providers for the time being. The heterogeneity of climate-related disclosures among firms and financial institutions implies that the granular and country-level results will be subject to refinements as progress is made in addressing data gaps and obtaining more complete data. A **Data Supplement** accompanying this report details insights gained as part of this mapping of climate drivers to economic and financial risk in the EU. Moving from measurement to modelling, the incorporation of second-round effects, including adjustments of firms and financial institutions over time, as well as prospective non-linearities would further enrich results. Ultimately, the transmission of risks to the financial system and its prospective timing still needs to be better understood – including more precisely locating all relevant physical touchpoints; adaptation measures by both financial and non-financial firms; risk mitigation from collateralised lending and insurance; and the interplay of acute versus chronic physical risk drivers. While these challenges are material, the advances in empirical understanding of risks already provide a valuable evidence-based foundation, which should help to support macroprudential policy considerations in an increasingly heated policy debate.

1 Introduction

Improved measurement and modelling of the impacts of climate change on financial stability is needed to underpin a policy debate that is gaining momentum. This report deepens quantitative insights for the European Union, adding to a growing body of international research examining the impacts of climate change on financial stability. In particular, it seeks to fill key gaps in the empirical understanding of the impacts of climate-related risk drivers on financial stability in two key ways. First, it builds on findings from a 2020 report[2] to map more comprehensively climate-related drivers to financial risk in the European Union – bringing new insights on physical risk, as well as deepened insights on the financial impacts of transition risk. Second, the report harnesses a growing number of modelling initiatives in the EU official sector thereby permitting a consistent scenario analysis tailored to European banks, insurers and investment funds. Notwithstanding measurement and modelling uncertainties to tackle this complex topic, the report sheds further light on the quantitative dimension of climate risk to help underpin ongoing policy analysis.

The empirical findings of this report suggest that while financial stability risks for the European financial system are manageable, they are both concentrated and path dependent. Climate change is expected to have aggregate financial impacts that are pervasive in nature. At the same time, the interplay of climate risk drivers and existing financial vulnerabilities may be unevenly spread across geographies, sectors and firms. This report builds on these findings to present a granular exposure analysis, which involves mapping millions of firm and address-level climate risk drivers to financial balance sheets of European Union financial institutions and financial markets to detect spatial risk concentrations. Drawing on this exposure mapping, which translates high-level scenarios into actionable granular form, the report goes on to set out a forward-looking assessment of risks over a decades-long timeframe. Running these scenarios consistently through the prism of the entire EU financial sector, that is, banks, insurers and asset managers, suggests temporal risks to the financial system are lowest in a timely and orderly transition towards achieving Paris-aligned temperature goals.

With regard to measurement, a granular mapping of climate drivers to more familiar economic and financial risk suggests material spatial risk concentration along geographic and sectoral dimensions.

- **Exposure mapping suggests flooding is a key widespread risk for EU financial institutions, although a coalescing of natural hazards could significantly amplify risks in some cases.** Matching physical risk drivers to data for 1.5 million euro area firms highlights the importance of floods as a key climate risk driver in the EU – alongside pronounced risks from wildfires, heat stress and water stress in some countries. While the exposure of the banking system to firms that are already highly affected by physical risks is moderate, high or increasing, physical risks could together affect up to 30% of the euro area banking system exposures to corporates. Of more concern is the fact that these exposures to physical risk drivers appear to be more relevant for weakly capitalised and/or less profitable banks, while also being highly concentrated (70% of banking system credit exposures to firms subject to

[2] See ESRB (2020) "**Positively green: Measuring climate change risks to financial stability**".

high or increasing physical risks being concentrated in the holdings of only 25 banks). And, while the prospect of risk mitigation may limit losses associated with climate-related risk, the widespread availability of mitigants may be compromised in the event of systemic stress. On the one hand, physical collateral, backing the majority of collateralised exposures, may itself be compromised by climate hazards, thereby subject to "wrong way risk". On the other hand, an insurance protection gap may ensue in the event of extreme risk manifestation, given that currently only 35% of economically relevant climate losses on average are insured in the EU.

- **An extended mapping of firm emissions confirms risks to European financial institutions which are limited but concentrated both across and within sectors.** A review of exposures across millions of firms worldwide suggests limited exposure in the euro area banking and insurance sector to sectors with the highest emissions intensity, although this varies greatly by sector, also reflecting the use made of financial instruments. While the average balance sheet exposure of euro area banks to high-emitting sectors is relatively low at 14%, the emissions intensity within industries varies greatly, giving rise to pockets of vulnerabilities owing to exposure concentration. Indeed, banking system losses could increase by almost 10% in the event of credit rating downgrades to high-emitting firms stemming from rapid rises in the carbon price to ensure alignment with the Paris Agreement levels. For euro area investment funds, exposure is clearly oriented towards highly emitting sectors – with over 55% of investments tilted towards high-emitting firms, suggesting a need for quite a large degree of greening of portfolios. It is particularly noteworthy that the estimated alignment of EU fund portfolio holdings with the EU Taxonomy is very low at only 1% of assets. Spillovers across financial intermediaries may be sizeable, in particular since investments in funds account for about 30% of investments by insurers.

- **These firm and sectoral exposures are susceptible to potentially large financial market repricing.** As financial markets are factoring in climate-related risks at a breakneck pace, this has not yet translated into a material widespread pricing differential, leaving open a potential large repricing. Many studies have examined the question of a carbon premium in financial markets, but evidence is at best mixed on the question of whether climate risks are fully priced in on the transition risk side or on the physical risk side. This is despite rapid market growth in green finance and environmental, social and governance (ESG) investing, which are increasing towards the financial market scale required to meaningfully mitigate climate risks. The amount of bonds labelled green in Europe now exceeds €500 billion with issuance growing at 20-30% per annum for several consecutive years and with an even more impressive growth in ESG funds worldwide. While growth in both green bonds and equities has been strong, carbon markets and market hedging mechanisms such as derivatives or catastrophe bonds remain limited in scope. Importantly, green debt labelling has had a mixed impact on carbon reductions to date, suggesting that greenwashing remains an issue.

Leveraging this granular measurement, long-term scenario analysis methodologies suggest net financial system benefits which accumulate with time from proactive and sustained policies and technological innovation to tackle global warming. Forward-looking scenario analyses suggest net benefits to banks, insurers and investment funds of timely and orderly macroeconomic climate policies to tackle path-dependent climate-related risks. In order to construct forward-looking quantitative analyses, in a first step, the benchmark high-level scenarios

established by the Network for Greening the Financial System (NGFS) need to be made actionable at the granular level for 55 economic sectors. In a second step, methodologies need to be selected for analysing the interplay between physical and transition climate risks over a suitably long horizon, while accounting for new interactions between macro-financial models that include both physical and transition risk-related climate change. The high climate risk scenarios described in this report –namely a *disorderly transition*, a *hot house world* with high levels of physical risk – are compared to a reference scenario consisting of an *orderly* climate transition benefiting from timely policy adjustment complemented by effective carbon dioxide removal technologies. While methodologies analysing long-dated horizons are subject to several uncertainties, initial indications are that physical risk losses, particularly for high-emitting firms, would become dominant in around 15 years in the event of an insufficiently orderly climate transition – with falls of up to 20% in global GDP by the end of the century should mitigation prove to be insufficient or ineffective.

The **forward-looking assessments** of financial losses building on these scenarios substantiate both credit risk of banks and market risk of insurers and investment funds. These *climate stress tests* show consistently that *disorderly transition* and *hot house world* scenarios would lead to higher loan defaults and asset valuation losses.

- For **banks**, the expected loss in 30 years in the high climate risk scenarios relative to an orderly reference scenario is between 1.60% and 1.75% of the risk-weighted assets of medium to large-firms' exposures. This magnitude is around half that under the adverse scenarios used in conventional macroeconomic stress test exercises, albeit with a far shorter horizon. That said, bank losses are concentrated in certain sectors only, in particular the electricity and real estate sectors, which together account for over half of the total impact. Turning from the average impact on banks to the broader distribution of the impact across the banks considered, the impact of the hot house world scenario is consistently more negative than the disorderly scenario.

- An analogous exercise for the **insurance sector** is augmented by modelling production levels and technologies (for example coal, oil and renewable power) in individual sectors relative to target greenhouse gas (GHG) emissions and adapting to the NGFS-based scenarios. Results suggest that average 15-year-ahead revaluation losses in climate-sensitive sectors under the disorderly scenario are relatively modest, about 5 percentage points higher than the orderly scenario. Equities are particularly severely impacted, while losses are also quite concentrated – with losses of 15% in oil, gas and vehicles.

- Applying the high climate risk scenarios to **investment funds** results in a direct asset write-down of 1.2% in holdings of equity and corporate bonds in the next 15 years, which together make up over 60% of around €8 trillion in investment fund assets. Losses are strongly concentrated at the sector and fund level and could be amplified in case of fire sales. The overwhelming majority of losses among the fund universe are driven by investments in energy producers. At the fund level, higher CO2 investment portfolios are hit relatively harder, with losses of up to 14% across the EU investment fund universe.

While these results fill key gaps in both measurement and consistently applied methodologies, much remains to be done. Notwithstanding notable progress on collections for physical and transition risks, data granularity and forward-looking aspects still represent an issue –

this is corroborated by the significant recourse made to private data providers in drawing up this report, which provided the estimates needed to fill any gaps. This issue of data availability and quality continues to undermine the effective and efficient financial pricing of climate risk. Existing initiatives should help to address outstanding issues related to data gaps and ensure more robust disclosures, providing a more complete picture of climate-related financial risk. By contrast, taxonomies remain far from complete, in particular risk-based approaches that account for emissions-intensive exposures. It will be essential to have consistent climate-related data, including ways of assessing credible forward-looking Paris-alignment commitments, in order to develop efficient market mechanisms. It should be noted that forward-looking disclosures are essential since this forward-looking nature is inherent in physical and transition risks. As far as modelling is concerned, apart from caveats that apply, including limited coverage, modelling second-round effects and prospective non-linearities would further enrich results. Moreover, a better understanding is needed of the transmission of risks to the financial system, including more precisely locating all relevant physical touchpoints (facilities, supply chains); adaptation measures by both financial and non-financial firms alike; risk mitigation from collateralised lending and insurance; and the interplay of acute versus chronic physical risk drivers. Lastly, meeting the challenges of forward-looking scenario analysis largely involves identifying adjustment paths over long-dated horizons, which requires key assumptions about where financial stability risks may gradually unfold over time in contrast to the abrupt materialisation of risks over a short period of time.

2 Physical risk

2.1 Physical risks for the financial system

Key physical risk drivers in Europe include floods, water stress and heat stress, including wildfires.[3] These risk drivers arise from different weather and climate-related hazards, including extreme precipitation, sea level rise, a warming and drying trend and extreme temperatures (IPCC (2014a)). Global warming is at around 1.19ºC above pre-industrial levels,[4] and "high multiple interrelated climate risks" are projected in some regions with a high degree of confidence even with a warming of 1.5ºC (IPCC (2018)). The most severe outcomes can still be prevented, but emissions driving climate change need to be reduced drastically and immediately.[5]

Physical risks to the financial system depend on the physical hazard itself, but also on entities' exposures to these hazards, their vulnerability, and on the risk mitigation measures in place, including insurance coverage. For example, credit and market risk for banks may increase (BCBS (2021a)), and the underwriting risk of (re)insurers may rise, jeopardising asset values and potentially challenging business strategies (IAIS (2018)). More generally, physical risks are assumed to be transmitted to the financial system through both macroeconomic and microeconomic impacts, including impacts on corporates, households, sovereigns or other financial institutions. Through financial system exposures, climate-related risks give rise to financial risks (BCBS (2021a); NGFS (2019)). Corporates may, for example, be impacted by physical risks through the destruction of physical capital, but also through the disruption of production and supply chains, adaptation costs or deteriorations in macroeconomic conditions (IPCC (2014b)).

Assessing financial system exposures to physical risk drivers requires granular information on the geo-spatial characteristics of financial institutions' exposures, combined with data on physical risk drivers. In many cases information on the location of the counterparty is only available at an aggregated level, which does not indicate the exact address of a counterparty but only its postcode or NUTS[6] territory. In addition, these data collections do not usually include the geographical locations of all relevant subsidiaries or facilities of companies. Beyond the granularity of the location of the counterparty, physical risk analysis relies on the spatial granularity of physical risk drivers and the temporal perspective: physical risk indicators relying on historical information

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3 This risk assessment is based on Table 23-5 in **IPCC (2014)**. The terminology and classification of physical risk drivers varies in the literature and often derives from existing classifications used, for example, by the catastrophe modelling community or insurance sector. Not all hazards commonly included in these types of classification may necessarily be impacted by climate change. See the Annex 1 to this report for a detailed classification of the hazards considered in each category."

4 EU Copernicus Climate Change Service: **Global temperature trend monitor**; value refers to March 2021.

5 Beyond IPCC (2018a) see, e.g. EEA (2017), Climate change, impacts and vulnerability in Europe 2016. EEA Report No 1/2017. EEA (2020), "**EEA climate state and impact (CLIM) indicators**".

6 Nomenclature of Territorial Units for Statistics: the 27 members of the EU are divided into 87 NUTS1 units of major socio-economic regions, 241 NUTS2 units of basic regions for the application of regional policies and 1,196 NUTS3 units of small regions for specific diagnoses with, on average, a population of around 200,000. For further detail see the **Eurostat explanatory website**.

may fall short of capturing the risks that can be expected as a result of climate change, raising the need to integrate forward-looking information.[7]

2.2 Banking sector exposures to physical risks

This section assesses banking sector exposures to non-financial corporations (NFCs) affected by different physical risk drivers in Europe. The analysis is structured into (i) risk identification and (ii) exposure mapping and measurement. The first step describes physical risk drivers for firms in Europe. The second step combines physical risk indicators from the "Four Twenty Seven"[8] data collection with banking system exposures to firms from AnaCredit. This allows aggregate bank exposures to firms subject to high or increasing physical risks and the concentration of physical risks among banks to be assessed. The location at which a firm may be impacted by physical risks is the location of the firm's headquarters and for largest listed firms also the location of subsidiaries. Combining these gives an aggregate coverage of 89% of credit to NFCs, of which 31% match directly at firm address level, with some relevant differences across countries (see Chart 1.1 in the Data Supplement).

The results presented below can be considered a first estimate of the range of exposures that may be affected by the physical risks stemming from climate change. A limitation is imposed by the need to consider the location of firms' headquarters as a proxy for the location at which a firm may be impacted by physical risks, which may lead to either over or under-estimation of risks.[9] As indicated, beyond their location, the impact depends on the firm's activities. For example, it may depend on the resources used for production or their technological processes – but not all potential impacts in key economic sectors are well understood (IPCC (2014b)). In addition, this analysis considers firm-level factors enhancing or limiting vulnerability only to a limited extent.[10] Finally, risk enhancing or risk mitigation factors, such as the potential impact on collateral, or insurance coverage are not yet fully considered in this analysis (see discussion of data needs in Section 2.4).

2.2.1 Physical risks for EU firms

From the perspective of larger firms in Europe, the main climate-related physical risks are floods, water stress, heat stress and wildfires (Chart 1, left panel). This is based on the analysis of Four Twenty Seven risk indicators for around 1.5 million firms in Europe with varying data coverage and degree of representativity across countries. A significant share of these firms is located in areas that are already highly exposed, that are projected to be highly exposed to physical hazards over the next 20 years or that are in areas that are exposed today and where the exposure

7 For further details on assessing physical risks, please refer to Section 1 in the Data Supplement.

8 **Four Twenty Seven** is an affiliate of Moody's; more detail on the data is provided in the Data Supplement.

9 See the Data Supplement for a discussion of this assumption.

10 Flood risk scores include regional flood protection; heat and water stress scores include sensitivity factors in parts determined by a firm's dependence on resources (e.g. water, energy, labour) – this dependence is proxied using the firm's country and industrial sector.

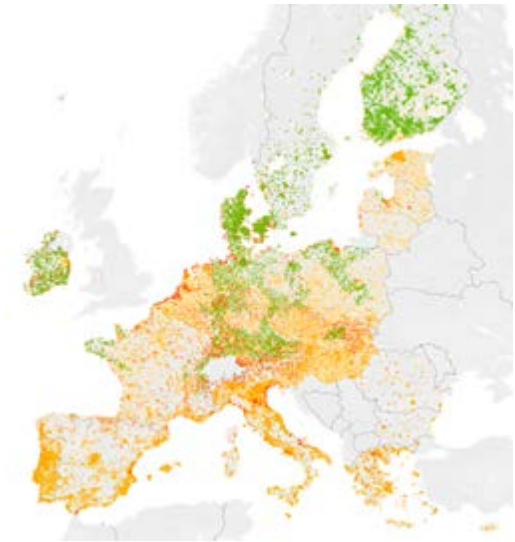
level is increasing (Chart 1, right panel). These firms will sometimes be labelled as “high exposure firms”.[11]

Firms with high or increasing physical risk exposures are distributed differently across Europe depending on the hazard. Floods are a relevant risk driver in many countries, although with a stronger concentration in central or northern Europe (Box 1). Heat stress, water stress and wildfires predominantly affect southern Europe. A number of areas have a high exposure to water stress also through other countries, which are often driven by a combination of a drying trend and high water demand.

Chart 1

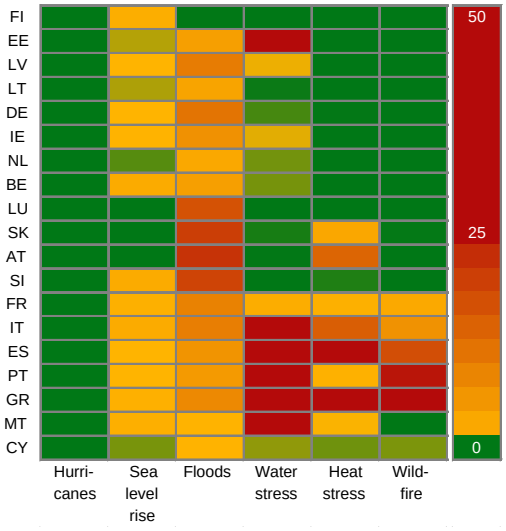
Physical risks to firms in Europe stemming from climate change mainly arise from floods, wildfires, heat stress or water stress

Maximum firm exposure to physical hazards



Share of firms in areas of high or increasing exposure to a physical hazard

(percentages)



Sources: Four Twenty Seven, an affiliate of Moody’s, and ECB calculations.
Notes: The location of firms’ headquarters and that of their largest subsidiaries are used as proxies for firm location. Data coverage varies by country, selected firms may not be representative of all firms within the country. Left panel: Based on 1.5 million firms in Europe. Each dot stands for one firm, its colour refers to the maximum exposure level across six hazards, including hurricanes, sea level rise, floods, water stress, heat stress and wildfires. Right panel: Based on 1.1 million firms in the euro area. The share of firms with “high present/projected exposure” or “increasing exposure” in all firms in the sample within the respective country is shown. No firms in the sample have high or increasing exposure to hurricanes.

[11] Firms’ exposures to physical risks are taken from Four Twenty Seven. Four Twenty Seven describes the exposure of firms to physical hazards at five different levels: “highly exposed to historical and/or projected risks” (“high present/projected exposure”), “exposed today and exposure level is increasing” (“increasing exposure”), “exposed to some historical and/or projected risks” (“some present/projected exposure”), “not significantly exposed to historical or projected risks”, and “no exposure” (the latter two summarised as “no significant exposure”). The risk indicators integrate information on the extent of current and projected hazards up to 2040.

Box 1
Deep dive – flood risk in Europe

Between 1980 and 2017, weather and climate-related events caused approximately €453 billion in economic losses in the European Economic Area (EEA) (plus the United Kingdom (UK)).[12] The 2002 flood in central Europe and the 2000 flood in Italy and France are among the most expensive weather-related events to have occurred in the European Union since 1980, causing €21 billion and €13 billion worth of losses respectively. Flood events in the EEA since 1995 account for more than 40% of total economic losses reported for natural catastrophes.[13]

At present, riverine floods cause €7.8 billion worth of damages in the EU and UK (around 0.06% of current GDP) and affect more than 170,000 people annually (JRC (2020b)).[14] Riverine floods are the most frequent and the most destructive type of flood: more than 60% of flood events are caused by river inundation and such events have generated close to 70% of the overall historical economic losses reported since 1995.[15]

If no further mitigation and adaptation measures are taken, economic losses are expected to grow to nearly €50 billion[16] **per year by the end of this century under a 3°C global warming scenario (JRC (2020b)).** However, compared with unmitigated climate change, limiting global warming to 1.5°C would halve economic losses and population exposure to river flooding, while adaptation measures could reduce them by more than 70%.

Floods along rivers and coasts are a relevant risk driver across many regions in Europe (Figure A, left panel). However, current levels of flood protection prevent much of the risk (Figure A, right panel). This highlights the importance of taking into consideration protection or adaptation measures already in place for the analysis of physical risks.[17] Generally, existing adaptation measures may be implemented at local, regional or national level by governments, but may also relate to firm-level measures. At the same time, the literature points to the need to further enhance adaptation measures in order to prevent high levels of risk (e.g. IPCC (2014a); JRC (2020)). Strategies are being designed to help Europe to adapt to a changing climate, including the EU strategy on adaptation to climate change.[18]

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12 See **Economic losses from climate-related extremes in Europe**.

13 Based on EM-DAT: The Emergency Events Database – Université catholique de Louvain (UCL) – CRED, Guha-Sapir, Brussels, Belgium. The Emergency Events Database is a publicly available global database on natural and technological disasters maintained by the Centre for Research on the Epidemiology of Disasters. The database covers total damages caused by 142 flood events that have occurred in the European Economic Area (including the United Kingdom) since 1995. For 54 of these events it provides information on the total and insured losses.

14 The JRC Peseta IV study on river floods, see JRC (2020b), simulates the changes in river flow under different climate scenarios (1.5°C, 2°C and 3°C warming), by mid- and end-century, and estimates the impacts on the economy and society under future socioeconomic conditions. The changes in temperatures are converted into the corresponding changes in frequency and severity of floods using biophysical models, which are then transformed into financial losses for the entire economy.

15 Figures based on EM-DAT, but economic and insured losses are not always available or are based on estimations. Detailed information on the total damages is available only for slightly less than 45% of the reported flood events.

16 Expected annual damage (2015 values) for all EU countries taking into account future socioeconomic conditions (2100 economy) and 3°C warming climate scenarios.

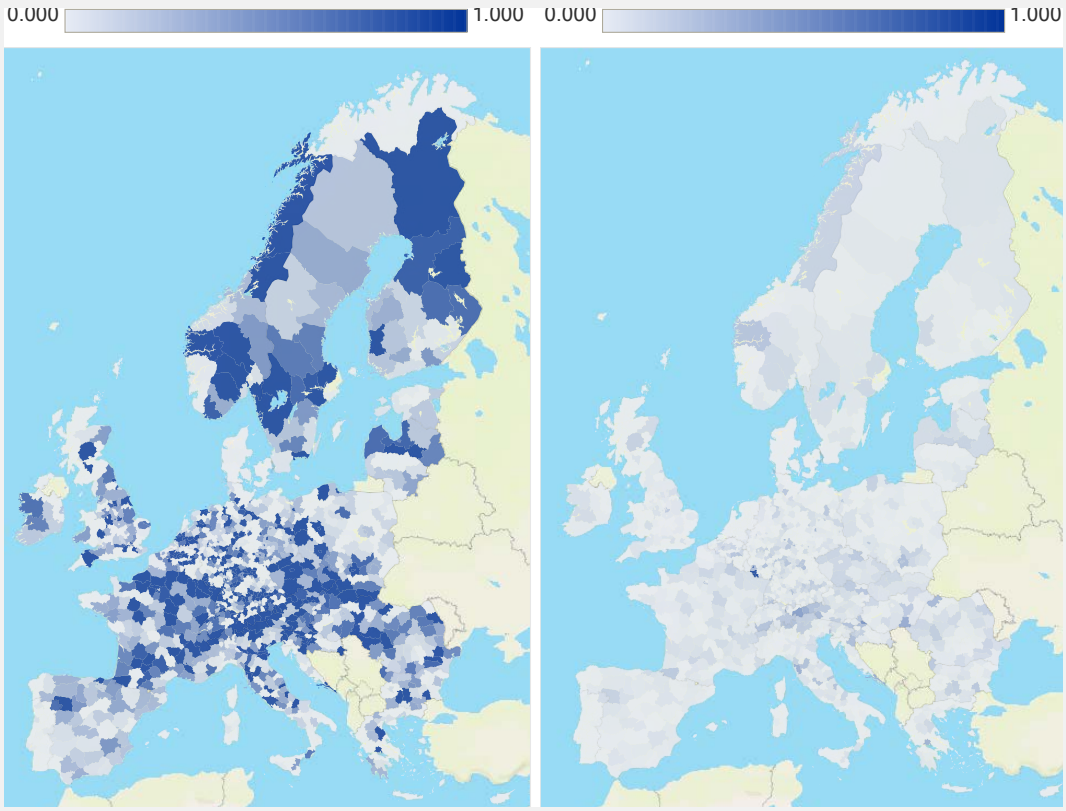
17 See the Data Supplement for a description of the underlying data and calculation of indices.

18 See **EU strategy on adaptation to climate change**, 24 February 2021.

Figure A

Protection measures are important aspects of flood risk analysis

(one-year flood probability, percentages)



Sources: JRC RDH and ECB calculations.
Notes: Values refer to the flood probability for industrial/commercial areas within each NUTS3 territorial unit. Please see the Data Supplement for details on the calculation and underlying data.

A recent study[19] sheds some light on the likely magnitude of changes in flood risk and the impact on the European insurance sector. The results show that average annual insurance losses due to inland flooding are expected to increase under all scenarios, with a greater impact in northern and western European countries. Although subject to high uncertainty, the projected increase in average annual losses ranges between 26% and 80% by mid-century depending on the degree of warming modelled. Targeted risk-reduction efforts including adaptation to climate change (such as changes in building codes and practices or investments in flood defence systems) would likely reduce these impacts.

[19] For further information, please see the RMS White Paper, "**Modelling Future European Flood Risk**".

2.2.2 Exposure mapping and measurement – physical risks in the banking system

2.2.2.1 Exposure to high-risk firms

Around 30% of euro area banking system credit exposures to NFCs are to firms exposed to high or increasing risk owing to at least one physical risk driver. Around 10.6% of bank credit exposures to NFCs are subject to high or increasing flood risk,1.4% to coastal floods/sea level rise, 11.2% to heat stress, 12.2% to water stress and 4.8% to wildfires (Chart 2, left panel). Even for exposures to NFCs located in areas with a low (< 0.1%) average annual probability of flooding, the expected median flood depth may exceed one metre for around 59% of the exposures considered (Chart 2, right panel). This probability rises to around 73% and 82% of exposures respectively for exposures with medium (0.1-0.2%) or high (0.2-1%) annual probability of flooding.[20] The distinction between hazard probability and intensity becomes important when translating hazards into economic damage. For example, a flood of one metre is expected to lead to damages of approximately 30% of the building value for commercial buildings in Europe (JRC (2017)).[21]

[20] This complementary information is obtained from flood risk data from the JRC Risk Data Hub (see Data Supplement for details).

[21] Calculations for economic losses from intensities of other hazards are not available but would be needed to strengthen the quantitative underpinning of loss assessments.

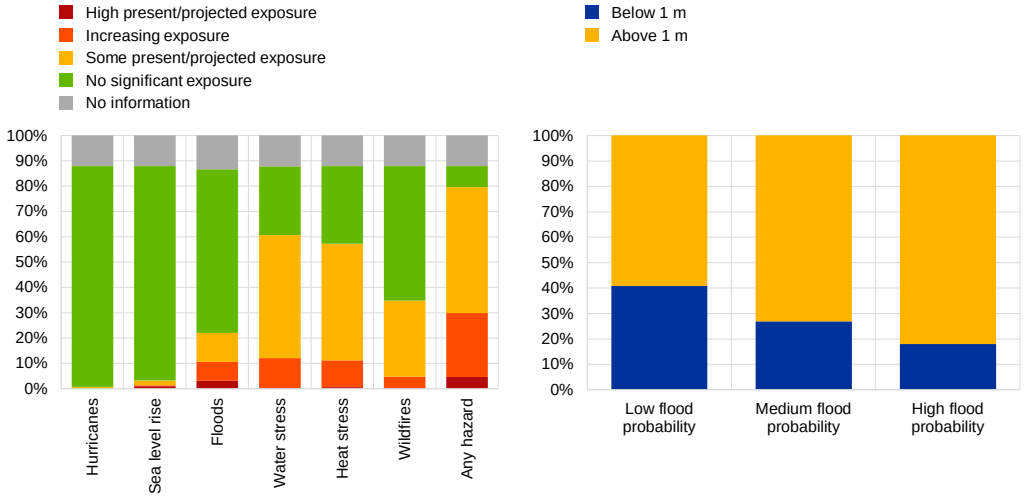
Chart 2

Around 30% of euro area banking system credit exposures to NFCs are to firms exposed to high or increasing risk, while it is possible for low probability events to have a large impact

Share of euro area banks' credit exposures to firms by corporate physical risk level
(percentages of total bank exposures to NFCs)

Average flood depth for different flood probabilities

(percentages of bank exposures to NFCs with corresponding flood probability)

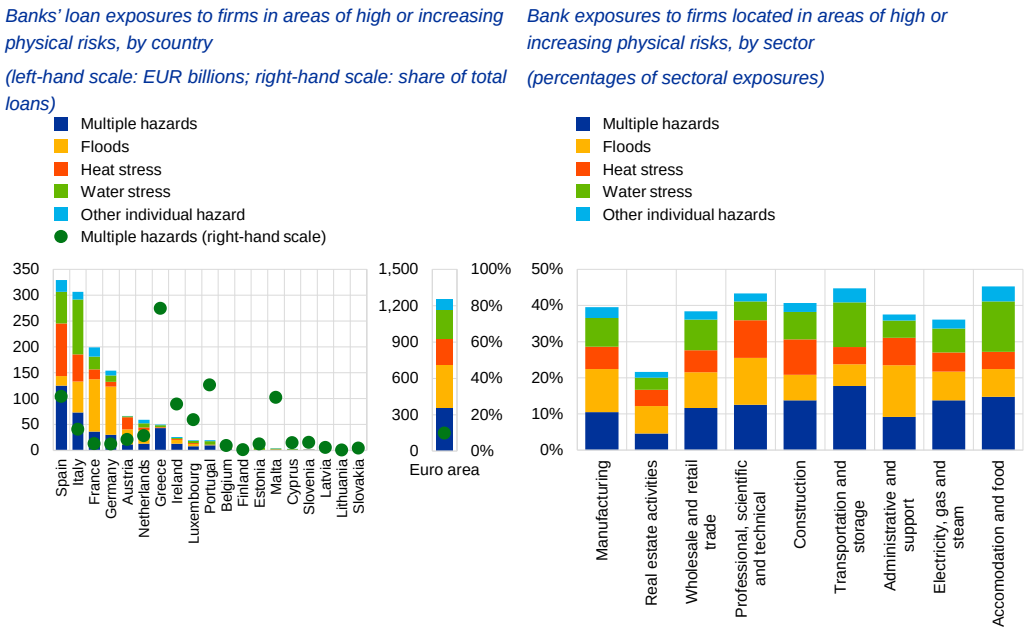


Sources: AnaCredit, Four Twenty Seven, JRC RDH and ECB calculations.
Notes: Bank loan exposure is taken from AnaCredit and matched with Four Twenty Seven data at corporate level. Credit exposures to NFCs above €25,000 are considered; total exposures amount to €4.2 trillion. 31% of exposures can be matched directly, 58% are matched using postcode-level aggregates of the Four Twenty Seven corporate level indicators and 11% cannot be matched this way due to missing geo-locational information in AnaCredit ("no information"). Right panel: The bars refer to euro area banking system exposures to NFCs located in areas with low, medium or high flood probability. See Data Supplement for details on the calculation of indicators and matching with AnaCredit exposures. Data as at December 2020.

Banking system exposures to firms located in areas with at least some present or projected exposure to physical risk drivers amount to up to 80% (Chart 2, left panel). These figures are based on an integrated assessment of current and projected risks up to 2040. Banking exposures affected by physical risks beyond 2040 will depend crucially on measures for reducing emissions and on the degree of adaptation to climate change (see the discussion on scenarios in Section 5).

Chart 3

Bank exposures to firms in areas of high or increasing physical risks appear to be concentrated in selected regions and sectors



Sources: AnaCredit, JRC RDH, Four Twenty Seven and ECB calculations.
Notes: Credit exposures to NFCs above €25.000 are considered; €4.2 trillion of exposures overall; NFC location used to assign risk levels refers to the headquarters; country breakdown refers to the bank's country of residence. The right panel shows only sectors with aggregate absolute exposures to firms located in areas of high or increasing physical risks above €50 billion. Data as at December 2020.

Almost 10% of euro area banking system exposures to NFCs are subject to multiple high or increasing physical risk drivers (Chart 3, left panel). These become particularly relevant in the case of increases in compound or connected events (see, for example Zscheischler et al. (2018); Raymond et al. (2020)), which may amplify the impact of the respective risk drivers.[22] The most common combination of risk drivers in our data sample consists of water stress and wildfires, complemented by heat stress in the presence of three risk drivers. Consequently, the relative share of exposures of banks to firms in areas affected by multiple risks is particularly relevant for banks located in Greece, Spain and Portugal.

The share of exposures to firms located in areas of high or increasing physical risks varies among sectors and is highest in the accommodation and food sectors as well as the transportation and storage sectors (approximately 45%, Chart 3, right panel). In addition, around 40-44% of exposures to NFCs in manufacturing, professional/scientific/technical activities and construction are subject to high or increasing physical risks by one or multiple risk drivers.

[22] According to Raymond et al. (2020) (Box 1), compound events involve temporally or spatially correlated hazards, cascading hazards, or concurring hazards related to a single event. They further define connected events as those that are linked through their impacts on societies.

2.2.2.2 Risk concentration among banks

Less capitalised and less profitable banks are on average more exposed to firms located in areas of high or increasing physical risk, suggesting that physical risks may amplify existing bank vulnerabilities (Chart 4, left panel). Without considering mitigating factors such as collateral, banks' median exposure to firms subject to high or increasing physical risk is six times higher among the 25% least well capitalised banks (by CET1 ratio) relative to the 25% most well capitalised banks. Similarly, the median exposure at risk held by the quartile of banks with the lowest return on equity (ROE) is twice as big as that for the 25% most profitable banks. Physical risks from climate change may therefore interact with other banks' vulnerabilities, exacerbating the potential implications for financial stability.

Exposures to firms in areas of high or increasing physical risks are concentrated in a few – relatively large – banks (Chart 4, right panel). More than 70% of the banking system credit exposures to the identified high-risk firms are held by 25 banks, reflecting the fact that physical risk factors are concentrated among a few large banks. These banks are generally large (with total assets ranging between €68 billion and €2,355 billion, with an average of €672 billion and a median of €386 billion), well diversified across asset classes and regions, and have additional capital buffers given their status as global or other systemically important banks. As a result, their loan exposure to firms in areas of high or increasing physical risks is generally lower than 7% of their total assets, with seven banks having exposures of more than 10%.

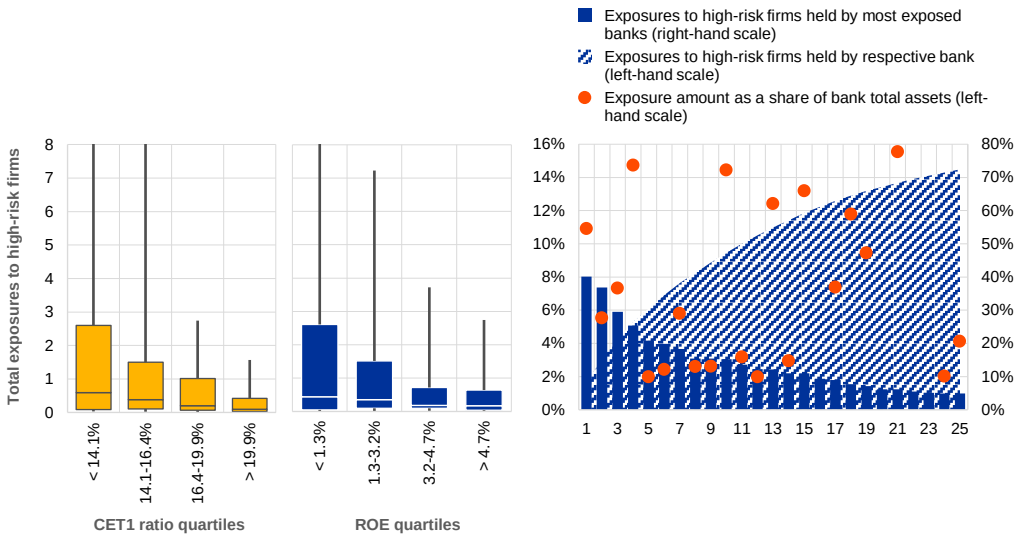
Chart 4

Physical risks concentrated in small number of banks and interacting with other vulnerabilities

Distribution of banks' exposures to firms located in areas of high or increasing physical risk, by level of capital and profitability
(EUR billions)

Concentration of banks' exposures to firms located in areas of high or increasing physical risk in the banking system

(EUR billions)



Sources: ECB supervisory data, AnaCredit, Four Twenty Seven data and ECB calculations.
Notes: Maximum risk level across the following risk categories is considered: floods, sea level rise and wildfires; only credit exposures to NFCs above €25.000 are considered; €4.2 trillion of exposures overall; NFC location used to assign risk levels refers to the headquarters; sample of 357 banks (significant institutions and major less significant institutions in the euro area). CET1 stands for Common Equity Tier 1; ROE stands for return on equity. Data as at December 2020.

2.2.2.3 The role of collateral

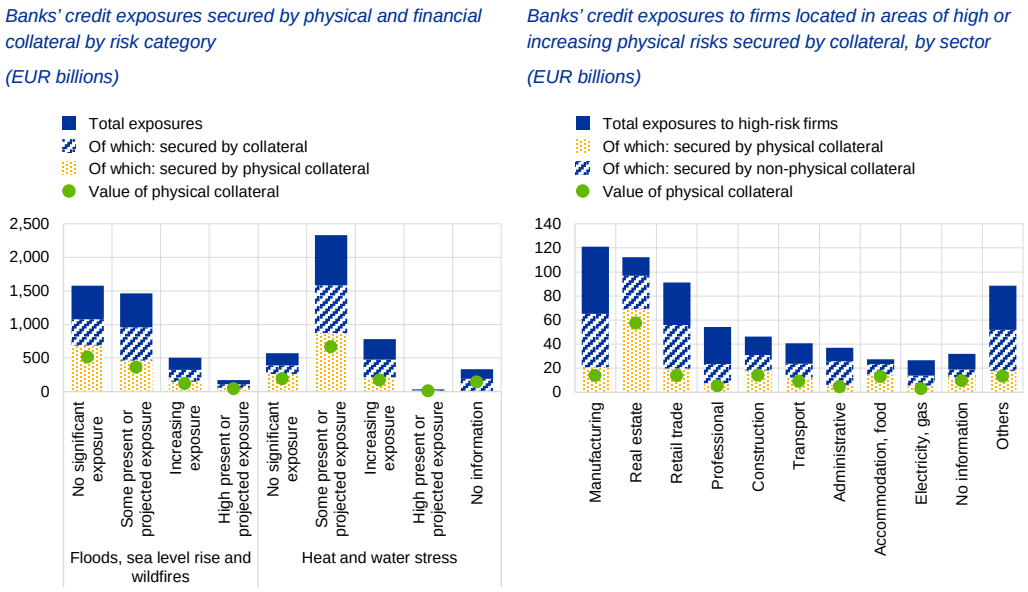
Two-thirds of exposures to firms located in areas of high or increasing physical risks are secured by collateral (Chart 5, left panel). Collateral plays an important role in mitigating losses for banks but may itself be subject to damage or loss of value. The use of collateral ensures that bank losses from credit exposures are mitigated. However, climate-related damage causing firms to default is also likely to have an impact on the physical collateral used to secure the exposures.[23] Such "wrong-way climate risk" reduces the loss-mitigating ability and increases potential losses for banks in the event of firms' default. Financial assets used as collateral could also be indirectly affected; for example, securities issued by a firm experiencing damages could lose value and be subject to fire sales. The same applies to firms perceived to be at risk owing to their location or specific characteristics.

[23] The combination of bank exposures to firms subject to physical risks protected by collateral in areas subject to physical risks still needs to be evaluated more thoroughly and is currently impeded by the lack of granular information on the location of collateral, and a relatively low coverage and unclear quality of information on the location of collateral even at aggregate (NUTS3) level.

The share of collateralised exposures to firms subject to high or increasing physical risks, as well as the composition of the collateral portfolio differ across sectors (Chart 5, right panel). The different degree of collateralisation for high-risk exposures reflects sector-specific characteristics. Banks are most exposed to firms in the manufacturing and real estate sectors, with more than two-thirds of exposures to sectors like real estate activities, construction, and accommodation and food being covered by collateral (mainly physical assets). This raises some concerns on its potential devaluation. Only around 45% of exposures to firms subject to physical risks in the manufacturing sector are secured by collateral, suggesting potentially higher losses in this sector. In addition, this sector may be particularly exposed to physical risks through firm supply chains, which has not been considered in this analysis.

Chart 5

More than 60% of banks' exposures to firms that are subject to physical risks are secured by collateral, half of which consists of physical collateral



Sources: AnaCredit, Four Twenty Seven data and ECB calculations.
Notes: Maximum risk level across the following risk categories is considered: floods, sea level rise and wildfires; only credit exposures to NFCs above €25,000 are considered; €4.2 trillion of exposures overall; NFC location used to assign risk levels refers to the headquarters; the total collateral value at instrument level is capped at the value of the instrument; insurance coverage not included. Data as at December 2020.

2.3 Insurers exposures to climate risk: a widening of the insurance protection gap?

While publicly available and regulatory reporting data on the level of individual perils is somewhat scarce, some insights into the importance of key perils faced by the insurance

sector[24] can be obtained by analysing Solvency II data reported to the European Insurance and Occupational Pensions Authority (EIOPA). Looking at aggregated results for insurance undertakings[25] using the standard formula to calculate natural catastrophe risk charge, non-life and composite undertakings are heavily exposed to flood risk in Europe. The total exposure in three key countries for which data were reported (France, Germany and the United Kingdom) represents 72% of total exposures across all regions. Moreover, the natural catastrophe risk charge for the flood risk module accounts for 57% of the total natural catastrophe risk charge after diversification and mitigation. In terms of capital charges, the flood risk module is the second most relevant hazard among the standard formula perils after windstorms, followed by earthquakes, hail and subsidence. EIOPA therefore included an in-depth analysis of flood risk in its sensitivity analysis of climate change-related risks.[26] A summary of the key findings is available in the Data Supplement.

In the light of climate change, the insurability of natural catastrophe-related risk and the affordability of insurance coverage may also become of increasing concern. In the past, only 35% of the total losses caused by extreme weather and climate-related events across Europe were insured. The historical uninsured part of about 65% of the losses for climate-related events is an indication of what can be considered a protection gap, see EIOPA (2019b).

Climate change poses a number of challenges to the insurability of climate-related risks that may potentially widen the protection gap. For instance, climate change means that the assumption that past event losses are a reliable way of estimating future losses may no longer hold true. Climate change could also have an impact on the randomness and correlation of events. These effects could put pressure on insurance reserves and capitalisation, and therefore insurance supply. Moreover, if losses to properties and businesses grow owing to climate change, the price of insurance may increase, affecting insurance demand.

EIOPA has therefore developed a pilot protection gap dashboard.[27] The main goal of the pilot dashboard is to establish a framework for identifying key risk drivers of the protection gap for natural catastrophes and for collecting relevant evidence and data. The methodology for deriving the relevant scoring and the existence of data gaps will be subject to review and will be updated based on further evidence and discussion in the future. The dashboard provides an estimation of today's protection gap using information about hazard, vulnerability, exposure and insurance coverage at the present time, as summarised in Table 1.

The pilot dashboard shows that protection gaps vary significantly among Member States and across different perils. Taking all EU countries together, the protection gap is low (for any type of peril). This can be explained in particular by geographical diversification (i.e. not all countries are impacted by the same perils).

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24 In this context, a peril is considered the cause of loss. A hazard makes a peril more likely to occur or makes it worse (a condition that increases the probability of loss).

25 The sample is based on 623 solo undertakings reporting a positive flood risk charge and using the standard formula. In terms of total assets, the sample represents more than 45% of the EEA non-life, composite and reinsurance market.

26 See EIOPA (2020b) "**Sensitivity analysis of climate-change related transition risks**". This is a pilot version which was developed based on publicly available data and expert judgement. It was developed to establish a framework for identifying key risk drivers of the protection gap for natural catastrophes and for collecting relevant evidence and data.

27 **EIOPA Pilot dashboard on protection gap for natural catastrophes**.

Table 1

Estimation of protection gap for European countries for a set of key perils[28]

COUNTRY	Estimate of protection gap today All perils	Estimate of protection gap today Earthquake	Estimate of protection gap today Flood	Estimate of protection gap today Wildfire	Estimate of protection gap today Windstorm
EU	1.0	1.0	1.0	1.6	1.0
Austria	2.0	1.8	3.4	2.6	0.0
Belgium	1.7	1.3	1.9	2.0	1.6
Bulgaria	2.0	3.2	1.7	2.0	1.2
Croatia	2.4	2.8	2.0	3.0	1.6
Cyprus	1.9	2.5	1.0	3.0	1.0
Czech Republic	1.9	1.8	2.0	2.0	1.6
Denmark	0.0	0.0	0.0	0.0	0.0
Estonia	1.1	0.0	0.0	3.0	1.5
Finland	0.7	0.0	1.0	0.0	1.8
France	0.5	0.0	0.0	2.0	0.0
Germany	1.6	1.6	2.6	1.0	1.1
Greece	2.2	3.5	1.7	2.0	1.6
Hungary	1.3	1.3	1.9	1.0	1.1
Iceland	1.0	1.0	1.0	n/a	1.0
Ireland	0.7	0.0	0.0	1.0	1.9
Italy	2.4	3.5	1.7	2.0	2.5
Latvia	0.9	0.0	1.0	1.0	1.7
Lithuania	1.3	0.0	1.0	2.0	2.0
Liechtenstein	n/a	n/a	n/a	n/a	n/a
Luxembourg	1.6	1.3	2.0	2.0	1.1
Malta	2.3	2.8	1.7	3.0	1.6
Netherlands	1.9	2.0	4.0	0.0	1.6
Norway	0.0	0.0	0.0	0.0	0.0
Poland	1.6	2.0	1.0	1.0	2.3
Portugal	2.0	1.8	1.6	3.0	1.7
Romania	1.7	3.1	1.6	1.0	1.2
Slovakia	2.4	1.9	3.0	3.0	1.6
Slovenia	1.5	2.4	1.3	1.0	1.2
Spain	0.9	0.0	0.0	2.0	1.4
Sweden	0.4	0.0	0.0	0.0	1.6

0	No risk
1	Low risk
2	Low/medium risk
3	Medium/high risk
4	High risk
n/a	Not available

Source: EIOPA.

Note: A protection gap of below 3 is not expected to be material.

2.4 Data gaps in exposure mapping

Improving data collections is essential in moving from initial exposure analyses to more comprehensive risk assessments. The following data issues emerge as priorities in this context (see also the **Data Supplement**).

1. Geo-spatial attributes of existing credit registers (e.g. AnaCredit) remain patchy and require extensive cleaning and standardisation. Future enhancements should improve the availability and consistency of granular spatial attributes.

[28] For further details on the current methodology please refer to: EIOPA (2020c) "**The pilot dashboard on insurance protection gap for natural catastrophes**".

2. Data on the location of firm facilities and on physical risks affecting firms' supply chains is not readily available, therefore potentially masking an important part of the physical risk exposure of NFCs.

3. Existing data collections integrate data on firm vulnerability only to a limited extent, as detailed knowledge on firms' activities and infrastructure is required; for example, firms requiring outdoor work are more vulnerable to heat stress than firms in which work is conducted in air-conditioned office buildings.

4. Current and planned climate change adaptation measures, including the cost of adaptation for firms, are currently available only to a limited extent and should be integrated increasingly into existing data collections.

5. Granular information on insurance coverage is required to monitor potential insurance protection gaps in order to attribute losses among financial institutions.

Uncertainties related to data and risk driver heterogeneities still need to be better understood. Data uncertainty can be understood to some extent by testing the sensitivity of results to different datasets, but overall uncertainties related to choices in data and indicator compilation in the assessment of physical risks still need to be better explored (see BCBS (2021b)). In addition, there is a high degree of heterogeneity characteristic for the assessment of climate-related financial risks (for example, BCBS (2021a, 2021b)). Country-specific characteristics of firms located in areas of high or increasing physical risks, as well as differences in bank exposures to these firms, therefore still require further work, ideally in cooperation with national or local authorities. Finally, given the high degree of specialisation required to fully understand the complexities of physical risks for the financial system, there is considerable scope for central banks and macroprudential authorities to cooperate across disciplines with relevant stakeholders.

3 Transition risk exposure mapping

Measuring entities' carbon footprint (i.e. CO2 emissions and/or emissions intensity) is a commonly used approach to assess transition risks. However, it is by no means sufficient given the multiple drivers and transmission channels, as well as the importance of assessing the decarbonisation trajectory and the potential for technological innovation. Different approaches are conditioned in particular by sector specificities and data availability, which are reflected in the mapping of exposures to transition risk for the three sectors covered in this section. In addition, data availability and consistency issues create challenges for transition risk assessment and comparability across different sectors. Nonetheless, the different measures and approaches used in this report share common elements, such as the sector classification based on their relevance for climate change policy, or the reliance on firm-level CO2 emissions data.

3.1 Banking sector exposures

The banking sector plays a pivotal role in intermediating funds to corporates and is thereby exposed to firms' transition risk via credit and market risk. The extent to which credit and market risk affect banks' solvency or liquidity risks and wider financial stability risks depends on the clustering of exposures together with the specific transmission of risks via either firm defaults or asset valuations.[29]

Bank loan exposures to climate policy-relevant sectors (CPRS) in the euro area amount to around half of total loans to NFCs, with more than two-thirds of CPRS exposures being to the housing sector, followed by the energy-intensive sector. The overall domestic CPRS exposures amount to €1.9 trillion,[30] representing 52% of the euro area total domestic NFC loan portfolio, with at least one-third of bank loan exposures in any of the EU Member States considered. The exposures to the housing and energy-intensive sectors amount to 36% and 8% respectively of total NFC loans across the euro area as a whole.

The weighted emissions intensity broadly reflects a tilt towards less polluting sectors, but with pockets of vulnerabilities in some sectors. The weighted emissions intensity of the domestic NFC loan portfolio, defined as the ratio of emissions to firm revenues and weighted by bank loans, is around one-third lower than the emissions intensity of firms located in the euro area. This implies that bank loans are tilted towards firms emitting less than the economy. While a sizeable contribution to the emissions intensity of exposures stems from the highly leveraged utility sector, the share of bank loans to this sector is relatively low (Chart 6). Moreover, the majority of exposures in the euro area domestic NFC loan portfolio are to low to moderate emissions-intensive

[29] The exposure assessment in this section is based on datasets available to the ECB and contributions from some national authorities based on their access to national credit registries, including Austria, Italy, Malta, Portugal, Romania and Slovenia. A comparison of exposure data from AnaCredit and those from national credit registries gives a broadly consistent picture of the overall share of CPRS exposures and their sectoral breakdown in the NFC portfolio, notwithstanding minor differences.

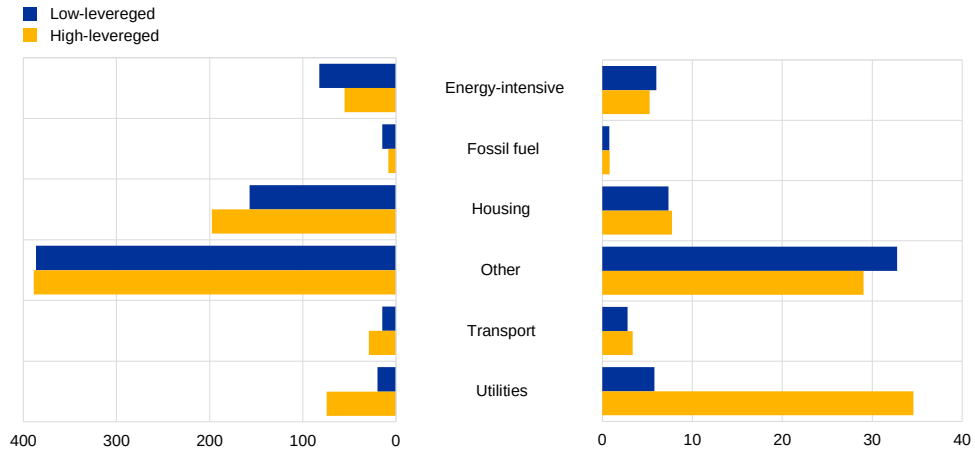
[30] For a definition of the climate policy-relevant sectors see the Data Supplement and Battiston et al. (2017).

sectors rather than to high emissions-intensive sectors.[31] The top 15 emissions-intensive NACE 2 sectors, mainly concentrated in the manufacturing, electricity, transportation and construction sectors, contribute to around two-thirds of bank loan-weighted emissions intensity, and account for 11% of the euro area NFC loan portfolio. The concentration of emissions intensity in particular sectors and the relatively smaller loan exposure to these sectors indicates current pockets of vulnerabilities in the banking system during transition.

Chart 6

Pockets of vulnerability are concentrated in highly indebted firms and emissions-intensive firms

(left panel: loans in EUR billions by sector for high and low indebtedness bucket; right panel: average emissions intensity in g CO2e per euro of revenue by high and low indebtedness bucket)



Source: AnaCredit, Orbis, Urgentem and iBach.
Notes: Emissions intensity is calculated as total emissions (g CO2e of scope 1 and scope 2 emissions) over revenue (in euro). Emissions intensity contributions are calculated as the weighted average of each sector within each bucket, where the weights are represented by the number of firms. High-leveraged firms refers to firms with a liability to assets ratio above 0.737 (i.e. 75th percentile). Low-leveraged firms includes firms with a liability to assets ratio below 0.625 (i.e. 25th percentile). Other refers to all NACE sectors not included in the CPRS definition.

The analysis suggests limited but concentrated transition risks for the banking system, stemming predominantly from credit risk. The majority of CPRS exposures are concentrated in the loan rather than the securities portfolio. The share of CPRS exposures in the NFC loan portfolio amounts to 52% compared with 39% in the NFC securities portfolio for the euro area. This implies a lower risk of sudden asset repricing for the banking system and a relatively larger pocket of vulnerability for the upcoming energy transition in the corporate loan portfolio. Given that these exposures account for a share of 14% in the total balance sheet, risks to financial stability appear broadly manageable. Further analysis requires consideration of the concentration of risks to potential shifts in the technological mix and the role of the banking system in financing the technological change in risky sectors (such as the utility sector).[32] Moreover, further transition risks

[31] Based on AnaCredit data, following EBA Pilot Analysis on climate risks, December 2020.

[32] See, for example, the PACTA method developed by the 2° Investing Initiative (2DII) used in the EIOPA sensitivity analysis of the insurance sector.

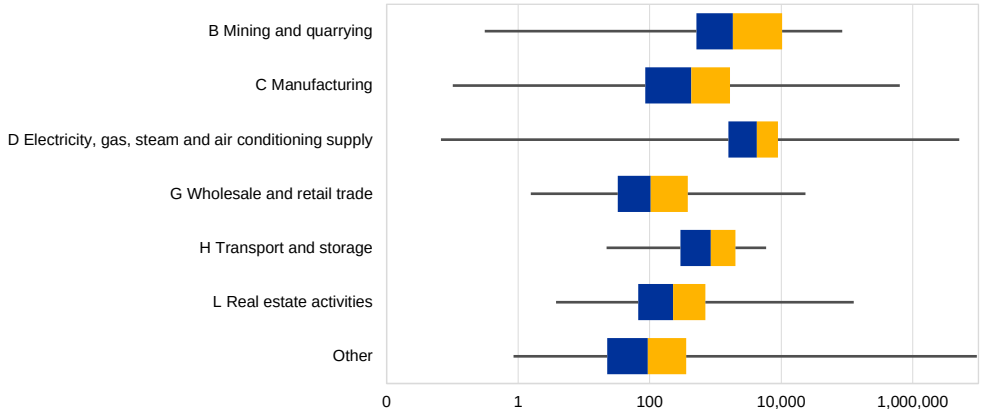
may arise from exposures to sectors which are not captured in the CPRS classification used in this analysis, but that may play an important role in preserving financial stability, such as agriculture.[33]

Greater data granularity in terms of firm-level data and forward-looking transition strategies can further strengthen transition risk assessments.[34] Firm-level emissions data reveal the intra-sectoral heterogeneity beyond cross-sectoral discrepancies (see Chart 7). Such heterogeneity points at a range of activities and technologies operating within the same sectors and targeted policies for emissions reductions would impact these firms very differently.

Chart 7

Firm-level emissions intensities within and across sectors in the euro area

(x-axis: scope 1, 2 and 3 emissions in tonnes of CO2 equivalents per USD million revenue; y-axis: NACE 1 sectors)



Source: Urgentem.
Note: Only firms directly reporting emissions are considered (approximately 3,000 euro area firms).

The euro area banking system may be exposed to tail risks in the event of sudden changes in carbon prices if firms do not reduce their emissions, but the impact would be contained with more gradual or efficient emissions reductions by firms. The granular firm-level emissions data serve as a basis for model-based calculations beyond the exposure assessment. Using a banking system interconnectedness model allows the euro area banking system sensitivity to changes in carbon prices to be tested (see Belloni et al. (2021)). The analysis builds on granular exposures of loans and securities by euro area banks to firms. The study makes the assumption that changes in carbon prices impact firms' assets proportionally to their emissions, which in turn has an impact on firms' probabilities of default. In particular, transition risk-adjusted probabilities of default are assessed firm by firm, based on the Merton framework. It therefore accounts for the heterogeneities in terms of corporates' emissions as well as banks' exposures to such firms.

[33] In Romania, agriculture accounted for 6-7% of value added in 2019 and a fifth of total employment in 2020, which could amplify risks in the household sector as well.

[34] See the Data Supplement.

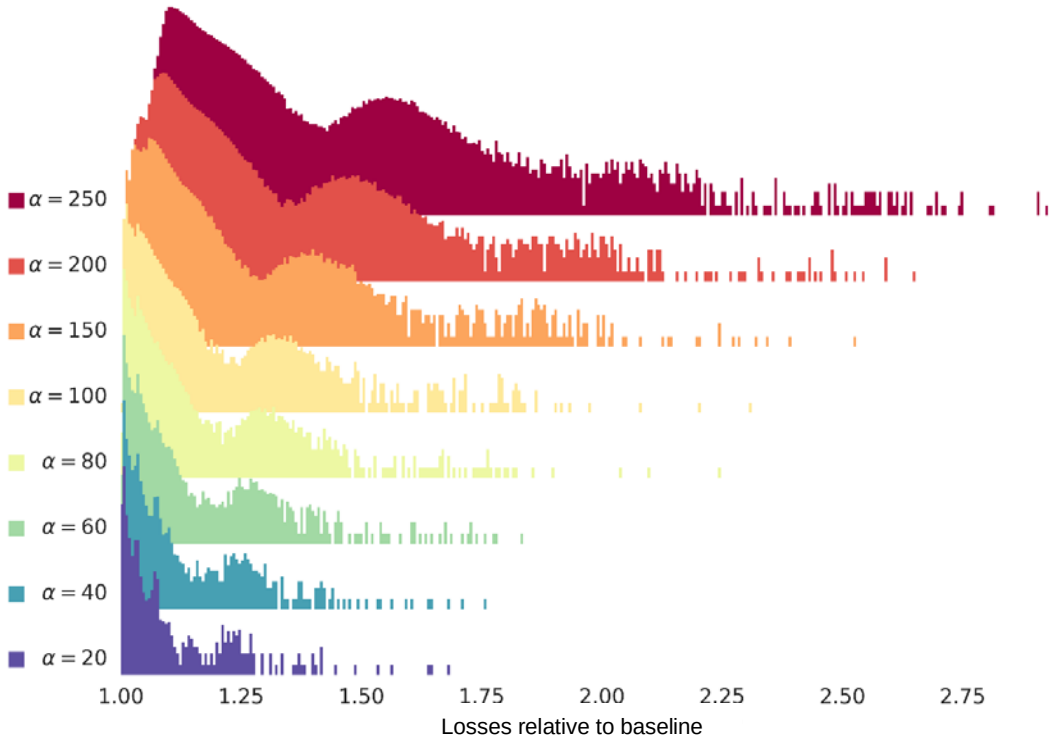
Compared with a baseline scenario where no change in carbon pricing occurs,[35] banking system tail losses at the 99th percentile of the losses distribution increase by approximately 13% with a change in the carbon price of €100/tonne CO2e. The model assumes no reductions in firm emissions and makes the assumption of a full pass-through of the carbon price to the firm (Figure 1, $\alpha = 100$). For more abrupt, larger changes in carbon prices (i.e. €250/tonne CO2e, or $\alpha = 250$), tail losses can increase by more than 40% compared with the baseline. Ambitious emissions reductions at firm level consistent with the Paris Agreement are likely not to lead to systemic stress for the banking system, even if carbon prices increase towards the higher end of currently discussed pricing. This suggests that there are important benefits – also for the banking system – from an immediate implementation of emissions reduction strategies. Assessing implementation scenarios over time requires dynamic adjustments of corporate emissions to be taken into account, as well as the banking system exposures to emitting firms.

[35] Baseline scenario refers to a scenario with no changes in carbon price. Scenarios corresponding to different changes in the price of carbon (corresponding to different values of α) are assessed by recomputing climate-adjusted probabilities of default.

Figure 1

Banking system losses for different changes in carbon price

(alpha: change in carbon price; loss difference calculated as loss in simulation relative to baseline)



Sources: Supervisory Statistics, Urgentem and ECB calculations.
Notes: Results are based on a sensitivity study using a banking system interconnectedness model based on firm-level exposures and emissions of euro area large exposures. The quantifications assume full pass-through of the changes in carbon (alpha) price to firms and no reductions in firm emissions for different levels of carbon price. Data gaps in firm-level emissions are filled with country-sector averages. Firms' assets are impacted proportionally to their emissions, in turn affecting their PDs (Merton model). Loss distributions are based on 250,000 Monte Carlo simulations. Heights are log-densities.

3.2 Investment fund exposures

Non-banks such as funds are also heavily exposed to high-emitting firms[36] through their securities holdings. Euro area investment funds are more active than other financial institutions in the equity market and invest around €1.3 trillion in equity and debt securities issued by high-emitting firms operating mainly in the industrial, energy and materials sectors (Figure 2). Exposure to carbon-intensive firms is quite heterogeneous across funds and the median exposure to polluting assets accounts for 57% of total holdings.[37] While the relative share of high-emitting firms in the

[36] In this section, high-emitting firms are identified as firms within the top 33rd percentile of all firms in which European funds are invested.

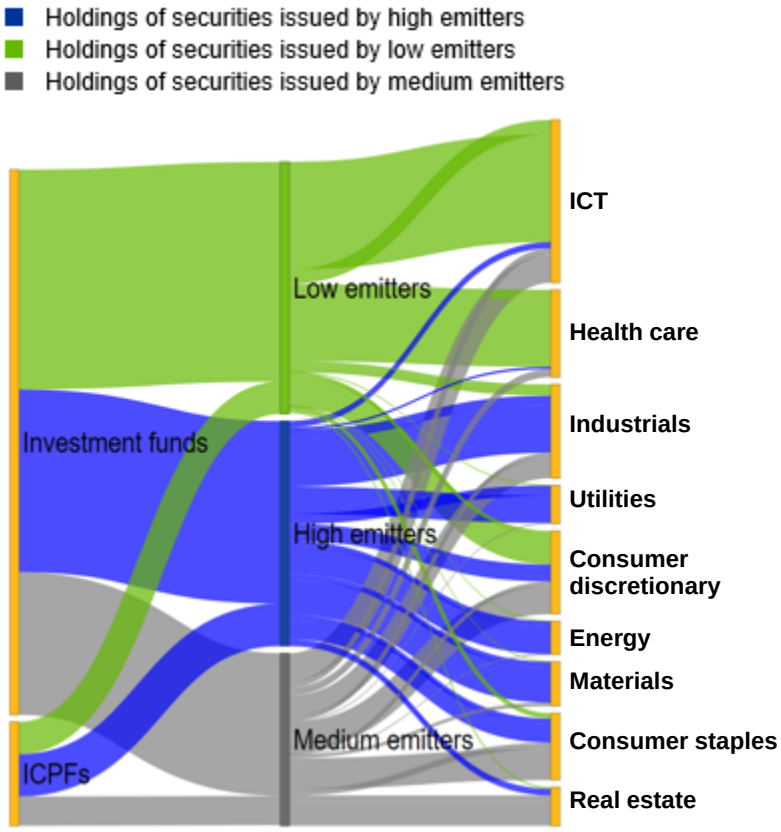
[37] Based on a sample of 23,965 EU-domiciled investment funds. See ESMA (2021), **"Report on Trends, Risks and Vulnerabilities"**, No 1.

portfolio of funds has remained broadly stable over the past seven years at around 30%, its nominal amount has almost doubled, from €700 billion in 2013 to €1.3 trillion in 2019.

Figure 2

Non-banks' exposure to transition risk via equity and debt securities

(exposures and emissions: Q4 2019; total holdings of NFC securities by sector)



Sources: SHSS, Urgentem, Eikon and ECB calculations.
Notes: The panel captures the exposure of non-bank financial institutions to firms that issue bonds or are listed in the equity market. These firms are classified as low, medium and high emitters according to their emissions intensities (scope 1, 2 or 3) in December 2019, i.e. the ratio of CO2 emissions to revenue. Low emitters are firms with less than 309 CO2 equivalent tonnes/USD million of revenue (33rd percentile), while high emitters are firms with more than 1,068 CO2 equivalent tonnes/USD million of revenue (66th percentile).

An analysis of EU investment fund portfolio holdings shows that EU funds have sizeable exposures to climate policy-relevant sectors, amounting to €1.4 trillion or 22% of their assets, underscoring their potential vulnerability to transition risks. More than half of this exposure is to the energy-intensive sector, in particular reflecting the high share of manufacturing in funds investing in equity. Exposure to the fossil fuel sector in particular amounts to 2% of assets and

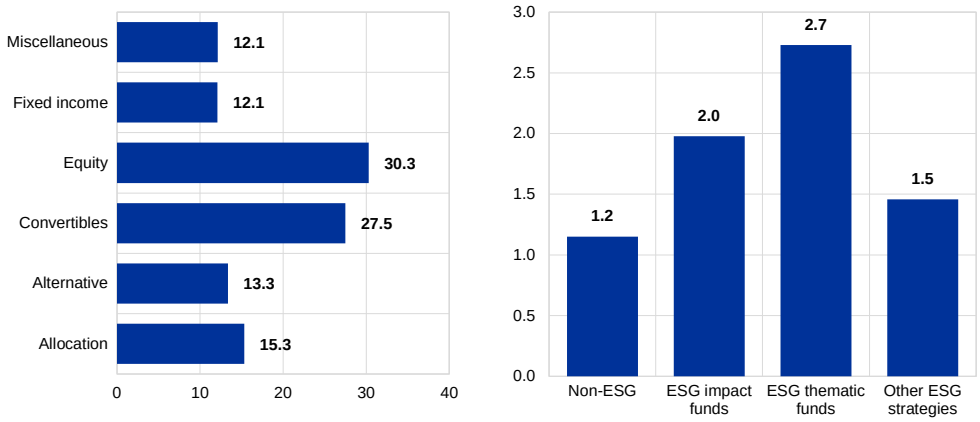
tends to be smaller (but non-null) for environmental, social and governance (ESG) funds (Chart 8, left panel).[38]

The estimated alignment of EU fund portfolio holdings with the EU Taxonomy is low, at 1% of assets.[39] The low share of EU Taxonomy-aligned activities in the European economy translates into a low share of EU Taxonomy-aligned[40] fund portfolio holdings underscoring the scope for greater funding of activities aligned with environmental objectives. The estimated alignment of ESG funds tends to be higher, especially for impact and thematic funds (reflecting allocation to sectors with higher potential alignment with the EU Taxonomy) and may in reality be much higher for some funds, according to case studies conducted by asset managers (Chart 8, right panel).[41]

Chart 8

Share of CPRS holdings in fund assets by fund type (left panel) and estimated fund portfolio alignment with the EU Taxonomy (right panel)

(by fund type, percentages)



Sources: Morningstar, Refinitiv EIKON and ESMA.
Notes: Left panel: Share of EU funds' equity and corporate bond holdings in climate policy-relevant sectors, by fund type, percentages; Right panel: Estimated alignment of EU funds' equity and corporate bond holdings with the EU Taxonomy, by environmental, social and governance strategy.

For the majority of EU funds, companies with relatively higher CO2 emissions account for the largest share of their portfolio (Figure 3). To an extent this is driven by the fact that funds invest in companies with larger market capitalisations, which tend to emit more CO2 (all other things equal). However, it also highlights the role that funds play in financing carbon-intensive activities. Another key takeaway is that portfolio CO2 emissions are around 30% lower and the weighted average carbon intensity is also 10% lower in ESG funds.

38 Analysis is based on a sample of 15,000 European funds (55% equity, 30% mixed, 12% bond and 3% other types) with combined holdings of €4.3 trillion (Morningstar data), including 2,000 ESG funds as identified by Morningstar.

39 This estimate is based on estimated Taxonomy-aligned coefficients developed at NACE four-digit sector level in Alessi et al. (2019). As such, it reflects the portfolio allocation of funds to financial instruments issued by companies within sectors that are potentially aligned with the EU Taxonomy.

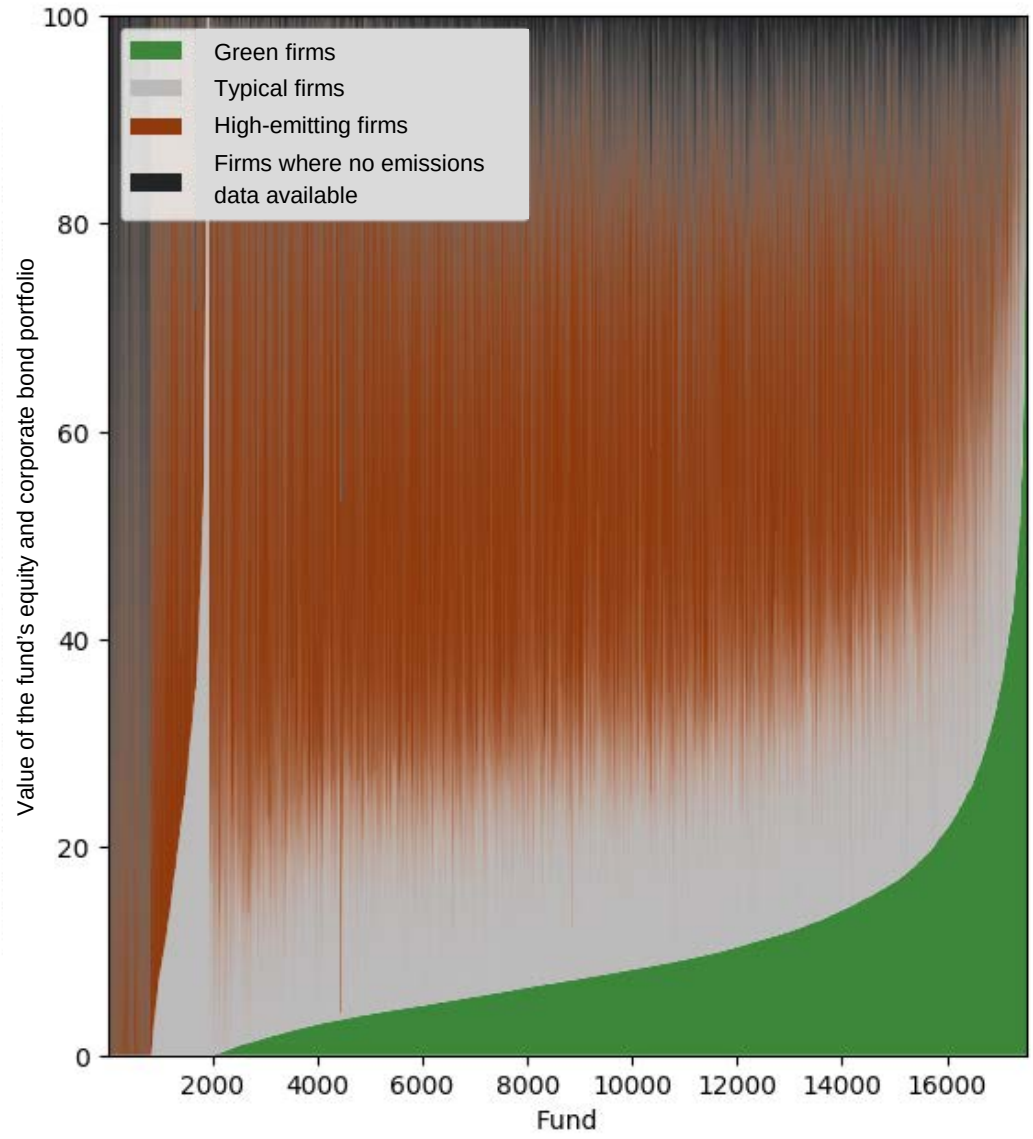
40 See ESMA (2021), *Final Report: Advice on Article 8 of the Taxonomy Regulation*, Annex VII.

41 See UN Principles for Responsible Investment, EU Taxonomy alignment case studies.

Figure 3

Share of EU fund portfolios by “green” firms compared with that of “high-emitting” firms

(number of firms, percentages)



Sources: Morningstar, Refinitiv and ESMA.

Notes: Percentage share of each individual fund’s equity and corporate bond portfolio (vertical axis) that is allocated to firms classified according to their portfolio emissions: firms with emissions that are below the 33rd percentile for the data sample (“Green firms”); firms with emissions greater than or equal to the 67th percentile (“High-emitting firms”); firms with emissions that fall between these two groups (“Typical firms”); and also firms for which no emissions information is available. The horizontal axis denotes individual funds, sorted according to the percentage share of exposures to green firms in the portfolio (from lowest to highest share).

3.3 Insurance companies' exposures

By mapping insurers' equity and corporate bond holdings to individual firms and the technology they use in production, it is possible to obtain a view on insurers' exposure to climate-relevant sectors. The mapping was carried out on an ISIN-by-ISIN level, linking each individual asset to its (ultimate parent) issuer in collaboration with 2° Investing Initiative (2DII).[42] The analysis relies on information for listed equity and corporate bonds obtained through this cooperation[43] and the scope is defined by the availability of data and methodology of the 2DII PACTA toolset.[44] The focus of this work is on listed corporate bonds and equity holdings mainly in the automotive, fossil fuel extraction and power sectors.[45] The transport, cement and steel sectors are also covered in terms of identifying the assets.[46]

The analysis shows relatively substantial holdings in particular in the power sector, oil and gas sectors and in vehicle production (Table 2). While in most cases these amounts are manageable compared with overall holdings because insurers hold relatively well-diversified portfolios (and many insurers have already announced divestment plans for high-carbon assets), such investments may still expose the insurance sector to transition risks in the event of a drastic re-alignment of economies to an outcome in line with the aims of the Paris Agreement to limit global warming. Moreover, the amounts identified should be interpreted as a lower estimate because not all investments could be mapped using the PACTA toolset (see the Data Supplement for details).

On a country-level basis, there is a certain degree of heterogeneity, but the relative dominance of the power sector is evident in asset portfolios in most countries. The power sector is fundamental in terms of climate change. The energy transition required to limit global warming and meet the targets defined by the international community means that power generation needs to shift away from fossil fuel to renewable energy, with potentially large consequences for the valuation of the assets in this sector. The relatively sizeable holdings in renewable energy are therefore particularly noteworthy.

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42 As part of this collaboration, 2DII provided a bespoke implementation of the PACTA service and resources.

43 More findings are available in the report on the "**Sensitivity analysis of climate-change related transition risk**".

44 The **2DII PACTA methodology** is free and open source. EIOPA used a bespoke implementation in cooperation with 2DII for this work.

45 Assets reported to be issued by real estate corporations are excluded from the analysis. Covered bonds and money market instruments are also excluded. The full list of CICs included is 21, 22, 25, 28, 31, 34, 41, 42 and 44. In this report "corporate bonds", "equity" and "funds" refer to these CICs only unless specified otherwise. Assets with negative reported market value have been excluded.

46 While the PACTA toolset covers key climate policy-relevant sectors in terms of their contribution to overall CO2 emissions, it is not exhaustive. In particular, property investments and investments in the agriculture sectors are very likely to be climate policy-relevant but are not covered in this analysis due to lack of consistent data and methodology. Investments in the real estate sectors account for about 8% of total investments at EEA level. Investments reported to be in the agriculture sector account for less than 0.1%. Second-round effects in the financial sector are also out of scope.

Table 2

Value of investments by insurer in key climate policy-relevant sectors. Corporate bonds and equity, including look-through of funds (CIUs) where possible

(all undertakings, including unit linked; EEA excluding United Kingdom; EUR billions)

Coal	**Coal extraction**	5.35	[11.14]
Oil and gas	**Gas extraction**	28.64	[48.57]
	Oil extraction	35.51	[59.92]
Power	**Coal**	14.90	[23.90]
	Gas	25.13	[40.42]
	Hydro	19.02	[30.06]
	Nuclear	13.92	[21.85]
	Oil	4.02	[6.71]
	Renewables	20.53	[33.79]
	Coal	14.90	[23.90]
Automotive	**Electric**	1.97	[2.81]
	Hybrid	1.75	[2.66]
	ICE	42.37	[62.27]
Aviation	**Freight**	0.02	[0.04]
	Mix	0.00	[0.00]
	Other	0.01	[0.01]
	Passenger	2.95	[4.82]
Cement	**Grinding**	0.87	[3.34]
	Integrated facility	5.11	[19.33]
Steel	**Ac-Electric Arc Furnace**	1.68	[5.34]
	Bof Shop	3.24	[11.91]
	Dc-Electric Arc Furnace	0.11	[0.40]
	Open Hearth Meltshop	0.01	[0.04]

Source: Solo insurance undertakings reporting under Solvency II for the fourth quarter of 2019.
Notes: The coal and oil and gas sectors represent fossil fuel extraction. The power sector represents the fuel used to generate energy. The value in brackets extrapolates the holdings taking into consideration the fact that technology is not available for some investments. Moreover, the values in brackets assume that the non-listed and non-mapped corporate bonds and equities have the same share of climate-relevant exposures as the mapped corporate bonds. For funds, the share of climate policy-relevant exposures is assumed to be the same in the part where the underlying asset is identified and where it is not.

Insurance companies' exposures may also arise through collective investment undertakings – noting that investments in funds account for about 30% of all investments by insurers.[47] While the data reported by insurers under Solvency II includes a look-through of fund holdings with general asset categories, additional data is required to assess the climate-relevance of these holdings. Taking advantage of the data made available via the PACTA service described in the previous section, it was possible to identify 44% of the underlying assets in these fund holdings, adding €871 billion to the pool of assets included in the analysis above.

It is possible to add descriptive information about the fund holdings of insurers using the aggregate information on individual funds prepared for this report. Overall, €816 billion worth of fund holdings could be matched (40% of total holdings in equity, fixed income and mixed funds; 29% of total collective investment undertaking (CIU) investments) using this new dataset, of which 80% belong to unit-linked or index-linked business. The sample is thus tilted towards assets in unit-linked or index-linked business, which would make sense as these funds tend to be publicly marketed funds, whereas insurance undertakings act mostly as intermediaries.

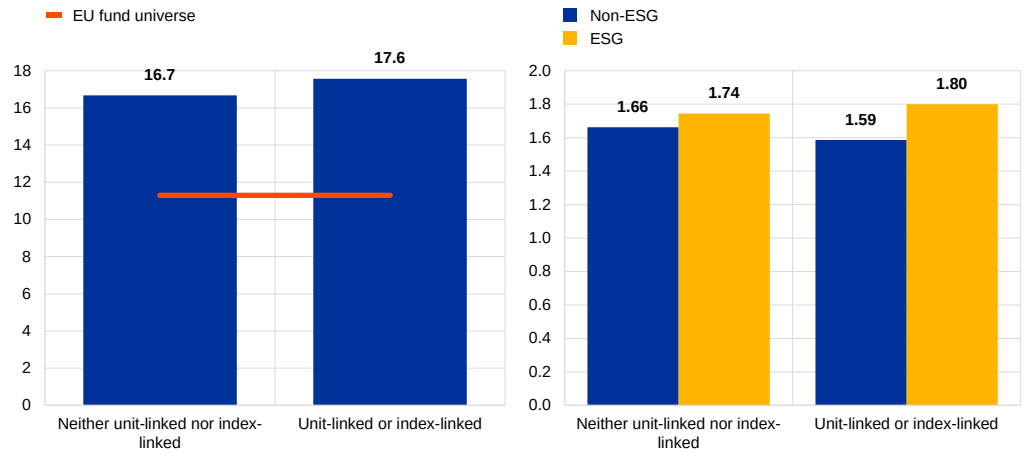
Within that sample, more than 17% of insurance investments in investment funds are labelled as ESG funds (7% of total insurance holdings). Funds belonging to unit-linked or index-linked business exhibit a slightly higher share at 17.6% than business that is neither unit-linked nor index-linked at 16.7% (Chart 9, left panel). This is higher than the share of ESG funds in the universe of EU funds, which amounts to 11% and cannot completely be explained by equity funds being overrepresented in the sample.

[47] Equity funds, fixed income funds and asset allocation funds (CIC 41, 42 and 44) are considered in this analysis. These account for about three-quarters of all investments in funds. The main categories not included are private equity, money market funds and real estate funds.

Chart 9

Share of ESG funds within matched sample of insurers' investment fund holdings (left panel) and estimated share of EU Taxonomy-aligned assets (right panel)

(percentages)



Sources: Morningstar, EIOPA and ESMA.
Notes: Left panel: Share of assets managed by funds with an ESG mandate in EU insurers' investment fund holdings, split between unit- linked and non-unit linked. The dotted line indicates the average for the entire sample of EU funds as described in Section 2.2. Right panel: Estimated alignment of insurers' investment fund holdings (equity and corporate bonds) with the EU Taxonomy, using sector-based coefficients developed in Alessi et al. (2019).

The estimated share of EU Taxonomy-aligned assets within the insurers' mapped portfolio[48] is relatively small at about 1.7%, although slightly higher than the estimated share for the EU investment fund universe at about 1%. In line with the slightly higher share of ESG funds in the insurers' portfolio compared with the market average, the same also holds for the share of EU Taxonomy-aligned assets within the insurers' portfolio. ESG funds exhibit a slightly higher estimated share of EU Taxonomy-aligned assets than non-ESG funds (1.8% compared with 1.6%) although the difference is marginal (Chart 3.7, right panel). This finding is robust across fund categories and is most pronounced for fixed income funds, which might however also result from the relatively smaller sample size.

Box 2
Transition risks on balance sheets of ccupational pension schemes

In the 2019 stress test of institutions for occupational retirement provision (IORPs), EIOPA for the first time assessed climate-related risks on the balance sheets of these institutions. A broader focus of the stress test was the environmental, social and governance (ESG) aspects of IORPs' investments. The participating IORPs provided a breakdown of their investments in three asset classes, namely equity, debt and other investments, and in ten economic activities based on

[48] For the asset classifications, a subset of the data encompassing €663 billion could be matched, with 78% in holdings belonging to unit-linked or index-linked business. The largest part of the subsample is made up of equity funds at 55%, while fixed income funds account for 29% and mixed funds for 16%.

the NACE section classification.[49] This information was then matched with Eurostat data on greenhouse gas (GHG) emissions intensities by economic activity[50] to provide insights into the overall GHG emissions intensity or carbon footprint of IORPs' investment assets.

Equity investments by IORPs have relatively high exposure to GHG-intensive industries, with the average carbon footprint exceeding the average GHG intensity of all economic activities in the European Union. Chart A shows a weighted average of the GHG intensities published by Eurostat and IORPs' equity and debt allocations to the ten economic activities.[51] The equity allocations[52] of IORPs to the most GHG-intensive economic activities (including mining and quarrying, manufacturing, agriculture, electricity, gas and stream production and transport and storage) amount to around 37%. Accordingly, the average carbon footprint of equity investments amounts to 0.37 kg per euro value added, while the average of all economic activities in the EU amounts to 0.26 kg per euro value added. Debt allocations of IORPs to GHG-intensive economic activities are low, at 10%, and relate to the high share of government bonds within the debt asset class.

[49] Ten NACE sectors included Agriculture, forestry, fishing (A), Mining and quarrying (B), Manufacturing (C), Electricity, gas, steam, air conditioning (D), Water supply and waste management (E), Construction (F), Wholesale and retail trade (G), Transportation and storage (H), Services (I-N), and Other, including public administration (O-U). To simplify the application, IORPs could allocate their assets using the Global Industry Classification Standard (GICS) developed by MSCI and S&P Dow Jones Indices. In this context, 40% of IORPs allocated investment assets directly to the NACE activities, 38% used the GICS classification as an intermediate step, 10% used a combination of both and 12% used an "other" approach. For investments in investment funds, the identification of the economic activity followed the underlying assets (i.e. "look through approach"), rather than the economic activity of the asset/fund manager or issuer.

[50] These data do not take into account the extent to which the various activities already consume energy produced by the electricity production activity and to what extent this implicitly adds to the measured GHG emissions. Similarly, they do not consider the emissions that occur further on in the value chain of producing final goods and services.

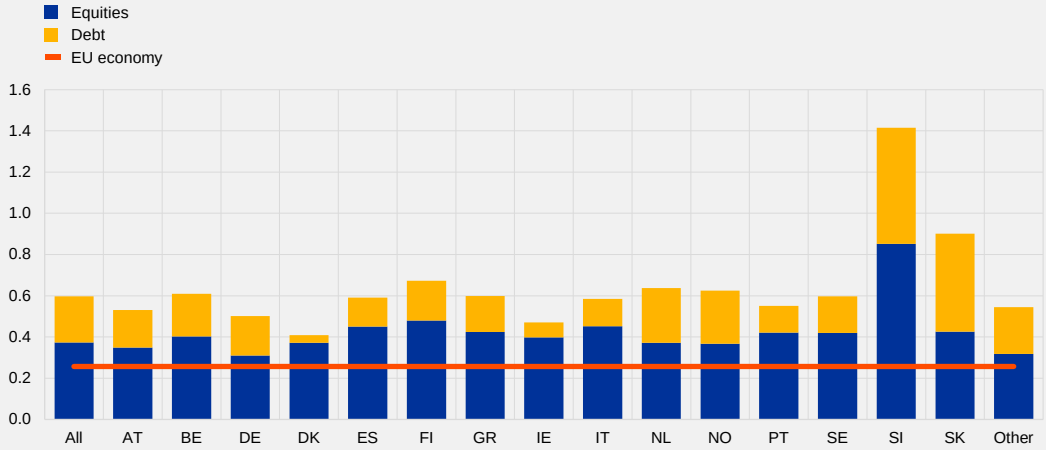
[51] The additional assumption used here is that debt and equity investments in activities outside the EU have the same carbon footprint as the corresponding activities within the EU.

[52] The results for the "other investments" category are not presented because of the relatively high proportion of these other assets (36%) not having been allocated to one of the ten economic activities.

Chart A

Greenhouse gas intensity of IORPs' equity and debt investments by country

(kilograms per euro of value added)



*Source: EIOPA, **Occupational pensions stress test 2019**.*

4 Financial markets and climate risks

4.1 Climate risk pricing

There is limited evidence on the pricing of transition risk in financial markets. Bolton and Kacperczyk (2021) document the existence of a carbon premium in stock markets, i.e. firms with higher emissions compensate investors by offering higher returns. More recently, the impact of climate-related disclosures has come into sharper focus. Mesonnier and Nyguyen (2020) find that such mandatory disclosures for French institutional investors led to divestment from fossil fuel companies, with financing down 40% relative to banks and investors located elsewhere. A recent report by the NGFS (2021) also highlighted that investors in certain energy-intensive sectors may be more sensitive to climate disclosures by issuers. Alessi et al. (2021) show the existence of a negative "greenium" in the European equity market, meaning that investors are willing to earn lower returns to hold greener stocks, but only if these companies are also more transparent about their environmental performance.

There is growing awareness of the role played by ESG factors in credit ratings, with climate-related risk increasingly being reflected in higher credit risk. Corporate disclosures are currently based on backward-looking metrics, but transition risk can affect a firm's capacity to service and repay its debt in the medium term.[53] Partly in response to this, an increasing number of companies are setting a path to reduce their emissions in line with the Paris Agreement goals. Our analysis suggests that firms which disclosed a target have reduced their emissions relatively more than other firms, while more ambitious and forward-looking targets are associated with better credit ratings. From this perspective, the adoption of net-zero emissions targets (such as those promoted by Science Based Targets[54]) by one-fifth of the world's 2,000 largest listed companies is encouraging.[55] However, questions have been raised about the credibility of these commitments owing to a lack of transparency and unclear definitions.

Physical risk does not appear to be priced in either. This is despite a more extensive body of literature, reflecting the fact that natural disasters have been scrutinised for years owing to their impact on livelihoods and the potential financial losses they can generate.[56] Analysis from the International Monetary Fund (IMF) shows that the reaction of equity prices to large climatic shocks over the past decades has been generally modest, and that physical risk does not appear to be reflected in global equity valuations.[57]

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53 Capasso, Gianfrate and Spinelli (2020) show that high emitters have shorter distance-to-default. Höck, Klein, Landau and Zwergel (2020) show that companies with higher environmental sustainability have lower credit spreads.

54 Science Based Targets (2020), *Foundations for science-based net-zero target setting in the corporate sector*, September.

55 See Reuters (2021), *Net-zero emissions targets adopted by one-fifth of world's largest companies*, March 23.

56 See, for example, Worthington and Valadkhani (2004), Mahalingam et al. (2018) and Siddikee and Rahman (2017).

57 IMF (2020), "Physical risk and equity prices", *Global Financial Stability Report*, April, Section 5.

4.2 Market mechanisms to mitigate climate risks

Financial markets can contribute to mitigating climate-related risks. Aside from pure insurance mechanisms, financial market participants can rely on market-based mechanisms (such as portfolio rebalancing and asset repricing) or on financial instruments (for example derivatives) to manage their climate-related risk exposures. The redistribution of risks to sectors or entities that are better equipped to deal with them or withstand associated losses is a standard feature of financial markets.

4.2.1 Green finance

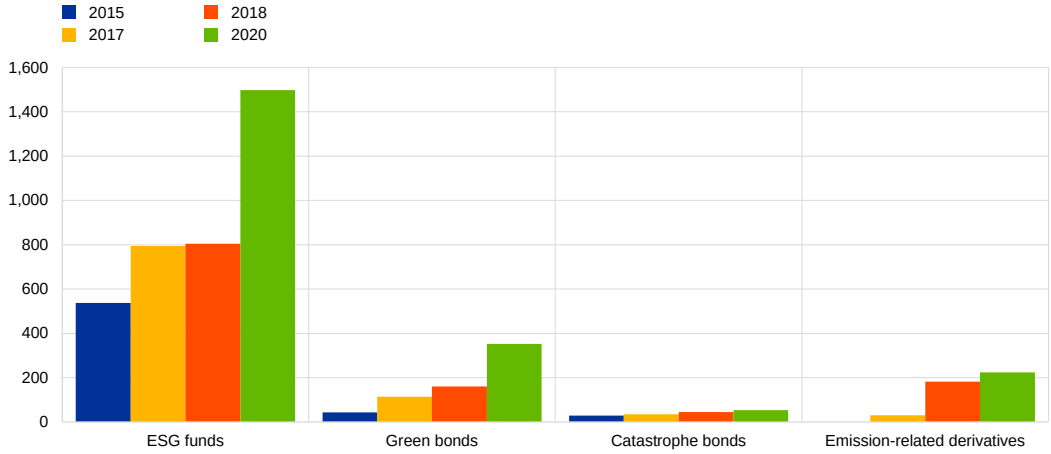
A prominent development in recent years with implications for climate-related risk is the growth of green finance and ESG investing. In particular, the amount of green labelled bonds outstanding in Europe now exceeds €500 billion with issuance growing by 20-30% per year for several consecutive years (Chart 10). Market intelligence also suggests that there is currently strong appetite for other green finance instruments, such as green securitisations. Similarly, European funds with an ESG mandate have experienced very strong momentum, with assets up by 170% since 2015.[58] Large flows into ESG funds have been sustained over time by increasing climate-related concerns, a gradual generational transfer of wealth towards millennials, and better disclosure and understanding of ESG risks. The development of "climate transition finance" may further help to reduce transition risk by reinforcing market-based incentives. For example, sustainability-linked instruments such as transition bonds offer compensation to investors when the issuer fails to achieve a pre-specified sustainability target (for example a minimum reduction in CO2 emissions).

[58] In the absence of official definitions until the Sustainable Finance Disclosure Regulation (SFDR) entered into force, the identification of ESG funds relied on the methodologies and choices made by data providers (such as Bloomberg or Morningstar).

Chart 10

Sustainable financial instruments

(outstanding amounts of different green instruments; EUR billions)



Sources: Artemis, Bloomberg, EMIR, EPFR, Lipper, EMIR data and ECB calculations.
Notes: Net assets of global ESG funds; outstanding amount of green bonds by euro area domiciled issuers; global catastrophe bonds outstanding; and outstanding amount of emission derivatives is the notional value of open positions reported in EMIR as of end- November to avoid end-of-year effects. 2015 values are not included due to data availability.

While these instruments and vehicles are important in helping to channel capital towards sustainable projects, there is mixed evidence as to their actual impact, while greenwashing concerns prevail. In the case of green bonds, the relationship between their issuance and CO2 emissions is not clearly established. Ehlers et al. (2020) do not find clear evidence that green bond issuance is associated with any reduction in carbon intensity over time. In the utilities sector, they document that green bond issuers have on average achieved smaller reductions in carbon intensity. Fatica and Panzica (2020) find that green issuers display a decrease in the carbon intensity of their assets after borrowing on the green segment, and that the effect is more pronounced when excluding green bonds with refinancing purposes. Regarding ESG funds, the absence of a common definition to date has hampered analysis of their long-term impact on sustainability-related matters (see the Data Supplement).

A robust framework would help to maximise the potential benefits of green finance. Fatica and Panzica (2020) show that the use of an external verifier when issuing a green bond signals a stronger commitment towards climate-friendly investment, which results in lower emissions intensity. Preliminary analysis suggests that green bonds satisfying all four International Capital Markets Association (ICMA) green bond principles (including second-party certification) exhibit statistically significant “greenium” – i.e. a green price premium – unlike green bonds that only satisfy the first principle (on the use of proceeds). Meanwhile, ESG funds have also shown better resilience than their non-ESG peers during the pandemic, while traditional equity and bond funds have not recovered as much despite similar returns. The higher resilience of ESG fund flows might reflect greater commitment from a more stable investor base but also requires greater transparency on the strategy and impact of such funds.

4.2.2 Other market-based mechanisms

The traditional (re)insurance model of pooling risks through diversification may become less suitable when faced with very large systemic risks. Climate-related catastrophe risks could potentially become uninsurable owing to growing frequency and higher losses. Market hedging mechanisms may have a role to play in this context. In many countries, derivatives markets have played a historical role in providing a hedge against natural disasters. For example derivatives have been used to hedge climate-related risk for more than 25 years in the United States,[59] for example through weather futures and options based on the number of heating or cooling degree days, with the market almost trebling in size in 2020.[60] Similarly, weather derivatives have been used for years to act as an agriculture price stabilising mechanism in countries where the agriculture sector is exposed to natural hazards (including, for example, Australia, India, Mexico, South Africa and the United States).[61] There is scope for EU derivatives to play a role in hedging climate-related risks, although recent attempts to launch weather derivatives in Europe have been met with lukewarm interest by market participants.[62]

"Catastrophe bonds" (also known as insurance-linked securities, or ILS) could also help the insurance industry cope with this problem by securitising insurance risks and passing them on to the broader capital markets. The issuance of ILS reached a new annual record in 2020, exceeding USD 14 billion for the first time, although some of this was pandemic-related. The outstanding amount of these securities is now over USD 45 billion. However, so far the market for catastrophe bond issuance remains dominated by US, and to a lesser degree by Japanese and Swiss, insurance and reinsurance companies.

Carbon markets such as the EU Emissions Trading System (ETS) have a crucial role to play in the management of transition risk exposures, with carbon pricing now seen as an integral part of the solution to achieve the Paris Agreement targets.[63] However, for carbon market incentives to work efficiently, this requires two conditions: carbon prices need to increase, and the scope of application needs to capture the highest emitting sectors. [64] The first point is particularly problematic, since there are 60 different carbon tax and trading systems in the world, with an average price of USD 2 per tonne of CO2 (tCO2).[65] Meanwhile, the IMF (2020) estimated that carbon prices need to reach between USD 40/tCO2 and USD 150/tCO2 in 2050 to achieve the Paris Agreement objectives, although there is a wide range of estimates.[66] From this perspective,

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59 US CFTC (2020), *Managing climate risk in the US financial system*.

60 CME (2021), *Managing Climate Risk with CME Group Weather Futures and Options*.

61 See for example, FAO (2006), *An introduction to market-based instruments for agricultural price risk management*, Stern (2001), Bhattacharya (2007).

62 See for example Reuters (2017), *Bourses' weather products hard to place in European energy market*. Possible explanations for the relative under-development of this market include a history of tight regulation in the energy sector (Piovani et al. (2012)) but also the size of the local insurance industry in several European countries.

63 Carbon Market Watch (2017), *Pricing carbon to achieve the Paris goals*, Policy briefing, September.

64 As part of the review of the EU ETS Directive, the impact assessment proposed to expand the scope to fossil fuels used in non-ETS sectors, such as buildings and road and maritime transport.

65 International Monetary Fund (2019), "Putting a price on pollution", *Finance & Development*, December.

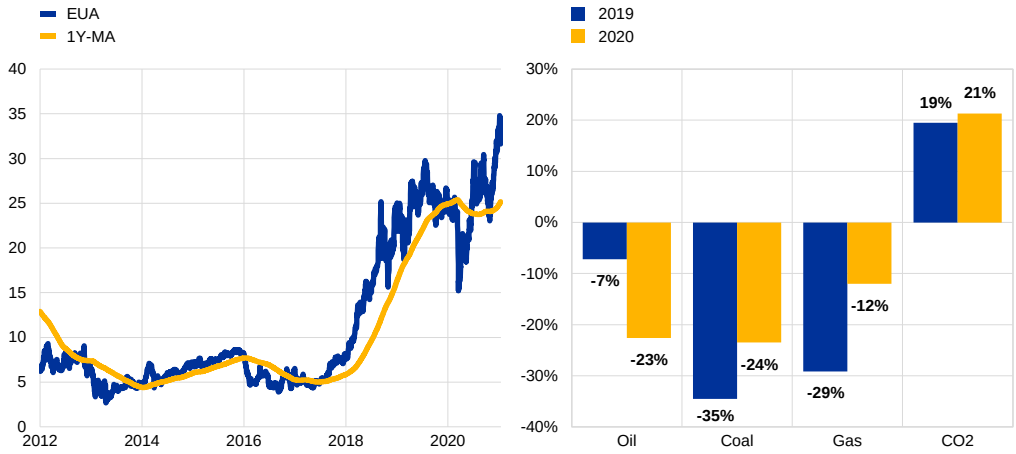
66 The IMF (2020) estimated that, when combined with a broader fiscal policy package including a green fiscal stimulus and compensatory transfers to households, carbon prices should reach between USD 10 and USD 40/tCO2 (depending on the country) in 2030, and between USD 40/tCO2 and USD 150/tCO2 in 2050. The range of estimates mainly reflects the (regulatory and fiscal) policy mix and choice of emissions reduction pathway (IPCC (2018a)).

the increase in the price of EU CO2 emission allowances (EUA) from below €10/tCO2 up to 2018 to an average of €25/tCO2 in 2020 is an encouraging sign, albeit insufficient (Chart 11, left panel). There are further signs that the EU ETS market is maturing, with on-exchange trading in EU emissions allowances growing by 45% in two years. This compares with a decline in fossil fuel derivatives trading (Chart 11, right panel),[67] reflecting the growing participation of financial sector firms, including for diversification purposes.[68]

Chart 11

EU emissions allowance prices and annual turnover in exchange-traded energy derivatives

(left panel: daily settlement price of EUAs on European Energy Exchange spot market, EUR/tCO2; right panel: change in annual turnover of selected exchange-traded commodity derivatives, percentages)



Sources: Refinitiv Datastream, EEA trading venues and ESMA.
Note: EUA stands for European emission allowances.

[67] ESMA analysis based on data reported by EEA trading venues under MiFID II.

[68] The Economist (2021), "Prices in the world's biggest carbon market are soaring", February 27.

5 Climate risks evolution through the lens of macrofinancial scenarios

Scenario analysis offers a flexible methodological framework that can take into account the forward-looking nature of climate-related risks. It provides a systematic way of making structured assumptions about different possible futures to explore the risks that could crystallise. Scenario analysis requires hypothetical but plausible scenarios to highlight the impact of climate risks on the financial institutions and system.

Climate scenarios by the NGFS help provide a common basis for central banks and supervisors to integrate climate risks into financial stability monitoring. The first release of climate scenarios, introduced in June 2020, include elements of both transition and physical risks. They estimate how different levels of climate change mitigation could be achieved under specific climate outcomes and socio-economic background assumptions.[69] The scenarios vary according to how policy action might evolve in the future. Mitigation policies can be introduced either immediately, later on, or remain insufficient, and include a number of technological assumptions, for instance regarding the availability of carbon dioxide removal (CDR) technologies.[70]

5.1 Scenario narratives

This section presents the narratives of three of these scenarios and the methodological approach proposed to complement the original macro-financial information released by the NGFS. The scenarios span the period from 2020 to 2100 and cover orderly, disorderly and "hot house world" pathways. These scenarios were purposely selected to show the range of risk outcomes from climate change stemming from either transition risks or physical risks.[71]

The orderly scenario assumes future pathways consistent with capping the rise in global average temperatures to well below 2°C above industrial levels (Chart 12, left panel). To meet the 2°C target under the 2015 Paris Agreement, global emissions would need to drop by 3% each year until 2030. The transition to a low carbon economy takes place in an orderly manner and policies are implemented immediately. In this scenario, emissions prices increase gradually as

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69 The NGFS scenario framework builds on the Intergovernmental Panel on Climate Change (IPCC) representative concentration pathways (RCP) and shared socioeconomic pathways (SSP) to provide information on climate outcomes and socio-economic background. The RCPs translate into different climate outcomes. The SSPs involve quantitative projections of variables such as GDP, population and the urbanisation rate, as well as detailed narratives describing technological advancement, international cooperation or resource use. All NGFS scenarios rely on the "middle of the road" SSP assumptions.

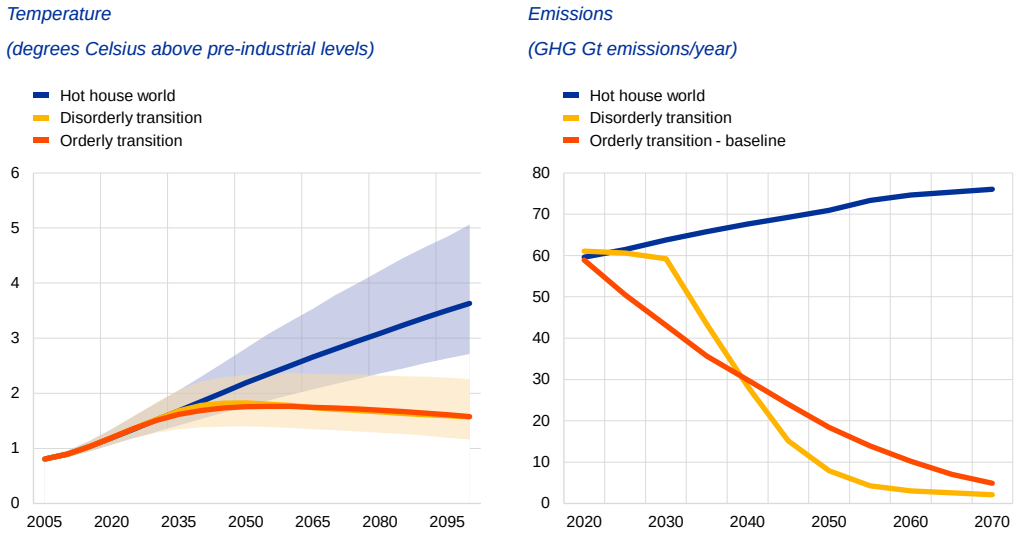
70 This report used the first vintage of NGFS scenarios. The updated scenarios provided in a second release in June 2021 bear a close relation to those used in this analysis, given, in particular similar methodologies to obtain needed sectoral resolution over a broad set of economic and financial variables.

71 The NGFS transition scenarios have been generated using integrated assessment models (IAMs). IAMs combine macroeconomic, agriculture and land-use, energy, water and climate systems. They generate cost-effective transition scenarios for different techno-economic and policy assumptions including climate targets. They also provide information about the overall mitigation costs and emissions price trajectories, required investments and necessary energy system transformations, and the emissions pathways. The IAMs models do not account for climate damages, and the corresponding elements of NGFS scenarios are supported by models included in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) and the CLIMADA (CLIMate ADAptation) model. See NGFS (2021) for further details.

shown in the right panel in Chart 12 which reports emissions trajectories and temperature outcomes derived from the cost-effective emissions abatement policies. This allows firms to adapt their business model and develop green technologies, and households to change their consumption behaviours.

Chart 12

GHG emissions and mean temperature across scenarios



Source: NGFS climate scenarios.
Notes: Left panel: lines are median values, and shaded areas are 90% confidence intervals; Right panel: GHG stands for greenhouse gases, Gt stands for gigatonnes emissions. GHG emissions include carbon dioxide, methane, nitrous-oxide and fluorinated gases.

The disorderly scenario emphasises the risks ensuing from late implementation of policy measures to fight climate change. The goals of the Paris Agreement are met but policy measures are implemented late and abruptly, resulting in an equally abrupt revision of the emissions price. More stringent measures need to be implemented from 2030 onwards to meet climate targets, such that emissions prices jump to USD 700 per tonne of CO2 by 2050 leading to higher transition risk.

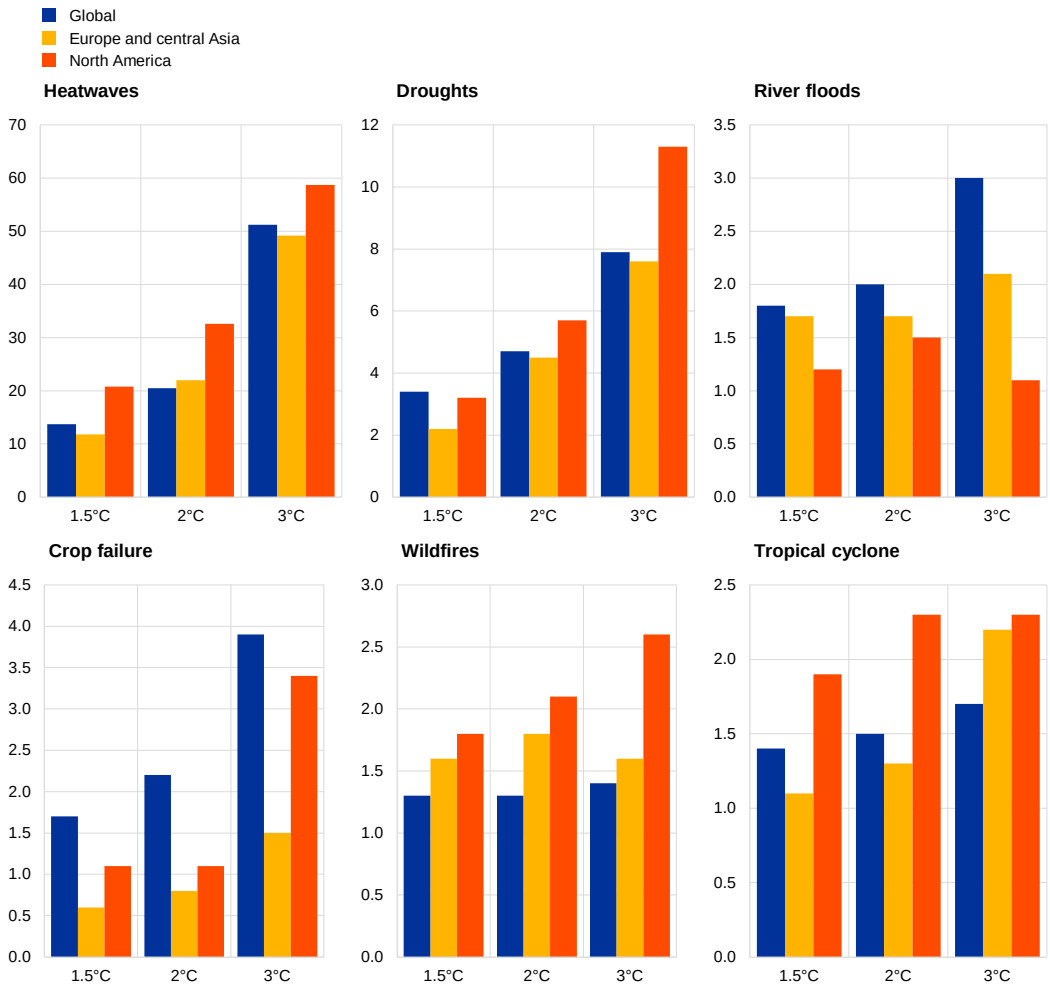
The current policies – or hot house world – scenario illustrates a failure to meet the 2015 Paris Agreement. In this scenario, only current policies are implemented, and emissions continue to increase steadily (Chart 12, right panel) leading to a rise in estimated median temperature of about 3.5°C by 2100. The increase in the price of carbon is insignificant, and the economic actors do not change their behaviours. Failure to transition to a low carbon economy translates into acute impacts, such as increasing frequency and severity of climate-related weather events (for example storms, floods or heat waves); and chronic impacts, like irreversible long-term changes in climate patterns (for example ocean acidification, rising sea levels or changes in precipitation). Ten to twenty times more people are expected to be exposed to hazards, such as heatwaves, droughts and river floods (Chart 13), leading to increased damages. The direct losses from river floods alone would double globally by the end of the century (NGFS (2021)). These changes in exposure and

losses are unevenly distributed across regions, with South Asia expected to face the largest increases in overall exposure.[72]

Chart 13

Change in population exposed to extreme events across scenarios by 2100

(times (x) increase)



Source: NGFS climate scenarios.
Note: Change in global population annually exposed to extreme events by 2100 at different levels of global warming, relative to pre-industrial climate conditions.

All scenarios include several technological assumptions regarding the availability of CDR technologies. Direct carbon dioxide removal from the atmosphere can come, for instance, from bioenergy with carbon capture and storage and/or land-related sequestration (for example afforestation). While the orderly scenario assumes that (CDR) technologies are available, the disorderly scenario relies on only limited development and deployment of these technologies. In the

[72] See NGFS (2021) for further details.

hot house world scenario, no major progress is observed in terms of energy production and use. Table 3 summarises the main elements of the narratives of the three NGFS scenarios.

Table 3

Main elements of the narratives of the three selected NGFS scenarios

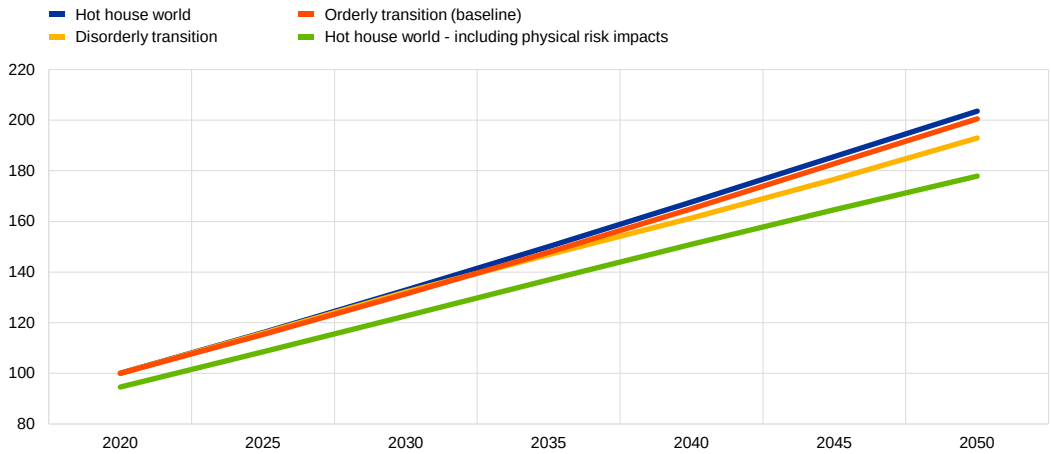
Scenario	Orderly (baseline)	Disorderly	Hot house world
NGFS label	Orderly 2°C with CDR	Delayed 2°C with limited CDR	Current policies 3.5°C
Policy	Immediate action (emissions price introduced in 2020) taken to reduce emissions in line with the Paris Agreement	More stringent policies need to be implemented from 2030 onwards, translating into an abrupt increase in emissions price	Only current policies are implemented ("business as usual scenario")
Median temperature rise by 2100	well below 2°C	below 2°C	about 3.5°C
CDR technologies	The use of CDR permits negative emissions in the second half of the century	Only limited CDR technologies available	No major progress

The projected trajectories of the physical and transition variables impact economic and financial variables. Chart 14 shows the impact on GDP, separately, for both transition and physical risks. Under the disorderly transition scenario, a tightening of climate policies generates negative supply shocks, and transition risks would lower GDP by 3.5% until 2050 worldwide, and by 2.3% in the EU, compared with the orderly scenario. In the hot house world scenario, physical risks reduce GDP by up to 12% by 2050 compared with the orderly scenario, which would represent a larger loss of GDP than the impact from the transition. However, the bulk of these impacts results from past emissions, constituting a shock that continues to create physical damage whether or not transition measures are implemented. Box 3 provides a tentative integrated assessment of the simultaneous economic impacts of transition and physical risks.

Chart 14

Impacts of transition and physical risks on world GDP

(index; base 100 in 2020)



Sources: NGFS climate scenarios and ECB calculations.

Box 3

Assessing the long-term trade-offs and cost of inaction

This box discusses the cost of inaction by integrating transition and physical risks in the same modelling framework.[73] The joint treatment of risks complements the NGFS scenarios included in this report where transition and physical risks are considered separately. The box uses the ACCL (Advanced Climate Change Long-term) scenario-building model – a long-term global projection tool which projects future economic growth for different levels of CO2 emissions and average temperatures and includes five different types of energy input (see details in Alestra et al. (2020)).

The long-term trade-offs are encapsulated in three scenarios: one compatible with the Paris Agreement, and two "Too-little too-late" scenarios. While the first scenario comes close to the NGFS orderly scenario, the two "Too-little too-late" scenarios include both high transition and physical risks and match the narrative of analogous but still unreleased NGFS scenarios. The two "Too-little, too-late" scenarios differ in terms of the parametrisations of the damage function for a

[73] Very few existing methodologies combine physical and transition risks and allow the trade-off between them to be assessed. The common approach is to examine the impact of physical hazards under different transition scenarios. For example, the RMS, a catastrophe risk solutions company for the insurance industry, has developed a set of climate change models to help (re)insurance undertakings in assessing the impact of various natural hazards under different representative concentration pathways (RCPs) scenarios and time horizons. In a similar vein, S&P's Trucost develops climate change physical risk analytics for different RCPs. Carbon Delta's Climate Value-at-Risk (cVaR) assesses the potential financial sensitivity to climate risks and opportunities, i.e. the potential financial impact of different climate scenarios.

given temperature outcome and level of net CO2 emissions[74]: the Nordhaus (2017)'s scenario incorporates moderate output costs of temperature increase, and the excessive scenario the relatively high costs. Chart A highlights that delayed and initially insufficiently tight transition policies imply a continued increase in net emissions up to 2060 and fail to limit emissions and the increase in temperature.

Chart A

Long-term scenarios and climate targets

Source: ECB calculations.
Note: Gt stands for gigatonnes.

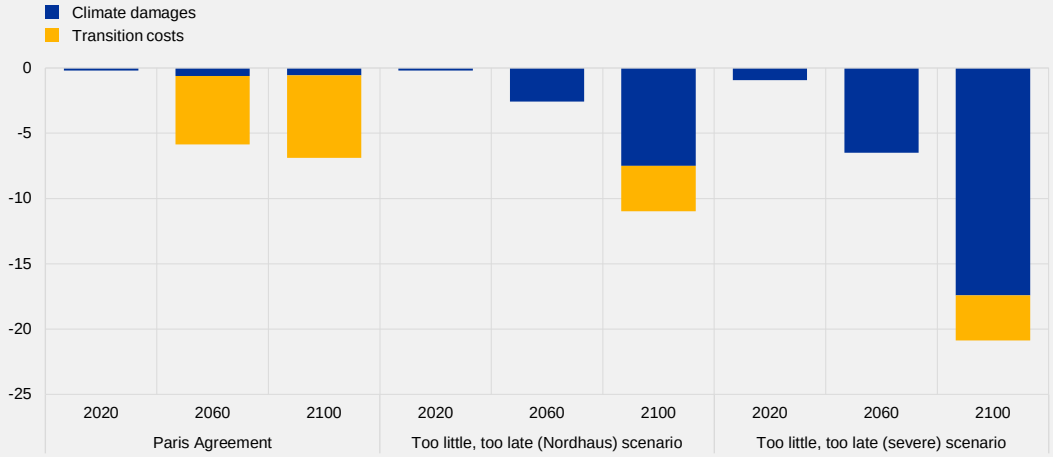
The long-run GDP losses depend on the timeliness and the degree of ambition of the transition policy. Chart B breaks down the GDP losses under the three scenarios into the costs of transition and physical damages. Under the "Paris Agreement" scenario, a fall in GDP amounts to 5.2% in 2060 and 6.3% in 2100, and most of this reduction can be attributed to transition policies. Under the "Too-little too-late (Nordhaus)" scenarios defined by the NGFS, the transition costs are limited, but by the end of the century the impact of physical risks leads to losses that amount to more than 7% of world GDP. Adding the costs related to the belated transition (implemented only from 2060 onwards), the overall loss amounts to more than 10% of world GDP. Under the second "Too-little too-late (severe)" scenario, the overall loss climbs to more than 20% by 2100.

[74] Damage functions capture the relationship between climate variables, such as temperature or GHG concentrations, and economic welfare, taking adaptation into account. They differ in terms of functional forms, the climatic input variables, the economic output (production versus growth), the assumptions regarding adaptation (implicitly or explicitly modelled) or the representation of uncertainty (deterministic versus probabilistic). The parametrisation of the damage function of the first "Too-little, too-late" follows Nordhaus (2017)'s review, whereby the damage function is: $DGDP_t = \eta_1 Temp_t + \eta_2 Temp_t^2$ with $\eta_1 = 0.38$ and $\eta_2 = -0.48$. In the second "Too-little too-late" scenario, $\eta_2 = -1.00$ to account for possibly more severe impacts.

Chart B

Climate damages and transition costs

(percentages of world GDP)



Source: ECB calculations.

5.2 Augmenting macro-financial and sector-level insights

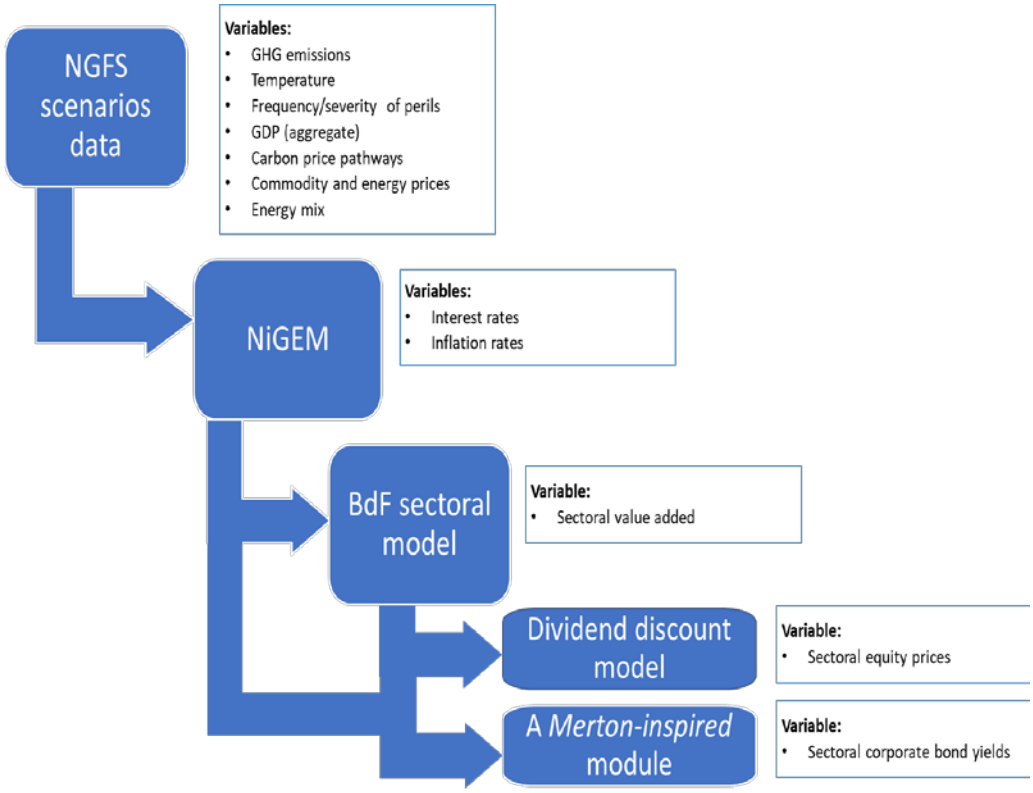
Building on a set of original NGFS variables, complementary models have been used to provide the additional macro-financial impacts required for financial risk assessment. In line with the Banque de France modelling framework (Allen et al. (2020)), the approach taken in this report relies on a suite of models that translate the NGFS high-level transition scenarios into macroeconomic, sectoral and financial information. The approach is very much aligned with ongoing work at the NGFS, which builds on a suite of models to project macro-financial variables over long time horizons.

First, a multi-country macroeconomic model NiGEM (National Institute Global Econometric Model) is used to provide a more complete set of macroeconomic and financial information. The variables added include inflation, unemployment, exchange rates and interest rates. A neo-Keynesian model, NiGEM features a well-specified supply side, with nominal rigidities, and international trade linkages, accounting for the impacts of prices, exchange rates and the patterns of asset holding and associated income flows. Although NiGEM is not a climate model, it has recently been extended to simulate the macroeconomic impacts of some climate policies, such as a carbon price.[75]

[75] See Hantzsche et al. (2018) for more details on NiGEM.

Figure 4

Modelling approach



Initial inputs from the NGFS scenarios are used to calibrate the model to reproduce the NGFS GDP path for a number of country blocks (including the EU, the United States and the rest of the world). More specifically, the NGFS emissions prices trajectories are used as inputs to set carbon tax rates in NiGEM, a key factor in generating adverse policy shocks. Productivity shocks are then calibrated so that the combined impact with the policy shocks matches the GDP trajectories of the NGFS scenarios.

A key feature of climate change and of the transition to a low carbon economy is that it will affect sectors very differently, with the producers of energy inputs and energy-intensive sectors likely to be more exposed and sensitive to the associated structural transformations. The scenarios therefore need to be informed at a sufficiently detailed level of sectoral granularity to assess financial risks.

First, this work provides granular information on economic and financial variables for 55 sectors for selected macro-financial scenarios. It builds on a sectoral model that translates transition scenarios into their impacts on value added at the sectoral level. The model has been developed at the Banque de France and builds on the production network literature (Baqaee and Farhi (2019); Hebbink et al. (2018)). It features emissions prices on both fossil fuel consumption and GHG emissions inherent to sectoral production processes. This approach accounts for the

general equilibrium effects that would occur should an emissions price be introduced or increased. See Devulder and Lisack (2020) for more details on the sectoral model.

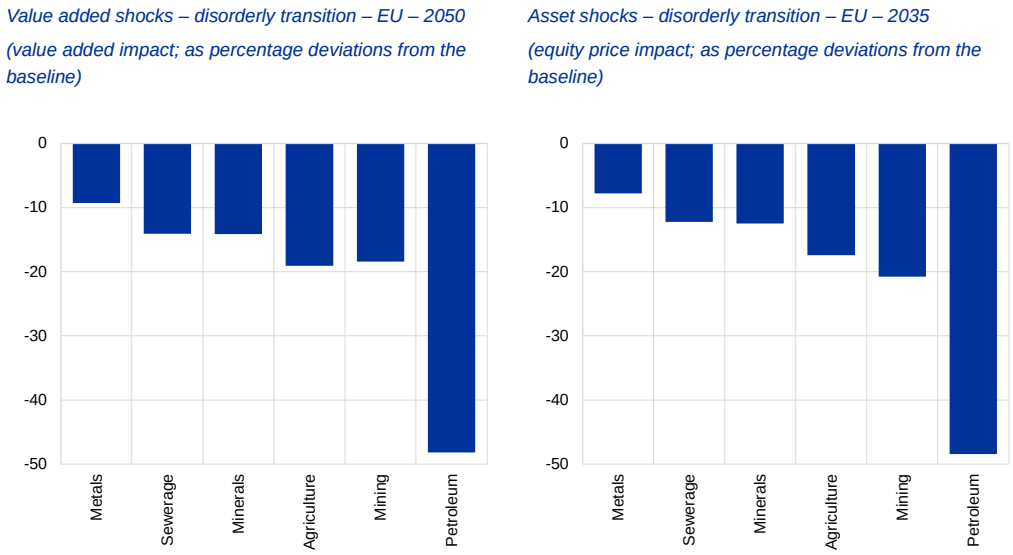
The results generated using this model can also give an indication of the sensitivities of sectoral value added to the introduction of a carbon tax or price. Following the transition vulnerability factors computed by De Nederlandsche Bank (DNB) (Vermeulen et al. (2018)), the sectoral model provides estimates of the impact of a carbon tax by sector. But it goes further by accounting for substitution effects across inputs, in particular energy inputs, hence providing a more complete assessment of the disruptive structural transformations associated with a disorderly transition.[76]

Further financial models complement real economy variables with projections of corporate credit spreads and equity price shocks. Stock price variations can be estimated for each sector and geographical zone using a dividend discount model (see Annex 2 "Detailed look at existing methodologies: Handbook", H.4.1.) and corporate credit spreads with a calibrated Merton's model (see Annex 2 "Detailed look at existing methodologies: Handbook", H.4.2.).

While the economy-wide impact of scenarios might appear relatively moderate, they can have a pronounced effect on selected sectors. In the case of the disorderly transition scenario, fossil fuel producers and large-scale emitters are most exposed to risks, since their value added is impacted by up to 50% by the end of the period, at least if they are unable to adjust their production processes (Chart 15). Likewise, their equity prices should contract when market participants revise their expectations following the implementation of the policy measures in 2030.

Chart 15

Sectoral impacts from transition risks – value added and equity price shocks



Source: NGFS climate scenarios and ECB calculations.

[76] The TVFs allow the impacts on macroeconomic and financial variables of the introduction of or increase in a carbon tax (or price) to be disaggregated by sector, with each sector impacted proportionally to its scope 1 and 2 emissions.

6 Climate stress testing – a new kid on the block

In recent years progress has been made on climate stress testing and scenario analysis methodologies. This has been possible thanks to growing experience and the increased availability of datasets. The following three sections discuss the challenges of climate-related scenario analysis for the financial sector. The first two discuss trends in the area of forward-looking scenario analysis, while the third and the last section of the report puts these methodologies into use in a coordinated climate-sensitivity analysis of the European financial sector.

The Handbook in Annex 2 "Detailed look at existing methodologies" provides a complete overview of off-the-shelf methodologies developed in European institutions. The Handbook is designed as a practical guide for practitioners and aims to foster the development of climate-related methodologies in other institutions. It describes in detail different approaches to estimate key parameters that connect the non-financial sector, which could be impacted by climate-related shocks, and the financial sector's balance sheets.

Since the publication of the first report of the ECB/ESRB Project Team on climate risk monitoring, central banks and supervisors have intensified their efforts to develop climate-related stress testing frameworks.[77] International organisations have also joined the call to incorporate climate-related risks in stress-testing exercises, including the International Monetary Fund (IMF) (2020a, 2020b), the Bank for International Settlements (BIS) (2020), the Financial Stability Board (FSB) (2020, 2021), and the Network for Greening the Financial System (NGFS) (2021).[78] European Union authorities have completed or are in the process of conducting or planning 18 climate stress test exercises (Chart 16 and Annex 1 Table A.1).

The climate-related scenario analysis is gradually shifting towards stressing both physical and transition risks. As shown in Chart 16 (left panel), all of the stress testing and sensitivity initiatives completed up to 2020 focus on transition risks. However, from 2021 there is a growing number of exercises covering physical and transition risks.[79] This trend is coupled with an extension of the horizon used in scenario analysis (Chart 16, right panel). The initial transition risk-focused stress test exercises relied on scenarios with a five-year horizon. This was an extension compared with the more standard three-year horizon used in regular stress test exercises, but far shorter than the horizon of up to the year 2100 included in NGFS scenarios. The ongoing exercises are bolder, extending to a 30-year horizon in most cases. The NGFS scenarios are becoming a common reference for ongoing and planned exercises, in particular, the orderly transition, the

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77 See Lagarde, Christine (2021) and de Guindos, Luis (2021), which discuss the importance of considering climate risks in banking sector stress testing exercises and highlight the ECB's efforts to assess their impact on the European banking sector over a 30-year horizon. Bailey, Andrew (2020) discusses the importance for the banking sector of managing climate-related risks, and describes the plans of the Bank of England to conduct stress testing on physical and transition risks for the UK economy. Brainard, Lael (2021) discusses the interest and the resources being considered by the US Federal Reserve Bank in order to assess the financial stability impacts of climate-related risks in the United States.

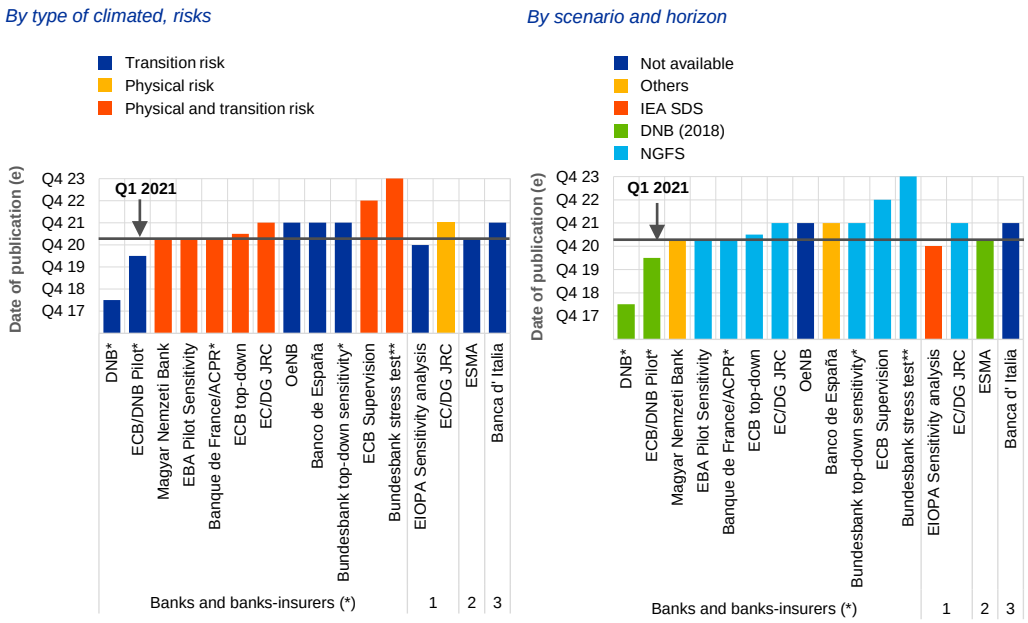
78 These add to earlier calls in, for example, ESRB (2016); TCFD (2017); and NGFS (2018).

79 However, the modelling of scenarios that combine both physical and transition risks still faces technical difficulties owing to the complexity and uncertainty regarding the interaction between physical and transition shocks, among others. Consequently, the ongoing and planned initiatives still treat physical and transition risks separately.

disorderly transition (with two variants, namely with effective and ineffective transition policies) and the “hot house world” scenario discussed in Section 6.

Chart 16

Initiatives of climate-related stress test and sensitivity analysis in European Union institutions

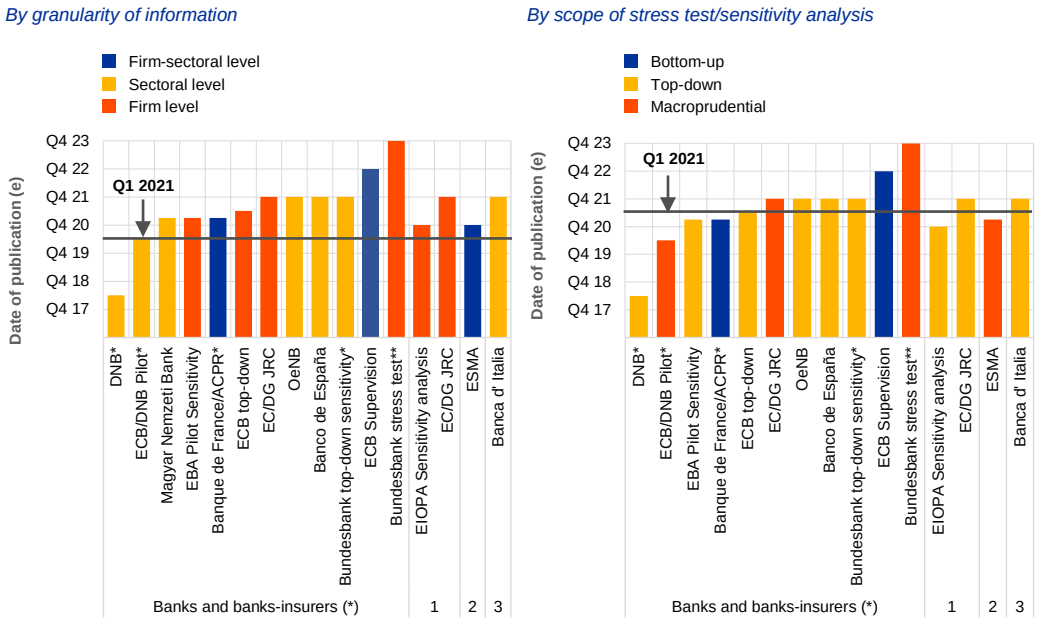


Sources: Survey ESRB institutions, central banks and financial regulatory authorities.
*Notes: 1) Insurers; 2) Investment funds; 3) Other. Left panel: The Polish Financial Supervision Authority (KNF) and the Malta Financial Services Authority have planned climate-related risk initiatives, but their publication dates have not been determined. The Malta Financial Services Authority's project covers transition risks. The KNF's project has not yet disclosed the type of risk covered. “3) Others” in the vertical axis refers to households and non-financial corporations. Right panel: “IEA SDS” refers to the International Energy Agency's sustainable development scenarios. “Others” refers to scenarios produced by E3ME Cambridge Econometrics with a 30-year horizon. * means that the initiative covers both banks and insurance companies; ** means that the initiative covers banks, insurers and investment funds. (e) means expected date.*

Climate-related stress-testing and sensitivity frameworks have evolved towards the use of increasingly granular data. As shown in Chart 17 (left panel), early exercises employed mostly sector-level information, e.g. sector-level CO2 intensity. It reflected the fact that disclosure of climate-related risks from private entities has been insufficient, heterogeneous and patchy. As databases of climate risk and exposure information have been gradually improving and are made available, several institutions have started or are planning stress-testing exercises extensively using firm-level information or, in some cases, transaction-level information.

Chart 17

Initiatives of climate-related stress test and sensitivity analysis in European Union institutions



Sources: Survey ESRB institutions, central banks and financial regulatory authorities.
*Notes: 1) Insurers; 2) Investment funds; 3) Other. Left panel: The Polish Financial Supervision Authority (KNF) and the Malta Financial Services Authority have planned climate-related risk initiatives, but their publication dates have not been determined. The KNF's project uses firm-level information. The Malta Financial Services Authority's project uses asset-level information. Right panel: The Malta Financial Services Authority's and the KNF's projects are top-down exercises. Macroprudential initiatives cover second-round effects due to inter-linkages of the financial sector and the real economy, and/or system-wide financial sector interconnections. * means that the initiative covers both banks and insurance companies; ** means that the initiative covers banks, insurers and investment funds. "3) Others" refers to households and non-financial corporations. (e) means expected date.*

Another trend is the predominance of top-down exercises and growing interest in macroprudential aspects. For example, a macroprudential banking sector scenario analysis featured in the first report of the Project Group included macro-financial feedback effects related to banks' deleveraging and the funding-solvency loop. A similar avenue is currently explored by the Deutsche Bundesbank. The European Securities and Markets Authority (ESMA) exercise covers system-wide interconnections: the exercise includes indirect exposures of investment funds to non-financial sectors via exposure to other investment funds. This trend can be observed in Chart 17 (right panel).

Finally, despite the variety of methodologies and approaches used, there is a clear convergence to common reporting standards. The impact of climate-related shocks on the financial sector is frequently reported as an increase in credit and market risks for banks (i.e. impact on probability of default (PD), loss given default (LGD), risk-weighted assets (RWAs), revaluation of trading book, or capital shortfalls), or a revaluation of equity and corporate bond holdings for insurance companies and investment funds.

Over a dozen stress tests are ongoing or completed in non-European Union institutions (Annex 1, Table A.2). There are 15 initiatives altogether, by the International Monetary Fund (pilot

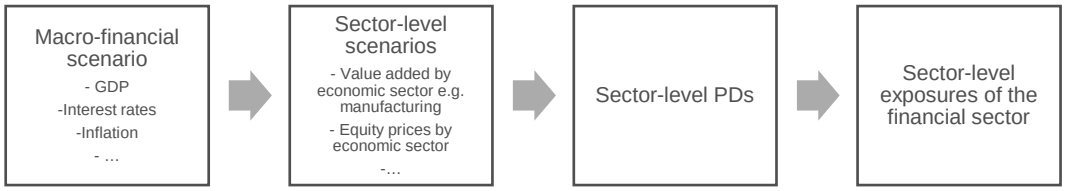
Financial Sector Assessment Program (FSAP) exercises in Denmark, the Bahamas and the Philippines), the Bank of England, the US Commodity Futures Trading Commission, the Australian Prudential Regulation Authority, the Korean Financial Supervisory Service, the central banks of New Zealand, Canada, Japan, China and Brazil, and the Monetary Authority Boards of Hong Kong and Singapore. In most cases, these initiatives cover both transition and physical risks (8 out of 15 exercises) and are focused on the banking sector or a combination of firms with different financial institutions. Most of the exercises conduct analysis in a combination of firm and sector levels and with a top-down approach. Finally, most of the initiatives are in a “planned” stage with undetermined methodology and date of publication.

7 Developments in climate stress test methodologies

The heterogeneous impact of climate-related risks on different sectors of the economy was recognised early as a challenge for stress testing. In the first climate stress testing frameworks, macroeconomic scenarios were directly mapped onto sector-level financial parameters, such as probabilities of default (PDs), as illustrated in Figure 5. Then, these sector-level parameters were used to update balance sheets of financial institutions with exposures broken down by sector. Macroeconomic scenarios can be described either on an economy or sector level (De Nederlandsche Bank (DNB) (2018); ESRB, (2020)). For transition risks, the approach recognises cross-sectoral heterogeneity in carbon footprints such as a decrease in operating margin of certain sectors owing to an increased cost of emitting CO2 in a transition scenario. Carbon pricing policies will affect the price of coal, which is an important driver of the financial performance of energy-intensive industries (e.g. utilities) and fossil fuel producers (e.g. mining). To this end, the approach can employ either direct or composite (direct and indirect) measures of sectoral vulnerability (transition vulnerability factors, see Vermeulen, R et al. (2018)).

Figure 5

Sector-level approach to credit risk in climate stress tests



Source: ECB.

Sector-level analysis pushed ahead in the first climate-related stress test exercises but necessarily ignored important differences within industries. Its main advantages are relatively low data demands and relative ease of adaptation to the existing stress testing infrastructures. Furthermore, models relying on the data with very granular sectoral breakdowns can substitute well for missing firm-level information (see Box 4).[80] However, there is growing evidence that there can be a large variation between firms operating in the same sectors of the economy in terms of GHG emissions (see Data Supplement), for example utility companies producing electricity from coal versus wind. Furthermore, firms' vulnerability will depend not only on the type of economic activity

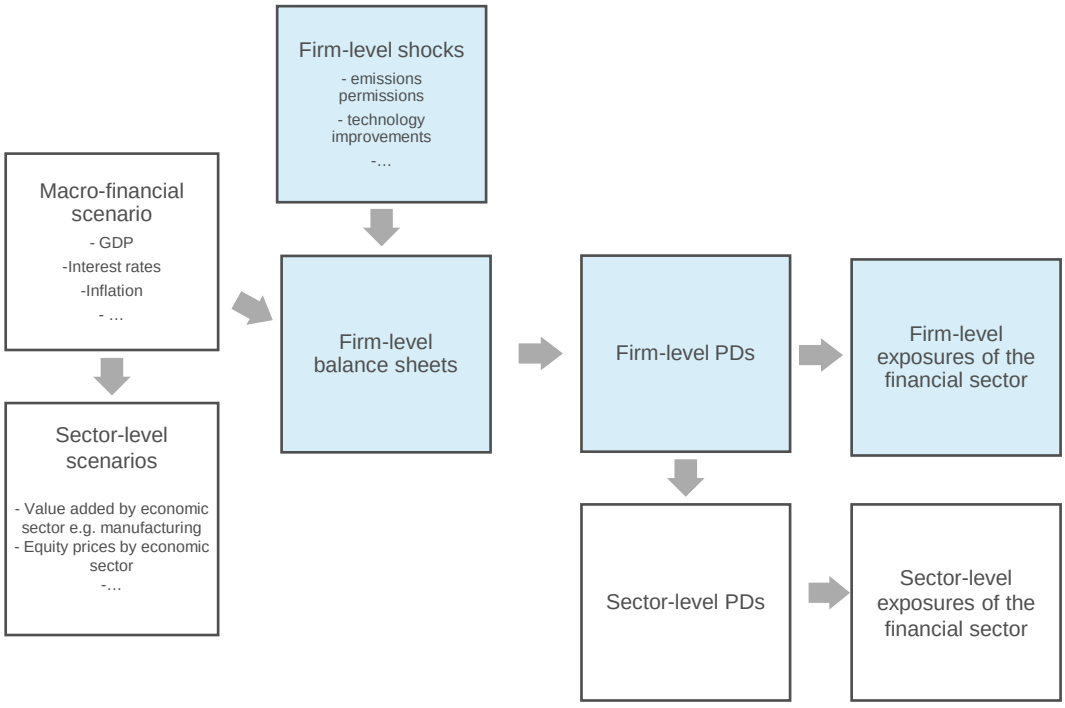
[80] For examples of parameter estimation using a sector-level approach, see Annex 2 "Detailed look at existing methodologies: Handbook"; H.1.1, H.1.2, H.1.3, H.2.1, H.2.2, H.4.1 and H.4.2.

but also on particular firm characteristics, such as the location of facilities and the geographical network of supply chains and sales markets.

Accordingly, climate stress testing methodologies are moving towards firm-level models to fully explore the distribution of climate-related risks in the corporate sector. The first approach is to link the balance sheet or profit and loss information on non-financial firms to changes in macro-financial or sector-specific conditions (Figure 6). The macro-financial scenario can be described on an economy-wide level (as in the European Central Bank's (ECB) top-down climate stress-test exercise, forthcoming) or on a sectoral level (ACPR, (2020)). The firms' stressed balance sheet indicators are then fed into credit rating models, allowing to project relevant stress test parameters relying on historical elasticities between firms' balance sheets and, for example, PDs. The estimated firm-level PDs could be directly applied to financial sector balance sheets (loans, equity, bonds, etc), but more often are aggregated at a granular sectoral level and applied to the balance sheets accordingly (as in the forward-looking scenario analysis for the banking sector in Section 8, which relies on PDs from the ECB's top-down stress test).[81]

Figure 6

Firm-level approach to credit risk in climate stress tests



Source: ECB.
Note: PD stands for probability of default.

Firm-level models will reflect the intra-sectoral heterogeneity of GHG emissions and financial conditions. For example, they allow the macro-financial and sectoral scenarios to be

[81] For examples of parameter estimation using firm-level approach, see Annex 2 "Detailed look at existing methodologies: Handbook"; H.1.4, and H.1.5. For the insurance sector, see H.3.2 and H.3.3.

translated into firm-specific shocks (see Box 5 for an application to Germany) with firms' balance sheets affected differently under the various scenarios depending on a firms' emissions intensity, and readiness for transition, or the vulnerability of a specific location to natural disasters. They can also capture firms' heterogeneity in terms of financial conditions and reflect the fact that entities with strong balance sheets and better profit-generating capacities are in a better position to absorb additional costs related to the transition to a green economy. Some firms may also be more capable of financing investments in green technologies without defaulting on their debt obligation towards lenders, or more likely to be insulated from weather disasters. Consequently, the derived firm-level PDs would incorporate varying shift factors in the scenarios producing a greater dispersion of individual PDs within sectors.

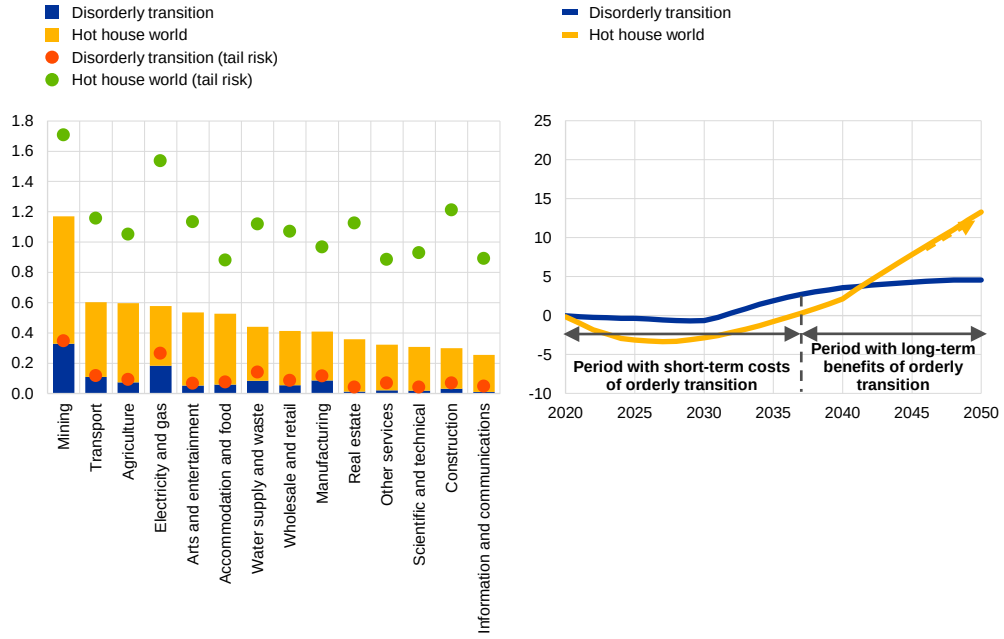
An example of the extensive use of firm-level data is the upcoming ECB 2021 top-down climate stress test.[82] The ECB's methodology for deriving PDs integrates both transition and physical risks, as well as their interactions (see Annex 2 "Detailed look at existing methodologies: Handbook", H.1.3). Thanks to the use of granular data, the methodology recognises that transition policies can affect the cost-revenues structure of carbon-intensive firms, and that natural disasters and the resulting disruption of physical capital can influence firms' debt structure.

[82] "Shining light on climate risks: the ECB's economy-wide climate stress test", blog post by Luis de Guindos.

Chart 18

Probability of firm defaults under the ECB's top-down stress test

(percentages)



Source: ECB.

Notes: Differences in firms' default probabilities under the two adverse scenarios with respect to the orderly transition scenario, by sector and group of firms (mean firms and firms mostly exposed to physical risk). The bars represent the median changes in default probabilities over the next 30 years; the dots report the changes in default probabilities when considering the firms that are most exposed to physical risk (95th percentile based on firms' physical risk score). Right panel: solid line is median across all firms in the sample, dashed line is the average of most exposed/vulnerable firms in the sample.

Initial results from the ECB's climate stress test suggest that, in the absence of further climate policies, the impact of extreme physical events on firms' PDs will rise substantially over the 30-year time horizon (see Chart 18, left panel). The PD for a median firm initially rises in the orderly transition scenario compared with the transition scenario, reflecting the short-term costs of introducing climate policies in an orderly fashion (see Chart 7.3, right panel). In a "hot house world", by contrast, PDs rise rapidly in the second half of the time horizon, particularly for more vulnerable firms, far beyond the levels of the orderly transition. This outcome highlights the long-term benefits of rolling out climate policies and conversely the long-term costs of taking no action to combat climate change. The same chart also demonstrates the limited short-term benefits and the subsequent high long-term costs of a disorderly transition rather than an orderly transition.

The shift towards the use of more granular data is being accompanied by increasing use of firm and security-level data. Modelling of the pass-through of transition risks requires information on the GHG emissions of individual borrowers or insurance holders. Modelling the pass-through of physical risks requires the geographical location of a firm's assets (production facilities, offices, warehouses, etc.) mapped to the vulnerability of the locations to damages related to future extreme weather events (see the first two columns in Table 4). The modelling of physical risks can be further advanced by taking into account (i) the characteristics of a firm's supply chain network, as the

sourcing of input goods from sectors or geographies which are more likely to be affected by physical risk will result in more disruptions to the firm's supply chain, or (ii) the characteristics of its sales markets, as customers' locations and business models will influence how physical risks impact a firm's revenue.

Table 4

Available exposure data by financial sector and risk type for climate stress testing exercises

	Information by climate risk type needed for stress testing		Data availability for exposures and granularity of information	Mapping to climate risk metrics (external data)		Modelling of propagation mechanism (PD/LGD models)
	Transition risk	Physical risk		GHG emissions	Geo-location of assets and collateral	
Banks Credit risk	Exposure to non-financial corporations by carbon emissions intensity of borrowers	Exposure to non-financial corporations by geography of borrowers' assets and collateral	Sector-level: Supervisory reporting (COREP-FINREP)	Only country-level	No	Very limited (low granularity of data for exposures and credit quality)
			Borrower-level: ECB large exposure statistics National credit registers	Yes (firm or industry)	Yes	ECB large exposure statistics: limited (incomplete data on exposures and PDs) National credit registers: Yes
			Loan-level: AnaCredit National credit registers	Yes (firm or industry)	Yes	Yes
Market risk	Holdings of securities by carbon emissions intensity of issuers	Holdings of securities by issuers, industries and geographies of insurers' assets	Security-level: Securities holdings statistics with CSDB information	Yes (firm or industry)	Yes	Yes (after matching with price data)
Insurance/ pension funds Credit and market risk	Holdings of securities by carbon emissions intensity of issuers (via ISIN or NACE codes)	Holdings of securities by issuers, industries and geographies of insurers' assets	Sector-level: SHS	Yes (per sector)	Yes (per sector)	Limited
			Security-level: Solvency II IORP reporting	Yes (firm or industry)	Yes	Potential
Underwriting risk	Not applicable	Insurance underwriting exposure, ideally by category and geography	Solvency II	Not applicable	Not applicable	Not applicable

	Information by climate risk type needed for stress testing		Data availability for exposures and granularity of information	Mapping to climate risk metrics (external data)		Modelling of propagation mechanism (PD/LGD models)
	Transition risk	Physical risk		GHG emissions	Geo-location of assets and collateral	
Financial markets	Holdings of securities by carbon emissions intensity of issuers	Holdings of securities by issuers, industries and geographies of insurers' assets	Security-level: Morningstar	Yes	Yes	Yes (after matching with price data)

Source: ECB.
Note: The column "mapping to climate risk metrics" assesses whether an exposure database can be mapped to data from external providers on transition and physical risk. ISIN stands for International Securities Number; NACE stands for Statistical classification of economic activities in the European Community.

Table 4 further explores the different types of dataset available for climate stress testing.
The availability of exposure datasets such as AnaCredit (see also Box 6) or national credit registers allows the impact of transition and physical risks on banks' credit risk to be explored. For modelling the transmission of banks' market risk, the high granularity of information in the securities holdings statistics (SHS), complemented by data from the Centralised Securities Database (CSDB), allows mapping to the relevant risk metrics at the level of the issuer or sector. As for banks, the stress from climate risks on credit and market risk in the insurance sector may be estimated after mapping the exposure data to external data on climate risk indicators at different levels of granularity. At the same time, the impact of climate risk on insurers' underwriting risk may be more constrained, as supervisory data on insurance catastrophic claims may not be sufficiently granular. For investment funds and other financial intermediaries, it is possible to map holdings of securities to individual issuers and their associated climate risk based on granular security-level data from the private provider Morningstar, which has a coverage of about 80% of the EU investment fund universe.[83]

[83] However, it is worth pointing out that insurers own data on catastrophic insurance claims is much more detailed than the exposures reported to the supervisors (e.g. claims at the level of individual addresses). Insurers use these granular data for calculating their underwriting risk in internal models. Hence, the more granular data could be used in bottom-up climate stress testing exercises in which insurers calibrate the physical shocks on underwriting risk in-house.

Box 4
Modelling loan defaults with individual bank-sector exposures

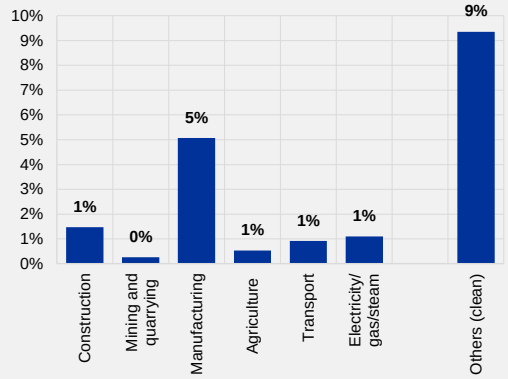
More granular sector-level data can well support modelling of credit risk parameters for the purpose of climate stress testing. To illustrate this point, this box employs the time-series information on banks' exposures along with the four-digit NACE classification for 41 Polish banks from the third quarter of 2013 to the fourth quarter of 2019 to estimate the share of non-performing loans (NPLs), used as a measure of the probability of default (PD), dependent on macro-financial variables and environmental performance indicators related to carbon and coal prices.

Chart A

Exposures to carbon-intensive sectors (left panel) and relationship between NPLs and the share of carbon-intensive sectors in total banking sector corporate loans (right panel)

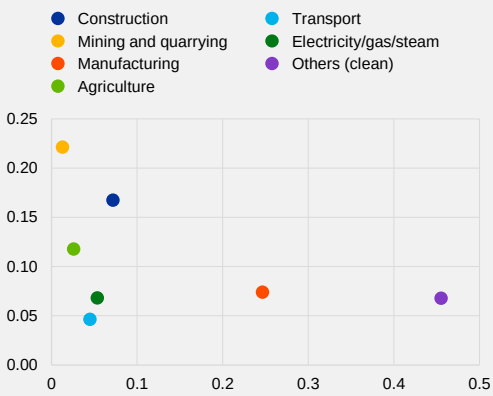
Exposures to carbon-intensive sectors

(share in total assets; percentages)



Relationship between NPLs and the share of carbon-intensive sectors in total banking sector corporate loans

(y-axis: NPL ratio; x-axis: share in the corporate portfolio; percentages)



Source: ECB calculations.
Notes: CLEAN includes all other sectors of the economy (less carbon intensive sectors).

Table A reports regression estimates distinguishing between six carbon-intensive sectors and the less carbon-intensive sectors (CLEAN) pooled together. Approximately 9% of the Polish banking sector's assets at the end of 2019 were exposures to sectors responsible for the bulk of CO2 emissions (Chart A, left panel). Furthermore, as Chart A (right panel) shows, the six most carbon-intensive sectors exhibit higher credit risk measured by the NPL ratio compared with the aggregate portfolio of less carbon-intensive sectors. The negative sign of the coefficient for country-level GDP for the manufacturing sector (column 4) implies that stronger economic growth leads to better loan performance. The opposite effect is observed in the less cyclical energy sector

(column 5). It is also found that the quality of banks' loans is not affected by changes in the level of sovereign bond yields.

Carbon and coal prices significantly impact the performance of loans to climate-sensitive sectors. NPL ratios for the manufacturing, energy and transport sectors presented in columns (4), (5) and (7) show a positive relationship with carbon prices (CARBON). Accordingly, for these sectors, the transition to a low-carbon economy and an increase in the cost of pollution allowances are likely to lead to further deterioration in borrowers' ability to repay their debts. The NPL ratios for energy production in column (5) depend positively on the coal price (COAL), reflecting the fact that the energy sector in Poland, which relies heavily on coal combustion to generate electricity, is sensitive to changes in the price of coal. By contrast, a higher price of coal contributes to a lower NPL ratio in the mining sector (column 3). Interestingly, neither the carbon nor the coal price has a pronounced impact on loan performance in less carbon-intensive sectors (column 1).[84]

[84] Among other control variables, the size of the balance sheet and high bank profitability are both negatively correlated with NPLs. Bank solvency is insignificant for almost all sectors, while lower loan-to-deposit ratio correlates negatively with NPLs for industries that emit the most carbon (mining and energy) and positively for other high-emitting sectors (transport, industrial production and agriculture).

Table A

The regression results

	(1) Clean	(2) Agriculture	(3) Mining	(4) Manufacturing	(5) Energy	(6) Construction	(7) Transport
				Macro-financial variables			
GDP	0.0395	0.0412	-0.0326	-0.0957*	0.353***	-0.0738	-0.0573
		-0.0636	-0.148	-0.0506	-0.125	-0.0698	-0.117
5Y	-0.0667	0.145	0.00116	0.210*	-.0.242	0.105	0.589**
	-0.054	-0.109	-0.173	-0.122	-0.377	-0.101	-0.29
				Climate-related financial variables			
CARBON	0.00717	0.0104	-0.0125	0.0220***	0.0254*	-0.00241	0.0496***
	-0.00811	-0.00739	-0.012	-0.00855	-0.0144	-0.0108	-0.0149
COAL	0.00205	0.000761	-0.00264*	0.000683	0.0200***	0.0047	0.00577
	-0.00164	-0.00293	-0.00149	-0.00238	-0.00667	-0.00332	-0.00462
R2	0.122	0.29	0.352	0.194	0.348	0.134	0.279
Bank-specific variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector-specific variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bank fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector fixed effects	Yes	No	No	No	No	No	No
Observations	6,509	600	480	715	519	689	657
No. of banks	41	31	25	36	27	34	38

Source: ECB calculations.

*Notes: Regression estimates from a fractional response model with bank and sector fixed effects (Papke and Wooldridge (1996); Wooldridge (2010)) using data for 2013 Q3–2019 Q4. The dependent variable represents the non-performing loan ratio broken down into NACE 4 level sectors of the economy. The explanatory variables include a set of standard country macro-financial variables (GDP, YIELDS, i.e. government bond yield) the price of coal (COAL) and CO (CARBON). Other regressors are bank-specific indicators (the logarithm of total assets, the capital adequacy ratio, ROA and loan-to-deposit ratio), financial sector characteristics (operating margin, index of current financial liquidity and debt/EBITDA ratio). Data relating to banks' financial statements including the exposure (performing and non-performing) to economic sectors are from FINREP. Standard macro-financial variables come from Datastream. Data on the carbon and coal price are retrieved from the ICE Futures Europe trading platform. The information on the financial situation of industries (according to the NACE 2 breakdown) is gathered from the Central Statistical Office in Poland (GUS). All regressors enter the regression lagged by one period to address potential endogeneity problems stemming from simultaneity. The parameters in the table provide the sign of the marginal effect of the covariates on the outcome. Robust standard errors are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels respectively.*

The estimates are then applied to follow the evolution of NPL ratios by sector of economic activity for the two NGFS "orderly" and "disorderly" scenarios for the period 2021-2050.[85]

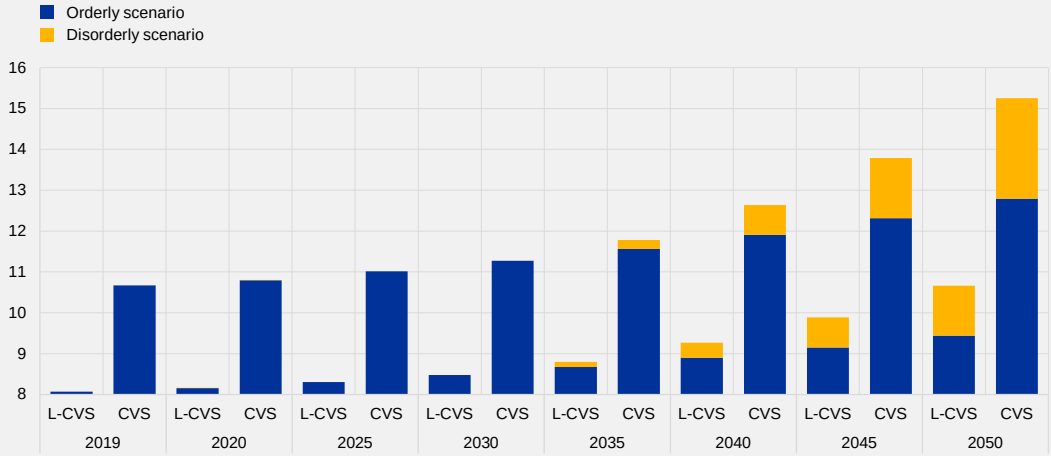
[85] Growth rates for the EU economy are used as a proxy for Polish GDP information.

Chart B shows that climate-relevant sectors are more vulnerable to changes in economic activity and climate-related variables projected under both scenarios. This may be due to the higher sensitivity of these sectors to changes in coal and CO2 emission prices. In addition, in both possible transition scenarios, banks' NPL ratios are expected to increase. However, the "disorderly" scenario entails much higher credit losses for banks in the sample.

Chart B

Impact of NGFS scenarios on banks' NPL ratios for climate vulnerable sectors (CVS) and less climate vulnerable sectors (L-CVS)

(NPL ratio; percentages)



Sources: Own calculations and NGFS.

Box 5
Mapping macro-financial scenarios to firm-level data

How firms perform in the transition to a green economy will have an impact on credit and market risk of corporate loans and securities. This box uses balance sheet data of non-financial firms in Germany and data reported under the EU Emissions Trading System (ETS) to illustrate how the data can be used to forecast costs and profitability under different carbon price scenarios. The analysis relies on firm-level balance sheet indicators and reported emissions and allocated free allowances in the EU ETS. Firms' operating expenses including depreciation in 2018 are sourced from the database of the Deutsche Bundesbank on annual financial statements of non-financial firms in Germany. Firms' costs and profitability are then projected under the assumption that firms will reduce their emissions in proportion to changes in aggregate emissions pathways.[86]

Applying the approach to orderly and disorderly scenarios reveals that firms' expenses for emissions allowances increase most sharply under the disorderly scenario. The NGFS scenarios are applied for the period 2021-2040 and supplemented with the assumption that the firm-specific share of free ETS allowances available for firms in sectors other than power generation (a maximum of 30%) in total emissions is constant until 2025, and then gradually declines to zero in 2030.[87] Under the disorderly scenario, expenses for allowances as a share of total costs rise gradually in the initial years, but spike from 2030 onwards as a result of the abrupt and sudden adjustment (see Chart A, left panel), while the rise in expenses begins to level off after 2030 under the orderly scenario. For the median firm, expenses rise up to 3.8% of total costs under the disorderly scenario and to 2.5% under the orderly scenario. More emissions-intensive firms (95th percentile) are disproportionately affected, with an increase in expenses of 40% in the disorderly and 30% in the orderly scenario. The increased costs of emissions allowances translate into lower profitability of firms, especially under the disorderly scenario (Chart A, right panel). Although firms' profitability declines under both scenarios, the adverse impact on profitability is stronger under the disorderly scenario, in which the return on sales decreases by up to 40 percentage points compared with 2018 for emissions-intensive firms in the sample (95th percentile). This compares with a reduction in profitability of up to 30 percentage points under the orderly scenario. The median effect is up to -3.5% under the disorderly and -2.2% under the orderly scenario. Moreover, the estimates suggest that by 2040 the adverse impact of transition on firms' performance will lead to negative profitability for 31% and 39% of included firms under the orderly and disorderly scenarios respectively (compared with 7% of firms in 2018).

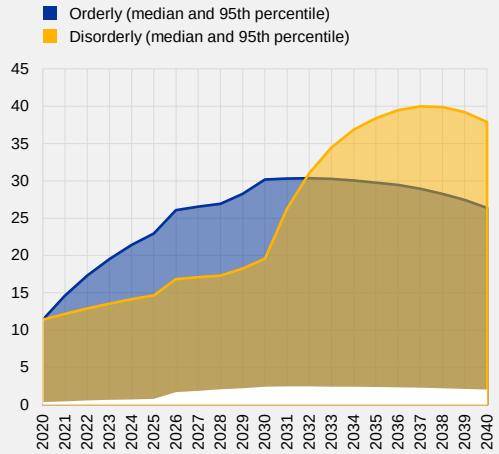
[86] Otherwise, it is assumed that firms do not adapt their behaviour. This implies that the balance sheet indicators used in the analysis, such as total costs and profitability, only change relative to 2018 as a result of price and volume effects in the ETS market. Another implicit assumption is that rising costs are not passed on to other firms or consumers.

[87] The current proposal for the next phase of the EU ETS anticipates the phasing-out of free allocation. See **EU ETS Revision for phase 4 (2021-2030)** for further details.

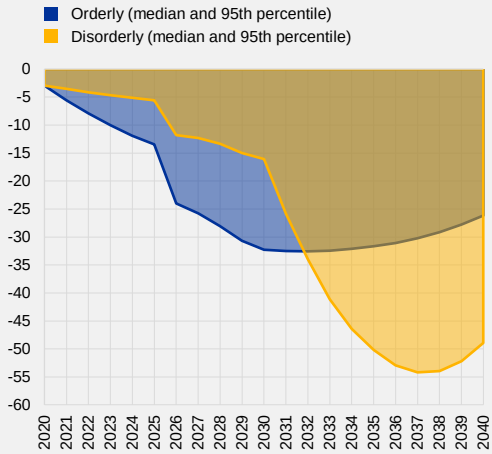
Chart A

Firms' expenses on emissions allowances (left panel) and firms' profitability (right panel) under NGFS carbon price scenarios

(expenses for allowances; percentage of total costs)



(change in profitability; return on sales))



Sources: Deutsche Bundesbank, EU Emissions Trading System (ETS) and NGFS.
Notes: Estimated projections for firms' expenses (median and 95th percentile) related to the purchase of emissions allowances in the EU Emissions Trading System (ETS). The projections are calibrated using firm-level data for non-financial firms in Germany in 2018 and CO2 price and emissions trajectories under the NGFS orderly and disorderly scenarios in the period 2021 2040. The five year scenario data has been transformed into yearly data by linear interpolation and converted from US dollars into euro (using an exchange rate of 1/1.2). For 2020 the estimations rely on observed prices in the EU ETS spot market throughout the year (average of €24.58).

Box 6

AnaCredit and modelling of credit risk parameters

AnaCredit (analytical credit datasets)[88] can support models that map climate stress test scenarios to banks' credit risk parameters. A significant number of lenders in the euro area report information on credit losses over time, facilitating the estimation of models like the loss given default (LGD) model described below.

LGDs derived from AnaCredit can be linked to a set of macro-variables, and sector and firm-level variables. First, instrument-level LGDs on unsecured exposures are derived as a ratio of accumulated write-offs to the sum of accumulated write-offs and cumulated recoveries since default for all instruments derecognised from the balance sheet, i.e. fully written off or sold.[89] The

[88] AnaCredit includes detailed information on individual bank loans in the euro area. It uses and harmonises data from national credit registers.

[89] A more common approach to modelling LGDs relies on market price-inferred data. A crucial advantage of the market-based models (which are often built on the structural approach proposed by Merton (1978)) is that they do not require access to granular loss data that are primarily in the possession of individual institutions extending the credit.

instrument-level LGDs are then regressed on country-level macro-financial variables and energy prices (see Table A).

Table A

Pilot LGD model regression estimates

Model specification	(1)	(2)
Macro-financial variables		
EQUITY (1Y LAG)	1.4770*** (0.1920)	1.4665*** (0.1898)
EQUITY (2Y LAG)	3.4481*** (0.0998)	3.2281*** (0.1028)
H. PRICE (1Y LAG)	-4.9931*** (0.4501)	-4.3410*** (0.4609)
H. PRICE (2Y LAG)	7.6783*** (0.5464)	7.1359*** (0.5540)
Debtor-specific variables		
N. EMPLOYEES	0. 0002*** (0.0005)	0.003*** (0.0005)
Climate-related financial variables		
ENERGY P	1.2493*** (0.1167)	1.2980*** (0.1188)
ENERGY P x USE	0.4373*** (0.0898)	
ENERGY P x H_USE_SEC		0.6283*** (0.0025)
Country fixed effects	Yes	Yes
Sector fixed effects	No	Yes
Observations	67,663	67,663

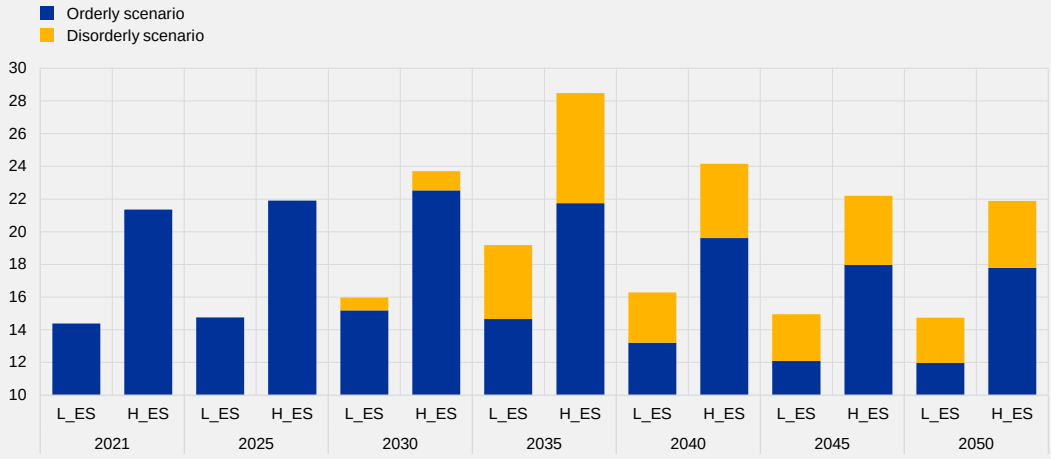
Source: ECB calculations.
*Notes: Regression estimates fractional response model (Papke and Wooldridge (1996); Wooldridge (2010)) with robust standard errors using data for the years 2012 2020 for 29,123 individual debtors from 13 EU countries (AT, DE, EE, ES, FI, FR, GR, IE, IT, MT, NL, PT and SK). The dependent variable represents the LGD estimate derived from the AnaCredit dataset. The explanatory control variables include 1 year and 2 year lagged values of country equity and house-price indices. The number of employees of a debtor serves as a proxy for firm size. The index of energy price consists of an average of gas and electricity price indices, deflated with a GDP deflator. It is included directly and in the form of interaction with energy use. Energy use is measured in terajoules and is provided on NACE level 2. In the alternative version of the model, energy use is included as a dummy variable that takes the value of one for sectors in the 4th quartile of energy use distribution on a country level. Macro-financial variables are sourced from the ECB Statistical Data Warehouse and energy variables from Eurostat. *, **, and *** denote significance at the 10%, 5% and 1% levels, respectively. Robust standard errors are reported in brackets.*

LGDs are countercyclical but generally increase with a rise in energy prices. This effect is stronger for high-energy use sectors, which is highlighted by the positive sign of coefficient of interaction term between an increase in energy prices and use of energy by sector. In addition, the positive sign of the coefficients for the variables associated with the financial cycle (equity and two-year lag of house prices) supports countercyclical behaviour of the LGD estimates.

Applying the model parameters to NGFS scenarios reveals that sectors with high-energy use are more strongly affected under the orderly and disorderly scenarios. Chart A illustrates the evolution of LGDs under the two NGFS scenarios. The difference in the impact on LGD for high-energy use and low-energy use sectors peaks in 2035 for both scenarios. It amounts to approximately 7 and 9 percentage points for the orderly and disorderly scenarios respectively.

Chart A

Impact of change in energy price on LGDs under the orderly and disorderly NGFS scenarios for low-energy and high-energy sectors



Source: ECB calculations.

AnaCredit can support the evaluation of physical risk along with transition risks. To this end, AnaCredit allows collateral value to be tracked over time and as such can be used to track the impact of physical risk shocks on collateral in the form of real estate. Although not presented, analogous to unsecured LGDs estimation, the regressions of collateral values that feed into LGDs for secured exposures can be linked to a range of macroeconomic and climate-relevant variables.

8 Forward-looking scenario analysis of the European financial system

Three forward-looking scenario analyses apply NGFS scenarios to the banking, insurance and investment fund sectors respectively. The NGFS orderly transition scenario serves as a reference baseline scenario in which financial markets gradually price in climate risks, the creditworthiness of borrowers remains stable, and physical damages are insurable. For the banking sector only, the report uses, as a starting point, banks' balance sheets as a reference for calculating bank losses. Both disorderly transition and "hot house world" scenarios feature increased financial stability risks. Climate risks are not fully reflected in asset prices and their ensuing realisation will have an unfavourable impact on asset quality, equity or corporate bond prices. Table 5 summarises the main characteristics of the three analyses.

The scenario analyses are run in a top-down fashion and focus on assets of financial institutions, even if they emphasise slightly different sector-specific channels. The assessment for the banking sector concentrates on banks' banking books and stresses the impact of transition and physical risks on credit risk. The assessment for the insurance and investment fund sectors focuses on the impact of transition risks on market risk (revaluation of mark-to-market assets). The differing accents in the three exercises are reflected in the choice of horizon, with the analysis for the banking sector applying credit risk parameters for 2050 (after 30 years), and the analysis for insurance and investment funds for 2035 (after 15 years). Finally, all analyses rely on a conservative assumption of a constant balance sheet, with no adjustments in the size and the composition of assets of financial intermediaries.

Table 5

Main characteristics of the three scenario analyses

	Banking sector	Insurance sector	Investment funds
NGFS scenarios	Disorderly Hot house world	Disorderly compared with orderly (baseline)	Disorderly compared with orderly (baseline)
Horizon	30 years	15 years (data as at 2035)	15 years (data as at 2035)
Alternative scenarios		IEA-based sustainable development scenario	DNB policy scenario
Sample	26 volunteer EU banks participating in the European Banking Authority (EBA) pilot exercise[90]	1,569 EEA (excluding the United Kingdom) domiciled insurance companies on a solo basis	23,332 (of which 18,513 UCITS, 1,555 AIFs and others not classified) (€8 trillion investment holdings[91])
Financial exposures	Non-SME exposures to non-financial obligors domiciled in EU countries	Equity, corporate debt (excluding covered bonds)[92] to climate-sensitive sectors (power, fossil fuels, transport, manufacturing)	Equity, corporate debt exposures to 21,107 unique NFCs
Value of exposures	€1.45 trillion of exposures value	€1.3 trillion direct and €0.9 trillion indirect (via collective investments undertakings)	€4.3 trillion direct (3.2 million positions) and €0.7 trillion indirect (12 million positions) (via equity holdings in other funds)
Starting point	End-2019	End-2019	End-2019
Transmission channels	Credit risk via change in PD and LGD	Asset price revaluation (equity and corporate bond prices)	Asset price revaluation (equity and corporate bond prices)
Type of climate-related risk considered	Transition and physical	Transition	Transition
Relevant information	Data collected in the EBA pilot exercise as at end-2019 (at the level of obligor) PDs from ECB's top-down stress test exercise (2021)	Regulatory reporting under Solvency II.[93] Detailed technology and production level data level data via 2° Investing Initiative (PACTA)	Morningstar, Refinitiv, ESMA

Exposures to the corporate sector are at the heart of the analysis, although the exact counterparty coverage depends on data and methodological constraints. The exercise for the banking sector focuses on direct bank exposures to the non-SME corporate sector. The exercise for the insurance sector looks at equity and debt exposures to selected segments of the corporate

90 The original sample included 29 banks. Of these, six banks are headquartered in Germany, five in Spain, four in the Netherlands, three in France, two in Finland, with the remaining ones in Austria, Denmark, Ireland and Italy. Three banks were excluded from the scenario analysis owing to insufficient information about their 2019 exposures. Please see: **EBA publishes results of EU-wide pilot exercise on climate risk**.

91 The €8 trillion of these funds' assets compares with roughly €15.7 trillion of net assets among EU UCITS and AIFs at the end of the first quarter of 2020 (EFAMA (2020)).

92 The full list of complementary identification codes (CICs) included is as follows: 21, 22, 25, 28, 34, 41, 42 and 44.

93 EIOPA's regulatory database including 1,894 undertakings reporting on a solo basis.

sector that are most exposed to climate-related hazards. These include the production of power, oil and gas, coal, steel, cement, aviation, and automotive industries, but exclude two other energy-intensive sectors, namely agriculture and real estate. The exercise for the investment funds has the broadest coverage and encompasses all equity and debt asset holdings to the corporate sector, although it is limited by the impossibility of mapping the full portfolio of assets.

The measurement of sectoral exposures for the insurance and investment funds sector also involves indirect or "look-through" exposures. This involves unpacking the investment network, i.e. insurance shares in collective investment undertakings,[94] and investment funds' shares in other funds, with the downstream assets held by that counterparty.

An important consideration is that sample representativeness for the EU differs for banking, insurance and investment funds. The banking sector exercise relies on very granular loan-level information on bank exposures, but only for a limited number of institutions. The sample of insurers and investment funds exercise covers, instead, a substantial share of institutions in the respective sectors.

In recognition of the fact that climate-related scenario analysis is still a "learning exercise", two out of the three analyses employ additional transition scenarios. For insurance companies, this is the sustainable development scenario, referred to as a "2°C scenario" developed using the PACTA methodology of the 2° Investing Initiative.[95] For investment funds, an alternative transition scenario is the DNB policy scenario and has already been applied to the banking and insurance sectors by the ESRB (2020). As shown in Box 7, these scenarios differ not only in terms of narrative, but also in terms of horizon and shock distribution over time.

Box 7
Alternative climate-risk macrofinancial scenarios

Several macro-financial scenarios were developed in support of climate-related scenario analysis ahead of the publication of the NGFS scenarios. As early as 2018 DNB developed four relevant transition scenarios (Vermeulen et al. (2018)). These scenarios concentrate on a shorter-term five-year horizon and emphasise transition risks taking the form of a sudden policy adjustment, asymmetric technological shock and uncertainty. The climate-relevant scenarios of the International Energy Agency (IEA) (2020) have a horizon up to 30 years and centre around transition risks relating to technological progress in energy production and emissions targets. They build on a large-scale World Energy Model designed to replicate world energy markets (i.e. energy consumption, energy transformation and energy supply) and the environmental impact of energy use.

Table A compares all of the scenarios employed in the forward-looking scenario analysis. The DNB's transition policy shock scenario is formulated as the deviation from a business-as-usual (or any other relevant) baseline and reflects the consequences of a belated policy action, being close, in terms of narrative, to the NGFS disorderly transition scenario. The IEA's sustainable

[94] "Look through" was possible for about half of the insurers' investments in CIUs.

[95] For further details, see EIOPA (2020b).

development scenario considers the sustainable reduction of air pollution and effective policies to combat climate change.

Table A

Comparison of the NGFS scenarios with the climate-relevant scenarios of the DNB and PACTA (IEA-based)

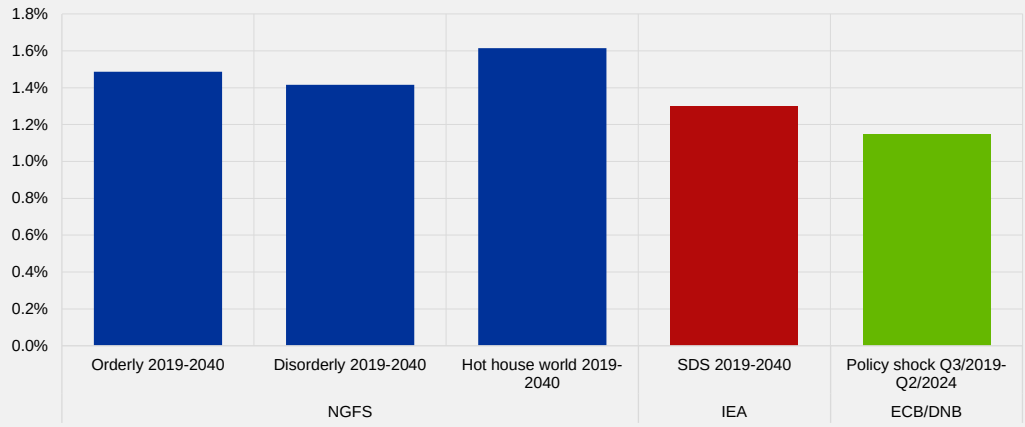
Source	NGFS	DNB	PACTA/IEA
Scope	Transition and physical	Transition	Transition
Selected scenarios	Disorderly transition Hot house world	Policy shock	Sustainable Development Scenario
Horizon	30 years	5 years	Variable
Modelling	IAM	NiGEM	PACTA framework IEA's World Energy Model (WEM).

Various ambitions, timelines and distinct underlying methodologies give rise to differences in scenarios' adversity. Chart A shows the average annualised EU GDP growth rate under the NGFS scenarios, compared with the IEA SDS scenario and the DNB policy shock scenario. The average annualised output growth is generally higher in the NGFS scenarios than in the IEA and DNB ones. This shows the nature of the NGFS scenarios as representing expected longer-term outcomes under varying assumptions about technological and policy developments, where scenario adversity – if present – is spread over time. The DNB policy shock scenarios, in particular, are far closer to standard stress testing scenarios as they emphasise plausible but still tail events.

Chart A

Comparing EU GDP growth under alternative scenarios

(average real GDP growth in percentages by scenario)



Sources: NGFS, IEA World Energy Outlook (2020), ESRB (2020) and ECB (2020).
Note: The time period was chosen to make GDP growth under different scenarios comparable over time.

8.1 Banking sector

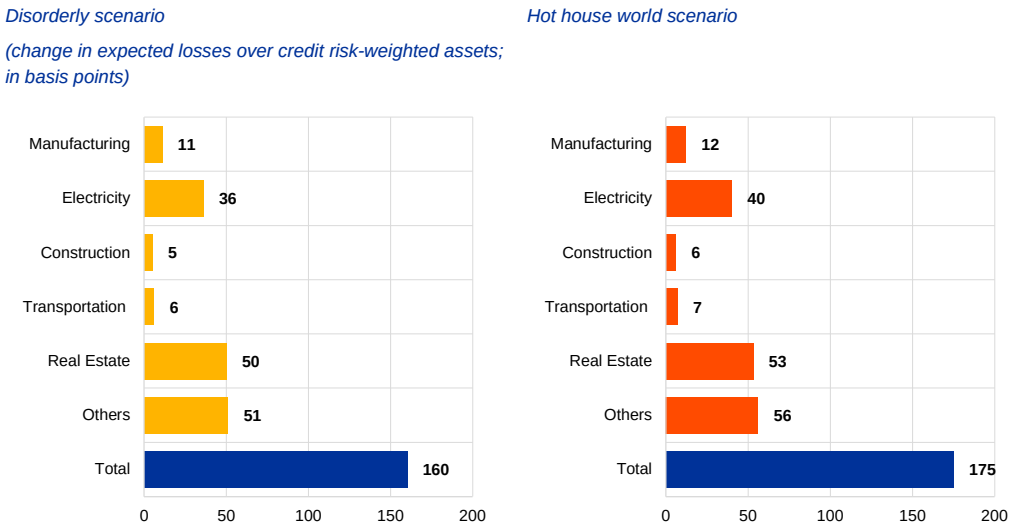
The banking sector scenario analysis combines the results of the EBA's 2020 pilot exercise (EBA (2021)) with credit risk parameters from the upcoming top-down ECB climate stress test. Corporate sector default probabilities are derived on NACE level 4 along with the methodology applied in the ECB's top-down stress test (see Annex 2 "Detailed look at existing methodologies: Handbook", H.1.3), while loss given default (LGD) parameters are derived using the methodology applied in the ECB/DNB pilot stress test 2020 (see Annex 2 "Detailed look at existing methodologies: Handbook", H.1.5). The impact of the climate scenarios on banks' balance sheets is computed as a change in expected loss (i.e. the product of PD, LGD and exposure value) as measured in 2050 compared with the starting point in 2019.

Both the disorderly and hot house world scenarios increase bank credit losses. Chart 19 reports EU weighted average losses (changes in loan-loss provisioning) by scenario and including the breakdown by sector of exposure. Losses are expressed as a ratio to the relevant risk-weighted amounts. At EU level the expected loss under the disorderly scenario is 1.60% of risk-weighted exposures to the non-SME corporate sector, and even higher under the hot house world scenario, at 1.75%.[96] Bank losses concentrate in certain sectors only – in particular electricity and real estate together account for over half of the impact.

[96] In order to put these numbers into perspective, the expected loss on non-SME exposures of SSM banks expressed as a ratio to risk-weighted amounts was -3.6% in the 2018 EBA/SSM stress test.

Chart 19

Bank credit losses including contributions to the overall impact by sector under the disorderly scenario (left panel) and the hot house world scenario (right panel)



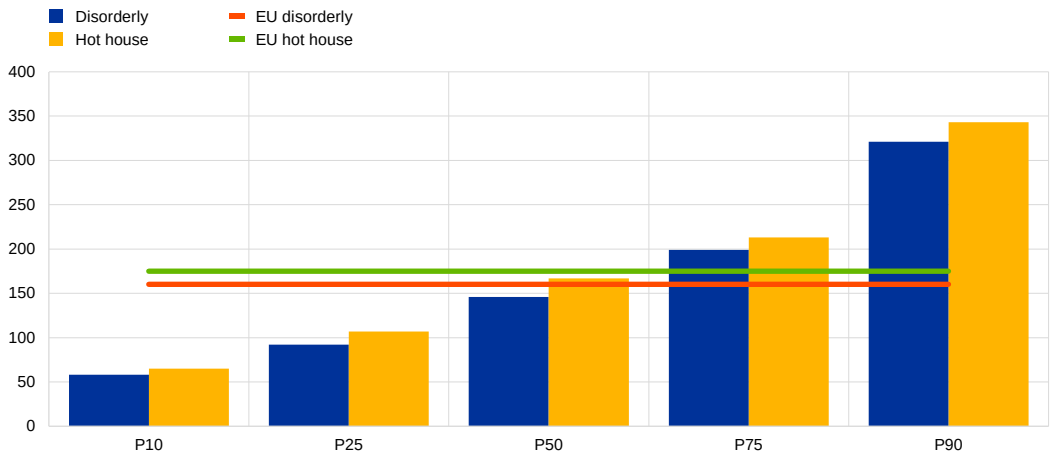
Source: ECB calculations.

The impact of the hot house world scenario is consistently more negative than that of the disorderly scenario across banks. Chart 20 shows the distribution of expected loss across selected percentiles of banks' distribution. Differences in individual banks' loan portfolios are reflected in a heterogeneous impact of both scenarios on their losses, ranging from 0.6 percentage points to 3.2 percentage points in the disorderly scenario, and 0.7 percentage points to 3.4 percentage points in the hot house world scenario.

Chart 20

Banks distribution by scenario

(expected losses over credit risk-weighted amounts in basis points)



Source: ECB calculations.

8.2 Insurance sector

The insurance sector scenario analysis relies on the analysis carried out by EIOPA in collaboration with 2° Investing Initiative (2DII).[97] Insurers' holdings of equity and corporate bonds are mapped to climate-relevant sectors, such as fossil fuel extraction, cement and steel production, and power generation. Potential price adjustments and changes in the production levels for each technology (for example coal power, oil power or renewable power) were estimated and translated into changes in equity prices using the PACTA methodology (see Annex 2 "Detailed look at existing methodologies: Handbook", H.2.3).[98] These equity price changes were subsequently re-calibrated to the NGFS scenarios[99] and used to inform the calibration of changes in corporate bonds.[100]

Revaluation losses on corporate bonds and equity investments in climate-sensitive sectors under the disorderly NGFS-based scenario are about 5.1 percentage points (see Chart 21). The largest impact comes from equity holdings with a decline of 15% in the value of re-priced assets, particularly in the oil production sector. The impact on corporate bond holdings is lower, in line with the methodological assumption that changes in sector-level profitability triggered by scenarios are likely to impact equity prices first and in a more substantial manner. The reference impact under the IEA-based sustainable development scenario was 6%.

97 See EIOPA (2020b) "**Sensitivity analysis of climate-change related transition risks**" for a detailed description.

98 The PACTA toolbox and methodology referenced in the "Handbook" in Annex 2 has been used to derive price changes for the power, oil and gas, coal and automotive sectors. Price adjustments in the aviation, cement and steel sectors are based on the shocks employed by the Bank of England (Prudential Regulation Authority (2019)).

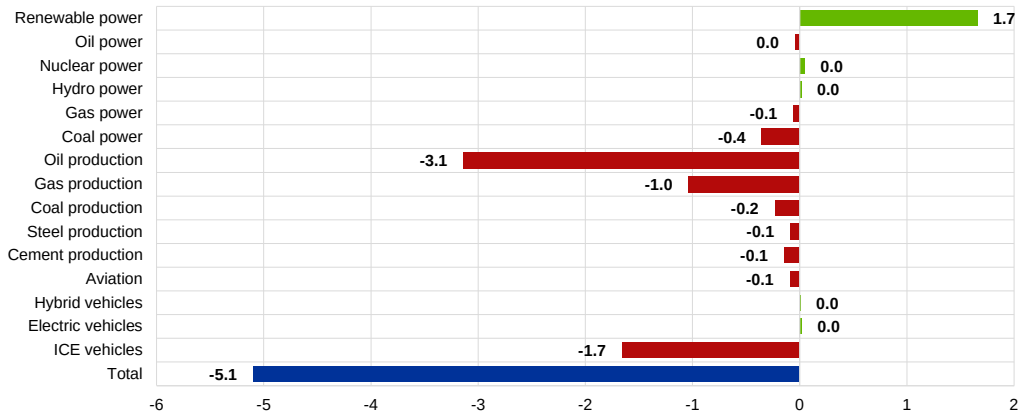
99 Consistent application of NGFS and IEA-based scenarios in PACTA requires a cross-methodology mapping of sectors. In particular, "Oil and coal" production is considered as "Manufacture of coke and refined petroleum products", gas production as "Mining and quarrying" which includes the extraction of natural gas, cement production as "Manufacture of other non-metallic mineral products" and steel production is mapped to "Manufacture of basic metals". For the energy sector, the NGFS application does not provide details on the source of energy produced. Accordingly, NGFS-based shocks for "Electricity production" are mapped to the technologies identified in the PACTA-based sensitivity analysis (coal, hydro, nuclear, oil and renewables) by assuming that the difference-to-mean shock is the same as that found in the sensitivity analysis. For the transport sector (automotive, aviation, shipping), the NGFS-based implementation does not provide sufficient detail to split by type of technology (i.e. a split between electric and ICE vehicles). Taking advantage of the fact that, overall, the NGFS-adapted scenario has about 3/5 of the impact under PACTA-based scenarios, price adjustments under NGFS scenarios are derived with a correction factor of 2/5.

100 Changes in corporate bond prices are derived as a fraction of changes in equity prices using a constant multiplier (15%). This simplification follows the approach of the Bank of England (Prudential Regulation Authority (2019)) and reflects the lack of available models which would be able to more accurately capture the impact of scenarios on corporate bonds. Government bond holdings were treated in the initial analysis following the approach by Battiston et al. (2019) and are discussed in the Handbook H.2.4.

Chart 21

Cumulative change in the value of re-priced equity and corporate bonds (including look-through where possible) including contributions to the overall impact by sector under the disorderly scenario

(percentages)



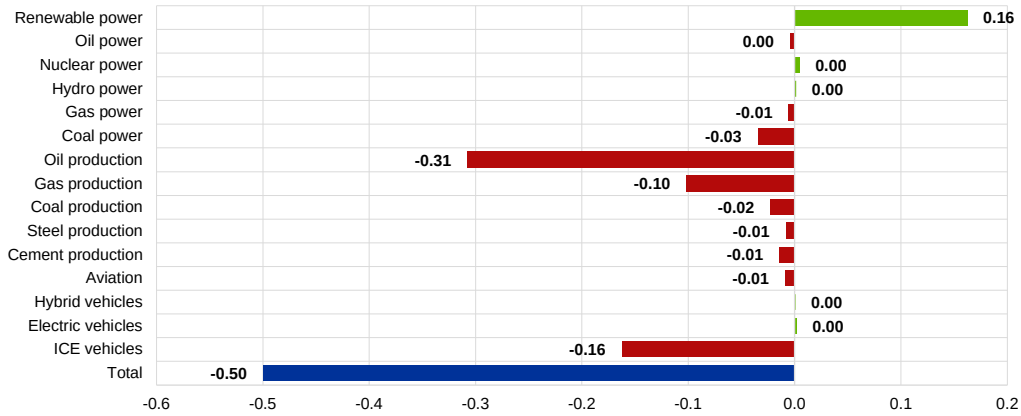
Source: Solo insurance undertakings reporting under Solvency II for the fourth quarter of 2019. Sector-definition based on the PACTA toolset. The NGFS-based scenarios are adapted as described in this report.

The resulting impact on the aggregate asset portfolio appears modest reflecting the low share of high-carbon investments in total assets of European insurers. Chart 8.4 shows the change in the value of investments as a share of all relevant asset holdings (i.e. not only those assets that were subject to price change). The impact is estimated to generate negative valuation changes of less than 1% of the corporate bond, equity and fund holdings. The moderate impact reflects the fact that Solvency II is a risk-based regime, and insurers generally hold well-diversified portfolios.

Chart 22

Cumulative change in the value of re-priced equity and corporate bonds as a share of all assessed equity and corporate bonds including contributions to the overall impact by sector under the disorderly scenario

(percentages)



Source: Solo insurance undertakings reporting under Solvency II for the fourth quarter of 2019. Sector-definition based on the PACTA toolset. The NGFS-based scenarios are adapted as described in this report.

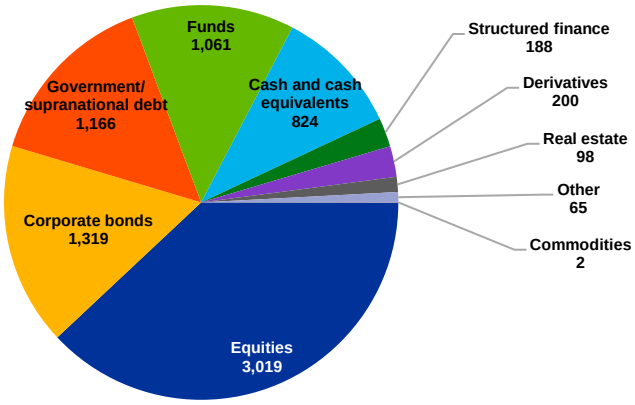
8.3 Investment funds

The scenario analysis focuses on equity and corporate holdings which jointly make up over 60% of all investment fund assets (Chart 23). The largest investment positions held by funds are equities (approximately €3 trillion), and corporate bonds (approximately €1.3 trillion), which are spread over 21,107 unique companies (located anywhere in the world). Holdings of shares issued by other investment funds (either UCITS or AIFs) make up the fourth largest asset class by value (approximately €1.1 trillion, spread out over 12,290 funds).

Chart 23

Portfolio holdings

(left panel: number of investments; right panel: EUR billions)



Sources: Morningstar, Refinitiv and ESMA.
Notes: "Cash and cash equivalents" comprises commercial paper, time deposits, certificates of deposit, and cash set aside to offset forwards, options, repurchase agreements, swaps, or futures. "Derivatives" comprises futures, forwards, swaps, options, and contracts for difference. "Other" comprises bank loans, infrastructure assets, "Other assets and liabilities" and "Undefined".

The impact of a scenario on asset valuation is derived at sector and region level. First, the latest available issuer information for the equity and corporate bonds is matched with issuer characteristics, including its economic sector at NACE level 4 and CO2 emissions.[101] The regions are the EU, the United States and the rest of the world. For equity exposures, the valuation change for each NACE sector[102] and geography compared with the orderly scenario has been applied to the corresponding equity holding within each fund portfolio. For corporate bond exposures, the Global Industry Classification Standard (GICS) sector and geography-specific impact of the disorderly scenario on corporate bond spreads (relative to the orderly scenario corporate bond spreads) has been applied to each bond holding within each fund's portfolio, by multiplying the relative spread impact (disorderly compared with the orderly scenario) by the bond effective duration calculated at the time of the portfolio valuation date (see Annex 2 "Detailed look at existing methodologies: Handbook", H. 2.2).

[101] CO2 emissions include both direct emissions and emissions arising from the generation of energy purchased by the firm and are defined as total CO2 or CO2 equivalent emissions.

[102] NACE sectors are subsequently mapped to GICS sectors to allow consistency in terms of sector contributions results as presented further in this section.

The impacts of the NGFS scenarios are summarised in Chart 24.[103] The average asset write-down under the disorderly scenario is 1.2%, amounting to €62 billion worth of losses, or 1.3% of asset fund assets. For comparison, under the DNB's policy shock scenario, asset write-downs are 5.2%, or €242 billion, or 4.9% of asset fund assets.

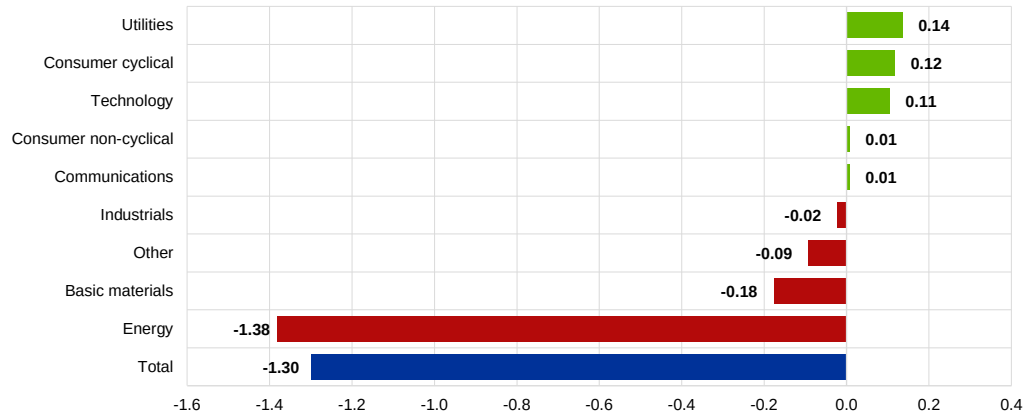
The overwhelming majority of losses among the fund universe are driven by investments in energy producers. The sectors, ranked in terms of contribution (highest first), are displayed in Chart 24 below, using the GICS classification. High losses on investments in energy producers are followed by holdings of equities and bonds issued by manufacturers of basic materials, such as chemicals, plastics and metals, as well as forestry and logging. A few sectors experience increases in valuations of equities and corporate bonds (this also offsets the impact of the losses of energy sector assets, which exceed total system-wide losses). These include technology, consumer cyclical (for example retail, hospitality, and textiles manufacturing) and utilities that supply the energy produced by the energy sector.

[103] The DNB policy and tech shock scenarios employed cover a time horizon of five years, which is short from the perspective of long-term climate change risks. As a result, the scenarios ignore second-round effects in terms of the interplay between energy transition risks and climate change. Nevertheless, the shorter time horizon works well from the perspective of investment fund assets, which are relatively shorter term, in contrast to longer-term exposures like bank loans or life insurance policies. The horizon is also long enough to allow an abstraction from the more typical concerns faced when simulating stressful situations for investment funds, including liability-side measures such as lock-out periods and other liquidity management tools (ESMA (2019)). These scenarios are sector specific and cover 88 individual NACE sectors (56 unique sectors). Asset write-downs for equity and corporate bond instruments can be assessed by linking macroeconomic conditions based on their exposure to carbon prices (via CO2 emissions). Therefore, the magnitude of the asset valuation impact varies depending on the economic sector in which a company is operating (i.e. depending on that sector's exposure to the respective type of climate risk being modelled). Indeed, the sectors most affected by the abrupt policy adjustment (electricity, gas and steam production) are different to those that are worst hit by asymmetric technological change (mining and quarrying, and certain manufacturing activities). Moreover, certain manufacturing sectors would actually observe improving equity valuations (up to 22%).

Chart 24

Investment fund losses including contributions to the overall impact by sector under the disorderly scenario

(percentage of funds' assets)



Sources: ESRB (2020), Vermeulen et al. (2018), Morningstar, Refinitiv and ESMA.
Notes: Application of energy transition risk asset valuation scenarios to EU fund equity, corporate bond, and fund-to-fund holdings, based on the NGFS Phase 1 "Disorderly" scenario developed by NGFS (2020a; 2020b), and adapted to financial markets by Allen et al. (2020) and Devulder and Lisack (2020). Each row shows the contribution of each GICS economic sector to system-wide losses, as a percentage of total system assets included in the scenario exercise (equities, corporate bonds and shares issued by other investment funds), for funds holding assets issued by firms in that GICS sector. Indirect holdings are also included, i.e. losses on fund investments in other funds that are exposed to markdowns in asset values are recorded. The United Kingdom and the Channel Islands are included in this sample.

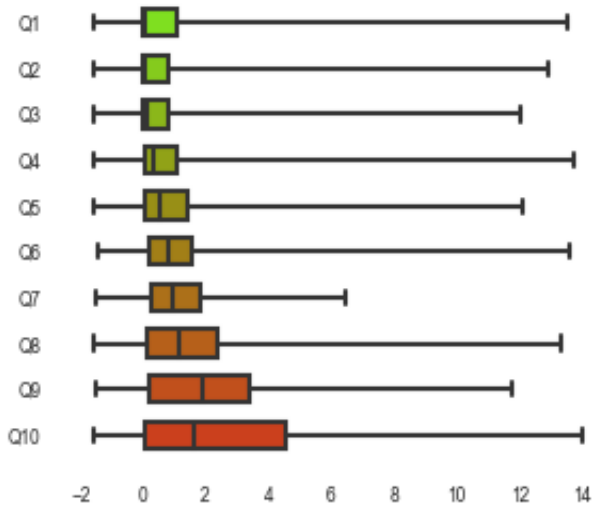
Elsewhere, percentage losses relative to total assets can vary significantly across investment funds. Furthermore, since the economic sector-specific stress impacts are calibrated according to the CO2 emissions embodied in that industry, a fund with relatively greater exposure to polluting industries suffers greater losses than a relatively less exposed fund, all other things being equal.

Chart 25 shows the distribution of losses across funds under the disorderly scenario. Investment funds have been grouped into deciles, based on each fund's average emissions per investment, weighted by the value of each investment position in each fund's portfolio. Funds in the lowest decile in terms of emissions are denoted as Q1 and are coloured green; funds in the highest decile are denoted as Q10 and coloured red/brown.

Chart 25

Losses under the NGFS disorderly scenario as a percentage of portfolio assets, by decile of CO2 equivalent emissions per investment in portfolio

(x-axis: losses under NGFS Phase 1 scenario as a percentage of portfolio assets included in the exercise; y-axis: fund quantile in terms of weighted average emissions in the portfolio)



Sources: Vermeulen et al. (2018), Morningstar, Refinitiv and ESMA.
Notes: Application of energy transition risk asset valuation scenarios to EU fund equity and corporate bond holdings, based on the NGFS Phase 1 "Disorderly" scenario developed by NGFS (2020a; 2020b) and adapted to financial markets by Allen et al. (2020) and Devulder and Lisack (2020). Each set of distributions displays the range in losses, as a percentage of total portfolio holdings of equities, corporate bonds and shares issued by other investment funds, for funds within the respective quantile (quantiles determined based on each fund's average emissions per investment, weighted by the value of each investment position) across funds recorded as domiciled in Europe. Emissions are recorded as CO2 and CO2 equivalent emissions (scopes 1 and 2). The vertical black line in each box shows the median percentage loss for funds in that emissions quantile. Box edges are the 25th and 75th percentiles of the fund losses for funds in that emissions quantile, and additional lines ("whiskers") illustrate the percentage losses that are either below the 25th or above the 75th percentiles for funds in that emissions quantile, reaching to the 1st and 99th percentiles. Indirect holdings are also included, i.e. losses on fund investments in other funds that are exposed to markdowns in asset values are recorded. Note that the United Kingdom and the Channel Islands are included in this sample.

8.4 Early conclusions

The three forward-looking scenario analyses comprise the first comprehensive application of NGFS scenarios to the European financial sector. This allows initial conclusions on the resilience of European financial institutions to transition risk and, to a lesser degree, to physical risk to be drawn. The exercises also uncover new challenges associated with the forward-looking climate scenario whereby financial stability risks unfold only gradually and over an extended time frame, in contrast with the abrupt materialisation of risks incorporated in most stress-test scenarios.

No or belated transition as reflected in the "hot house world" and the disorderly transition scenarios respectively leads to higher loan defaults and asset valuation losses. These findings are echoed by the partial analyses in Annex 2 "Detailed look at existing methodologies: Handbook", which find consistently that the disorderly transition scenario implies higher credit losses compared with the orderly transition scenario.

Furthermore, the disorderly and hot house world scenarios uncover a high concentration of climate risks in selected portfolios of European financial institutions. The aggregate difference between disorderly and orderly scenarios for measures of banks' solvency and losses of insurers and investment funds appear contained. However, it hides a significant concentration of losses in selected economic sectors which is consistent across banks, insurers and investment funds. For banks these consist of loan exposures to electricity and real estate. For insurers, the most sensitive assets appear to be equity holdings related to the production of oil, gas and vehicles and, for investment funds, holdings of assets related to energy sectors and basic materials.

It is worth noting the likelihood that the estimates only represent the lower bound for climate-related losses in the financial system. First, the scenario analysis does not cover all exposures of the financial system and accordingly transmission channels. For example, the scenario analysis for the banking system excludes stress testing of trading books or exposures to household sector; for insurers it abstracts from the impact of scenarios on their liability side; and for investment funds it excludes indirect losses from EU fund holdings of non-EU funds, which themselves invest in EU equities and corporate bonds (also the constituents of certain exchange-traded funds and other benchmarks that are popular with investment funds are not included in the dataset). Second, financial amplification channels such as portfolio rebalancing, the feedback loop with the real economy (see the pilot scenario analysis of the banking sector in ESRB (2020)), fire sales or interconnectedness (see Box 8) are largely missing in the analyses. This notwithstanding, some relevant layers are missing in the analysis which could also diminish the impact of climate risks, for instance substitution effects and dynamic adjustments in firms' behaviour.

The long-term nature of climate-related scenarios burdens the estimates with intense uncertainty and opens new modelling demands. For instance, the constant balance sheet perspective is not best suited to scenario analysis spanning over 30-year horizons. The assessment of climate risks requires further development of the stress testing and scenario analysis methods which could include the dynamic response of financial institutions, and potentially of the corporate sector, to adverse climate-related shocks. More explicit focus could be placed on the role of financial intermediaries in financing green innovation.

These new modelling challenges add to a more general call for increased data quality and coverage. For instance, for transition risks the open challenge is ensuring a broader coverage of verified firm-level GHG emissions, especially for smaller and non-listed firms. For physical risks it is to increase the availability of granular data on the geographical location of firms' assets and mapping of physical risk indicators into data on historical damage realisations. Provided that the remaining methodological challenges can be overcome, climate stress testing may become a useful tool to inform policy decisions by prudential authorities (see Box 9 for an illustrative case study).

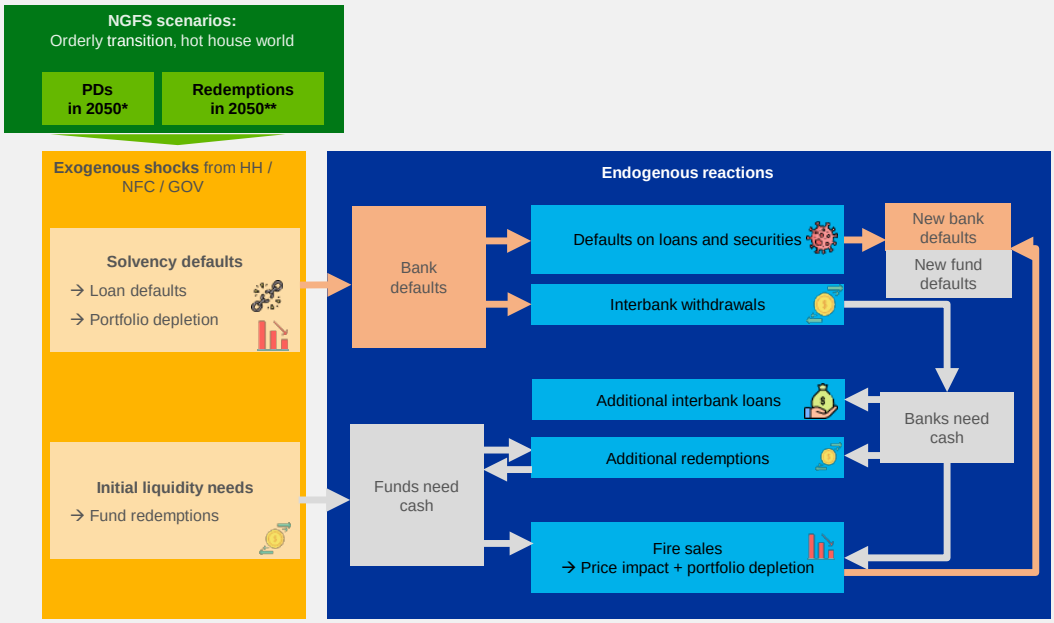
Box 8

Amplification of climate scenarios in an interconnected financial system of banks and investment funds

This box illustrates how climate risks may unfold in an interconnected financial system with banks and investment funds.[104] The basis of this analysis is a two-sector model that embeds a network of individual significant and less significant banks and open-ended investment funds, all of which are domiciled in the euro area.[105] Information on banks' banking book exposures is sourced from the supervisory reporting and combines counterparty-level detail for large exposures, and NACE 1 and country-level detail for remaining exposures.[106] Banks' trading book information is available on a securities level, as obtained from the securities holdings statistics (SHS-G). Fund-level information for the investment fund sector is based on commercial market data as collected in Lipper by Refinitiv.

Figure A

Climate risks, NGFS scenarios and their materialisation in the system-wide stress test model



*Notes: *: Output from ECB satellite models. For redemptions, see also Gourdel et al. (2019).*
ROA growth is growth of return on assets of NFCs. GICS sector is the sector according to the Global Industry Classification Standard.

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104 Such a modelling framework is particularly useful for central banks and supervisory bodies to help understand the amplification role of individual financial sectors jointly conditional on climate risk shocks. For a similar exercise, covering the Mexican financial system, see Roncoroni et al. (2021), "Climate Risk and Financial Stability in the Network of Banks and Investment Funds", Journal of Financial Stability, forthcoming.

105 For a detailed description of the modelling framework employed in this box, see Sydow et al. (2021), "Shock amplification in an interconnected financial system of banks and investment funds", ECB Working Paper, forthcoming.

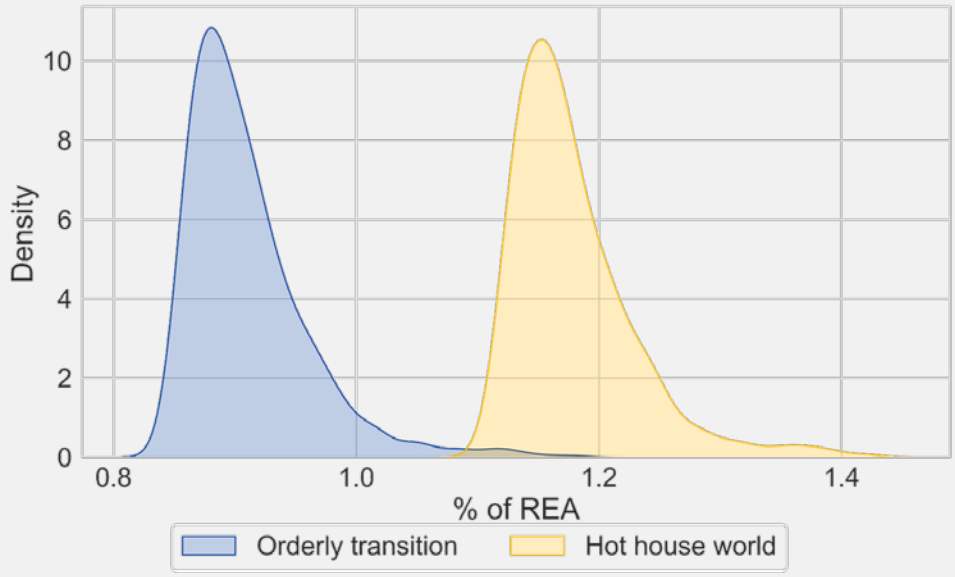
106 The share of granular large exposures to NFCs is 30% of total loans to NFCs.

The orderly transition and "hot house world" scenarios affect banks' balance sheets first via PDs on bank loan exposures and via fund redemptions (Figure A). PDs in 2050 are derived from the ECB top-down climate stress test explained in Section 8.1.1, used at country and NACE-2 sector-level. Projected fund redemptions for 2050 are driven by variables such as GDP, carbon emissions, carbon and energy prices and physical risk scores. At the same time, stock price changes[107] lead to asset price revaluations and, together with fund redemptions, trigger fire sales. In the model, shock transmission via the assets of individual entities entails credit risk losses through banks' banking books and revaluation losses through banks' and funds' securities holdings. These initial losses are further amplified through contagion effects owing to bank solvency defaults and indirect contagion via overlapping portfolios.

Second-round amplification effects generated by the two-sector model can lead to an additional decline of banks' CET1 ratios of 0.9 and more than 1.2 percentage points under the orderly transition and "hot house world" scenarios respectively (see Chart A). The difference in terms of magnitude between the two scenarios is driven by a different calibration, in terms of severity, of the market and redemption shocks under the two NGFS scenarios examined, with GDP developments as the main driver. Moreover, the second-round amplification losses, illustrated in this box, stem from endogenous reactions of banks and funds, where fire sales of common holdings of securities are the main driver, followed by redemptions of fund shares.

Chart A

Second-round amplification effects under the orderly transition and "hot house world" scenarios



Notes: Distribution of average CET1 capital depletion of banks across 1,000 Monte Carlo simulations. Simulations are generated using stochastic defaults of granular NFCs, which have either loans or securities issued in the portfolios of banks and investment funds. Losses are reported for two quarters in a forward-looking manner in 2050.

[107] Stock price changes are linked to the GDP development under the NGFS scenario applied in the model.

Box 9

Stress testing and impact assessment of the high-emitting penalizing factor

A high-emitting penalising factor, i.e. an increase in risk-weights for high-emitting assets, is one of policy options possibly accelerating the transition to a low-carbon economy. Relying on the European Commission's micro-simulation Systemic Model of Banking Originated Losses (SYMBOL), this box illustrates how stress-testing methods can support policy choices.[108] It employs the estimate of high-emitting assets, including debt securities, stocks and loans to non-monetary financial institutions, for a sample of 447 commercial, cooperative and savings banks. Such assets are defined as exposures to counterparties mainly active in the fossil fuel sector.[109]

The analysis is structured around four alternative policy paths. They differ in respect to capital risk charges for high-emitting assets: a baseline policy path, where high-emitting assets are considered no more risky than similar exposures to green counterparts, and three active policy paths where the riskiness of high-emitting assets is increased by 15%, 20% or 25%.[110] Figure A (left panel) shows the distribution of the increases in risk-weighted amounts (RWAs), aggregated at country level, in the active policy scenarios versus the baseline path. The average RWA increase varies from 0.5% to 1% depending on the scenario.

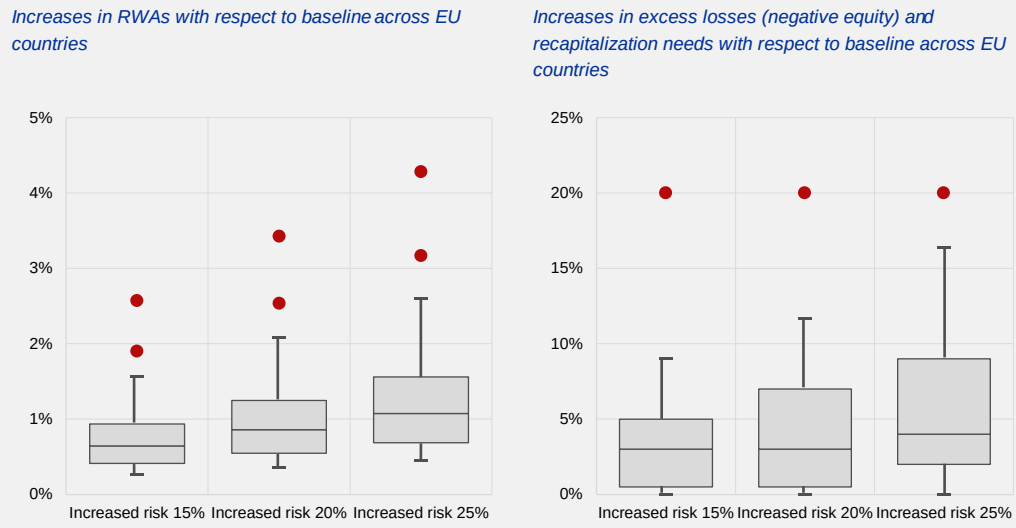
[108] This box is based on Alessi, L., Di Girolamo, F., Petracco-Giudici, M. and Pagano, A. (2021), *Accounting for climate transition risk in banks' capital requirements*, Joint Research Centre, European Commission, forthcoming.

[109] The initial shares of banks' non-green, high-emitting assets are calculated at country level using breakdowns of domestic and cross-border intra-euro area positions provided by the ECB. They are then increased by the amount of financing going to companies active in the utilities sector in proportion to the share of non-renewable and non-nuclear energy production by Member State. The allocation of bank exposures into the fossil fuel and utility sectors is based on Alessi et al. (2019), where ECB security-by-security confidential data is used and mapped into climate policy-relevant sectors (CPRS) following Battiston et al. (2017).

[110] Thomä and Gibhardt (2019) also test the 15-25% increase while Dafermos and Nikolaidi (2021) test a 25% increase.

Figure A

Increases in RWAs with respect to baseline across EU countries (left panel) and increases in excess losses (negative equity) and recapitalisation needs with respect to baseline across EU countries (right panel)



Source: ECB-JRC.

Bank outcomes are studied for each of the policy paths and under multiple alternative crisis scenarios.[111] The model simulates 100,000 banking crisis scenarios in which at least one bank needs to be recapitalised. It then tracks bank losses as losses that cannot be absorbed by capital (negative equity) and recapitalisations needed to bring the banks back to a viability status, i.e. a regulatory capital ratio at 10.5%. The focus is on the very tail of this distribution, i.e. on severe but plausible scenarios, that correspond to a drop in GDP larger than 2 standard deviations from the mean.

Looking at the EU banking sector as a whole, the transition risk that would be left uncovered by a high-emitting penalising factor could lead to an increase in bank losses of 3-4% at EU level.[112] The average losses in a crisis would increase from €127 to €133 billion, which corresponds to an increase of 4% (Figure A, right panel). At country level, results are quite heterogeneous, with some countries showing very mild (or almost zero) impact and others, where banks are particularly exposed to high-emitting activities, where losses increase by 15% or more.

111 De Lisa, R., Zedda, S., Vallascas, F., Campolongo, F., Marchesi, M. (2011), "Modelling Deposit Insurance Scheme Losses in a Basel II Framework", *Journal of Financial Services Research*, Vol. 40:3, pp. 123-141.

112 These figures are in line with those in Thomä and Gibhardt (2019).

9 Conclusions

This report outlines several advances made in filling analytical gaps, thereby providing a better foundation to quantify the risks to EU financial stability arising from climate-related drivers. The report notably fills two key analytical gaps specific to climate-related drivers: a comprehensive granular risk mapping with a broader coverage of both prospective physical and transition risk drivers, as well as long-horizon scenarios suitable for analysing the financial system trade-offs associated with temperature pathways. In particular, the report provides a new and comprehensive way of mapping physical risk to exposures of euro area financial institutions and enhances transition risk measurement by matching an enlarged emissions scope to nascent euro area-wide credit registers against the backdrop of a growing green financial market and the increasing role of non-bank financial intermediaries. Building on this exposure mapping, the report goes on to develop concrete, implementable scenarios for gauging both the potential for and time profile of system losses going forward, which are applied to long-horizon climate stress test analyses to determine banks' credit risk exposures, as well as the market risk exposures of insurers and investment funds. While still subject to uncertainties with regard to both the measurement and methodology, the results further sharpen a quantitative understanding of risks to EU financial stability – both in the cross-section and the time dimension.

This report finds that, on average, financial stability risks from climate change are both concentrated in sectors, geographies and firms and vary over the next decades given strongly path-dependent risks. With regard to climate risk measurement, the exposure mapping of physical risk drivers suggests that riverine flooding is the most widespread risk for EU financial institutions, although a coalescing of other natural hazards such as wildfires, heat and water stress could amplify that vulnerability in some regions. Such vulnerabilities would be borne, in particular, by weakly capitalised and/or less profitable banks – whilst also remaining concentrated at the bank level, with the majority of exposures in the portfolios of a few dozen banks. As for climate transition risk, an enlarged mapping to firms and banks reinforces earlier findings of limited, albeit concentrated, risks. Such credit exposures may be aggravated by the need for very large portfolio adjustments for investments by a broader spectrum of non-bank financial intermediaries. This market risk may come via a potentially sizeable repricing of climate-related risk, in particular given the absence to date of a clear and widespread financial pricing differential. With regard to climate risk assessment, this report presents forward-looking scenario analyses that build on the advances in terms of measurement. These suggest strong path dependence – that is that there are net benefits to be gained from timely and orderly macroeconomic climate policies to tackle climate-related risk, notably in the highest GHG-emitting sectors, which is a consistent finding across banks, insurers and investment funds. The material transition and physical risks to financial stability associated with climate change will clearly evolve depending on the extent of the inexorable rise in global temperatures, albeit governed by strong path dependence and hinging on the strength of mitigating policies and technological progress.

Notwithstanding the notable progress made in measuring and assessing the impacts of climate change on financial stability, much remains to be done. A high degree of measurement uncertainty continues to hamper a fully accurate assessment of granular exposures to climate risks – particularly at the regional and country level. In terms of data, the sufficiency of

reported information – including commonly agreed physical risk indicators, as well as transition risk indicators which accurately account for forward-looking commitments and downstream emissions intensity – remains a key issue, concerning both data availability and quality. For the moment, recourse to private data providers is essential to fill existing gaps. In time, ongoing official sector initiatives in Europe and in global standard-setting bodies alike to shore up disclosures, standards and taxonomies should go a long way in addressing outstanding issues. It will be essential to have consistent climate-related data, including ways to assess credible forward-looking Paris-alignment commitments, in order to develop efficient market mechanisms. As far as modelling is concerned, incorporating second-round effects, prospective non-linearities, value chain impacts and adaptation/risk mitigation measures would further enrich results. All in all, empirical advances to date have been laying the necessary foundations to inform nascent analysis on evidence-based policy – analysis which will benefit from continued momentum in the monitoring of climate-related risks to financial stability in the EU.

References

Alessi, L., Di Girolamo, F., Petracco-Giudici, M. and Pagano, A. (2021), "Accounting for climate transition risk in banks' capital requirements", European Commission – Joint Research Centre, forthcoming.

Alessi, L. et al. (2021), "What greenium matters in the stock market? The role of greenhouse gas emissions and environmental disclosures", *Journal of Financial Stability*, Vol. 54, June.

Alessi, L. et al. (2019), "The EU Sustainability Taxonomy: a Financial Impact Assessment", *JRC Technical Report*, European Commission.

Alestra, C., Cette, G., Chouard, V., Lecat, R. (2020), "Long-term growth impact of climate change and policies: the Advanced Climate Change Long-term (ACCL) scenario building model", *Working Paper Series,* No 759, Banque de France.

Allen, T. et al. (2020), "Climate-related scenarios for financial stability assessment: an application to France", *Working Paper Series*, No 774, Banque de France, July.

Antofie, T., Luoni, S., Eklund, L. and Marin Ferrer, M. (2020), *Update of Risk Data Hub software and data architecture*, Publications Office of the European Union, Luxembourg.

Autorité de Contrôle Prudentiel et de Résolution (2020), "**Scenarios and main assumptions of the ACPR pilot climate exercise**", Banque de France, July.

Baqaee, D.R. and Farhi, E. (2019), "The Macroeconomic Impact of Microeconomic Shocks: Beyond Hulten's Theorem", *Econometrica*, Vol. 87, Issue (4), pp. 1155-1203.

Bailey, A. (2020), "The time to push ahead on tackling climate change", speech at the Corporation of London Green Horizon Summit, Bank of England, London, 9 November.

Bank for International Settlements (2020), "A global sudden stop", editorial, *BIS Annual Economic Report*, Basel, Switzerland, June.

Bank of England (2019), "**Insurance stress test 2019**", 18 June.

Basel Committee on Banking Supervision (BCBS) (2021a), *Climate-related risk drivers and their transmission channels*, April.

Basel Committee on Banking Supervision (BCBS) (2021b), *Climate-related financial risks – measurement methodologies*, April.

Battiston, S. and Monasterolo, I. (2019), "A Climate Risk Assessment of Sovereign Bonds' Portfolio", *Working paper*.

Battiston, S. et al. (2019), "Climate risk assessment of the sovereign bond portfolio of European Insurers", *Financial Stability Report*, EIOPA, December, pp. 69-89.

Battiston, S., Mandel, A., Monasterolo, I., Schutze, F. and Visentin G. (2017), “A climate stress-test of the financial system”, *Nature Climate Change*, Vol. 7(4), pp. 283-288.

Belloni M., Kuik F., Mingarelli L. (2021), “Euro Area banks’ sensitivity to changes in carbon price”, ECB Working Paper (under review).

Berg, F. et al. (2019), “Aggregate confusion: The divergence of ESG ratings”, *MIT Sloan Working Paper*, 5822-19, May.

Bhattacharya, H. (2007), “Commodity derivatives market in India”, *Economic & Political Weekly*, Vol. 42, No 13.

Black, F., and Cox, J. (1976), “Valuing corporate securities: some effects of bond indenture provisions”, *The Journal of Finance*, 31(2), May.

Bolton, P. and Kacperczyk, M.T. (2021), “**Global pricing of carbon-transition risk**”.

Brainard, L. (2021), “Financial stability implications of climate change”, speech at the Ceres 2021 Conference, Boston, Massachusetts, 23 March.

Budnik, K. et al. (2020), “Banking euro area stress test model”, *Working Paper Series*, No 2469, ECB, September.

Capasso, G., Gianfrate, G. and Spinelli, M. (2020), “Climate change and credit risk”, *Journal of Cleaner Production*, Volume 266, September, 121634.

Dafermos, Y. and Nikolaidi, M. (2021) “How can green differentiated capital requirements affect climate risks? A dynamic macrofinancial analysis”, *Journal of Financial Stability*, forthcoming.

Daniëls, T., Duijm, P., Liedorp, F., and Mokas, D (2017), “A top-down stress testing framework for the Dutch banking sector”, *Occasional Studies*, Volume 15-3, De Nederlandsche Bank.

De Guindos, Luis (2021), “**Shining a light on climate risks: the ECB’s economy-wide climate stress test**”, *The ECB Blog*, 18 March.

De Lisa, R., Zedda, S., Vallascas, F., Campolongo, F. and Marchesi, M. (2011), “Modelling Deposit Insurance Scheme Losses in a Basel II Framework”, *Journal of Financial Services Research*, Vol. 40:3, pp. 123-141.

Devulder, A. and Lisack, N. (2020), “Carbon Tax in a Production Network: Propagation and Sectoral Incidence”, *Working Paper Series*, No 760, Banque de France, August.

Di Girolamo, F., Petracco-Giudici, M., Pagano, A. and Schoutens, W. (2021), “Climate physical risk: impact on insurers’ defaults and public finances”, European Commission – Joint Research Centre, forthcoming.

Ehlers, T.et al. (2020), “**Green bonds and carbon emissions: exploring the case for a rating system at the firm level**”, *BIS Quarterly review*, September.

ESRB (2020), *Positively green: measuring climate change risks to financial stability*, European Systemic Risk Board, June.

European Banking Authority (EBA) (2021), *Mapping climate risk: Main findings from the EU-wide pilot exercise*, May.

European Insurance and Occupational Pensions Authority (EIOPA) (2020a), "**Climate change stress tests**", Second discussion paper on methodological principles of insurance stress testing, European Insurance and Occupational Pensions Authority, June.

European Insurance and Occupational Pensions Authority (EIOPA) (2020b), "**Sensitivity analysis of climate-change related transition risks**", European Insurance and Occupational Pensions Authority, December.

European Insurance and Occupational Pensions Authority (EIOPA) (2020c), "The pilot dashboard on insurance protection gap for natural catastrophes", December.

European Insurance and Occupational Pensions Authority (EIOPA) (2019a), "**Institutions for Occupational Retirement Provision (IORPs) Stress Test Report**", European Insurance and Occupational Pensions Authority, December.

European Insurance and Occupational Pensions Authority (EIOPA) (2019b), "EIOPA Staff Discussion Paper Protection gap for natural catastrophes", European Insurance and Occupational Pensions Authority, September.

Fatica, S. and Panzica, R. (2020), "Green bonds as a tool against climate change?", *JRC Technical report*, European Commission.

Financial Stability Board (2020), *The implications of climate change for financial stability*, November.

Financial Stability Board (2021), *To G20 Finance Ministers and Central Bank Governors*, FSB Chair's letter to G20 Finance Ministers and Central Bank Governors, 24 February.

Gordon, M.J. (1959) "Dividends, Earnings, and Stock Prices", *The Review of Economics and Statistics*, 99-105.

Gourdel, R. et al. (2019), "Investment funds under stress", *Working Paper Series*, No 2323, ECB, October.

Hantzsche, A. et al. (2018), "Using NiGEM in uncertain times: Introduction and overview of NiGEM", *National Institute Economic Review*, Vol. 244, May.

Hebbink, G. et al. (2018), "The price of transition: an analysis of the economic implications of carbon taxing", *DNB Occasional Studies*, No 1608, De Nederlandsche Bank, Research Department.

Höck, A., Klein, C., Landau, A. and Zwergel, B. (2020), "The effect of environmental sustainability on credit risk", *Journal of Asset Management*, Vol. 21, pp. 85-93.

Intergovernmental Panel on Climate Change (IPCC) (2018), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, **IPCC Special Report**.

Intergovernmental Panel on Climate Change (IPCC) (2014a), "**Climate Change 2014: Impacts, Adaptation, and Vulnerability**", Part B: Regional Aspects: Europe, Chapter 23.

Intergovernmental Panel on Climate Change (IPCC) (2014b), "**Climate Change 2014: Impacts, Adaptation, and Vulnerability**", Part A: Global and Sectoral Aspects, Key Economic Sectors and Services, Chapter 10.

International Association of Insurance Supervisors (IAIS) (2018), "**Issues paper on climate change risks to the insurance sector**", July.

International Energy Agency (IEA) (2020), "World Energy Outlook 2020", October

International Monetary Fund (IMF) (2020a), "Mitigating climate change – growth and distribution-friendly strategies", *World Economic Outlook*, Chapter 3, October.

International Monetary Fund (IMF) (2020b), *Global Financial Stability Report*, Chapters 1 and 5, Washington DC, October.

Joint Research Centre (JRC) (2020), "**Climate change impacts and adaptation in Europe**", JRC PESETA IV final report, Feyen, L., Ciscar, J.C., Gosling, S., Ibarreta, D. and Soria A. (eds.), European Commission.

Joint Research Centre (JRC) (2020b), "**Adapting to rising river flood risk in the EU under climate change**", PESETA IV project – Task 5, Dottori, F., Mentachi, L., Bianchi, A., Alfieri, L. and Feyen, L., *JRC Technical Report*, European Commission.

Joint Research Centre (JRC) (2017), "**Global flood depth damage functions**", Huizinga, J., de Moel, H. and Szewczyk, W., *JRC Technical Report*, European Commission.

Lagarde, Christine (2021), "Climate change and central banking", keynote speech at the ILF conference on Green Banking and Green Central Banking, Frankfurt, 25 January.

Mahalingam, A. et al. (2018), *Impacts of Severe Natural Catastrophes on Financial Markets*, March.

Merton, R. (1973), "An intertemporal capital asset pricing model", *Econometrica*, 41 (5), September.

Mesonnier, J.-S. and Nguyen, B. (2020), "**Showing off cleaner hands: mandatory climate-related disclosure by financial institutions and the financing of fossil energy**", *Working Paper Series*, No 800, Banque de France.

Network for Greening the Financial System (NGFS) (2021), *Adapting central bank operations to a hotter world: Reviewing some options*, Paris, France, March.

Network for Greening the Financial System (NGFS) (2020a), *NGFS Climate Scenarios for central banks and supervisors*, Paris, France, June.

Network for Greening the Financial System (NGFS) (2020b), *Guide to climate scenario analysis for central banks and supervisors*, Paris, France, June.

Network for Greening the Financial System (NGFS) (2019), "**A call for action – Climate change as a source of financial risk**", First comprehensive report, April.

Nordhaus, W. D. (2017), "Projections and uncertainties about climate change in an era of minimal climate policies", *NBER Working Paper*, No 22933.

Piovani, G. et al. (2012), "Weather Derivatives Market and the Italian Case", *European Journal of Social Sciences*, 30(3), May, pp. 352-365.

Prudential Regulation Authority (2019), "**General Insurance Stress Test 2019 Scenario Specification, Guidelines and Instructions**", Bank of England, 18 June.

Raymond, C. et al. (2020), "**Understanding and managing connected extreme events**", *Nature Climate Change*, 10, pp. 611-621.

Refinitiv (2021), "**Refinitiv ESG Carbon Data and Estimate Models**", accessed on 31 March 2021.

Roncoroni, A., Battiston, S., Escobar Farfán, L. and Martinez Jaramillo, S. (2020), *Climate risk and financial stability in the network of banks and investment funds*, November.

Siddikee, N. and Rahman, M.M. (2017), "Effect of catastrophic disaster in financial market contagion", *Cogent Economics & Finance*, Vol. 5, Issue 1.

Stapleton, S.O., Nadin, R., Watson, C. and Kellett, J. (2017), *Climate change, migration and displacement: the need for a risk-informed and coherent approach*, Overseas Development Institute, November.

Stern, H. (2001), "**The application of weather derivatives to mitigate the financial risk of climate variability and extreme weather events**", *Australian Meteorological Magazine*, Vol 50, pp. 171-182.

Sydow, M. et al. (2021), "Shock amplification in an interconnected financial system of banks and investment funds", *Working Paper Series*, ECB, forthcoming.

Task Force on Climate-related Financial Disclosures (2017), *Recommendations of the Task Force on Climate-related Financial Disclosures –Final Report*, Financial Stability Board, June.

Thomä, J. and Gibhardt, K. (2019), "Quantifying the potential impact of a green supporting factor or brown penalty on European banks and lending", *Journal of Financial Regulation and Compliance*, Vol. 27, No 3, pp. 380-394.

Vasicek, O.A. (2016), "Loan Portfolio Value", Chapter 19, in *Finance, Economics and Mathematics*, Vasicek, O.A., John Wiley & Sons, NJ, United States, pp. 149-159.

Vermeulen, R., Schets, E., Lohuis, M., Kölbl, B., Jansen D. and Heeringa, W. (2019), “The Heat is on: A framework measuring financial stress under disruptive energy transition scenarios”, *Working Paper*, No 625, De Nederlandsche Bank, February.

Vermeulen, R. et al. (2018), “An energy transition risk stress test for the financial system of the Netherlands”, *DNB Occasional Studies*, Vol. 16-7, De Nederlandsche Bank.

Worthington, A. and Valadkhani, A. (2004), “Measuring the impact of natural disasters on capital markets: an empirical application using intervention analysis”, *Applied Economics*, Vol. 36, Issue 19, pp. 2177-2186.

Zscheischler, J. et al. (2018), “**Future climate risk from compound events**”, *Nature Climate Change*, 8, pp. 469-477.

Annex 1 Overview of climate risk stress-testing and sensitivity exercises

Table A.1

Main features of past, ongoing and planned climate risk stress-testing and sensitivity exercises by ESRB institutions

(sorted by data granularity, top-down/bottom-up approach and date of publication)

Institution	Release date	Status of the climate exercise	Institutions covered	Climate risk covered	Data granularity	Geographical coverage	Number of scenarios	Scenario horizons	Source of stress	Top-down/bottom up
Deutsche Bundesbank stress test (2023)	Q4 2023	Final results planned for 2023 Q4. Earlier publications of intermediate findings possible	Banks, insurance companies, investment funds	Physical and transition	Scenarios disaggregated at sectoral level. Impact on NFCs estimated at firm level	Banks, insurers and investment funds in Germany	To be defined. NGFS scenarios + internal scenario design	2023-2050	Carbon prices and damages/costs due to natural hazards	Top-down
ECB Top-down exercise (2021)	Q4 2021	Ongoing	Banks	Physical and transition	Firm-level assessment for NFCs; Country-level assessment for HHs	Worldwide firms, euro area banks	4 scenarios:1 orderly transition, 2 disorderly transition and 1 physical risks. Scenarios aligned with the NGFS	2020-2050	Carbon tax, oil price shock, frequency and magnitude of natural catastrophes	Top-down
EBA 2020 Pilot sensitivity exercise (2021)	Q2 2021	Ongoing	Banks	To be defined	Firm and sectoral levels	EU banks from 10 countries	NGFS scenarios	2050	To be defined	Top-down
European Commission-JRC	Q2 2021	Ongoing	Insurers	Physical	Firm level	EU-27	Disorderly transition scenario NGFS	2050	Variation in the exposure of the insurance sector to natural hazards	Macroprudential

Institution	Release date	Status of the climate exercise	Institutions covered	Climate risk covered	Data granularity	Geographical coverage	Number of scenarios	Scenario horizons	Source of stress	Top-down/bottom up
European Commission-JRC	Q2 2021	Ongoing	Banks	Physical and transition	Firm level	EU-27	Disorderly transition scenario NGFS	2050	Impact of green supporting factor and non-green, high-emitting penalising factor	Macroprudential
Polish Financial Supervision Authority (KNF)	Not available	Internal analysis conducted on a regular basis	Banks	Not available	Firm level and asset level (credit register NB300, exposures bigger than 500 000 PLN).	Not available	Assumption that all debtors from given branch (e.g. NACE: B - mining) default at one time (loans are not repaid) and check the impact on banks' profits and capital requirements	Not available	Not available	Top-down
ESMA (2021)	Q1 2021	Finished	Investment funds	Transition	Firm level and asset level (ISIN-level)	EU-27	4 scenarios from Vermeulen et al. (2018): 3 adverse transition risk scenarios (policy shock, technology shock, and policy + technology shocks) and 1 confidence shock scenario	5 years	Increase in carbon price, technological breakthrough	Top-down Macroprudential
EIOPA Sensitivity analysis (2020)	Q4 2020	Finished	Insurers	Transition	Individual firm level and sectoral level	European insurers	1 disorderly transition scenario	2050	Increase in carbon price per tonne by the end of this decade	Top-down
Banca d'Italia (2021)	Q4 2021	Planned	Households and financially vulnerable firms	Transition	Households and firm-level data	Italian firms and households	3 scenarios with various levels of income and/or interest rate stress for HHs and NFCs	Not available	Energy price, energy demand, households' expenditure and income, firms' operating costs and	Bottom-up

Institution	Release date	Status of the climate exercise	Institutions covered	Climate risk covered	Data granularity	Geographical coverage	Number of scenarios	Scenario horizons	Source of stress	Top-down/bottom up
									EBITDA	
Deutsche Bundesbank sensitivity analysis (2021)	Q4 2021	Ongoing	Banks, insurance companies, investment funds	Transition	Scenarios disaggregated at sectoral level. Impact on NFCs and financial institutions' exposures estimated at sector level.	Banks, insurers and investment funds in Germany	To be defined. NGFS scenarios + internal scenario design	To be defined	Carbon prices	Top-down Macroprudential
OeNB (2021)	Q1 2021	Ongoing	Banks	Transition	Sectoral level	Austrian banks	To be defined	5 years	To be defined	Top-down
ECB/DNB (2020)	2020	Finished	Banks and insurers	Transition	Sector level (NACE 2 level, 56 sectors)	EU (insurers) euro area (banks)	2 scenarios: 1 disorderly transition and 1 rapid adaptation to asymmetric technological innovation	Banks: 5 years Insurers: immediate	Increase in carbon price, technological breakthrough	Top-down
DNB (2018)	2018	Finished	Banks, insurers and pension funds	Transition	Sectoral level (NACE 2 level, 56 sectors)	Entities located in the Netherlands	4 ad hoc transition scenarios: technology shock (the share of renewable energy doubles); policy shock (the carbon price rises globally); confidence shock (HHs and NFCs postpone investments and consumption); and double shock (technology + policy shocks)	5 years	Increase of the share of renewable energy in the energy mix, increase in the carbon price globally by USD 100 per tonne, postponement of consumption and investment by HHs and NFCs	Top-down
Banque de	Q1	Scenar	Bank	Physi	Sectoral	French	4 scenarios: 1 orderly	2020-	Increase	Bottom-

Institution	Release date	Status of the climate exercise	Institutions covered	Climate risk covered	Data granularity	Geographical coverage	Number of scenarios	Scenario horizons	Source of stress	Top-down/bottom up
France /ACPR (2021)	2021	ios already available; Results expected in Q1 2021	and insurance companies	cal and transition	level (WIOD database, 55 sectors)	banks and insurance, exposures towards France, Europe, the US, and rest of the world	transition, 2 disorderly transition and 1 physical for insurance companies only matching 8.5 scenario of the IPCC. Scenarios aligned with the NGFS for transition risks	2050	of the carbon tax in 2025 and 2030	up
Magyar Nemzeti Bank (2021)	Q1 2021	Ongoing	Banks	Physical and transition	Sectoral level (21 NACE sectors)	Not available	3 scenarios: 1 orderly transition, 1 disorderly transition and 1 physical risk	Not available	Carbon prices, confidence shock, severe physical risks materialising.	To be defined
Malta Financial Services Authority	Not available	Planned	Banks, insurance companies and investment funds	Transition	Equity/bond level	Not available	Not available	Not available	Carbon tax, calibration based on NGFS	Top-down
ECB Supervision	2022	Planned	Banks	Physical and transition	Not available	EU	Not available	Not available	Not available	Bottom-up

Source: Institutions' website and publications.

Table A.2

Main features of past, ongoing, and planned climate risk stress-testing and sensitivity exercises by non-ESRB Institutions

(sorted by data granularity, top-down/bottom-up approach and date of publication)

Institution	Release date	Status of exercise (finished, ongoing, planned)	Institutions covered	Climate risk covered	Data granularity	Modelling approach	Source of stress	Top-down/bottom-up
Australian Prudential Regulation Authority	Executed in 2021, Release date not available	Ongoing/Planned	Authorised deposit-taking institutions (ADIs)	Physical and transition	Firm and sectoral levels	Vulnerability Assessment on balance sheet	Not available	Top-down
IMF and World Bank (Philippines)	2021	Finished	Banking sector	Physical	Sectoral level	IMF bank solvency stress test model to assess potential decline of banks' capital ratios, with a climate change scenario (World Bank) as its base	Increase in temperature, extreme weather events (i.e. typhoons) and/or pandemic	Top-down
IMF (Denmark)	2020	Finished (research study)	Comprehensive industry coverage and households sector	Transition	Firm and sectoral levels	ETS, BCA and revenue-neutral feebate	Carbon pricing, carbon tax, vehicle registration tax, tax schemes to discourage the overconsumption of meat, transition away from intensive animal farming and fishing	Top-down
Hong Kong Monetary Authority	Not available	Ongoing/Planned	Banking sector	Physical and transition	Firm and sectoral levels	Not available	Increase in temperature, rises in sea levels and more intense cyclones	Top-down and bottom-up
Singapore	2020	Ongoing/Pla	Locally incorporated	Physic	Firm	Incorporat	Carbon	Bottom-up

Institution	Release date	Status of exercise (finished, ongoing, planned)	Institutions covered	Climate risk covered	Data granularity	Modelling approach	Source of stress	Top-down/bottom-up
(MAS)	(Guidelines), June 2022 (Results)	nned	banks	al and transition	level	e risks both qualitatively and quantitatively into the scenarios and project its financial conditions under a base scenario and stress scenarios	pricing and tax, temperatures, extreme events	
Bank of England/PRA (2019) Exploratory exercise	2019	Finished	UK insurance sector	Physical and transition	Firm level	3 scenarios: 1 orderly transition, 1 disorderly transition and 1 physical risk	Not available	Bottom-up
IMF (Bahamas)	2019	Finished	Domestic banking system (all 7 commercial banks), 2 Largest credit unions and 10 large offshore banks	Physical	Sectoral level	TD approach for sensitivity analysis and macroeconomic scenarios (1 baseline and 3 adverse based on risk assessment matrix) in solvency, liquidity and contagion tests	Hurricane impact and/or US recession	Top-down
Bank of England/PRA	2021	Ongoing	UK banks and insurance companies	Physical and transition	Sectoral level (NACE level 1 or level 2)	3 scenarios: 1 orderly transition, 1 disorderly transition and 1 physical	Increase in global carbon prices, global average temperature increase by 2080	Bottom-up

Institution	Release date	Status of exercise (finished, ongoing, planned)	Institutions covered	Climate risk covered	Data granularity	Modelling approach	Source of stress	Top-down/bottom-up
						(chronic and acute risks). Scenarios aligned with NGFS		
USA (Commodity Futures Trading Commission)	Not available	Ongoing/Planned	Financial institutions	Physical and transition	Sectoral level	Testing of balance sheets against a common set of scenarios covering how financial institutions might respond to climate-related risks and opportunities over specified time horizons. Three common scenarios are (i) Paris-aligned (ii) current trajectory and (iii) in-between.	Event-based, GHG prices, carbon prices	Not available
Bank of Canada	Not before end 2021 (expected)	Ongoing/Planned	Six banks and insurers	Physical and transition	Sectoral level	Multi-region and sector recursive dynamic CGE model (MIT EPPA model) - DICE model (Nordhaus (2017)). Exogenous: GDP growth rates, population, technological	Global GHG emissions, carbon pricing and tax, temperatures	Not available

Institution	Release date	Status of exercise (finished, ongoing, planned)	Institutions covered	Climate risk covered	Data granularity	Modelling approach	Source of stress	Top-down/bottom-up
						advancements and resource assets Endogenous: savings and investment and the depletion of fossil-fuel reserves		
Reserve Bank of New Zealand	Not available	Ongoing/Planned	Insurance sector, house prices, farms, stress testing framework	Physical and transition	Not available	Not available	Not available	Not available
Korea (FSS)	Not available	Ongoing/Planned	Korean banks	Transition	Not available	Not available	Not available	Not available
Bank of Japan	Not available	Ongoing/Planned	Not available	Not available	Not available	Not available	Not available	Not available
Bank of China	Not available	Ongoing/Planned	Not available	Not available	Not available	Not available	Not available	Not available
Banco Central do Brasil	April 2021	Ongoing/Planned	Not available	Not available	Not available	Not available	Not available	Not available

Sources: Institutions' website and publications.

Annex 2 Detailed look at existing methodologies: Handbook

H.1 Credit risk in the banking book

The probability of default

H.1.1 Parameter: Probability of default

Exercise: DNB top-down climate stress test (Vermeulen et al. (2019); Daniëls et al. (2017))

Scope: **Transition risk**

Sectoral detail: 56 NACE 2 level sectors

Data: Common Reporting supervisory reports

The probability of default (PD) in the standard DNB top-down stress test model depends on the macroeconomic risk drivers (Daniëls et al. (2017)). The through-the-cycle PDs in this model are translated into point-in-time parameters via:

$$PD_{t,stress} = PD_{corep} \times F_{ttc \to pit} \times G_{t,stress} \quad (1)$$

where $PD_{t,stress}$ is the PD under a particular "stress" scenario at time t; PD_{corep} is the PD reported by banks to the common reporting supervisory reports; $F_{ttc \to pit}$ is adjustment factors that translate the reported through-the-cycle parameters (ttc) into the point-in-time value (pit) parameters; and $G_{t,stress}$ is the stress factors determined for each portfolio at time t. To this end, the stress factors are multiplied by scalars $M_{G,t}$ that depend on changes in macroeconomic risk drivers as defined in the scenario. The sensitivity of the scalar is captured by a vector β of elasticities with respect to the risk drivers, e.g. $M_{G,t} = \beta' \Delta X_t$, where ΔX_t represents the macroeconomic shocks specified in the scenario for time t. The stress factor hence becomes $G_{t,stress} = M_{G,t} G_{t-1,stress}$. Assuming a scenario with shocks on GDP and equity prices, the stress factors $G_{t,stress}$ can then be simplified as

$$G_{t,stress} = (1 + (\varepsilon_{GDP} \times \Delta GDP) + (\varepsilon_e \times \Delta E)) \times G_{t-1,stress} \quad (2)$$

Climate sensitivities were accounted for by adjusting the change in GDP and equity returns in each of the four transition scenarios respectively. GDP growth and equity returns were first obtained from running the NiGEM model for each scenario. The industry classification of loans was taken into account when calculating the PDs. Equity returns were disaggregated to the relevant industry level

using the transition vulnerability factors (TVFs). More specifically, the industry-specific estimates in each scenario become:

$$G_{i,t,stress} = (1 + (\varepsilon_{GDP} \times \Delta GDP) + (\varepsilon_e \times \Delta E \times TVF_i)) \times G_{i,t-1,stress} \quad (3)$$

where *i* stands for industry. The TVFs are used to capture the asymmetric effects of climate across industries.

H.1.2 Parameter: IFRS9 transition probabilities

Exercise: ECB/DNB top-down pilot exercise (ESRB (2020))

Scope: **Transition risk**

Sectoral detail: 56 NACE 2 level sectors

Data: EU-wide stress test reporting templates, FINREP/COREP

The ECB/DNB pilot exercise combines the transition rate equations in the BEAST model (Budnik et al. (2020)) with the transition vulnerability factors (TVFs) described in Vermeulen et al. (2019). The original equations for calculating transition rates in the BEAST model are estimated based on the banks' own estimates of the sensitivity of IRFS9 transition rates to macroeconomic variables in the European Banking Authority (EBA) stress tests[113] following the approach of Niepmann and Stebunovs (2018). The transition probabilities between stages 1, 2 and 3 are modelled jointly in a seemingly unrelated equations (SUR) setup. Each transition probability is a function of lags of all the transition rates and a set of macro variables. The general model specification is the following:

$$TR^{S,C}_{Y,i,t} = f\left(TR^{S,C}_{S1,S2,i,t-1}, TR^{S,C}_{S1,S3,i,t-1}, TR^{S,C}_{S2,S1,i,t-1}, TR^{S,C}_{S2,S3,i,t-1}, X^{C}_{t-p}\right) \quad (1)$$

where $TR^{S,C,P}_{Y,i,t}$ is the projected transition rate, and $TR^{S,C,P}_{SA,SB,i,t}$ is the transition rate from IFRS9 stage A to stage B, with A and B = 1, 2 or 3. Those transition rates are estimated for bank i, for sector S (non-financial corporations, households – loans for house purchase, households – consumer credit, financial institutions and sovereign exposures) in country C and scenario P. X^{C}_{t-p} corresponds to a set of macro variables including GDP, unemployment, and short and long-term interest rates for the country of exposure C.

The sensitivity of transition probabilities to sector-specific climate risks is introduced by modifying their sensitivity to GDP developments. The estimated coefficient that captures the impact of GDP β^{S}_{GDP} on transition rates for corporate exposures is scaled by exposure-weighted

[113] At the time of model creation in 2018, no information on the historical behaviour of IRFS9 transition rates was available as IRFS9 standards entered into force only in 2018.

bank and portfolio-specific transition vulnerability factors $TVF_i^{S,C}$ to approximate the asymmetric impact of climate risks on economic sectors and later asset quality:

$$TR_{Y,i,t}^{NFC,C,P} = f\left(\sum_{A,B} TR_{SA,SB,i,t-1}^{NFC,C,P}, X_{t-p}^{Other\ C,P}, ShareLE_i^{NFC,C} * \beta_{GDP}^{NFC} * TVF_i^{NFC,C} * GDPgr_{t-p}^{C,P} + (1 - ShareLE_i^{NFC,C}) * \beta_{GDP}^{NFC} * GDPgr_{t-p}^{C,P}\right) \quad (2)$$

This adjustment is performed only for a fraction of the corporate portfolio $ShareLE_i^{NFC,C}$ reflecting the fact that granular information about banks' NACE 2 level exposures was available via the large exposure statistics (LE) in FINREP/COREP only for a share of bank-level portfolios. Accordingly, for the remaining part of each portfolio, the impact of climate risks is silently assumed to be proportional to their impact on GDP.

H.1.3 Parameter: Probability of default

Exercise: ECB top-down stress test (2021)

Scope: **Transition and physical risk**

Data: Orbis, EIKON and Bloomberg for financial information, Urgentem for GHG emissions, Four Twenty Seven for physical risk

The default probabilities of non-financial corporations in the ECB climate risk stress test are linked to firm-level, macro-financial and climate variables. The historical firms' default probabilities are regressed, using a standard Altman Z-score approach, on firms' profitability and leverage, which in turn depend on macro-economic conditions (e.g. GDP) and climate variables (e.g. energy prices, emissions pathways):

$$PD_t^i = f(Profitability_t^i, Leverage_t^i, \sum_i firmlevel_t^i, \sum_c macro_t^c) \quad (1)$$

Profitability of firm *i* ($Profitability$) is defined as earnings normalised by total assets, and leverage ($Leverage$) is defined as debt over total assets. Both of these variables are assumed to be a function of scenario-specific macro-financial and firm-level variables (such as revenues and operating expenses), as described by equations (2) and (3).

$$Earnings_t^i = f(revenues, production\ costs) \quad (2)$$

$$Leverage_t^i = f(\, debt_{t-1}^i, \sum_i firmlevel_t^i, \sum_c macro_t^c) \quad (3)$$

Climate policies are considered to impact the economy as a Pigouvian tax in that both producers of GHG and consumers of carbon-intensive goods will be required to pay their share of CO2 emissions. Hence, to better capture this mechanism, the demand and supply side of earnings are modelled separately via revenues and production costs respectively: they are also a function of macro-financial and firm-level variables (e.g. energy consumption, total assets) as described in equations (4) and (5).

$$Revenues_t^i = f(, \sum_i firm - level_t^i \;, Scope\ 3, Revenues_{t-1}^i, \sum_c macro_t^c) \quad (4)$$

$$ProdCosts_t^i = f\begin{pmatrix} ProdCosts_{t-1}^i, energy\ price_t^i, Scope1{,}2, insurance\ premia,\ carbon\ price, \\ \sum_i firm - level_t^i, \sum_c macro_t^c \end{pmatrix} \quad (5)$$

Policies to facilitate the transition, such as a carbon tax, can increase the prices of some goods (for example the ones that rely heavily on carbon emissions during the production process) and fossil fuel energy. Changes in firms' debt are also estimated, owing to the possible disruption of physical capital from natural disasters on the one hand, and/or of technological substitution to transition towards a less carbon-intensive production chain on the other. Mitigants and amplifiers of climate risks have also been considered. Insurance coverage can mitigate the losses to physical capital from natural disasters; by contrast, operating costs can be affected by changes in insurance risk premia, especially for firms located in vulnerable geographical areas. The combined impact of transition and physical risk on firms' profits, operating costs and debt allows the estimation of firms' default probabilities under different climate scenarios.

H.1.4 Parameter: Probability of default

Exercise: Generated for quality control of banks' results from the ACPR pilot bottom-up exercise (Allen et al. (2020))

Scope: **Transition risk**

Sectoral detail: firm level

Data: FIBEN database (for yearly firm accounting data), French national central credit register (for payment default data)

The methodology to derive firm-level default probabilities employs the Banque de France's In-house Credit Assessment System (ICAS). The rating system can assess credit conditions of

260,000 non-financial corporations and groups in France. Included in the sample are firms with a minimum turnover of €0.75 million. The model uses a set of sector-specific financial ratios for firms (ratios chosen based on their discriminatory power and experts' assessment), each assigned to one of the following financial themes: profitability, solvency and financial structure, liquidity, and financial autonomy. All ratios in the same financial theme are discretised and summarised into a theme-based categorical variable. Scenario-specific sectoral value added shocks are transmitted to firms via financial aggregates that compound firms' financial ratios.

PD is calculated as follows.

First, the main default variable is the one-year horizon binary default:

$$d_i^t = \begin{cases} 1 & if\ firm\ i\ defaults\ during\ year\ t \\ 0 & otherwise \end{cases} \quad (1)$$

where d_i is the realisation of a random variable *D* that takes the value 1 with probability $1 - \pi$, and 0 with probability π. The variable *D* follows a Bernoulli distribution with parameter π, defined by:

$$P\{D = d_i\} = \pi^{1-d_i}(1-\pi)^{d_i} \quad (2)$$

Second, the default probability π is estimated conditional on a vector of observed covariates X_i, which represents the theme-based categorical variables for firm *i*. The estimation of probabilities of default is performed on a macro-sector basis (only for non-defaulted entities at the beginning of each year, clustered into seven sectors, including four macro-sectors: Retail and Trade, Industry, Services, and Construction, and three specific sectors: Real estate, Machinery and Equipment, and Holdings), using a logistic model:

$$P(D = 1|\, X_i) = 1 - \pi = \frac{1}{1 + exp(\beta_0 + X_i\beta_1)} \quad (3)$$

where (β_0, β_1) are the parameters of the logistic regression. Empirical delimitation of credit quality steps is estimated using smoothing cubic spline methodology.

Loss given default

H.1.5 Parameter: loss given default

Exercise: ECB/DNB pilot exercise (ESRB (2020)), banking sector forward-looking scenario analysis 2021

Scope: **Transition risk**

Sectoral detail: NACE 2

Data: EU-wide stress test reporting templates, FINREP/COREP

The ECB/DNB pilot exercise combines the transition rates equations in the BEAST model (Budnik et al. (2020)) with the transition vulnerability factors (TVFs) described in Vermeulen et al. (2019). The original loss given default (LGD) equations are estimated applying a seemingly unrelated regression (SUR) framework and a logit transformation for the sector-specific LGDs. The LGD scenario sensitivities are estimated based on the EBA stress test data.

For LGD from S1 and S2 to S3 the general model specification is the following:

$$LGD_{i,X3,t}^{S,C} = f\left(LGD_{i,13,t-1}^{S,C}, LGD_{i,23,t-1}^{S,C}, Cure\ Rate\ PIT_{i,t}^{S,C}, GDP_{t-1}^{C}\right) \quad (1)$$

where $LGD_{i,X3,t}^{S,C}$ is the LGD for exposures transitioning from stage X (X=1,2) to stage 3, $LGD_{i,13,t-1}^{S,C}$ and $LGD_{i,23,t-1}^{S,C}$are the lagged LGD from stage S1 and S2, $Cure\ Rate\ PIT_{i,t}^{S,C}$ is the cure rate (i.e. transition from S3 to either S2 or S1) at point-in-time, and $GDPgr_{t-1}^{C}$ stands for GDP growth in the country of exposure C.

The reaction of LGDs to climate-related shocks is introduced to this system via a scenario-specific global stock market shock. Analogous to the transition rate treatment, the ECB/DNB pilot exercise applies a TVF-dependent adjustment factor in the LGD model equations. It is assumed that the LGD models capture the overall scenario impact but miss the additional corporate losses conditional on the scenario-specific climate transition risk. Hence, an additional global stock market shock $ESXshock$ derived from the DNB policy and technology shock scenarios is added to the LGD model proportional to the large exposure information coverage given by $ShareLE_{i}^{NFC,C}$.

$$\begin{aligned} LGD_{i,X3,t}^{NFC,C} = {} & f\left(LGD_{i,13,t-1}^{NFC,C}, LGD_{i,23,t-1}^{NFC,C}, Cure\ Rate\ PIT_{i,t}^{NFC,C}, GDPgr_{t-1}^{C}\right) + ShareLE_{i}^{NFC,C} \\ & * f\left(LGD_{i,13,t-1}^{NFC,C}, LGD_{i,23,t-1}^{NFC,C}, Cure\ Rate\ PIT_{i,t}^{NFC,C}, GDPgr_{t-1}^{C}\right) \\ & * TVF_{i}^{NFC,C} * ESXshock_{t-1} \end{aligned} \quad (2)$$

The adjusted LGD model leads to higher LGD for banks with large exposures to carbon-intensive, and therefore high TVF, corporate subsectors. The global stock market shock is assumed to have a uniform impact per carbon intensity unit of the exposures and is only applied for the first four quarters of the scenarios, otherwise $ESXshock = 0$.

H.2 Revaluation losses

H.2.1 Parameter: Revaluation of equity holdings

Exercise: DNB climate stress test (Vermeulen et al. (2019)), later DNB/ECB pilot exercise (ESRB (2020))

Scope: **Transition risk**

Sectoral detail: 56 NACE 2 level sectors

Data: Securities holding statistics (SHS)

The methodology links sector-level equity price changes to aggregate equity indices and sector-specific transition vulnerability factors (TVFs). The method relies on an extended capital asset pricing model (CAPM) where the sector-specific energy transition risk captured by the TVFs is included as an additional risk factor. In the standard CAPM framework, each stock return is determined by a stock-specific excess return and loading on the excess market return. In the extended CAPM it will be the TVFs and the scenario-specific excess market returns that together determine how the equity of a firm in each industry is affected as a result of, for example, a carbon price increase.

Bank-level revaluation losses are derived from the sector-level equity price changes using their trading book exposure shares. Information about banks equity holdings at the NACE 2 level is retrieved from the SHS. Another study applying an extended CAPM framework is Alessi et al. (2021), where the CAPM is extended by including a "greenness and transparency" factor. This factor is built based on firms' CO2 emissions and the quality of the information they disclose on their environmental performance. The authors find that in a severe but plausible scenario where greener stocks outperform non-green, high emitting stocks, even halving such exposures would not be enough to avoid losses.

H.2.2 Parameter: Revaluation of corporate bonds

Exercise: DNB climate stress test (Vermeulen et al. (2019)), later ECB/DNB pilot exercise (ESRB (2020))

Scope: **Transition risk**

Sectoral detail: 56 NACE 2 level sectors

Data: Securities holding statistics (SHS)

In this approach, the fixed-income financial asset is impacted by changes in bonds' credit ratings and in risk-free interest rates. Changes in bond risk premia are derived from rating transition matrices using TVFs to account for the carbon intensity of the bond issuer's sector. The impact of changes in risk-free interest rates is proportional to the duration of the bond. An

assumption for these calculations is that the projected changes in ten-year government bond yields serve as a proxy for the change in the risk-free rate at all maturities.

1. Credit risk spread of bonds

As a starting point, the module uses a rating transition matrix (available from rating agencies), which contains the probability that a bond will transition to a higher/lower rating, including the PD. To adjust the transition probabilities in times of stress, the module uses a stress factor, which is calculated based on macroeconomic inputs (GDP growth and aggregate stock prices).

After calculating a new PD for each bond, the change in credit spread can be derived as the difference between the new and old PD. To simplify the modelling of credit spread impacts, coupon payments are ignored. It follows that the credit spread of a zero-coupon bond with a residual maturity of one year is equal to the PD for that year, assuming 100% LGD. The change in credit spread is therefore given by the difference between the new and old PD.

As a final step, the change in credit spreads is translated to a change in the value of each bond using the following formula:

$$Value_{NEW} = Value_{OLD}\ x\ (1 - \Delta\ cumulative\ PD) \quad (1)$$

where $\Delta\ cumulative\ PD$ is the cumulative change in PD.

An additional step is included, which links the sector-specific stock returns derived via TVFs with credit rating downgrades, in order to reflect the connection between large equity losses and the associated large deterioration in credit quality.

2. Duration impact

A second important channel in bond revaluation gains and losses is captured by a bond's sensitivity to interest rate changes. A bond's duration is used to calculate the price impact due to changes in interest rates. Given the maturity date of a bond (N), the Macaulay duration is defined by:

$$Duration = \frac{\sum_{i=1}^{N} t_i\ x\ PV_i}{\sum_{i=1}^{N} PV_i} \quad (2)$$

where PV is the present value of cash flow i occurring at time point t. Further simplifying assumptions are given by setting the duration of a floating rate bond equal to zero and assuming that all bonds are bullet bonds without prepayment options.

Information about banks' bond holdings at the NACE 2 level is retrieved from the SHS.

H.2.3 Parameter: Price sensitivity of equity holdings

Exercise: EIOPA sensitivity analysis of climate-change related transition risks (2020b)

Scope: **Transition risk**

Sectoral details: asset level for climate-sensitive sectors, i.e. energy generation, industrial production, transport, agriculture and construction

Data: Solvency II and PACTA (2° Investing Initiative) on a security-by-security basis (ISIN)

The method focuses on the fact that energy transition required by a policy shock ingrained in transition scenarios impacts companies' revenues and expenses. These changes in the companies' profits will subsequently impact their market value. Relying on standard evaluation approaches to capture these changes, the changes at production (technology) level are calculated. In detail, in order to calculate equity shocks, one starts by calculating for each individual production (technology) level considered, the net profits under the two scenarios as:

$$\text{Net Profits} = (\text{Production Volume} * \text{Price} * \text{Net profit margin}) \quad (1)$$

Equity market price is a linear function of future dividend flows (Gordon (1959)). The assumption is that dividends for a given year are proportional to the net profits of a company for the considered year. By aggregating the production profiles to technology level, an estimate of the net present value of this technology is computed based on future cash flows.

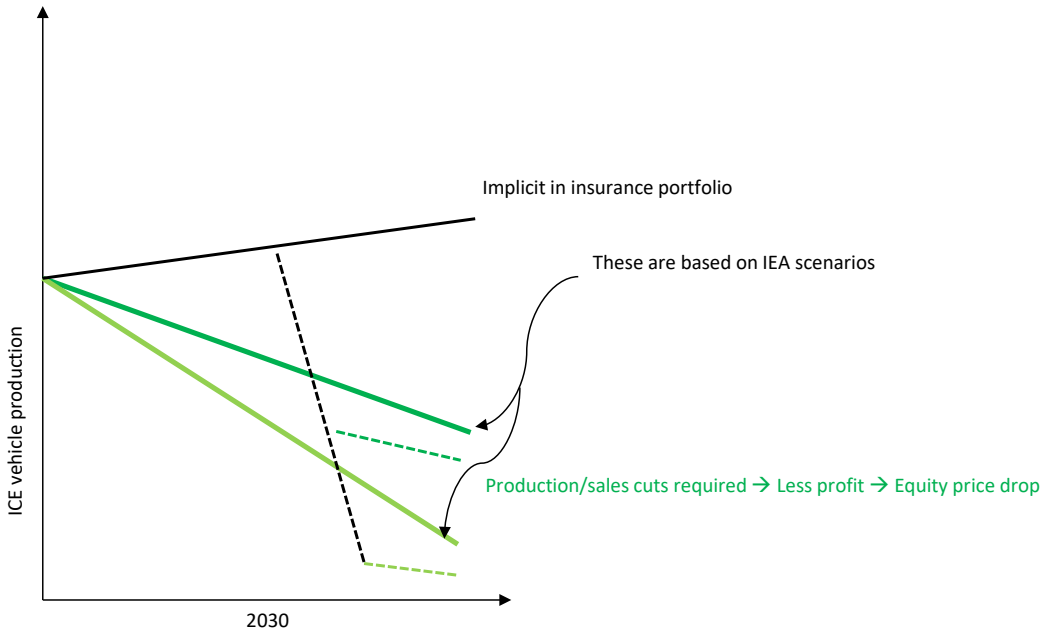
$$V_{E,t_0} = a \sum_{t_0}^{t_b} \frac{P_t}{(1+r)^t} \quad (2)$$

With P_t the net profits made in year t, t_b the date until the cash-flows are projected, r the risk-free rate assumed to be 2% for simplicity and a the proportionality coefficient between net profits and dividends.

The difference between V_{E,t_0} under the projected production plans in the transition versus the baseline scenario is the equity value put at risk by the transition. Consistent with the scenario, a price change for each of the identified technologies is calculated, which can be brought back into the insurance portfolio to understand the impact of the shock.

Figure A.1

Illustrative example of methodology used for production alignment and modelling of production adjustments



Source: ***EIOPA Sensitivity analysis****.*

H.2.4 Parameter: Price sensitivity of sovereign bonds holdings

Exercise: Battiston et al. (2019) and EIOPA sensitivity analysis of climate change-related transition risks (2020)

Scope: **Transition risk**

Sectoral details: Asset level

Data: Solvency II asset-by-asset reporting

This methodology analyses the impact of climate-related shocks on profitability, market share and gross value added (GVA) for climate-relevant sectors. It follows the approach by Battiston and Monasterolo (2019) which is based on the CLIMAFIN model developed by Battiston et al. (2019). Climate-relevant sectors are defined along with Battison et al. (2017) and include, e.g. fossil-fuel extraction and electricity. Policy changes affect the performance of issuers in the sectors via a change in economic activities' market share, cash flows and profitability, eventually affecting the GVA of the sector.

Sector-level corporate profitability serves as a basis to calculate the impact on fiscal revenues of sovereigns. This is in turn used to assess impacts on government bonds. Because the role of fossil fuels and renewable energy technologies in the sovereign's GVA and fiscal revenues can considerably affect the fiscal and financial position of a country, countries that have

already started to align their economy to the low-carbon transition may face better refinancing conditions.

H.3 Physical risk in the insurance sector

H.3.1 Parameter: Value at Risk (VaR) after physical risk shock

Exercise: European Commission – Joint Research Centre (Di Girolamo et al. (2020))

Scope: **Physical risk**

Sectoral details: EU Member States (country-level), river floods

Data: Expected exposure from the Risk Data Hub (RDH), expected loss using the RDH methodology, premium and technical provisions for the total insurance sector from EIOPA

This model is an adaptation of the Vasicek (2016) model, which is specifically suited to assessing credit risk in large portfolios and forms the basis of the Basel III internal ratings-based approach. The key equation of the model is the following:

$$VaR_{\alpha} = EAD * LGD * N\left[\frac{N^{-1}(1-\alpha)\sqrt{\rho+\delta(1-\rho)}+N^{-1}(PD)}{\sqrt{1-\rho-\delta(1-\rho)}}\right] \quad (1)$$

The “Value at Risk (α)” (VaR) estimates the maximum loss expected over a set time period (in this case one year) and with a confidence level of α for the insurance sector as a whole. In the analysis, the parameter α is left to vary to derive the whole distribution of insurers’ losses for all considered confidence levels.

The input parameters needed to generate the loss distribution are as follows.

i) The “exposure at default” (EAD), which estimates the maximum amount for which the guarantor could be exposed towards the defaulting counterparty. Given the focus of the model on the exposure of the insurance sector to natural hazards, the share of technical provisions and solvency capital requirements allocated to natural perils is taken as an estimate of the EAD related to natural catastrophes. Notably, the technical provisions are assumed to be proportional to the economic expected loss. The monetary loss is calculated using the exposure to natural catastrophic events provided in the RDH and following the approach explained in Antofie, Luoni, Eklund, and Marin Ferrer (2020).

ii) The PD and LGD. The former is assumed to be equal to the 0.5%, which is the maximum PD which should be attained under the Solvency II framework and therefore marks an upper boundary to the probability distribution of defaults. The LGD is set as equal to 15% in line with previous exercises.

iii) A parameter reflecting the concentration of exposures (δ) and a correlation coefficient (ρ).

The model can be extended by replacing the VaR by the expected shortfall, while the underlying Gaussian dependency structure can be adapted to a non-Gaussian setting to account for systemic tail risk.

H.4 Sector-level scenario elements

H.4.1 Parameter: Dividend streams and elasticities of asset prices

Exercise: Banque de France (Allen et al. (2020))

Scope: **Transition risk**

Sector detail: Sector level

Data: Banque de France sectoral model

This methodology estimates share prices as discounted dividend streams by scenario, economic area and sector. The estimation follows three steps. First, projections of turnover and value added between 2025 and 2050 are estimated at scenario, economic region and sector levels from NiGEM and sectoral models.

Second, the model assumes that distributed dividends are 50% of return on capital, where return on capital is equivalent to 33% of sectoral value added.

Third, the stream of dividends is discounted using the dividend discount model. For a given scenario α, there is a dividend stream $\left(D^{\alpha}_{j,m,t}, D^{\alpha}_{j,m,t+1}, \ldots.\right)$ for country *m*, sector *j*, and time $t \in [2025, 2050]$. Dividend $D^{\alpha}_{j,m,t} = 0.5 * (0.33 VA^{\alpha}_{j,m,t})$, where $VA^{\alpha}_{j,m,t}$ is the projection at date *t* of the value added of country *m* and sector *j*, in scenario α.

Let $\left(R^{\alpha}_{j,m,(s,t)}\right)^{-1}$ be the associated discounted factor over the period (s,t) and $R^{\alpha}_{j,m,(s,t)} = 1 + \overline{r_m} + rp^{\alpha}_{j,m,(s,t)}$. The rate $\overline{r_m}$ is the average index stock return, and $rp^{\alpha}_{j,m,(s,t)}$ is the relevant premium component.

The value of stock at date s=2020 (evaluation date), for scenario α is given by:

$$\mathrm{P}^{\alpha}_{\mathrm{j,m}}(2020) = \mathrm{D}^{\alpha}_{\mathrm{j,m}}(2025)\left(\mathrm{R}^{\alpha}_{\mathrm{j,m}}(2020,2025)\right)^{-1} + \cdots + \mathrm{D}^{\alpha}_{\mathrm{j,m}}(2045)\left(\mathrm{R}^{\alpha}_{\mathrm{j,m}}(2020,2045)\right)^{-1} + \left[\frac{\mathrm{D}^{\alpha}_{\mathrm{j,m}}(2050)}{\mathrm{R}^{\alpha}_{\mathrm{j,m}}(2049,\ 2050)\ - 1 - \mathrm{g}}\right]\left(\mathrm{R}^{\alpha}_{\mathrm{j,m}}(2020,2050)\right)^{-1} \quad (1)$$

H.4.2 Parameter: Corporate credit spreads

Exercise: Banque de France (Allen et al. (2020))

Scope: **Transition risk**

Sectoral details: Country, sector (GICS) maturity

Data: Banque de France's rating model (for France), Risk Management Institute (RMI) (for Germany, Italy, Spain, United Kingdom, United States and Japan).

The methodology estimates credit spreads at country, sector and maturity level. Let $CS_{j,m}(\tau)$ be the credit spreads of country *m*, sector *j*, and maturity τ. $CS_{j,m}(\tau)$ is calculated following Merton (1973) and the Black and Cox (1976) formula:

$$CS_{j,m}(\tau) = -\frac{1}{\tau} ln\left[1 - (1 - RR)N\left[N^{-1}\left(PD(\tau)\right) + \theta\sqrt{\tau}\right]\right] \quad (1)$$

where $PD(\tau)$ is the historical PD at the same horizon, *N* is the cumulative distribution function of a centred and normalised Gaussian distribution, θ is the asset Sharpe ratio, and *RR* is the recovery rate, assumed constant at 40%.

For any country and sector, four maturity brackets are considered: one year, two years, three years and five years. For any maturity bracket, country and sector, the Sharpe ratio parameter is calibrated to match the order of magnitude of the CDS spreads for the same horizon and sector. Projections, for each scenario, of one-year-maturity credit spreads are calculated using and mimicking the projections of one-year PDs described in Section 8. Projections of credit spreads with longer than one-year maturities are calculated: (i) estimating a Bayesian VaR(1) model (Minnesota priors) on the credit spread vector $(CS_{j,m}(1year), CS_{j,m}(2\ year), CS_{j,m}(3\ year), CS_{j,m}(5\ year))$, for each country m, sector j, and scenario α , using data between 1991 and 2009; ii) given the future path from 2020 to 2050 of $CS_{j,m}(1year)$, function of relevant scenario, the conditional forecast (projections) of the credit spreads for the remaining horizons and over the same period.

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For specific terminology please refer to the **ESRB glossary** (available in English only).

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