EUROPEAN CENTRAL BANK
EUROSYSTEM

Occasional Paper Series

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The Road to Paris: stress testing the transition towards a net-zero economy

The energy transition through the lens of the second ECB economy-wide climate stress test

No 328

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Abstract

The transition to a carbon-neutral economy is necessary to limit the negative impact of climate change and has become one of the world's most urgent priorities. This paper assesses the impact of three potential transition pathways, differing in the timing and level of ambition of emission reductions, and quantifies the associated investment needs, economic costs and financial risks for corporates, households and financial institutions in the euro area.

Building on the first ECB top-down, economy-wide climate stress test, this paper contributes to the field of climate stress testing by introducing three key innovations. First, the design of three short-term transition scenarios that combine the transition paths developed by the Network for Greening the Financial System (NGFS) with macroeconomic projections that account for the latest energy-related developments. Second, the introduction of granular sectoral dynamics and energy-specific considerations by country relevant to transition risk. Finally, this paper provides a comprehensive analysis of the impact of transition risk on the euro area private sector and on the financial system, using a granular dataset that combines climate, energy-related and financial information for millions of firms within the euro area credit register and securities database, and country-level data on households.

By comparing different transition scenarios, the results of the exercise show that acting immediately and decisively would provide significant benefits for the euro area economy and financial system, not only by maintaining the optimal net-zero emissions path (and therefore limiting the physical impact of climate change), but also by limiting financial risk. An accelerated transition to a carbon-neutral economy would be helpful to contain risks for financial institutions and would not generate financial stability concerns for the euro area, provided that firms and households could finance their green investments in an orderly manner. However, the heterogeneous results across economic sectors and banks suggest that more careful monitoring of certain entities and subsets of credit exposures will be required during the transition process.

JEL codes: C53, C55, G21, Q47, Q54.

Keywords: climate stress test, transition risk, climate scenarios, energy.

Non-technical summary

Climate change poses major risks to natural, human, and economic systems. To limit its impact, reaching carbon neutrality by 2050 has become one of the world's most urgent priorities (Intergovernmental Panel on Climate Change (IPCC), 2022). Previous climate change assessments, including the first ECB top-down, economy-wide climate stress test, have shown the importance of a timely transition in order to reduce the impact of physical risks in the long term. At the same time, the 27th Conference of the Parties (COP27) in November 2022 closed with a general feeling that an orderly transition that limits the temperature increase to a maximum of 1.5°C by the end of the century is no longer feasible.

The Russian war in Ukraine has further highlighted the risks and costs that arise from high dependency on fossil fuels, presenting several challenges but also opportunities to speed up the transition (International Energy Agency (IEA), 2022b; Panetta, 2023). It is also significantly changing the economic and energy environment in which that transition needs to take place. Adding to climate change-related considerations, these elements could push European firms towards an accelerated transition. Alternatively, they might trigger a stagnation of the carbon intensity of our energy systems over the next few years and raise the odds of a delayed – strong or mild – transition (NGFS, 2022b).

Given that the transition is necessary and inevitable, this paper assesses the impact of three potential transition pathways on the real economy and the financial system within a short-to-medium term horizon (2023 to 2030). Under the first scenario, the accelerated transition, the current energy crisis would trigger a green transition starting immediately, thereby allowing euro area economies to reach emissions reductions by 2030 that were compatible with the +1.5ºC maximum climate target by the end of the century. Under the second scenario, the late-push transition, recent adverse macroeconomic developments would lead to a green transition starting in 2025. It would be sufficiently intense to achieve similar emissions reductions by 2030, thanks to strong and decisive action, albeit also with higher costs than under the first scenario. Under the third scenario, the delayed transition, the transition would again start with a delay of three years and would be smoother, therefore being less costly. However, emissions would be on a path only compatible with a temperature increase of around +2.5ºC by the end of the century.

Leveraging the ECB top-down climate stress test framework, this paper enhances it in three ways. First, it elaborates on the current European energy environment and its future development and builds three plausible short-term scenarios around them. These scenarios combine the long-term transition paths developed by the NGFS with short-term macroeconomic projections and take into account the latest data on energy prices and consumption. Second, it analyses the impact of the green transition on non-financial corporates and households by capturing energy dynamics and sectoral interactions. Finally, it sets out the impact of the three transition scenarios on euro area financial institutions over the next eight years (until 2030), assessing the costs of the different options (although it does not translate the benefits stemming from emissions reductions into a monetary equivalent).

The results of these exercises show that acting immediately and decisively (the accelerated transition scenario) would provide significant benefits for firms, households, and the financial system, not only by maintaining the economy on the optimal net-zero emissions path (and therefore limiting the impact of climate change), but also by rapidly reducing their energy expenses and lessening the financial risk. If the transition is further delayed, the only way to reduce emissions compatibly with net-zero targets would be to act more intensively at a later stage, with an abrupt and strong transition that would lead to a weaker economy and higher annual expected losses for the financial system over the horizon set for this exercise, and probably further down the road (the late-push transition scenario). The results also show that an orderly and smooth transition, as in the best-case scenario of the NGFS (Net Zero 2050 scenario) but starting with a three-year delay (the delayed transition scenario), would lead, by 2030, to risk levels comparable to those implied by an immediate and accelerated transition. However, emission reductions would clearly undershoot the policy goal of a maximum rise in temperature of 1.5°, accelerating the impact of physical risks in the long term.

1 Introduction

Having acknowledged that climate change poses major risks to the environment and to society, economies worldwide pledged to combat its impact. Over the last four decades, the number of global natural disasters and the value of the associated economic losses have multiplied, exacerbated by human activity.[1] Rising temperatures and changes in weather conditions are expected to increase further in a non-linear pattern going forward, with irreversible environmental and economic consequences. Under the 2015 Paris Agreement, governments worldwide unanimously agreed to keep global average temperature increases to well below 2°C above pre-industrial levels and to further pursue efforts to limit the temperature increase to 1.5°C. Reducing the emission of greenhouse gases (GHG) and transitioning to a net-zero economy are the key to achieving this target, together with the objectives of attaining sustainable economic growth and preserving our ecosystems.

The first ECB economy-wide climate stress test showed that the short-term costs of a green transition would be more than offset by the long-term benefits. The increase in credit risk triggered by transition efforts over the first eight to ten years would be more than outweighed by the reduction in physical risks thereafter. The first stress text exercise also concluded that the impact for corporates and banks most at risk might be severe, with potential consequences for financial stability. Assessments in several other jurisdictions have reached similar conclusions. The Financial Stability Board (FSB) and NGFS member institutions have already completed 35 climate scenario analysis exercises, many of which found larger negative effects on GDP and financial losses in no-transition scenarios.[2] Against this background, the need for a green transition is no longer questioned and there is an increasing interest in how we can attain the transition to a net-zero economy and what the impact of the different transition pathways will be on the economy and the financial system.

Transitioning the European Union (EU) to a green economy is a complex challenge, requiring large-scale transformations and investments in the European energy landscape. The EU economy has already reduced emissions by more than 30% compared with 1990 levels, and the share of renewable energy sources, such as solar and wind, in the EU energy mix has almost tripled.[3] However, the road to net-zero emissions is still long. Based on the scenarios calibrated for this exercise, to achieve the temperature targets of the Paris Agreement by the end of this century, EU-wide GHG emissions would need to be drastically reduced by cutting current fossil fuel consumption by half until 2030. (NGFS, 2022b) Conversely,

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1 See the "Inventory of hazards & disasters worldwide since 1988" on the EM-DAT International Disaster Database website and the CarbonBrief Web page "Attributing extreme weather to climate change".

2 As at November 2022, when the Financial Stability Board and the NGFS published their report: "Climate Scenario Analysis by Jurisdictions. Initial findings and lessons".

3 On GHG emissions, see Emissions Database for Global Atmospheric Research (2022). On energy consumption, see Chart 1 in Section 2 of this paper, which is based on the Eurostat data set out in Annex 1.

the share of renewable energy sources in the EU energy mix would have to be further scaled up by three to four times the current level. All these measures would require large-scale investments in carbon mitigation efforts and the build-up of renewable-based energy capacity, funded by governments and the financial system.

At the same time, the green transition poses risks for European firms, households and, consequently, financial institutions. First, firms' energy expenses would increase as brown energy sources become more costly as a result of carbon taxes and supply-side bottlenecks. Second, firms' investments would need to increase to achieve the shift from brown energy to renewable-based energy and from polluting assets to energy efficient technologies. At the same time, households would need to invest in the energy efficiency of their properties, in addition to their discretionary income being impacted by changes in energy prices. Finally, financial institutions would be exposed to the transition-related risks of households and non-financial corporations, mainly through their loan portfolios and securities holdings. Their risks would therefore be linked to the vulnerability of their counterparties in both the credit and the market-risk channels. Mapping firm-level changes in probabilities of default against information on banks' individual corporate loans made it possible to assess the transmission of transition risk from firms to banks, the transmission of transition risk from households to banks being assessed on the basis of the projected deterioration in the credit quality of bank portfolios.

The well-known pre-existing challenges apart, the latest geopolitical developments are significantly changing the macroeconomic and energy environment in which the transition needs to take place. The Russian war in Ukraine significantly reduced the availability of gas in Europe and was followed by a sudden increase in gas, oil and electricity prices. Electricity and gas prices have doubled and tripled respectively relative to the end of 2020. Energy security concerns pushed EU governments to sign new – not necessarily green – energy contracts with third countries in an attempt to decrease quickly their dependence on Russian energy resources. At the same time, rising energy prices led to an upward trend in headline inflation, causing prices to increase overall by up to 10% in 2022 as compared with 2021. Consequently, the combination of supply-side energy shortages and inflationary pressures has led to downward revisions of economic growth prospects in many European economies, further exacerbated by high uncertainty about future geopolitical developments.[4]

Changes in the macroeconomic and energy environment coupled with upcoming transition challenges have inspired the calibration of novel scenarios. *"The ongoing global spike in energy prices represents a crossroads in the world's journey towards net zero"* (NGFS, 2021) and, from a climate perspective, presents challenges and opportunities for transitioning.[5] Three potential transition paths (or "scenarios") – namely accelerated transition, late-push transition, and delayed transition – are considered in this paper and cover a wide spectrum of possible developments over the short to medium term. Under the first scenario, the

4 For further detail, see "ECB staff macroeconomic projections for the euro area", March 2023.

5 See International Energy Agency (2022), which explores whether the energy crises will be a setback for clean energy transitions or a catalyst for greater action; and Panetta, F. (2023).

energy crisis would trigger an intense green transition starting immediately. Investments in renewables in the short term would reduce energy expenses in the medium term and allow euro area economies to reach emissions reductions by 2030 that were compatible with the +1.5ºC maximum climate target by the end of the century. Under the second scenario, the recent adverse macroeconomic developments would lead to the stagnation of carbon intensity over the next three years. The transition would start later but would be sufficiently intense to achieve similar emissions reductions by 2030, thanks to strong and decisive action, albeit also with more negative effects than under the first scenario. Under the third scenario, the transition would again start with a delay of around three years, but would be smoother and therefore too mild to achieve emission reductions that would be compatible with temperature targets below +2°C. Under this last scenario, the transition would have less impact on the economy, but emissions would be on a path compatible with an increase in temperature of around +2.5ºC.[6] [7]

Overall, this exercise is an important step forward in the field of climate stress testing. Building on the granular data infrastructure and firm-level models developed for the first ECB economy-wide climate stress test, this work adds to the literature in this area by contributing (i) newly designed eight-year transition risk scenarios, (ii) granular modelling of energy-related developments and sectoral dynamics relevant to the green transition, and (iii) ensuring unprecedented coverage of exposures and entities that now extends to corporates, households, and different types of financial institutions. The new modelling framework includes bottom-up modelling of green investment to replace brown assets and investment in renewable energy. It also takes into account revenue changes for the brown energy sectors arising from decreasing demand, as well as the corresponding changes for the electricity sector, which would play a key role in the transition. Finally, it allows for potential amplifications of transition risk through the supply chain, in the form of sectoral downstream and upstream shocks, based on revised input-output tables.

The results show that – all other things being equal – the earlier the transition happens, the smaller the financial risk, and consequently the less policy support is required to mitigate the costs. Assuming a specific target for emissions' reduction by 2030, an accelerated transition is preferable to a late-push transition, which would be more sudden and disruptive. A late-push transition might lead to energy prices similar to those experienced at the onset of the Russian invasion of Ukraine. Such energy price shocks would result in a severe deterioration in the profitability of energy-intensive firms. At the same time, the investment required to transition within a shorter time period would significantly increase their indebtedness. The two elements combined would, in turn, increase firms' financial vulnerability and therefore their credit risk. An accelerated transition would increase costs for households and firms in the short term, owing to a rapid increase in energy prices and investments. However, it would lead to lower financial costs and risks

[6] The considerations on temperature increases hold true on the assumption that all global economies reduce their emissions as envisaged under their respective (potentially frontloaded) NGFS scenarios. The emissions trajectories for different countries – taken together – would make it possible to achieve the scenario-specific temperature target by the end of the century.

[7] The technical aspects on the implementation of the transition scenarios are described in Box 1 in Section 3 of this paper.

overall in the medium term by reducing energy expenses earlier, thanks to the rapid build-up of renewable energy capacity.

By 2030, a delayed transition would lead to financial risk levels similar to those under an accelerated transition but would entail larger long-term transition and physical risks. Different transition paths could result in similar credit risk levels in the economy by 2030 but would imply very different exposures to climate risks, depending on the emission reductions achieved. Under a delayed transition scenario, credit risk would keep increasing until 2030, and potentially further due to a continuous increase in energy prices and limited availability of renewable energy capacity. Under the accelerated scenario, however, they would stabilise and decrease thereafter. Moreover, given that the emission reductions by 2030 under the delayed transition scenario would be less ambitious (down from the 1990 level by 55% under the delayed scenario as compared with 67% with the accelerated transition), higher increases in temperatures could be expected to lead to more frequent and severe materialisation of natural hazards in the long term. Since the temperature increases and physical risk levels would depend on the action taken at global level, these considerations hold true solely under the assumption that all global economies reduce their emissions as envisaged under the corresponding NGFS scenario.[8] In addition, in the event of a delayed transition, firms and households might be more vulnerable to the compounding of transition and physical risks.

Irrespective of the scenario, firms in the mining, manufacturing and utility industries would be among those most severely affected by the transition. They would face the largest balance sheet impact, and consequently the most adverse consequences for their credit risk. Due to their strong reliance on brown energy sources, such energy-sensitive sectors would bear the greatest costs, in the form of higher energy expenditure and a need for major investment in carbon mitigation activities and renewable energy. At a more granular level, transition risk would affect vulnerable firms within such sectors disproportionately, especially under a late-push transition scenario, further illustrating the benefits of an early-start transition to mitigate the costs and financial risks.

The green transition – be it accelerated, late-push or delayed – would increase banks' expected losses and provisioning needs in the short term, although the overall impact would be limited depending on portfolio size. On aggregate, the annual losses for the median bank over the eight-year horizon would range between 0.6% and 1% relative to portfolio size, depending on the scenario, and would be double that for the 10% of banks most vulnerable to transition risk, pointing to a limited impact relative to portfolio size and capital generation capacity of the banks concerned. Under a baseline scenario – a scenario in line with the current macroeconomic forecast and with no additional transition efforts beyond those arising under the current climate policies – annual expected losses by 2030 for the median bank would be 25% higher compared with 2022 given that banks had very favourable risk parameters in 2022 which are forecast to deteriorate later. By 2030,

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8 Therefore, compatibly with global temperatures increasing by 2100 by no more than 1.5°C (under the first two scenarios) or 2.6° (in the third scenario).

expected losses from transition-related developments alone would be 23% higher under the accelerated transition scenario, 53% higher under the late-push transition scenario and 23% higher under the delayed transition scenario compared with 2022 for the median bank. Such additional projected increases in annual expected losses due to transition risk would be attributable to transition efforts going beyond the current climate policies and should be added to those obtained for a baseline scenario without transition risk. It follows that banks would be required to increase their provisions by at least as much.

Banking sector financial exposures to transition-vulnerable sectors would tend to be concentrated in a subset of systemically important institutions (SIs), which would face higher increases in expected losses and provisioning needs. The current exercise found that large and systemically important institutions would experience a larger projected increase in transition-related credit risk than other banks under all three scenarios. Moreover, the credit risk increase for those banks most exposed to vulnerable firms would be non-linear, given that such firms account for a larger portfolio share. The wider distribution of bank-level increases in expected losses indicates a larger tail risk under the late-push transition.

This paper makes several contributions to the climate stress test literature by proposing novel solutions to some of the challenges currently faced in climate scenario design and climate risk modelling. Based on the review conducted by Acharya et al. (2023), one of the key challenges that need to be overcome in existing climate stress test approaches is the incorporation of “compound risk”, i.e. the interaction between climate, economic, financial, political, and other risks, in the design of scenarios. For the transition scenarios developed for this exercise, we combined non-climate developments stemming from current macroeconomic BMPE projections with the climate-related shocks identified by the NGFS. Another key aspect is the modelling of the deterioration in borrowers’ ability to repay loans with a typical maturity of less than 5-10 years. By focusing on the short-term impacts of transition risk in the current exercise, this work provides a close alignment of the time horizon of the exercise with banks’ balance-sheet structures. Furthermore, the need to develop short-term scenarios was recently identified as a key priority for improving climate scenarios in the first public feedback survey on climate scenarios run by the NGFS (NGFS, 2023b; NGFS, 2023a). The NGFS is working on a conceptual framework for short-term scenarios to better capture the adverse implications of a disorderly transition and severe natural disasters in the near future. Given that the NGFS is planning to start implementation by the end of 2023, our work could provide useful input on both the conceptual and methodological aspects.

This paper is organised as follows. Section 2 provides an overview of the European energy context and its latest developments. Section 3 introduces the three short-term scenarios and explains how they have been calibrated. Sections 4 and 5 present the channels for the transmission of transition risk drivers to corporates and households, respectively, and the results for these sectors. Section 6 describes how the transition risks would transmit to banks and other financial institutions. Section 7 concludes. More technical details are presented in the Annexes to this paper.

2 The European energy context

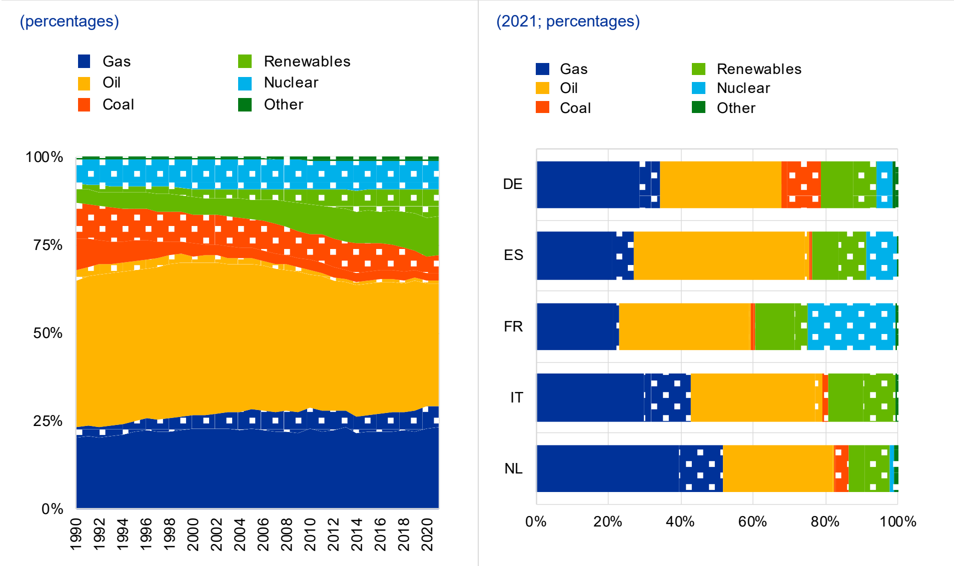
2.1 Recent energy-related developments

While the share of renewables in the EU energy mix has gradually increased over the past 30 years, reliance on carbon-intensive energy sources remains high. In 2021, EU member countries were mainly powered by oil products and natural gas, together accounting for 65% of total energy consumption (**Chart 1**, panel a). Although the aggregate consumption of gas and oil has been relatively stable over the past 30 years, the share of renewables has tripled and reached almost 20% of total energy consumption, primarily replacing coal (green area in Chart 1). The relative decline in direct consumption of carbon-intensive energy sources (the solid areas in blue, yellow and red in Chart 1) has been offset by a relative increase in the consumption of electricity (+17% over the past 30 years, see the dotted area in Chart 1) stemming from a gradual electrification of production processes and buildings. Across countries, the energy mix is heterogeneous. Among the five largest EU countries, the Netherlands and Italy rely on fossil fuels for more than 80% of their total energy consumption, while France makes extensive use of nuclear power (**Chart 1**, panel b).

Chart 1

The EU energy mix is dominated by oil and natural gas, but the share of renewable sources has more than tripled over the last 30 years

a) EU aggregate final energy consumption by source	b) Energy mix by country



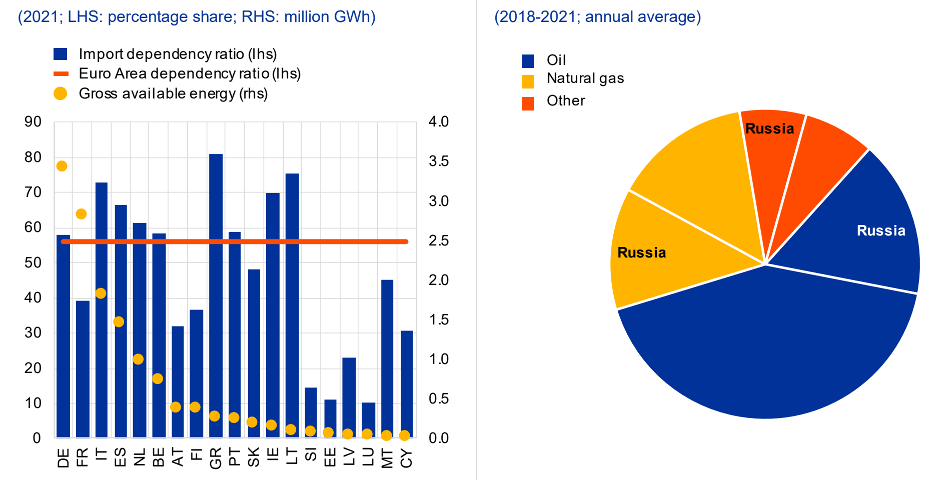
Source: ECB calculation based on Eurostat data.
Notes: Primary energy is represented by the filled areas and corresponds to energy consumed directly without transformation. Secondary energy is represented by dotted areas and is the transformation of primary sources into heat or electricity. Final energy consumption comprises both household and corporate energy consumption.

EU countries rely to a large extent on energy imports from third countries, particularly from Russia. In 2021 around 56% of the gross available energy in the euro area was imported from countries outside the EU. Germany, Italy, Spain, and the Netherlands imported between 58% and 73% of their energy from outside the EU, while the dependency ratio was slightly lower for France (**Chart 2**, panel a). More than 85% of EU energy-related imports were in the form of oil and natural gas, originating mainly from Russia. On average, 47% of natural gas and 28% of petroleum products imported to the EU between 2018 and 2021 were sourced from Russia (**Chart 2**, panel b). Other important, albeit much less significant, energy suppliers were Norway and the United States, each of which contributed less than 10% to EU energy-related imports.

Chart 2

Until 2021, the EU strongly relied on energy imports from Russia and other non-EU countries

a) Energy import dependency ratio by country | **b) Extra-EU energy imports by energy source and by supplier country (Russia vs other extra-EU)**



Source: ECB calculations based on Eurostat data.
Notes: LHS stands for left-hand scale. RHS stands for right-hand scale. The import dependency ratios in panel a are calculated as extra-EU energy imports minus exports divided by the sum of available energy per country. Extra-EU energy import shares are based on averages of imported energy in the net mass.

Geopolitical events in early 2022 triggered a large hike in energy prices, coupled with an increase in energy demand in the aftermath of the COVID-19 pandemic[9]. The Russian invasion of Ukraine in early 2022 was followed by a drastic reduction in gas supply to EU countries[10] as well as sharp increases in energy prices. In the preceding period, from 2008 to 2021, non-financial corporates and households in the euro area experienced a maximum year-on-year increase in gas price of 17.9% and 12.9% respectively. By June 2022, however, the average natural gas price for euro area firms jumped to almost €100/MWh, equating to a year-on-year increase of 141% (**Chart 3**, panel a). In the same period, firms experienced a 52% year-on-year increase in electricity prices, which reached the historic high of €208/MWh in June 2022. The increase in energy prices for households was more

9 After a 6% drop in aggregate euro area energy consumption in 2020, the total consumption of energy rebounded to pre-pandemic levels by the end of 2021.

10 Compared with 2021, the average monthly import of Russian natural gas decreased by 48% to 4.5 million tonne equivalents in the first three quarters of 2022.

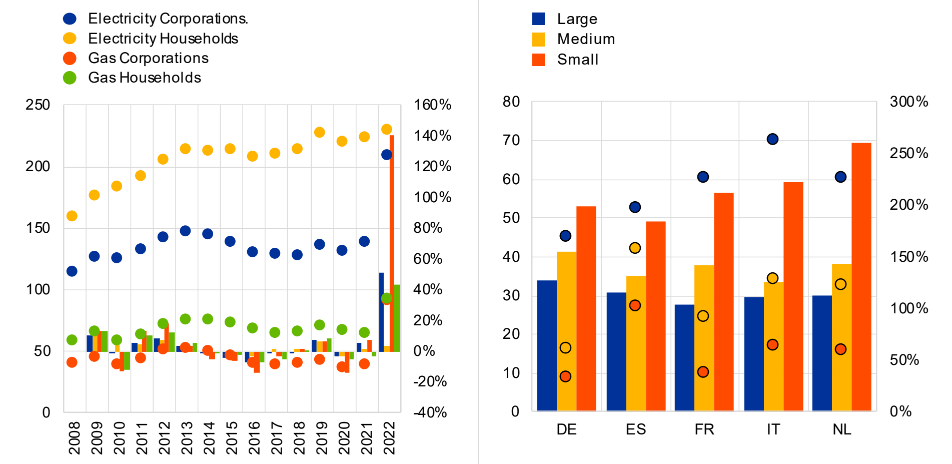
contained and less volatile, but still considerable: prices had increased by 43% for gas and 3% for electricity by June 2022 compared with the previous year.

Energy prices differ across EU countries and consumption bands, and they were differently impacted by the recent events. Gas prices in the euro area stood at between €30 and €55/MWh until 2021 and spiked in 2022, with heterogeneous impacts across countries. Among the largest countries, Spain and Italy faced the highest increase in average gas prices across consumption bands by June 2022 compared with the previous year (up by 187% and 159%, respectively) (**Chart 3**, panel b). Firms in France and Germany experienced a relatively milder twofold increase in gas prices over the same period. Depending on their energy consumption levels, firms are exposed to an additional layer of price (and price increase) heterogeneity. Large corporate consumers generally pay lower prices per unit of energy but were disproportionally more impacted by the 2022 shock.

Chart 3

Energy prices increased substantially in 2022 for both corporates and households

a) Energy price by consumer type and source	b) Average gas price and price increase in 2022 by country and corporate consumption level
(LHS: EUR/MWh (bars); RHS: year-on-year increase (diamonds))	(LHS: long-term average gas prices in EUR/MWh (bars); RHS: increase in 2022 relative to long-term average (dots))



Source: ECB calculation based on Eurostat data.
Notes: LHS stands for left-hand scale. RHS stands for right-hand scale. The gas prices in panel a are recorded at the end of June each year and include taxes and levies for euro area corporations (non-households). The prices are the mean values across consumption bands. Panel b summarizes the consumption bands across countries: "Large" refers to firms consuming more than 278 GWh per year and "Small" refers to firms consuming less than 2.8 GWh per year. The remaining firms are labelled "Medium". Gas prices are shown as long-term averages during the period 2007-2021. Price increases are computed based on June 2022 prices relative to the long-term price average.

2.2 Transitioning to net-zero: state of play

Despite increasing evidence of the risks of climate change and the benefits of transitioning to a net-zero economy, limited action has been taken so far. After the publication of the first ECB climate stress test (Alogoskoufis et al., 2021), climate risk assessments by other jurisdictions have confirmed the importance of a timely transition to a net-zero economy and highlighted the risks stemming from inaction or a delayed response to climate change.[11] However, despite multiple and alarming evidence, only limited progress has ensued. After decreasing by 10.8% in 2020, EU aggregate greenhouse gas (GHG) emissions rebounded in 2021, mainly driven by recovery from the COVID-19 pandemic and a greater uptake of energy sources with higher emissions (Emissions Database for Global Atmospheric Research (EDGAR), 2022). The IPCC reported in 2022 that, under the current circumstances, the world is already set to exceed the temperature target of +1.5ºC above pre-industrial levels within the next two decades and reiterated that drastic cuts in carbon emissions are needed to prevent irreversible environmental disasters (IPCC, 2022).

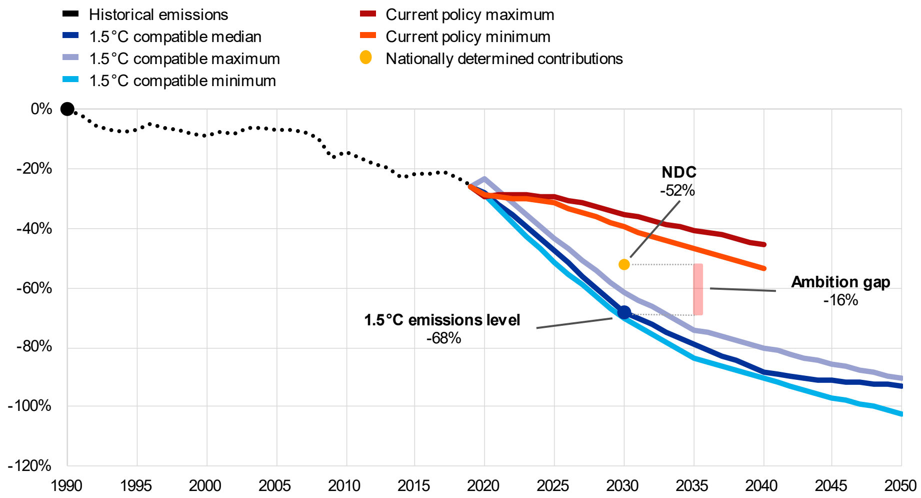
Progress appears to be limited when looking at projected emissions based on the current and planned climate policies. Looking at aggregate EU GHG emission projections, the ambition gap between +1.5°C-compatible scenarios and the current-policy scenario shows that progress currently made on the policy front is far from being sufficient (**Chart 4**). Even a scenario that incorporated all current nationally determined contributions (NDCs), i.e., all pledged policies even if not yet implemented, would miss the 2030 emission reduction target necessary to stay on a +1.5C°-compatible track by 16 percentage points.

Chart 4

Substantial ambition gap between 1.5°C-compatible scenarios and current policies

Historical and projected EU GHG emission reductions compared with 1990 levels

(percentages)



Source: Climate Analytics.
Notes: LULUCF stands for land use, land-use change and forestry. MtCO2e stands for metric tonnes of carbon dioxide equivalent.

The limited historical progress with green transition has been further exacerbated by an increasingly challenging geopolitical environment since the beginning of 2022. The Russian invasion of Ukraine significantly reduced the availability of gas in Europe and was followed by a sudden increase in gas, oil, and

[11] The 2021 Bank of England Climate Biennial Exploratory Scenario and the 2022 SSM climate stress test showed that banks' projected losses would be the lowest if early and well-managed actions are taken to reduce carbon emissions (Bank of England, 2022; ECB Banking Supervision, 2022). In all, the Financial Stability Board (FSB) and NGFS member institutions have already completed 35 exercises on climate scenario analysis, many of which found more significant GDP and financial losses under disorderly or no transition scenarios compared with an orderly transition (FSB, 2022).

electricity prices (see Section 2.1). Energy security concerns pushed EU governments to sign new energy contracts with third countries in a sudden attempt to decrease their dependence on Russian energy resources. More than 70 energy contracts have been signed in the EU since January 2022, mainly for the provision of gas, and only half of these are related to clean energy. (European Council on Foreign Relations, 2022). Most of these new energy contracts have a very long maturity (eight years on average) and will keep EU countries anchored to the use of brown energy for longer than expected. Before these developments, the European Green Deal, established in 2020, aimed at achieving carbon neutrality in the EU by 2050, through a series of policy initiatives. One of the main measures to achieve the EU climate targets is the 'Fit for 55' package, which comprises a broad set of legislative plans.[12] A key proposal in this package is to increase additional investment by €350 billion per year, in the energy systems alone and over the current decade, to meet the EU's 2030 emissions reduction target (European Commission, 2021).

It was made clear at COP27[13] that the transition pledges agreed in Paris in 2015 are not on track, recognising the risk of missing the totemic +1.5°C target. The COP27 meeting held in November 2022 closed with a general feeling that an orderly, smooth, and effective transition is not only unlikely, but also no longer feasible. The limited progress and the recent adverse macroeconomic and energy-related developments have put the world at a crossroad in its journey to a net-zero economy (NGFS, 2022b). One pathway would take us back in time by increasing the carbon intensity of our energy systems and raising the odds of overshooting the "well below +2°C" objective. The other pathway would lead us to net-zero but would require more sudden than expected changes through a decisive and coordinated move away from fossil fuels. Hence, the high fossil fuels prices currently might provide the right opportunity and incentive for taking the second path and acting immediately. A wait-and-see approach would have negative long-term consequences for physical risk, equating to the costs of an intense – and ultimately inevitable – transition.

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[12] The package aims to provide a coherent and balanced framework for reaching the EU's climate objectives, while (a) ensuring a just and socially fair transition, (b) maintaining and strengthening innovation and the competitiveness of EU industry, while ensuring a level playing field vis-à-vis third-country economic operators, and (c) underpinning the EU's position in leading the way in the global fight against climate change.

[13] The 27th session of the Conference of the Parties of the UNFCCC hosted by the Government of the Arab Republic of Egypt in November 2022.

3 Scenario narrative

Timely and accurate scenario design is essential to be able to provide insight into the different plausible future pathways to a carbon-neutral economy. Recent geopolitical events triggered a full-fledged energy crisis with broader implications for the entire economy and net-zero transition pathways. These developments have to be reflected in the narrative and calibration of climate scenarios. The scenarios designed in this current exercise are the means to answer the following questions: given the circumstances today, what is the optimal way of transitioning to net-zero emissions in the short and medium term? What would the impact of different transition pathways be on the real economy and the financial system? This section presents the scenarios at the core of this climate stress test and unveils the approach behind their calibration.

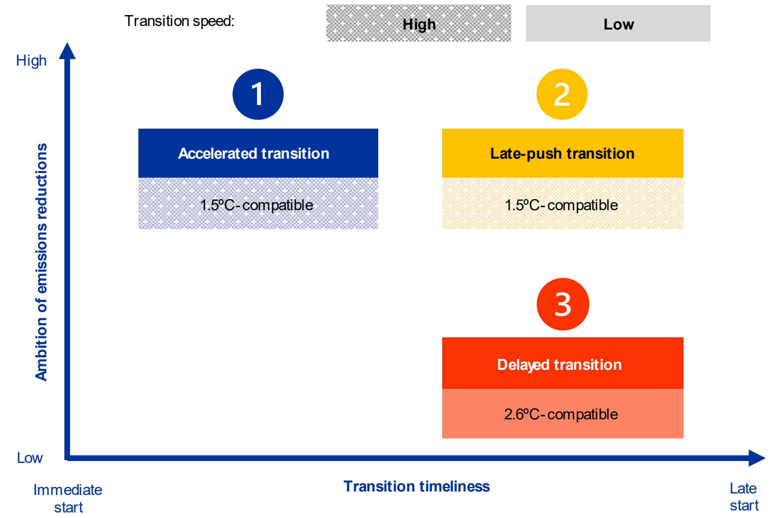
3.1 Transitioning to net zero: three plausible scenarios

The climate stress test exercise assesses three potential transition pathways based on scenarios spanning the period until 2030. The transition pathways incorporate the current energy-related and macroeconomic environment and are aligned to the emissions reduction objectives to be reached by 2030 based on the NGFS scenarios framework. Under all scenarios, the euro area economy and financial system transition to carbon neutrality, but with substantial differences in the transition timeliness and implied emissions reductions **(Figure 1)**.[14]

[14] The three transition pathways proposed in this exercise do not encompass all possible scenarios for transitioning towards net zero, but they aim to cover a variety of realistic future scenarios in light of the present economic circumstances. The pathways are built based on the NGFS climate scenarios framework, which was also used as a reference to expand certain considerations over a longer period.

Figure 1
The three potential transition pathways assessed in this exercise

Scenarios by transition timeliness and implied emissions reductions



Source: ECB.

The first scenario is that of an accelerated transition (S1). The Russian war in Ukraine has highlighted risks and costs that arise from high dependency on fossil fuels, the prices and supplies of which are extremely volatile in an uncertain geopolitical environment. Amounting to climate change-related considerations, these elements should push European firms towards an immediate and accelerated transition. High fossil fuel prices at the beginning of the period would be an incentive for firms to transition rapidly. Funding flows would be high, especially at the beginning of the period, and compatible with the need to speed up the transition process. Emissions would decrease by 67% in 2030 compared with 1990 levels, in line with the NGFS “net zero by 2050” scenario.

The second scenario is a late-push transition (S2). Measures to alleviate the energy crisis would result only in minor decreases in the carbon intensity of energy systems over the next three years. Despite being temporary, these developments would take us one step back in the transition process. The “real” transition would start later – around 2026 – and with a weaker economy. Nevertheless, it is assumed that it would be sufficiently intense to achieve emission reductions by 2030 comparable with those under the accelerated transition scenario. For this to happen, decisive and strong action would be needed at a later stage. Fossil fuel prices would remain high (but lower than under S1) before the transition starts and would increase more strongly thereafter. Funding flows would be very high and mainly concentrated over the period 2025-2030.

The third scenario is a delayed (and milder) transition (S3). As with the late-push transition scenario, the transition would start with a delay of around three years, when the current macroeconomic projections point to an economy that has recovered from the 2022 shock. However, in contrast with the late-push transition, it is assumed that a delayed transition would not be sufficiently intense to return to the optimal path described by NGFS "net zero by 2050" scenario, that is compatible with the objective of +1.5°C above pre-industrial averages by 2100. Fossil fuel prices would continue to be high before the transition starts (equal to a late-push transition) and increase more slowly thereafter. The funding flows required to implement an effective transition would be slightly lower.

3.2 A story translated into numbers

The NGFS scenarios are a key building block for analysis of climate risk; they require enhancements, however, to account for the current macroeconomic challenges and opportunities. In September 2022 the NGFS updated its set of climate scenarios. Nevertheless, It did not account for the current macroeconomic context and, more specifically, the impact of the Russian war in Ukraine on energy markets. They also lack the sectoral granularity necessary to assess transition risk.[15] The macroeconomic scenarios designed for the 2023 EU-wide stress test (the Broad Macroeconomic Projections Exercise – BMPE) provide an adequate representation of the developments recently observed in the energy markets, with projections covering a three-year time horizon.[16] Combining standard stress test scenarios with the NGFS-based climate scenarios made it possible to obtain more accurate economic and transition pathways that reflect the role of climate risks in the recent macroeconomic environment. Details of how the NGFS scenarios and BMPE macroeconomic projections were combined for this purpose are briefly discussed in Box 1 at the end of this section, and comprehensive technical documentation is provided in Annex A1.

At the current stage, the NGFS climate scenarios lack the granularity and representation of sectoral dynamics required to assess transition risk[17]. For this exercise, downscaling methodologies were designed to achieve the desired sector-level granularity of the scenarios and to evaluate the heterogenous impact of climate policies on different types of firms (see the details in Section 3.2.1). In addition, the NGFS climate scenarios were enriched with a wide set of firm-level climate-related and financial data to assess the impact of transition risk at granular level. To this end, the data infrastructure underlying the first ECB economy-wide climate stress test (Alogoskoufis et al., 2021) was enhanced to ensure greater data granularity, coverage, and quality (**Figure 2**). The sample of companies assessed was drawn from the universe of euro area non-financial corporations (NFCs) to

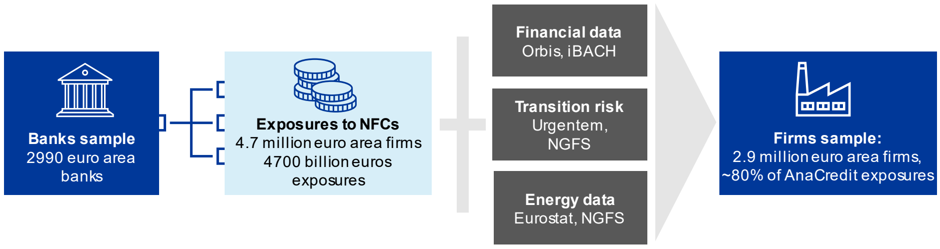
[15] The new vintage of scenarios (Phase III) reflects the latest country-level commitments to reach net-zero emissions by 2050 (including commitments made at COP26 and until March 2022), as well as the latest trends in renewable energy and mitigation technologies. Similarly, data for GDP and population were updated in line with the IMF World Economic Outlook 2021, including the impact of COVID-19. The modelling of physical risk was improved to partially account for acute physical risk through stochastic shocks. For references and further works of the NGFS, see the NGFS website and NGFS Scenarios Portal.

[16] These scenarios are based on the Eurosystem staff BMPE, which delivers the short and medium-term economic outlook for the euro area and for the individual euro area countries. For further details see "EBA launches 2023 EU-wide stress test" of 31 January 2023.

[17] In order to achieve its work program for 2022-2024, the NGFS has structured its work into six dedicated workstreams and task forces. Increasing the granularity of the scenarios has been identified has one of the key priorities of the workstream on "Scenario Design and Analysis" (See the Workstream "scenario design and analysis" mandate).

which euro area banks are exposed through their portfolios and comprising a total of 2.9 million firms, thereby covering around 80% of total outstanding exposures in the euro area Analytical Credit Register (AnaCredit) in 2022[18].

Figure 2
Size and scope of the exercise



Source: ECB.
Notes: The final sample of companies was drawn from the sample of AnaCredit debtors and depended on the availability of financial, transition risk and energy data. Where possible, proxies were calculated to fill data gaps.

In the process of scenario calibration, substantial effort went into capturing granular energy dynamics. Price, quantity, and type of energy consumed play a primary role in the transition to a greener economy. As shown in Section 2, the current macroeconomic context has been deeply impacted by the energy market shocks experienced as a result of the Russia-Ukraine war. Transitioning to a greener economy is essential to mitigate climate-related risks but is also desirable to alleviate some of the pressure that the markets have been experiencing in the wake of the energy crisis.

Box 1
Technical aspects of implementation of the climate stress test transition scenarios

The euro area climate stress test scenarios in this exercise were created by combining historical data, BMPE macroeconomic projections and NGFS climate scenarios. Historical data were updated with the latest available values to reflect the current situation. The EU-wide stress test scenarios (BMPE macroeconomic projections) covered the short-term horizon (2023 to 2025) and were used to determine the future pathways of macro-financial variables (see Appendix A1 for a complete list). The NGFS scenarios were employed for short-term projections of the climate-related variables (not covered in the BMPE macroeconomic projections) and to generate projections over the medium term (2026 to 2030). In addition, to derive sectoral breakdowns of the energy-related variables given in the NGFS scenarios at country level, use was made of data on companies' energy mix at country-sector level, historical GHG emissions at firm level, NGFS regional emission pathways downscaled to country-sector level and energy-to-emissions conversion factors by energy source.

Under the accelerated transition scenario, it was assumed that the NGFS disorderly transition started promptly in 2023, leading to immediate and tangible impacts on the overall economy. For this scenario, the economic and climate-related variables from the original NGFS delayed transition from 2030 were front-loaded and diluted using linear interpolation to design the

[18] The remaining share of AnaCredit exposures was not included due to missing information on emissions and balance-sheet items, or because of low data quality and reliability.

progression to a low-carbon-intensive system. For macro-financial variables specifically, the climate shocks from the NGFS scenarios were also combined with the growth rates from the BMPE projections for the years 2023 to 2025.

Under the late-push and delayed transition scenarios, the economy initiated its transition only in the medium term. The short-term developments of macro-financial variables evolved in line with the BMPE projections. All climate-related variables followed the original NGFS current policies scenario, with no further climate action being taken beyond the existing measures. It was assumed that from 2025 onwards, all the variables would align with the original NGFS delayed transition from 2030 onwards for the late-push transition scenario. Under the delayed transition scenario, the overall progress of the economy was dictated by the original NGFS net zero by 2050 pathway.

Table 1

Key features of the scenarios used

	S1 Accelerated transition	S2 Late-push transition	S3 Delayed transition
Scenario implementation	The NGFS delayed transition scenario was front-loaded and diluted through linear interpolation to model short-term climate shocks to macro-financial variables and produce medium-term projections.	The NGFS current policies scenario was used to model the absence of climate action in the short term. A front-loaded NGFS delayed transition would start only in the medium term.	The NGFS current policies scenario was used to model the absence of climate action in the short term. An orderly transition that would follow the NGFS net zero 2050 scenario would start only in 2026.
Emissions	Compatible with a +1.5°C temperature target by the end of the century.	Compatible with a +1.5°C temperature target by the end of the century.	Compatible with a +2.6°C temperature target by the end of the century.
Investments	High and spread over eight years, with more funding at the beginning.	Very high and concentrated in the medium term.	Medium, as required to implement an orderly transition.
Energy prices	Very high and increasing further in the first few years, providing an incentive for firms to transition rapidly.	Fossil fuel prices stay constant at a high level before the transition starts and increase thereafter; electricity prices are strongly penalised by late action in the medium term.	Constant at a high level before the transition starts and gradually increasing thereafter.

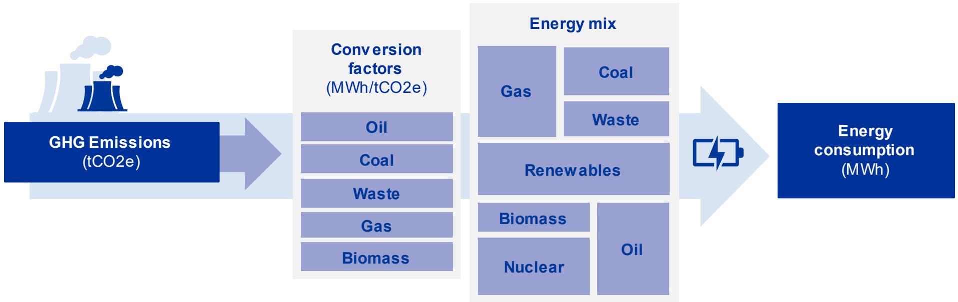
3.2.1 Sectoral breakdown of energy-related developments

Transition risk has strong sectoral components, as widely acknowledged in the literature concerned, and confirmed by empirical evidence (ECB/ESRB, 2022). Companies would be differently affected by the transition depending on their sector's activities and reliance on brown energy sources. While there is a significant degree of heterogeneity within each economic sector in terms of individual firms' level of exposure to transition risk, it is important to capture sectoral dynamics in the scenarios by displaying different economic and transition developments for winning and losing sectors, as well as by capturing the special role played by the energy sector in transition. In particular, a high level of granularity is needed for the emissions and energy-related variables employed to estimate company-level energy consumption.

Downscaling methodologies were developed to achieve the level of heterogeneity needed to capture sector-specific dynamics in the transition to net-zero emissions. More precisely, aggregate GHG emissions pathways for the European Union taken from the NGFS scenarios were broken down to country-sector level in two steps. In the first, the EU emissions pathway was broken down in proportion to the NGFS transition-implied GDP pathways of each country[19]. In the second, country-level emissions were downscaled at sectoral level in proportion to ECB projections of sector-level energy consumption[20].

A new methodology was developed to estimate direct (brown) energy and electricity consumption at company level (Figure 3). Companies produce direct emissions (i.e. Scope 1 GHG emissions[21]) by direct usage of brown energy sources in their production processes. Moreover, companies are responsible for the indirect emissions (i.e. Scope 2) generated by their consumption of electricity[22]. Firm-level energy consumption were calculated for each energy source by combining firm-level emissions with information on country-sector energy mix and energy-to-emissions conversion factors. Scope 1 emissions were converted to direct energy consumption, while Scope 2 emissions were converted to electricity consumption. For emissions stemming from electricity generation specifically, a weighted conversion factor was calculated by considering the energy mix of the electricity sector of each country. Further technical details are given in Annex A1.

Figure 3
Conversion factors were used in combination with information on energy mix to translate GHG emissions into energy consumption



Source: ECB methodology.
Notes: The conversion factors were expressed as tonnes of carbon dioxide equivalent per megawatt hour (tCO2e/MWh) and were available only for energy sources that produce GHG emissions. Energy consumption was adjusted proportionally to account for the share of non-emitting sources (i.e., renewables and nuclear). The relationship between emissions and energy consumption also holds true in the opposite direction.

19 Emissions were allocated to each country proportionally to the share of EU GDP that they represented at each point in time in the future. This assumption made it possible to account for the projected economic growth of each country, which would be sensitive to country-specific green transition pathways.

20 Companies' energy mix at country-sector level (sourced from Eurostat), historical emissions at firm level (sourced from Urgentem), the NGFS regional emission pathways and energy-to-emissions conversion factors by energy source were used for the calculation. For the downscaling, sector-level projected energy consumptions by energy source are converted to sector-level emissions by source by applying energy-to-emissions conversion factors. The sectoral granularity considered for the downscaling was NACE level 2. Technical details on how the NGFS emissions were downscaled at sectoral level are available in Annex A1.

21 See the Greenhouse Gas Protocol.

22 A third category of emissions, referred to Scope 3, includes all indirect emissions that occur in the upstream and downstream activities of an organization. As a result, Scope 3 emissions were not included in the estimation of company-level energy consumption but were allowed for in the emission reduction efforts of firms.

3.2.2 Macroeconomic and climate projections

GHG emissions pathways

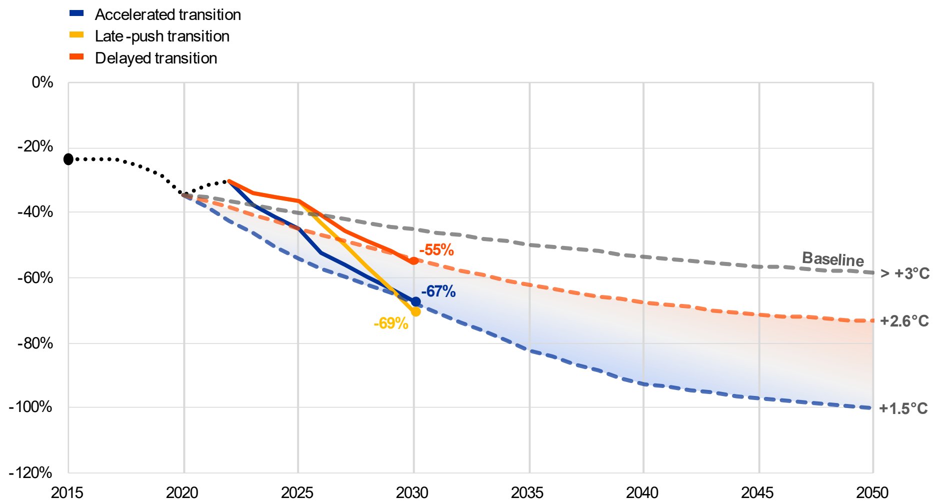
The emission pathways of the transition scenarios were calibrated based on historical data and the NGFS long-term climate scenarios (Chart 5). Historical emissions levels from 1990 were considered to set reduction targets that were consistent with the ongoing climate policy discussions. In 2020 the EU economy had already achieved an overall emissions reduction of 34.4% compared with 1990 levels, although a rising trend (of about 4 percentage points) was recorded in 2021 and 2022, due to the rebound from the large-scale shutdown of business activities during the COVID-19 pandemic. By 2030 the accelerated and late-push transitions would have achieved almost the same emission reductions in the euro area as implied by the NGFS net zero 2050 pathway, while the delayed transition was positioned on the NDCs pathway. It is important to note that the NGFS scenarios do not capture the whole spectrum of emission pathways that are compatible with net-zero emissions by 2050, but rather set out the optimal path for achieving the end-of-century temperature targets. They nonetheless provide a useful benchmark for evaluating the ambition of the new ECB transition scenarios.

Under the accelerated transition and late-push transition scenarios the level of GHG emissions in 2030 would coincide with that expected under the NGFS net zero 2050 scenario. Despite differences in the transition timeliness, the level of ambition embedded in both scenarios would be sufficient to keep the economy on the optimal path to reach net-zero emissions by 2050, as implied by the NGFS climate models. By the end of 2030 the two scenarios would record an overall 67% decrease in the level of GHG emissions as compared with the 1990 level, with only half of this decrease having been achieved by 2022. Such a drastic reduction is necessary to keep the economy close to a pathway that is compatible with the totemic climate target of limiting the increase in temperature to maximum of 1.5°C by the end of the century.

The delayed transition scenario has a less ambitious decrease in aggregate GHG emissions, implying higher temperature increases and greater physical risk in the long term. This scenario brings the economy onto the same track as under the NGFS NDCs scenario, under which only energy and emissions targets currently pledged would be pursued and reached in all countries. These targets would be reached with slower technological changes and milder policies compared with the accelerated and late-push transitions. On the other hand, the lesser effort put into reducing emissions implies that only a less ambitious temperature target of +2.6°C could be achieved by the end of the century, which would have more severe consequences for physical risk in the long term compared with the accelerated and late-push transition scenarios.

Chart 5

GHG emissions' pathways were calibrated to assess the impact of transition policies on the real economy



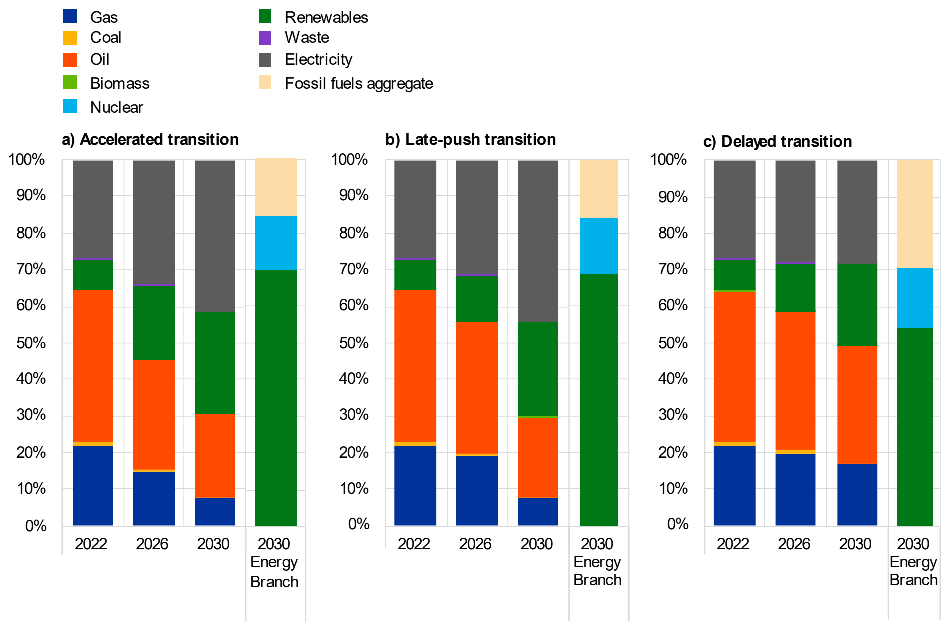
Source: ECB calculations based on European Environmental Agency (EEA), Eurostat and NGFS climate scenarios data.
Notes: Historical aggregated data on emissions were provided by the EEA and available until 2020. Quarterly emissions data for 2021 and 2022 were taken from Eurostat and aggregated at yearly frequency to complete the time series. The temperature increase refers to the year 2100. The emissions pathways until 2050 correspond to the NGFS net zero 2050 (+1.5°C), nationally determined contributions (+2.6°C) and current policies (>+3°C) scenarios.

Decarbonisation of energy consumption

During the transition, energy consumption would shift from carbon-intensive sources to electricity and renewable technologies, such as solar and wind energy. On aggregate, under the accelerated and late-push scenarios, the share of renewables-based energy directly consumed by non-energy sectors would increase by up to 20 percentage points (+300%) between 2022 and 2030, while the increase that is achievable with a delayed transition would only be about 15 percentage points (**Chart 6**). At the same time, more electricity would be generated by renewable energy until 2030, leading to a decline in indirect (i.e. Scope 2) GHG emissions. In 2022 electricity made up around 30% of total euro area energy consumption, of which 24% was based on renewable energy sources. In 2030 electricity would represent around 42% of the energy mix of final consumers under the accelerated and late-push transition scenarios, of which 70% would be generated from renewables. Under the delayed transition, the share of electricity in the energy mix would remain constant, with only 54% being generated from renewables until 2030.

Chart 6

Energy mix for final consumers and for electricity generation in 2030 (euro area aggregate)

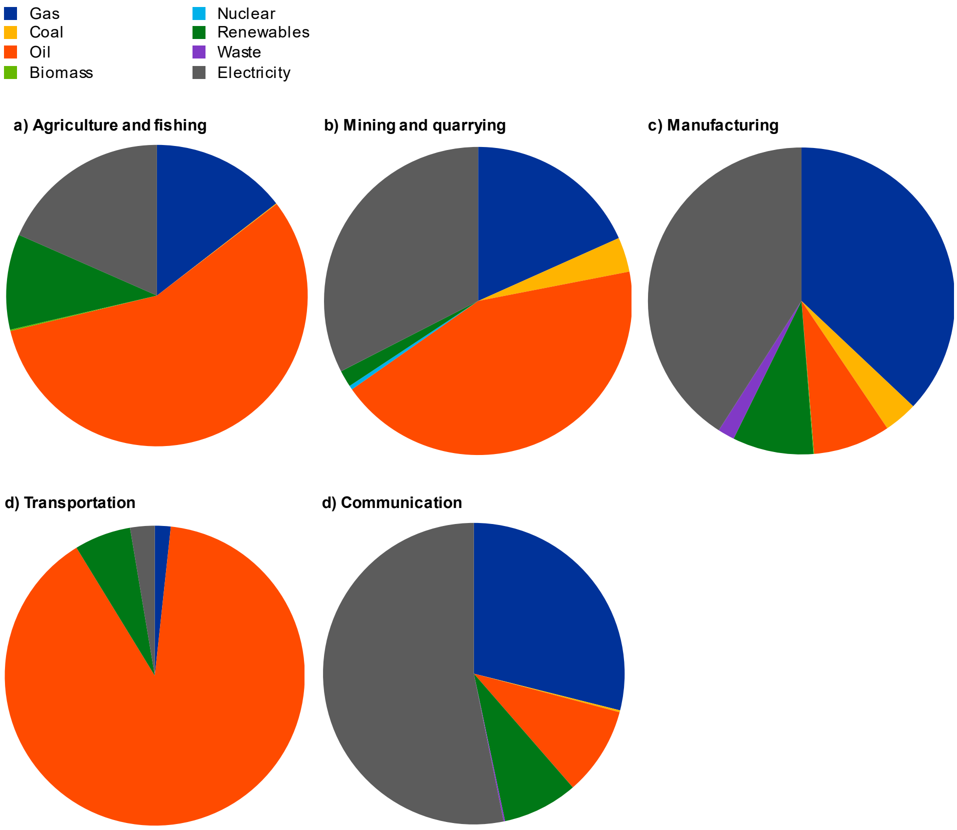


Source: ECB calculations based on Eurostat and NGFS climate scenarios data.

Some sectors are structurally more reliant on carbon-intensive energy sources than others due to the nature of their businesses (Chart 7). Capturing differences in the mix of primary energy sources across sectors is crucial to properly assessing the impact of transition policies. Sectors such as agriculture and transportation will most likely continue to rely substantially on brown energy sources, such as oil and gas, given that the electrification of certain vehicle categories is unrealistic in the short term. Other sectors that already rely heavily on renewable energy or electricity will continue to electrify their business activities during the transition process, resulting in higher consumption of renewables-based electricity.

Chart 7

Energy mix varies substantially across sectors



Source: ECB calculations based on Eurostat and NGFS climate scenarios data.
Notes: Data refers to the year 2020.

The electricity sector will play a crucial role in the transition towards net zero. If the electricity sector fails to switch to greener input sources, high fossil fuel prices in the future will translate into high electricity prices. Under the transition scenarios, the electricity sector would therefore be incentivised to transition rapidly towards renewable-based electricity production. Electricity prices were projected to increase in the short term due to a period of intensified green investments. In the medium to long term, however, renewables-based energy was expected to become cheaper thanks to cheaper production costs (economies of scale) and investment costs (more efficient production) (IEA, 2022a and 2023).

Transition efforts would differ substantially across euro area countries, depending on the composition of the primary energy sources of their electricity sector. Given that the distribution of electric power is mainly a domestic business,[23] it is essential to capture how electricity production in each country combines brown and green energy resources to sustain electricity demand. To illustrate this, **Chart 8** compares the energy mix employed for electricity generation in Germany and the Netherlands. Since 2020 Germany has relied on fossil fuels,

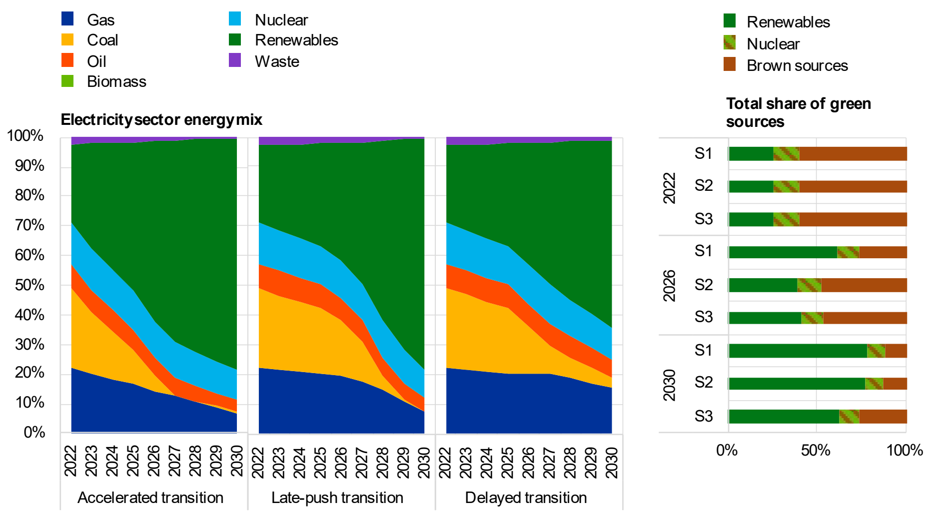
23 The share of electricity imported in the EU is around 3% (Eurostat).

including coal, gas, oil and municipal waste, for about 60% of total energy inputs. Coal, which represented about 30% of the total energy mix in 2020, would be fully substituted with renewables under the accelerated and late-push transitions, and its share would be reduced to 5% under the delayed transition scenario. On the other hand, the Netherlands relies on gas and oil for around 70% of total energy inputs. By 2030 the relative increase in the share of renewable energy would be larger in the Netherlands than in Germany, although the Netherlands would still be more reliant on brown energy sources (up to 55% in the Netherlands compared with 30% in Germany).

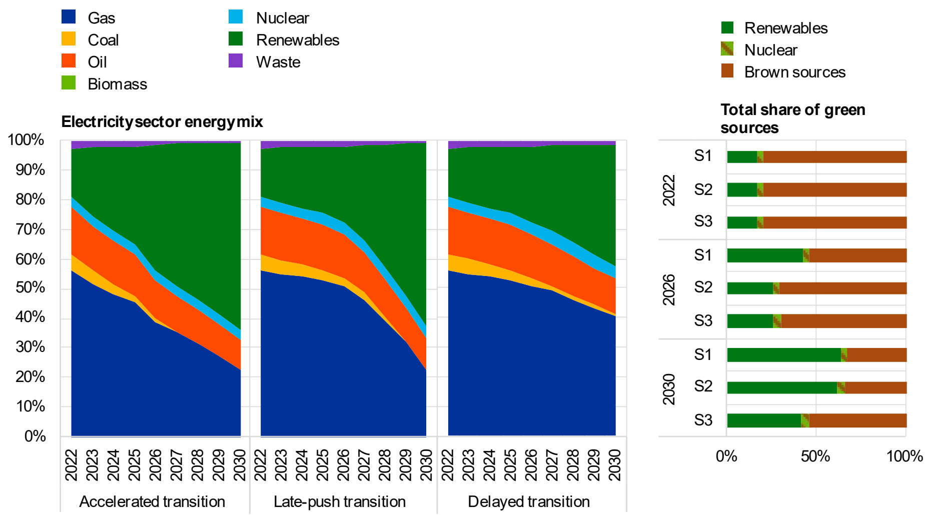
Chart 8

The electricity sector shifts to green sources for electricity and heat generation

a) Germany



b) The Netherlands

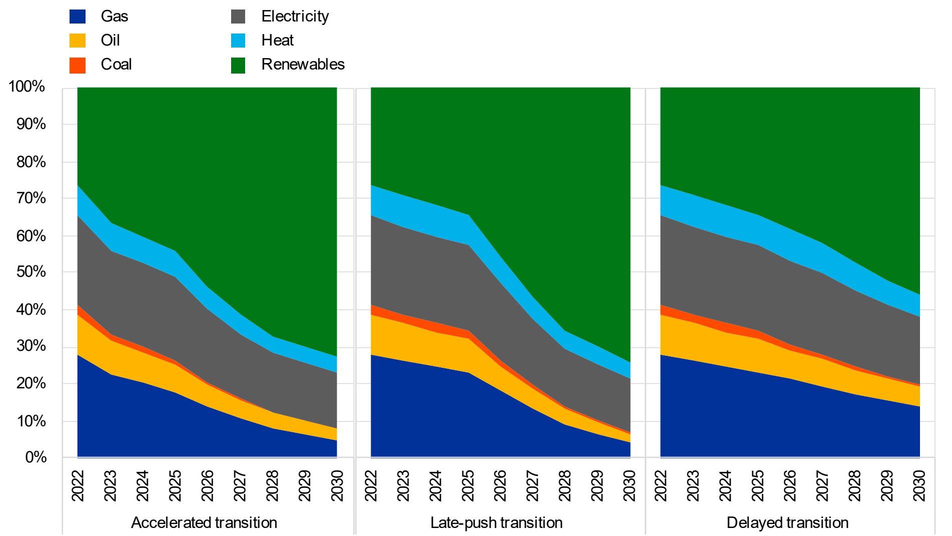


Source: ECB calculations based on Eurostat and NGFS climate scenarios data.
Notes: The energy mix of the electricity sector is calculated by considering the primary energy sources used as inputs for electricity and heat generation and the overall energy consumption for other support activities. S1, S2 and S3 refer to "Accelerated transition", "Late-push transition" and "Delayed transition" respectively.

Beyond the corporate sector, the transition to a greener economy is expected to have a strong effect on households' energy consumption. In the euro area, the energy mix of households is mainly composed of gas, electricity and renewable energy, and a minor share is represented by oil, coal, and heat. The shift to renewable energy is mainly driven by the adoption of photovoltaic and solar energy technologies, which would occur at a very different pace across scenarios. Under the accelerated and late-push transitions, the reliance on renewables would increase from 35% in 2022 to 72% in 2030, while under the delayed transition the share of renewables would reach just 55% in 2030 (**Chart 9**). Furthermore, under the accelerated and late-push transition scenarios, coal consumption would halt and gas consumption would be cut by 50% until 2030. Under all scenarios, the share of electricity consumption would slightly reduce over time as a result of the increased energy efficiency of residential buildings and stronger reliance of households on direct consumption of renewables.

Chart 9

Households' investments in photovoltaic and solar technologies result in a consistent increase in the share of renewables in the energy mix



Source: ECB calculations based on Eurostat and NGFS climate scenarios data.

Energy prices

Electricity prices reflect the most recent developments in the European energy market and are expected to increase with transition to net zero[24] Electricity prices have increased by an average of 89% across euro area countries since 2020, climbing from €86 to €163/MWh. The green transition will lead to further increases in electricity prices due to higher demand for electricity and large green investments by

[24] Electricity and gas prices were sourced from Eurostat and updated up to the second quarter of 2022. The level of prices observed around June 2022 was comparable to the prices observed in January 2023. To avoid unrealistic projections, the abrupt and exceptional increases observed during the summer of 2022 were not considered.

the electricity sector in renewables-based energy production (**Chart 10**, panel a).[25] Towards the end of the horizon, electricity prices would start to decline again under both the accelerated and late-push transition scenarios, thanks to a larger share of renewable energy in electricity production and cheaper production costs for renewables-based electricity. Fossil fuels would become more expensive over time, but their usage for electricity generation would shrink sufficiently fast to limit any pass-through to electricity prices. Under the delayed transition scenario, electricity prices would climb at a constant and lower pace and would be at their highest in 2030, due to lower substitution of brown sources as an input in electricity production and slower catch-up of investments in renewables-based energy.

Oil and gas prices were updated to account for the latest trends in the energy market and incorporate the projections of both the EU-wide stress test and the NGFS climate scenarios. In 2022 gas prices saw a 150% increase in the euro area compared with pre-pandemic levels. Crude oil prices recorded an extraordinary increase and peaked around June 2022; however, they had already reverted to pre-pandemic levels towards the end of that same year. Under the EU-wide stress test baseline scenario, gas and oil prices are projected to stay constant until 2025. Under the accelerated transition scenario, the start of the transition in 2023 would have a limited impact on oil prices but lead to an immediate increase in the price of gas, as a result of unfavourable carbon taxation (**Chart 10**, panel b). This would act as an additional incentive for firms to transition away from brown energy sources to green. Until 2030, gas prices would be the highest under the delayed and late-push transition scenarios given that carbon prices would need to increase more strongly than under the accelerated transition in order to achieve the emissions targets. This highlights the benefits of an early transition.

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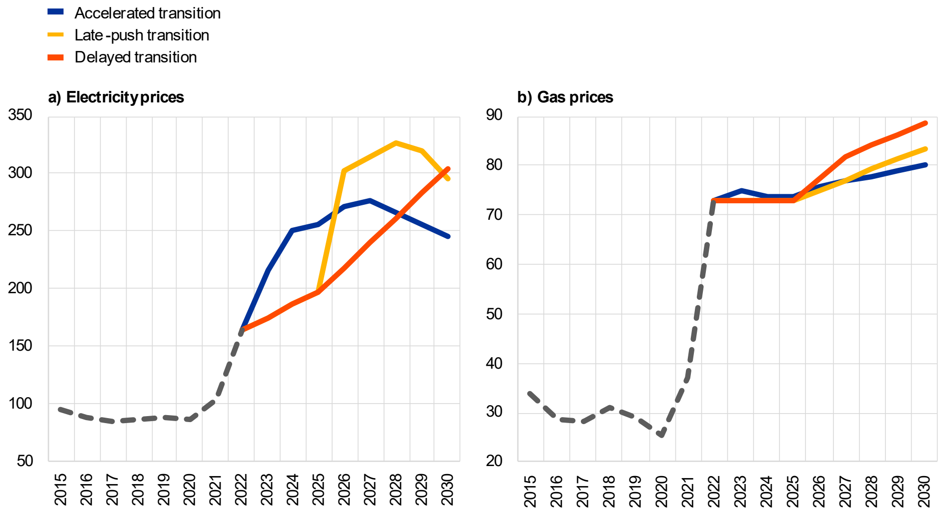
25 The NGFS long-term energy prices are mainly determined by the marginal production costs of the resources being exploited, but are also affected by demand changes, resource depletion and the development of exploration and exploitation technologies (NGFS, 2022a).

Chart 10

Electricity and gas prices have been deeply affected by the energy crisis, with further rises expected due to green transition

(EUR/MWh)



Source ECB calculations based on Eurostat and NGFS climate scenarios data.
Notes: The black dotted line represents historical data. For each country, Eurostat reports electricity and gas prices separately for different consumption buckets. An average for the euro area has been calculated.

Green investments

One of the key novelties of the current climate stress test exercise is the more granular and comprehensive calculation of green investments. For corporates, the two key pillars of green investments are (1) investments in carbon mitigation activities and (2) investments in the expansion of renewable energy capacity. For households, green investments mainly comprise investments in the energy efficiency of residential buildings and the adoption of renewable energy sources to reduce electricity consumption.

All firms would need to invest in carbon mitigation technologies in proportion to their reduction in absolute GHG emissions until 2030. The amount of investment needed by each individual firm would be proportional to the firm-level reduction in total GHG emissions envisaged between 2023 and 2030 (see **Chart 5**), multiplied by the cost of mitigating those emissions. The underlying mitigation costs were based on the calculations given in the IPCC report (IPCC, 2022) and were determined at a sector level, based on the mitigation options of the sector concerned and their potential contribution to net emissions reduction until 2030.

Firms in the electricity sector would be the main investors in renewables-based energy capacity. Their investments would be proportional to the individual amount of renewables-based electricity capacity generated across the euro area by each electricity company between 2023 and 2030.[26] The costs for investment in

[26] It was assumed that the higher the projected share of green electricity generated by an electricity firm, the higher those firms' investments in renewable energy would be.

renewable energy capacity are time and scenario dependent and were modelled using the 'experience curves' method[27], applying the approach adopted in Adrian et al. (2022). The concept assumes that the investment costs for renewables technologies would decrease over time owing to the 'learning-by-doing' effect as a function of (1) the aggregate cumulative renewable energy capacity, and (2) an energy-specific "learning factor", which suggests how much time and energy capacity would be needed to halve investment costs (see Annex A2 for further technical details).

Under the accelerated transition scenario, firms would benefit from a rapid increase in renewable energy capacity and reduced investment costs. Average investment costs would drop from around USD 1,200 per KWh in 2022 to close to USD 380 per KWh in 2025[28] under the accelerated transition scenario, driven by a sharp increase in total renewable energy capacity (**Chart 11**, panel b). Under the late-push transition scenario, investment costs would drop substantially in 2026 as the transition speeded up, and reach levels similar to the accelerated transition in 2030. The delayed transition scenario would have a much slower and linear decrease in investment costs given that renewable energy capacity would increase only gradually. While average investment costs would converge at around USD 300 per KWh in all scenarios at the end of 2030, the higher funding costs throughout the decade under the late-push and delayed transition scenarios would put more pressure on firms' indebtedness and make investments in renewable energy less attractive.

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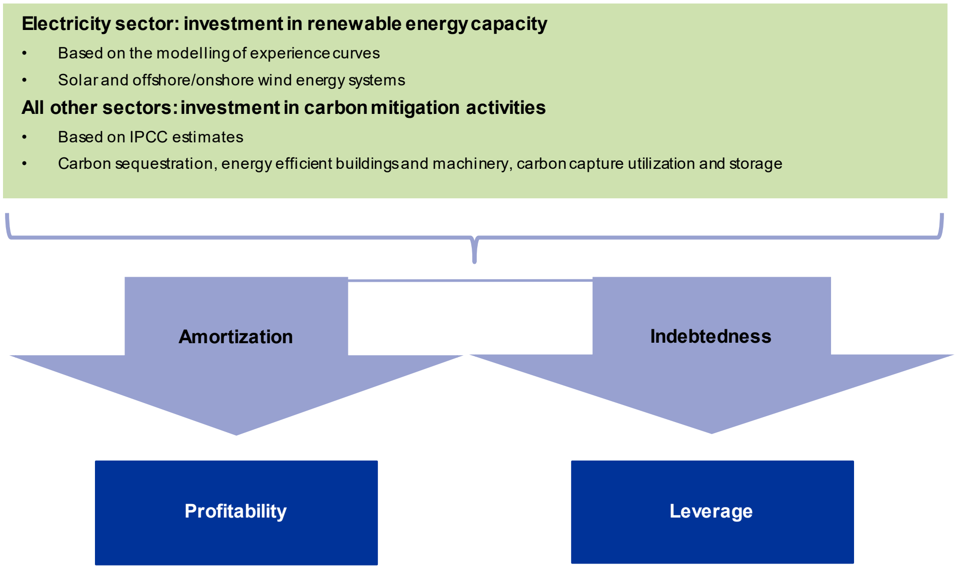
[27] Learning curves are used in industry to capture the efficiency gains from the experience of producing a good. The assumption is that the more times a task has been performed, the less time is required on each subsequent iteration (Wright's law). Different factors can be the drivers of learning, such as labour and resource efficiency, standardization, product re-design, network effects, etc.

[28] This corresponds to a cost reduction from EUR 1,100 per KWh to EUR 345 per KWh with the USD-EUR exchange rate as of June 2022.

Chart 11

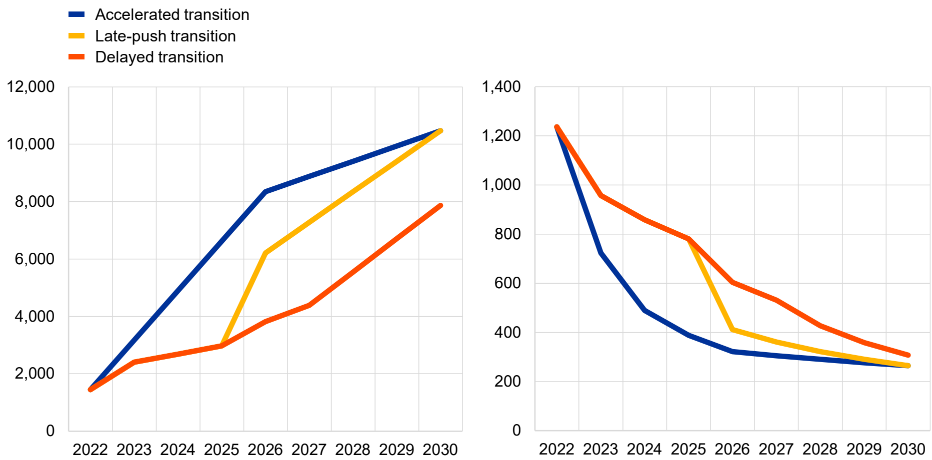
Modelling of green investments and renewable energy source investment costs

a) Types of green investments captured



b) Cumulative capacity in renewables-based electricity (LHS) and investment costs of renewable energy (RHS)

(left-hand scale: GWh; right-hand scale: USD (2021) / KWh)



Source: ECB and ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021) and IPCC (2022) data.

Notes: The costs for renewable energy capacity investment were calculated as the average costs for investment in global electricity capacity sourced from solar and onshore and offshore wind energy, weighted by the cumulative capacity of each renewable energy source in each year and scenario, and were based on global prices and capacities, on the assumption that regional prices are driven by movements in global markets. More details can be found in Annex A2.

As with firms, households were expected to incur green investments in proportion to the GHG emission reductions implied by the scenarios until 2030. Household emissions were approximated at country level based on information on the country-level energy mix of households and applying energy-specific conversion factors. The types of green investment considered were investments in the energy efficiency of buildings, changes in appliances and the installation of solar panels.[29] The cost of these activities were determined based on the activity-specific costs specified in the IPCC report (IPCC, 2022).

Sectoral gross value added

For the first time, the 2023 EU-wide stress test scenarios include a sectoral breakdown of gross value added (GVA).[30] GVA growth-rate projections were provided at country-sector level and were calibrated to also take into account the energy intensity of each sector and that sector's exposure to the future expected developments in the energy market. The transition to a greener economy, and more specifically the switch to non-brown energy sources, would have a positive impact on GVA given that it would boost investments and relieves some of the pressure imposed by the currently high energy costs. For this reason, under the accelerated transition GVA would grow significantly until 2025 and stay at its highest (on average) until 2027. This is in contrast to the situation under the late-push and delayed transition scenarios, under which the green transition was assumed to start three years later (**Chart 12**). Under the late-push scenario, the transition would be sudden and strong, and would result in an abrupt increase in electricity prices. GVA growth would therefore be slower than under the delayed transition, under which a delayed but smooth transition would play in favour of greater GVA increases.

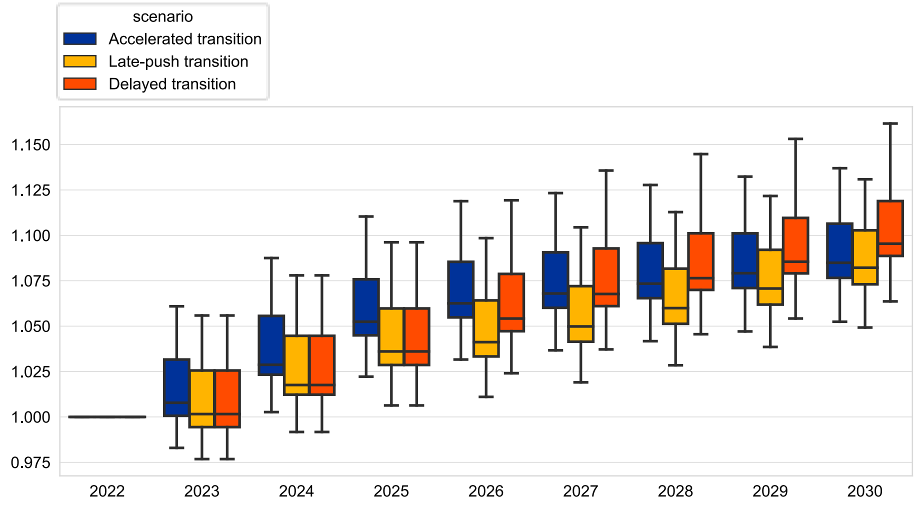
29 The assumption here was that households would only be allowed to invest in solar energy and not in wind and other renewables. Solar panels would allow in-house generation of electricity, leading to savings in households' energy costs.

30 GVA was defined as output (at basic prices) minus intermediate consumption (at purchaser prices). GVA was broken down by industry and/or institutional sector. The sum of GVA over all industries or sectors plus taxes on products minus subsidies on products gave the gross domestic product (source: Eurostat). GVA pathways were provided at NACE level 1 granularity. Additionally, the manufacturing sector was further broken down into low and high energy-intensive subsectors. More information can be found in the Template Guidance on the EBA website.

Chart 12

Distribution of GVA pathways at country-sector level

(Index, 2022 = 1)

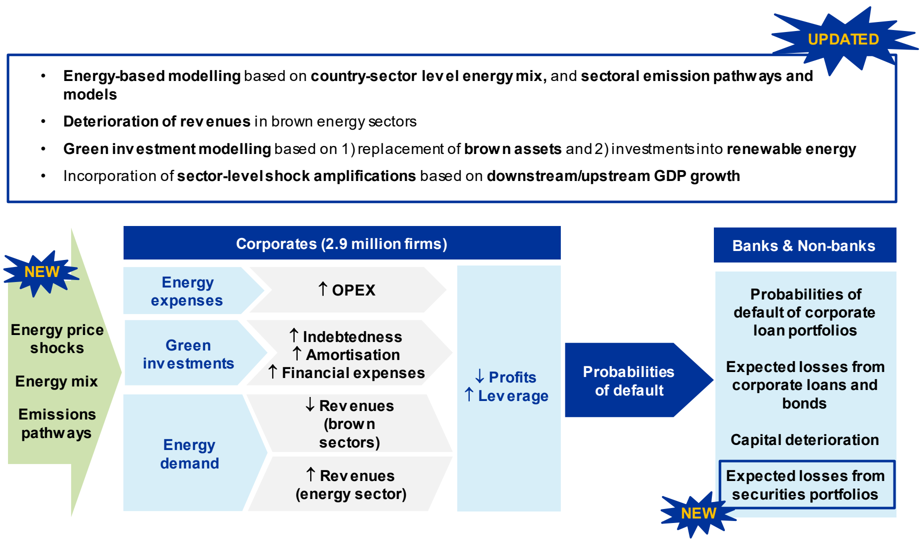


Source: ECB calculations based on BMPE macroeconomic projections and NGFS climate scenarios data.

4 Impact on corporates

This section assesses the impact of the three transition pathways on firms' balance sheets and probabilities of default. Leveraging the modelling framework established for the first ECB top-down economy-wide climate stress test (Alogoskoufis et al., 2021), the models for corporates were refined to account for more granular energy-related and sectoral dynamics and were recalibrated based on more recent data with extended coverage. **Figure 4** illustrates the transmission of the relevant transition risk drivers to firms' balance sheets and ultimately to financial institutions' portfolios. Micro-founded, firm-level models were used to estimate the impact of transition risk on firms' energy expenses and green investments, and on energy-sector revenues. The results were subsequently used to feed a credit risk model that estimated transition shocked firm-level probabilities of default (PD), based on changes in firms' profitability and leverage. In the final step, these firm-level PDs were mapped to granular data on corporate loan and bond instruments of financial institutions in order to calculate the expected losses of portfolios based on such instruments (see Section **6**).

Figure 4
Modelling framework for the transmission of climate transition risk to firms



Source: ECB.

In the short term, transition risk would impact firms' profitability through a supply-side, and partially carbon tax-induced, energy price shock, which would add to firms' production costs and operating expenses. The extent to which firms would be prone to energy price shocks would depend on their energy mix and level of brown energy and electricity consumption. Firms' absolute energy consumption at the starting point would depend on their absolute Scope 1 and 2 GHG emissions and the energy mix of the respective country sector. Energy expenses were determined by combining the projected consumption with the projected price pathways of each energy source. Sectors heavily relying on brown energy sources, and particularly energy-intensive firms, would experience a larger increase in energy expenses, and a proportional increase in operating expenses, as a result of gas and oil price shocks. It was assumed that firms would reduce their exposure to this type of shock during the transition process by shifting their energy mix towards greener energy sources.[31] Electricity was expected to play an important role in transitioning. Throughout the transition process, it would be generated with an increasing share of renewables in the energy input, enabling firms to gradually offset the energy-induced increase in operating costs while simultaneously reducing their carbon footprint.

Higher energy prices and climate change concerns would provide an incentive to invest in carbon mitigation activities and renewable-based energy. In our framework, funds for green investments were raised primarily through bank loans, thus increasing firms' indebtedness and interest rate expenses. Firms would have to invest in carbon mitigation activities to replace their current stock of brown assets and reduce their carbon footprint. At the same time, economy's renewable energy capacity would need to increase to meet the higher demand for non-polluting energy. In line with this, investments in renewable energy would mainly be taken up by the electricity sector to meet the higher demand for green energy of other sectors, assuming that renewable energy was then distributed to firms in form of purchased electricity. The investment costs for the generation and supply of renewable energy were assumed to be time and scenario-dependent and were modelled using the method of 'experience curves' (see Section 3.2 and Annex A2 for further details).

A key aspect of the transition towards a net-zero emissions economy would be the gradual phasing-out of coal and gas production, which would create transition winners and losers. On the one hand, renewable energy suppliers, mainly electricity companies generating "green" electricity, would be the largest long-term winners of the energy transition. An increasing demand for renewables-based electricity would push up electricity prices and consumption at the onset of the transition, as well as generating first-mover advantages. On the other hand, brown energy suppliers, such as oil, coal and gas companies, would either completely change their business models or face a deterioration in profitability due to lower demand for brown energy, resulting in lower revenues for affected firms.

The subsequent sections describe in more detail the impact of transition risk on different elements of firms' balance sheets and, subsequently, on credit risks. Specifically, the focus is on the impact of transition risk on firms' energy expenses and green investments, and on the revenues of the energy sector. The final section shows how all these elements combined affect firms' PDs, highlighting the heterogeneous impacts of transition risk on different sectors. Technical details and descriptions of the formulas and projections applied can be found in Annex A2.

[31] For the purpose of this exercise, green energy was defined as renewables-based energy comprising biomass, hydroelectricity, wind electricity, geothermal electricity and heat, solar electricity, hydrogen, and ocean energy. For further details, see NGFS Technical Documentation V3.1.

4.1 Transmission channels

4.1.1 Energy expenses

The increase in fossil fuel and electricity prices caused by the green transition would result in substantial changes to firms' energy expenses and consumption choices. On the one hand, firms' energy expenses would increase in the short term given that an immediate switch to renewables would not be feasible. However, it was assumed that firms would increase their energy efficiency in the medium to long term and would skew their energy mix towards renewable energy sources, gradually relying less on (more costly) brown energy sources and reducing their carbon footprint at the same time.

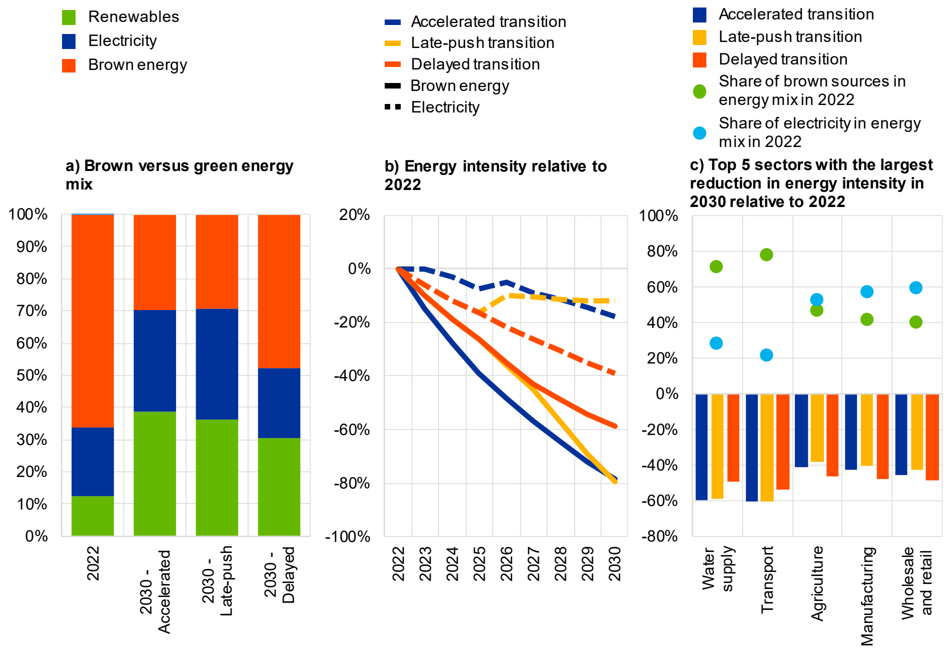
Under the transition paths assessed, energy efficiency would increase over the next eight years, with particularly strong reductions in brown energy intensity.[32] The relative share of renewable energy in firms' energy mix would substantially increase, from around 10% in 2022 to around 30% to 40% in 2030, thereby crowding out the consumption of brown energy sources (**Chart 13**, panel a). Consequently, brown energy intensity would fall by 60% under the delayed transition scenario and by 80% under the accelerated and late-push transition scenarios (**Chart 13**, panel b). As firms consume less energy relative to their revenues, electricity intensity would also decrease, albeit to a lesser extent than brown energy intensity. Under the accelerated and late-push transitions, electricity intensity would increase slightly in 2026, reflecting the stronger shift in demand from brown to (renewables-based) electricity stemming from the increased electrification of firms' business activities. Among the sectors that would experience the largest decrease in energy intensity, water supply and transport would become more energy efficient under the accelerated and late-push transition scenarios given that they initially relied on a higher share of brown energy sources in their energy mix (**Chart 13**, panel c); agriculture, manufacturing and retail would rely more strongly on electricity and therefore increase their energy efficiency the most under the delayed scenario, under which electricity intensity would decrease more strongly until 2030 than under the accelerated and late-push transition.

32 Energy intensity was defined as the amount of energy consumed (in GwH) to produce €1 in revenues, in aggregate terms.

Chart 13

Firms would become less energy intensive over time

(percentages)

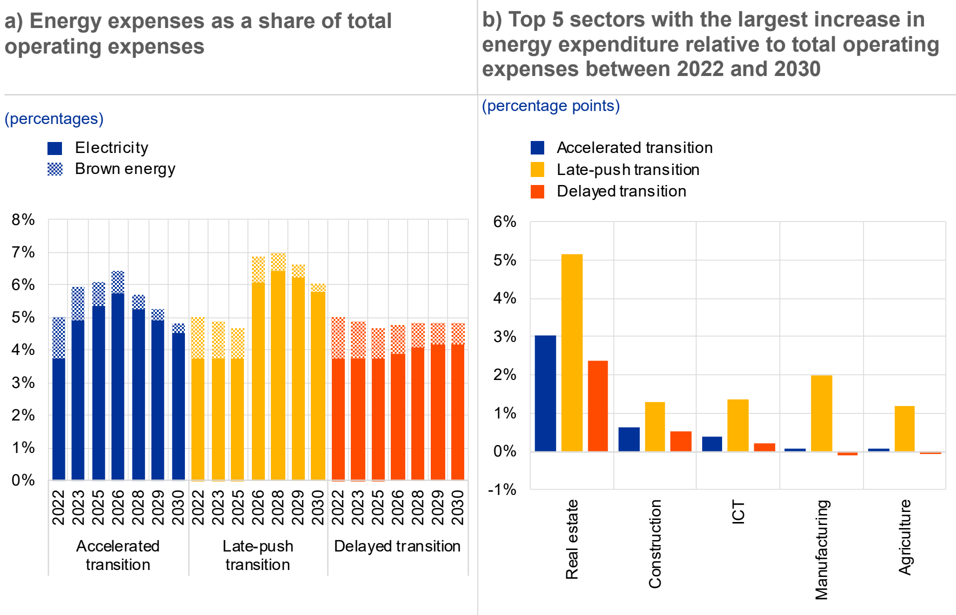


Source: ECB calculations based on Orbis, Urgentem, Eurostat and NGFS data.
Notes: Panels a and b exclude electricity firms. Brown (electricity) energy intensity is defined as the total annual consumption of brown energy sources (electricity) in GwH over total annual revenues. Brown energy comprises oil, gas, and coal energy.

Despite greater energy efficiency, higher energy prices would result in an increase in firms' energy expenses as a proportion of their total operating expenses, especially in the early stages of transition. By the end of the period, the share of brown energy expenses relative to total operating expenses would be more than halved under all scenarios (**Chart 14,** panel a). At the same time, the share of electricity expenses would increase under all scenarios, especially during the first years of transition when electricity demand would begin to rise. The largest increases in total energy expenses (relative to total operating expenses) would be experienced by the real-estate, construction, and information technology and communications sectors, whose expenses under a late-push transition would increase by up to 5 percentage points until 2030 (**Chart 14**, panel b).

Chart 14

Despite improvements in energy efficiency, firms' energy expenses would keep rising



Source: ECB calculations based on Orbis, Urgentem, Eurostat and NGFS data.
Note: Panel a excludes electricity firms. In Panel b, ICT stands for the Information and Communication Technology sector.

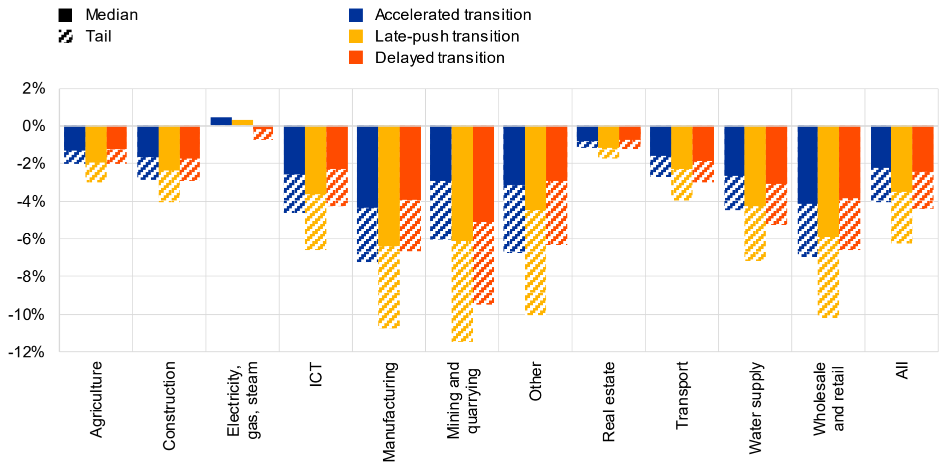
Higher energy expenses would result in a substantial decrease in firms' profitability, especially under the late-push transition scenario and in the tail of the distribution. Overall, profitability would decrease by 2 to 3 percentage points for the median euro area firm, and by twice as much for the median firm in energy-intensive sectors and for firms in the tail of the distribution (**Chart 15**). The impact on energy-intensive sectors would be the most severe. For the mining, manufacturing and retail sectors in particular, profitability for the median firm would decrease by 6 percentage points as a result of a stronger increase in energy-induced operating expenses. In contrast to other sectors, the delayed transition scenario would be more harmful than the accelerated transition for mining firms. The median decrease in profitability in the mining sector would be twice as high under the delayed transition scenario than under the accelerated transition; this would be due to smaller gains in energy efficiency and expenses, exacerbated by lost revenues due to lower demand for brown energy. The profitability of energy utility firms[33] would be the least affected; the median firm in this sector would experience a minor increase in profitability by 2030 under the accelerated and late-push transition scenarios. This would be due to gains in energy efficiency and higher revenues stemming from selling green energy to other firms, as will be discussed in a later subsection.

[33] The utility sector (NACE letter D) consisted of 20,350 firms involved in the supply of electricity and 898 firms manufacturing and distributing gas.

Chart 15

By 2030 energy-intensive sectors would experience the largest deterioration in profitability due to higher energy expenses

Change in sector-level profitability due to energy expenses between 2022 and 2030
(absolute difference in percentage points)



Source: ECB calculations based on Orbis, Urgentem, Eurostat and NGFS data.
Notes: Tails are defined as the 25th percentile firm in terms of profitability changes between 2022 and 2030 in each sector and scenario. Profitability is defined as the net profit (operating revenues minus operating and financial expenses) before tax over total assets. ICT stands for the Information and Communication Technology sector.

4.1.2 Green investments

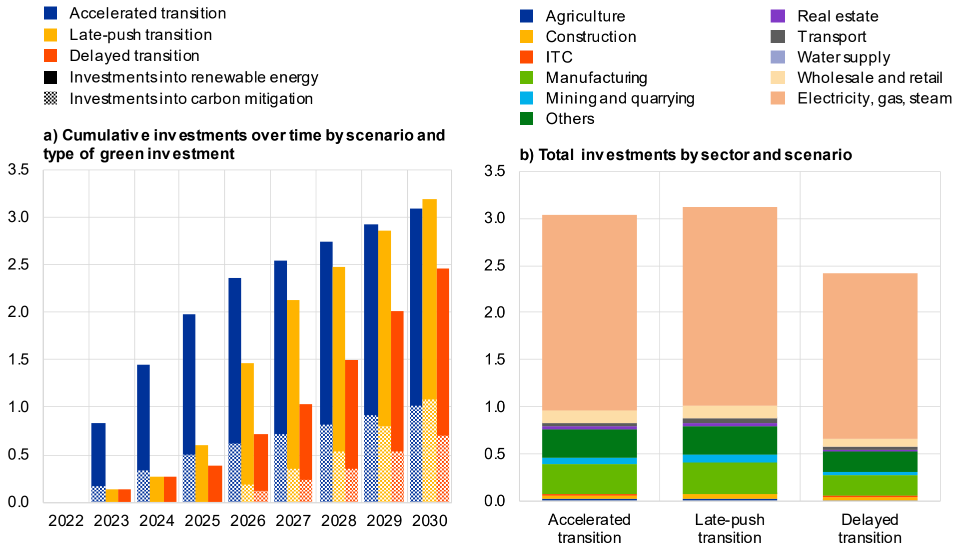
Higher energy expenses would incentivise firms to invest in carbon mitigation technologies and switch from brown to green energy consumption, while also reducing their carbon footprint. Under the climate stress test framework, green investments would be funded mainly through bank loans, which would increase firms' indebtedness and their financial expenses due to interest rate payments. At the same time, firms' amortisation costs would increase as a result of the accumulation of green assets.

The accelerated and late-push transition scenarios would generate the largest green investments due to their more ambitious emission targets and more favourable investment costs. Chart 16, panel a, shows that under the accelerated transition scenario, firms would already begin to invest in green assets and renewable energy in 2023. Annual investments would more than double until 2026, after which the investment rate would slowly start to slow down. Under the late-push and delayed transition scenarios, firms would invest in renewable energy capacity from 2023 onwards, but investment in carbon mitigation would only start in 2026 at the start of the transition. Across scenarios, total cumulative investments would amount to around €2.5 to 3.2 trillion until 2030. Chart 16,panel b, shows that, across sectors, electricity firms would incur the largest investments, mainly in renewable energy capacity, followed by investment by firms in the manufacturing and mining sectors. While both the accelerated and late-push transition scenarios would reach the same renewable capacity levels in 2030 (see Chart 10), cumulative investments would reach slightly higher levels under the late-push scenario due to the later start of the transition which would induce a slower learning curve for renewable energy production and therefore more expensive investments.

Chart 16

Green investments would be the highest for electricity firms, particularly under the accelerated and late-push transition scenarios due to their more ambitious emission reduction targets

(EUR trillions)



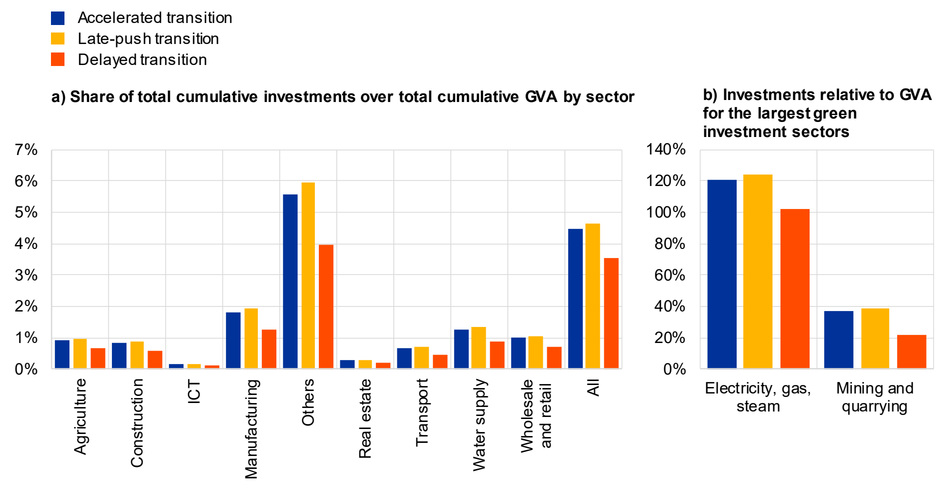
Source: ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021), and IPCC (2022) data.

Electricity firms would not only incur the largest green investments in absolute terms, but also relative to their GVA. Their total cumulative green investments as a share of total cumulative sector-level GVA would reach levels of between 3.5% and 4.5%, depending on the scenario, by the end of the period (**Chart 17**). Their green investment expenditures would exceed their total GVA by more than 100% until 2030, specifically what regards investments into renewable energy capacity. The mining sector would be the second biggest green investor. Given the large amount of brown assets it would have to replace by 2030, its total green investments would amount to almost 40% of its total GVA. For other sectors, such investments would reach between 1% and 6% of their respective GVAs and would be the highest under the late-push transition scenario.

Chart 17

Green investments relative to gross value added by sector

(percentages)



Source: ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021) and IPCC (2022) data. ICT stands for the Information and Communication Technology sector.

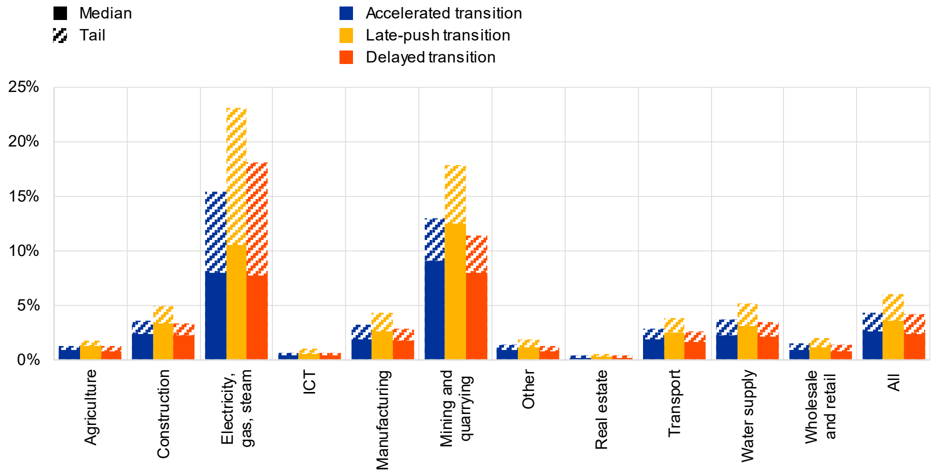
Green investments would predominantly affect the leverage and profitability of mining and electricity firms given the scale of transition required. The leverage ratio would increase by around 3 to 4 percentage points for the median firm across sectors, while it would increase by three to four times as much for the median firm in the mining and electricity sectors (**Chart 18**, panel a). In addition to higher indebtedness and leverage, green investments would lead to an increase in financial expenses and therefore a decrease in firms' net profits due to interest rate payments and the amortisation of green assets. The impact of green investments on firms' profits would result in an overall decrease in profitability until 2030 of 3 to 4 percentage points. As was the case with leverage, the impact on profits for mining and electricity companies would be greater. In contrast with the impact of energy prices on profitability (Section 4.1.1), firms in the tail of the distribution would not experience a disproportionate impact on their leverage and profitability relative to median firms. The only exception would be the indebtedness of electricity companies, where the increase in leverage would be around twice as large in the tail as for the median firm within the electricity sector.

Chart 18

Electricity and mining sector would experience the largest change in leverage and profitability due to green investments

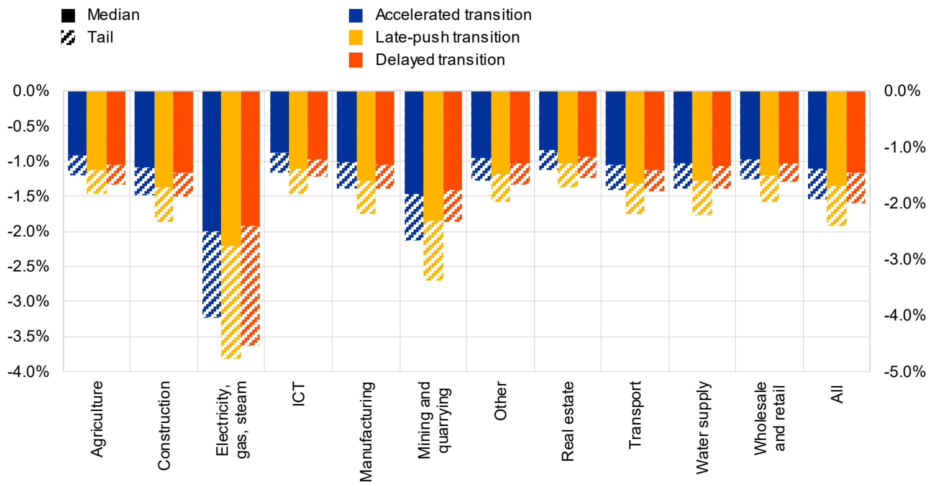
a) Change in sector-level leverage due to green investments between 2022 and 2030

(absolute difference in percentage points)



b) Change in sector-level profitability due to green investments between 2022 and 2030

(absolute difference in percentage points)



Source: ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021) and IPCC (2022) data.
Notes: Tails for leverage (profitability) were defined as the 75th (25th) percentile firms in terms of leverage (profitability) changes between 2022 and 2030 in each sector and scenario. Leverage was defined as total debt over total assets. Profitability was defined as the net profit before tax over total assets. Profitability was impacted by green investments through interest rate payments on green loans and rising amortisation rates for green assets. Panel b: the chart presents the impact of green investment on profitability in isolation from the impact of energy expenses on profitability, which is shown in **Chart 15**. ICT stands for the Information and Communication Technology sector.

4.1.3 Winners and losers of the green energy transition

The transition to a net-zero economy implies a decrease in demand for brown energy sources and a simultaneous increase in demand for green energy, revealing a first set of transition winners and losers. Although the full benefits of the green transition would materialise only in the long term, companies that changed their businesses to produce and supply renewable energy would already experience benefits from the green transition by 2030, in the form of higher revenues and profits. On the other hand, from the start of the green transition onwards, companies involved in the extraction, production and supply of oil, gas and coal should expect a fall in demand for their products due to lower consumption of emissions-intensive goods and services, resulting in lower revenues for this corporate sector[34].

Until 2030, the additional revenues generated by renewable energy suppliers would only partially offset the reduced revenues of brown energy suppliers. The increase in revenues of renewable energy supplier was assumed to be proportional to the marginal increase in aggregate demand for electricity over time, which would be different across scenarios. Additional revenues would start to materialise only from 2026 onwards under a late-push transition, when demand for electricity would increase due to the start of the green transition (**Chart 19**, panel a). In contrast, additional revenues under an accelerated transition scenario would materialise immediately and be equally distributed over the time. Under a delayed transition scenario, additional revenues would be relatively low and diminish until 2030, given that demand for renewable-based electricity would start to gradually stagnate from 2028 onwards. On average, cumulative additional revenues over the eight-year window would amount to around 4% of total revenues under the accelerated and late-push transition scenarios, and less than 1% in a delayed transition (**Chart 19**, panel b). The accelerated and late-push transition scenarios would lead to a wider upper tail for "winning" firms, suggesting that a disruptive increase in energy demand and prices would be particularly beneficial for the revenues of some green energy suppliers.

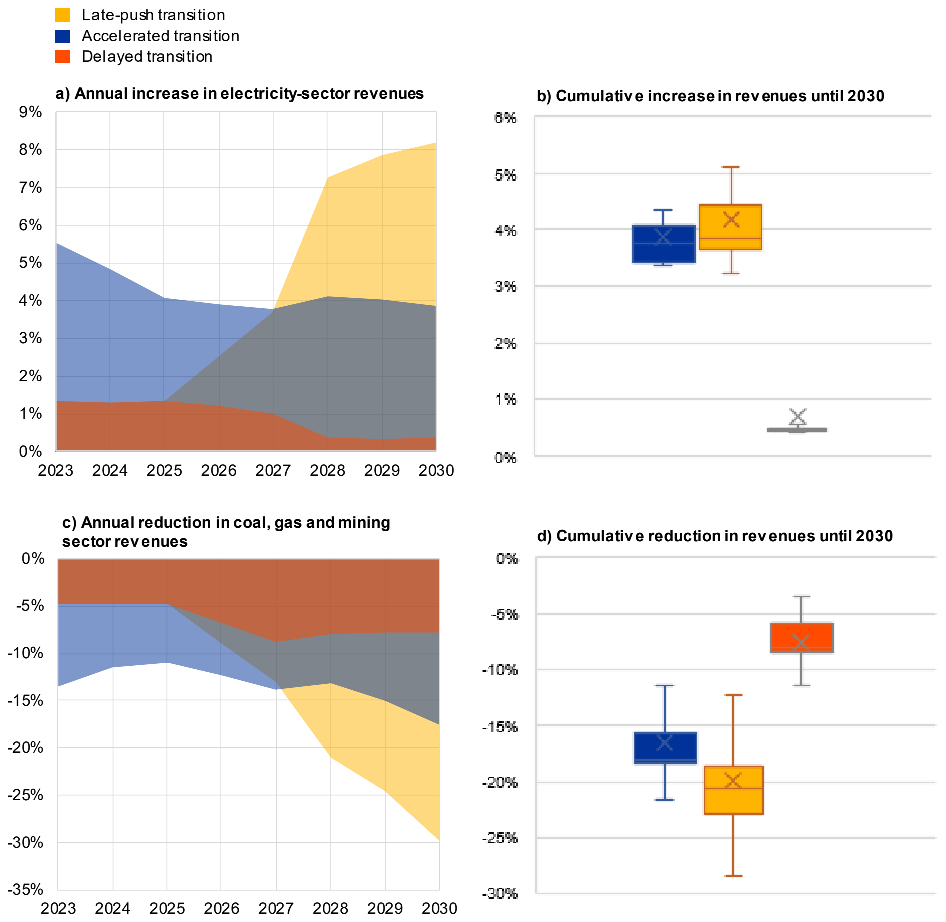
The reduction in the revenues of brown energy suppliers due to the transition would be substantially larger under the accelerated and late-push transition scenarios. The reduction in fossil fuel firms' revenues due to the energy transition was assumed to be proportional to the reduction in the consumption of coal, gas and oil of all other sectors, which would be different across scenarios. Brown energy suppliers would experience a deterioration in revenues already starting in 2023 (**Chart 19**, panel c). The accelerated transition scenario would result in reductions in revenues around three times higher than under the other two scenarios at the start of the eight-year horizon. A delayed transition would generate only moderate and stable reductions in revenues until 2030, while in the event of a late-push transition, revenues would start falling substantially from 2026 onwards when the net-zero transition would start. The average cumulated reduction in revenues until 2030 due to the transition would amount to around 15% to 17% under the accelerated and late-push transition scenarios (**Chart 19**, panel d). As was the case with the "winning" firms in the electricity sector, the tails of revenue losses for "losing" firms would be wider under a late-push transition scenario, indicating that some firms might be more severely affected under that scenario.

[34] Firms were classified as green energy suppliers if they operated in the electricity industry and belonged to the following NACE Level 4 sectors: 35-10, 35-11, 35-12, 35-13 and 35-14. Firms were classified as brown energy suppliers if they operated in the mining or electricity industry and belong to the following NACE Level 4 sectors: 05, 05-10, 05-20, 06, 06-10, 06-20, 35-20, 35-21, 35-22 and 35-23.

Chart 19

Brown energy suppliers would experience a decrease in revenues which would be only partially offset by the revenue increases of green energy suppliers

(percentage of baseline revenues)



Source: ECB calculations based on Orbis, Urgentem, Eurostat and NGFS data.
Notes: Panel a and b: 898 firms. Firms were classified as green energy suppliers if they operated in the electricity industry and belonged to the following NACE) Level 4 sectors: 35-10, 35-11, 35-12, 35-13 and 35-14. Panels c and d: 20,354 firms. Firms were classified as brown energy suppliers if they operated in the mining or electricity industry and belonged to the following NACE Level 4 sectors: 05, 05-10, 05-20, 06, 06-10, 06-20, 35-20, 35-21, 35-22 and 35-23. Baseline revenues were defined as the revenues of affected companies as projected on the basis of a no-transition scenario.

4.2 Corporate credit risk

The impact of green transition on firms' profitability and leverage was combined in this exercise to project their PDs until 2030 (Figure 4). Higher energy expense due to the energy price shocks and the green transition would decrease firms' profitability, thereby leading to higher firm-level PDs. Firms' higher indebtedness due to green investments would also increase their PDs over time. More details of how the results for profitability and leverage, set out in sections 4.1.1 to 4.1.3, were used to derive firm-level PDs are provided in Annex A2.

The results indicate that, at the end of the period, corporate PDs would increase the most under the late-push transition scenario, which would also

entail the largest risk for transition-vulnerable firms. The median corporate PD under the accelerated transition scenario would increase more at the start of the period due to the dual impact of both higher energy prices and transition shocks (**Chart 20**, panel a). Corporate PDs under the late-push transition scenario would show relevant increases only later but would result in the strongest increase by 2030 compared with 2022. At the end of the period, the distribution of corporate PDs would be wider under the late-push transition scenario, indicating more extreme behaviour in the tails. Comparing the median sector-level PDs at the start and at the end of the analysed period, the increases would be higher and more widespread across almost all sectors under the late-push and delayed transition scenarios (**Chart 20**, panel b).

The medium-term impact of transition risk would have long-term consequences for firms in terms of the impact of physical risk. The accelerated and delayed transition scenarios would lead to similar credit risk levels by 2030. It is only under the accelerated transition scenario that emissions reductions would be on a path to limit temperature increases to +1.5°C by the end of the century. According to NGFS projections, if global climate policy action were to mirror that of the EU, the impact of long-term physical risks under the delayed transition scenario would be much more severe.[35] Moreover, corporate credit risk would already start to decrease in the second half of the period under the accelerated and late-push transition scenarios; under the delayed transition scenario, it would, however, continue to rise. Credit risk is expected to increase further after 2030 in the delayed transition, first because the peak of the transition would not have been reached, and second, due to a higher temperature increase until 2050 (as illustrated earlier in **Chart 5**), leading to higher long-term physical risk. Overall, the delayed transition scenario implies not only that transition risk would continue to negatively affect corporations for a longer period, but also that physical risk would have a stronger effect on the economy.

The transition impact would be largely heterogeneous across sectors, with the strongest increases in credit risk being experienced in the electricity, mining and manufacturing sectors. The largest increase in sector-level PDs until 2030 would be seen in the mining and manufacturing sectors, where the median firm PD would increase by up to 1 percentage point compared with an increase of only 0.5 percentage points for median corporate PDs across all sectors (**Chart 21**). Looking at the tails of the mining and manufacturing sectors, the 75th percentile increase in corporate PDs would be around two to three times higher than for the median firm within these sectors. It is worth noting that PDs of mining firms would be much more negatively impacted under a delayed transition scenario than under an accelerated transition. This is because of the slower improvement in the energy efficiency of mining firms and their greater reliance on brown energy sources until 2030 under a delayed transition scenario.

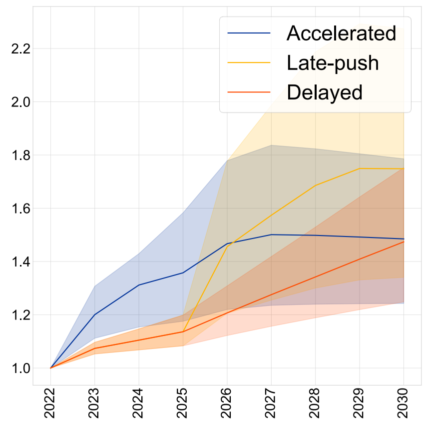
35 Temperature increases would depend on the action taken at global level. For this reason, the considerations as regards physical risk would hold true only on the assumption that each country would follow its respective NGFS trajectory. In other words, an accelerated transition would bring its benefits only if all countries contributed to it by frontloading their respective NGFS-implied transition path.

Chart 20

Credit risk would increase due to transition risk until 2030, especially under a late-push transition scenario

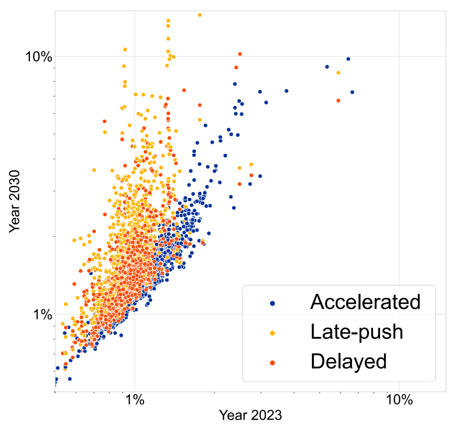
a) Change in probabilities of default relative to 2022

(index, 2022 = 1)



b) Median probabilities of default by sector

(index, 2022 = 1)



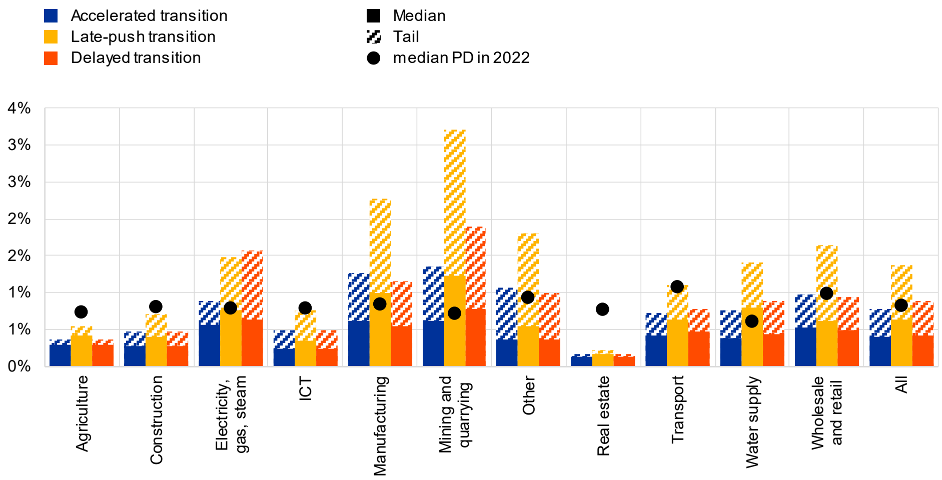
Source: ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021) and IPCC (2022) data.
Notes: Panel b: The probability of default is shown in logarithmic scale. Each dot corresponds to a NACE 4 sector. Sector-level PDs above 15% and below 0.5% have been excluded (820 out of 33,444 observations).

Chart 21

By 2030 the strongest rise in probability of default would be in energy-intensive sectors

Change in sector-level probabilities of default between 2022 and 2030

(absolute difference in percentage points)



Source: ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021) and IPCC (2022) data.
Note: Tails were defined as the 75th percentile of firms in terms of PD changes between 2022 and 2030 in each sector and scenario. ICT stands for the Information and Communication Technology sector.

5 Impact on households

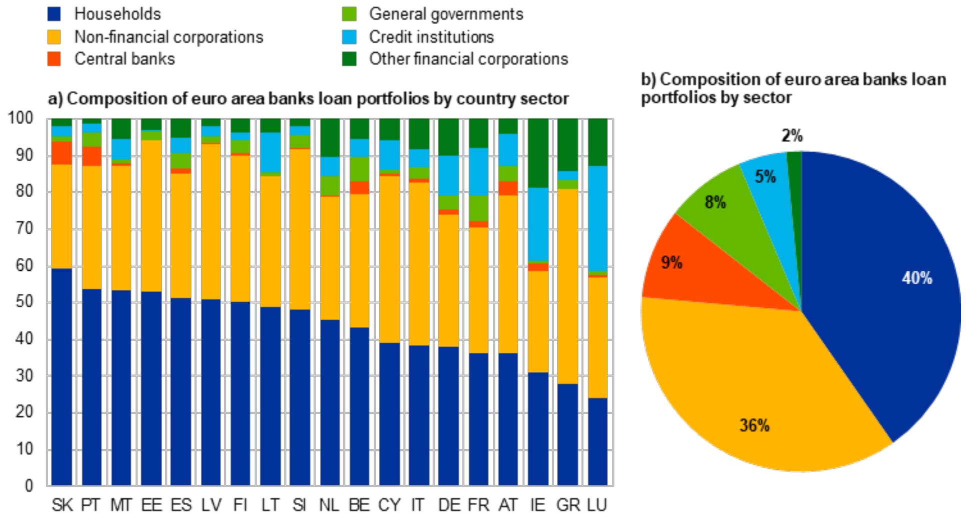
5.1 Transmission channels

The green transition would have a direct impact on households, with consequent spillovers to the financial sector. The first ECB top-down, economy-wide climate stress test focused on assessing the impact of climate risk on NFCs and banks' corporate portfolios, therefore providing a granular but only partial picture of banks' overall exposure to climate risks. The household sector represents an equally important category of banks' counterparties. Indeed, loans to households and NFCs constitute around 40% and 37% of euro area banks' total loan exposures respectively. The share of banks' loans to households has been broadly stable over time, but important differences exist across countries (**Chart 22**). Transition risks affecting the household sector might therefore have quantitatively meaningful implications for the banking system, with heterogenous effects across countries.

Chart 22

Households make up the largest share of euro area banks' loan portfolios

(percentages, quarter 3, 2022)



Source: ECB data and calculations.
Note: Household loans includes both mortgage and other type of household loans (secured and unsecured).
In panel a, the bars are sorted by the share of loans to households in descending order.

The green transition would affect households in terms of the energy efficiency of their buildings and their energy consumption. In 2020 across the euro area, space and water heating accounted for more than 70% of Scope1 and Scope 2 emissions of households and fully electrically powered appliances represented 19% of household emissions[36] (**Chart 23**). According to the International Energy Agency, around 8% of global GHG emissions could be cut through behavioural changes, from choosing greener means of transport through cutting air travel to using energy-

[36] While (reported or estimated) emissions are available at very granular level for corporates, here they have been estimated based on the energy mix of the household sector at country level.

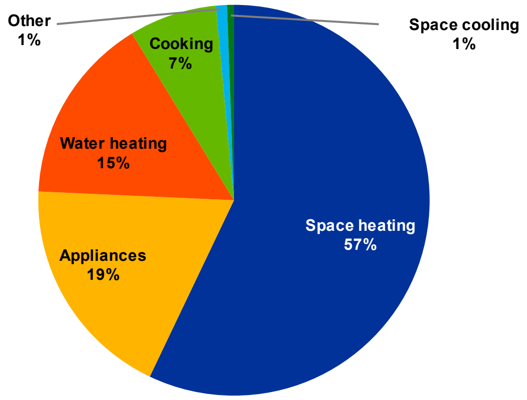
efficient appliances (IEA, 2021). Investments in improving the energy efficiency of residential buildings and of appliances would drastically reduce overall emissions. In addition, the installation of solar panels on new and existing buildings would foster electrification and the switch to renewable sources, decreasing the demand for other energy sources and leading to a subsequent decrease in emissions.

Chart 23

Space and water heating account for most household GHG emissions

Household GHG emissions by usage

(percentages, 2020)



Source: ECB calculations based on Eurostat and Greenhouse Gas Protocol data.

To foster the transition to net-zero, the European Commission is setting ambitious energy efficiency standards for buildings as part of the "Fit for 55" package[37]**.** Under that package, all new residential buildings will be required to have an Energy Performance Certificate (EPC) level of at least C and all existing homes to reach at least level D by 2033 through renovation. The aim is to revise the recast Energy Performance of Buildings Directive not only to improve the energy performance of buildings but also to reduce the reliance of the real-estate sector on fossil fuels. In this regard, solar energy installations would have to be installed on all new residential buildings by 2030.

Changes in the energy efficiency requirements for buildings might adversely impact the net worth of homeowners and the collateral value of their homes. Households would see their properties' value decrease if the investment required to meet higher energy efficiency standards was too high. In addition, improving the energy efficiency of buildings would require households to contract loans and increase their indebtedness, thereby potentially impacting on their solvency.

Furthermore, as highlighted by the recent energy shock, changes in energy prices impact households' energy expenses and consequently their discretionary income.[38] Higher energy prices reduce households' purchasing

[37] For further information, see the Council of the EU press release: "'Fit for 55': Council agrees on stricter rules for energy performance of buildings".

[38] In the model, only energy expenses and debt repayments (linked to green investments) are subtracted from disposable income. However, for simplification, the term discretionary income is used to refer to disposable income net of energy expenses and debt repayments (linked to green investments).

$$Discretionary\ Income_t^{c,s} = Disposable\ Income_t^{c,s} - Energy\ Expenses_t^{c,s} - Debt\ Repayments_t^{c,s}$$

power by directly increasing their energy expenses, as will be elaborated on further in the subsequent section. Moreover, this impact is heterogeneous across quantiles of the population, as it weighs disproportionally on lower-income households as compared with those in the middle and higher-income segments. Lower-income households spend a larger proportion of their income on basic goods, such as food, energy, and utilities, all of which are strongly affected by energy price increases. At the same time, low-income households tend to have a higher default risk than the other income segments (Dieckelmann et al., 2022).

The climate stress test framework was extended in this latest exercise by adding a module that analyses the impact of transition risk on households' solvency. The new module assesses households' financial resilience based on bank-to-country-level information on mortgages, combined with country-level information on households' energy consumption, emissions, and investments, as well as financial and macroeconomic variables (see Annex A3 for further information on the data sources).[39] Since it is not possible to measure individual households' PDs given the absence of granular data[40], the model was calibrated using country-level information on the share of new defaulted mortgages over the total of mortgages issued by banks to households in various countries. Specifically, the following aggregate ratio was defined at country-level, to track developments in the credit quality of banks' loans to households (HH):

$$CQD_t^c = \frac{\text{New defaulted loans to HH}_t^c}{\text{Total loans to HH}_t^c} \quad (5.1)$$

Transition risk would be channelled to households through energy expenses and green investments, which have a direct impact on households' discretionary income[38] and indebtedness. Higher energy expenses due to the green transition would diminish income. Green investments would increase debt levels, on the one hand, and decrease income, on the other, owing to debt repayments and interest rate costs. Both of these factors, together with developments in real-estate prices and long-term interest rates, would affect the credit quality of residential mortgages, with consequences in terms of potential losses on banks' mortgage portfolios and of banks' capital positions (**Figure 5**). In line with the approach used for corporates, the model for households was calibrated by identifying the relationship between these variables and credit quality deterioration (CQD) based on historical data; the result was then used to project

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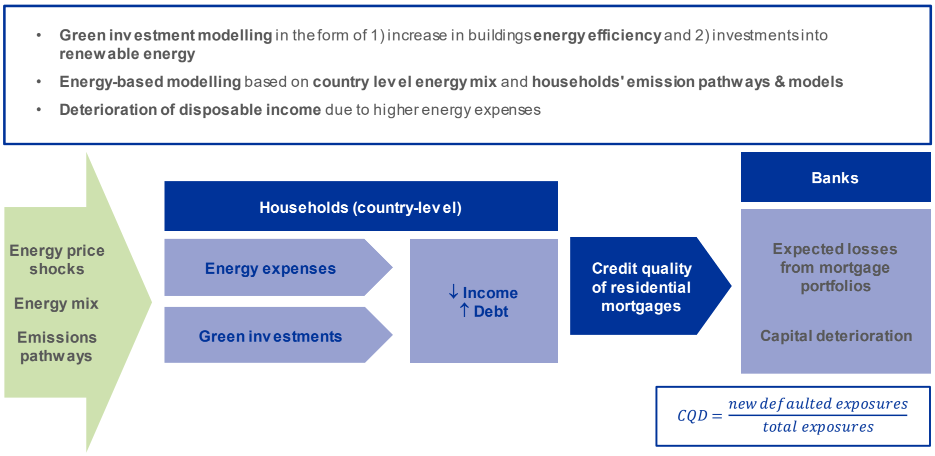
Where c denotes the country of residence of the household that contracted the mortgage, s denotes the scenario and t denotes the year. See Annex 3: Households model for further details of the formulas.

39 Households' ability to repay their loans was assessed on the basis of three different scenario assumptions that were designed along the same lines as for corporates. The main scenario variables for households were: energy prices, emission pathways, energy mix, real-estate prices and long-term interest rates. The development of these variables was fully consistent with the main narrative of the scenarios (see Section 3 and Annex 1 for technical details of the scenarios).

40 Since the euro area credit register does not yet cover exposures to households, a more granular approach was not possible at this stage. Information on euro area banks' loans to households was available only at aggregated level and with a breakdown by country of residence of the counterparty.

CQD over the time horizon of the three scenarios considered (for more further information on the model, see Annex A3).

Figure 5
Climate risk transmission to households



Source: ECB.

5.2 Household credit risk

The evolution of households' energy expenses shows the clear benefits of an early and rapid transition. The changes in energy expenses would be a combination of energy prices, which would increase in the first years of transition, and energy mix, which would become greener under the most ambitious transition scenarios. During the first three years, from 2023 to 2025, energy price shocks would lead to a 10% increase in households' total energy expenses under an accelerate transition scenario, which is double the figure under the other scenarios. After 2025, households' energy expenses would stabilise under the accelerated transition, and would increase substantially under the other scenarios (**Chart 24**, panel a). As a result, under the late-push and delayed transition scenarios, households' total energy expenses in 2030 would be 31% and 50% higher respectively than in 2022, due to the increase in fossil fuel prices and to a still strong reliance on brown energy sources under the delayed transition.

Chart 24

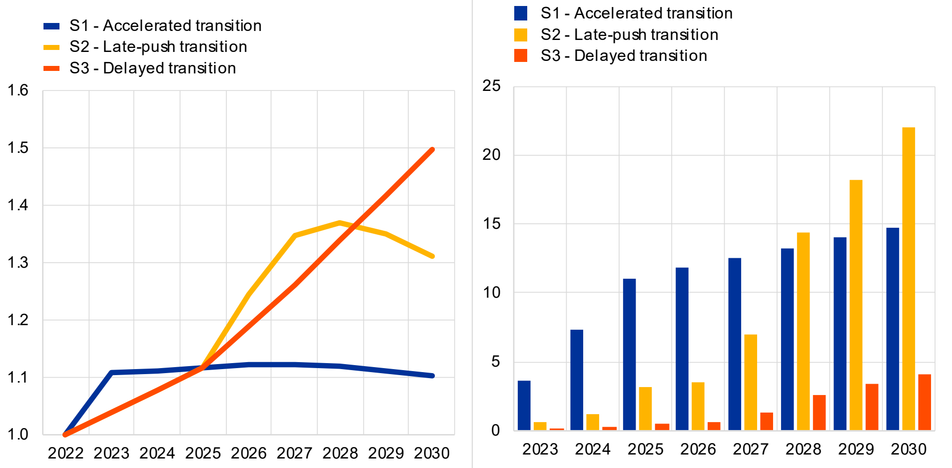
More ambitious emission reductions driven by timely and intense investments would lead to a greater reduction in energy expenses

a) Euro area aggregate of households' energy expenses over the eight-year horizon

(index; 2022=1)

b) Euro area households' green investments over the eight-year horizon

(EUR billions)



Source: ECB calculations based on ECB, Eurostat, NGFS, BMPE macroeconomic projections, Greenhouse Gas Protocol and IPCC (2022) data.
Notes: Panel b displays the euro area cumulative investments across time. They represent the debt taken on by euro area households under all three scenarios between 2023 and 2030, net of the repayments.

More ambitious emission reductions under the accelerated and late-push scenarios would require higher household investments. Household investments were estimated based on the same methodology as that used to estimate green investments for corporates (see Section 3.2.2). It was assumed that households would invest mostly at the beginning of the transition, which would result in higher debt levels in the beginning of the period under the accelerated transition scenario and in the second half of the period under the late-push and delated transition scenarios. Under the accelerated and late-push transition scenarios, the total amount of investments that would be made by households over the 2023-2030 time horizon would amounts to around €21-22 billion, the difference being that under the late-push scenario most of the investments would be made over a shorter period (2026-2030). In contrast, under the delayed transition, the less ambitious emission reductions would be obtained through lower investment, amounting to just €4 billion, mostly made from 2026 to 2030 (**Chart 24**, panel b).

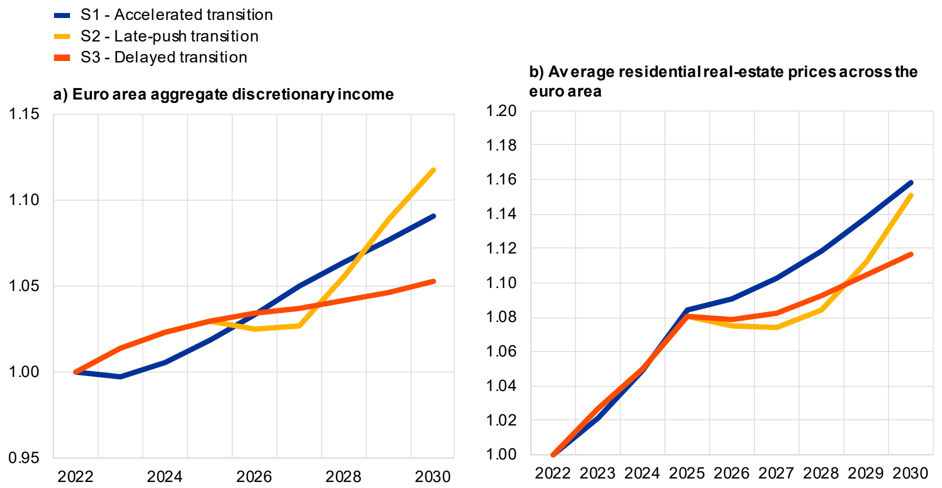
Green investments would affect households' credit risk through changes in debt levels and discretionary income. Presuming that households would cover their green investments by contracting new loans, the overall debt level would increase. At the same time, as soon as they started repaying their debt, their discretionary income would be reduced by loan repayments. The timeliness and ambition of the transition would have an impact on households' purchasing power. The former would determine the state of the economy at the starting point, the latter would determine the pace at which discretionary income decreased as climate policies were implemented and then recovered in the following years. Combining these factors over the 8 years considered, discretionary income would grow by between 10% to 12% under the accelerated and late-push transition scenarios and by around half as much under a delayed transition (**Chart 25**, panel a).

Green investments would have a positive effect on real-estate prices given that they would lead to a higher valuation for properties with higher energy efficiency. The change in GHG emissions and real-estate prices were derived from the NGFS scenarios (applying the methodology described in Box 1) and green investments were deemed to be proportional to the GHG emissions reductions. Under the accelerated and late-push transition scenarios, residential real-estate prices would reach similar levels in 2030, having increased by around 15% compared with 2022 levels; under the delayed transition, there would only be a 12% increase over the same period (**Chart 25**, panel b).

Chart 25

Green investments would affect income and residential real-estate prices

(index; 2022=1)



Source: ECB calculations based on ECB, Eurostat and NGFS data.

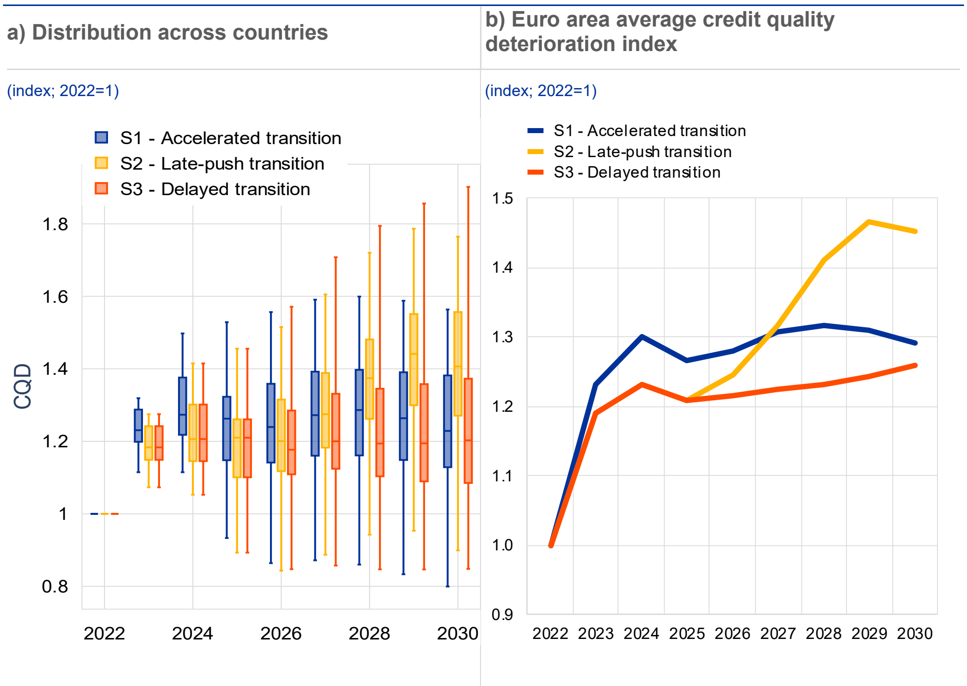
The accelerated and delayed transition scenarios would lead to similar credit risk levels for household by 2030 but would make different contributions to the long-term implications of physical risk.[41] During the first half of the period, the accelerated transition scenario would see the highest CQD due to rapid and strong transition-related developments (**Chart 26,** panel a). The credit quality under the late-push scenario would deteriorate significantly from 2026 and CQD would reach a peak in 2029, when the median CQD would register an increase as compared with 2022 that would be almost double that under the other scenarios. The results were driven by a combination of several factors: (i) lower income at the onset of the transition, especially under the accelerated and late-push transition scenarios; (ii) higher investment under the more ambitious transition scenarios, resulting in higher debt, especially under a late-push transition scenario; (iii) lower real-estate prices at the end of the horizon under the milder transition scenario. Overall, homeowners

[41] Projected physical risk levels would depend on the action taken at global level and in conjunction with the other sectors in the economy.

would have higher discretionary incomes in 2030 under the accelerated transition scenario, due to lower energy expenses and more energy efficient buildings, compared with under the late-push and delayed transition scenarios. While average household credit risk would be the lowest under the delayed transition by 2030 (**Chart 26,** panel b), the expectation is that it would increase more strongly after 2030. As illustrated in **Chart 5**, only the most ambitious pathways would reach the target of limiting the temperature increase to +1.5°C by the end of the century, while under the delayed transition pathway that temperature increase would be +2.6°C. Different temperature targets would lead to different levels of severity of physical risk in the long term. According to NGFS projections, if global climate policy action were to mirror that of the EU, the expectation is that impact of long-term physical risks under the delayed transition scenario would be much more severe.[42]

Chart 26

Household portfolio credit quality deterioration would be almost double under a late-push transition than under the other transition scenarios



Source: ECB calculations based on ECB, Eurostat, NGFS, BMPE macroeconomic projections, Greenhouse Gas Protocol and IPCC (2022) data.
Notes: CQD stands for credit quality deterioration. The chart excludes outliers with an indexed CQD above the 95% percentile and below the 5% percentile of the distributions.

This module is a first attempt to incorporate the impact of transition pathways on households' credit risk into the ECB economy-wide climate stress test and it could be expanded in several ways in the future. The impact of the transition on households would differ across population income levels and it would therefore be of benefit to capture this heterogeneity by assessing the CQD separately by income group. Another important extension would be the inclusion of more granular

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[42] Temperature increases would depend on the action taken at global level. For this reason, the considerations on physical risk would hold true only on the assumption that each country follows its respective NGFS trajectory. In other words, an accelerated transition would bring its benefits only if all countries contributed to it by frontloading their respective NGFS-implied transition paths.

information on banks’ exposures to individual households, e.g. based on household credit registers. Additionally, access to more granular information on the geographical location of residential buildings, especially of those that are collateral to mortgages, would be the key to gaining better insight into household exposure to physical risk and to different type of natural hazards. Furthermore, more granular information on the EPC labels of residential properties would assist in determining the different green investment requirements and consequently the different valuations of these properties. Including these sources of heterogeneity into the framework would give supervisors and policy makers a better picture of the effects of climate transition on households and the transmission of household transition risks to the financial system.

6 Transmission to the financial system

The last module of this exercise assesses the transmission of transition risk to the financial system through credit risk and market risk channels, applying a static balance sheet assumption. Section 6.1 presents the impact on euro area banks, focusing on financial risks stemming from banks' exposures to the real economy through loans to corporates and households, as well as through corporate bond holdings. Section 6.2 sets out the impact on non-bank financial institutions, namely investment funds, pension funds and insurance companies, that are impacted through their corporate bond portfolios.[43]

6.1 Banks

Mapping counterparty-level PDs to instrument-level information on banks' corporate credit portfolios and bond holdings made it possible to assess the transmission of transition risk from firms to banks. The PD of a corporate loan portfolio was defined as the exposure-weighted average of the default probabilities of the counterparties to which a bank is exposed, which was determined by using granular information on banks' corporate loan books derived from AnaCredit – the euro area credit register.[44] Using the same approach as in Alogoskoufis et al. (2021), the expected losses on banks' corporate loan portfolios were computed at instrument level for every scenario and year by multiplying the PD of the counterparty by the amount of exposure not secured by collateral; this data was subsequently aggregated at bank level.[45]

A substantial share of banks' corporate loan portfolios is directed towards energy-intensive sectors, making them vulnerable to transition risk. The total secured and unsecured loan exposure of the euro area banking system to energy-intensive sectors[46] is around 40% of the total portfolio and greater for significant institutions (SI) relative to other banks (42% of the total loan volume for SIs, **Chart 27**, panel a). Less than 10% of all banks account for 90% of all exposure to energy-intensive sectors. The top 10% of banks with the highest exposure to those sectors are responsible for one-third of total lending in the euro area (**Chart 27**, panel b). These two stylized facts imply that transition risk is relatively concentrated in the

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[43] The current framework measured first-round effects of the transmissions of corporate and household transition risk to banks and non-banks, while second-round effects and cross-sectoral interactions will be part of future extensions.

[44] See Section 4 of Alogoskoufis et al. (2021) and the Annexes to this current analysis for further details of the datasets that the ECB climate risk stress-testing framework employs.

[45] This corresponds to the standard formular for expected losses. For each loan, year and scenario, we calculated the outstanding exposure amount at the starting point (exposure at default, EAD), which was multiplied by the projected counterparty PD and by the share of the loan not covered by collateral (LGD). LGD was deemed to be that fraction of loans not protected by either physical or intangible collateral based on the assumption that only the non-collateralized part of the loan can default. It was assumed that the collateral value would not be affected by transition risks. The expected losses were then aggregated at bank portfolio-level to derive the sum of expected losses of individual banks.

[46] Energy-intensive sectors were electricity, gas, steam, wholesale and retail trade, manufacturing, mining and quarrying, and transportation corresponding to NACE level 1 codes B, C, D, G and H.

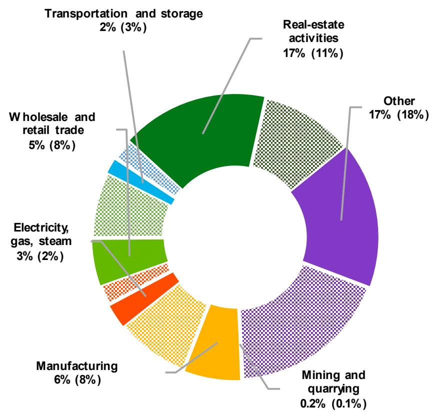
euro area banking system, resulting in heterogenous effects for credit risk across banks.

Chart 27

Exposure to energy-intensive sectors is concentrated across banks

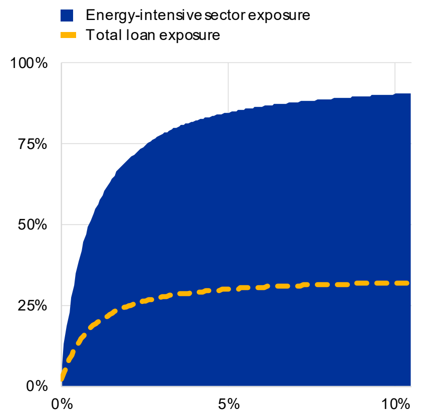
a) Loan exposure across NACE sectors

(share of loan volume)



b) Share of energy-intensive sector exposure of the 10% most exposed banks

(y-axis: cumulative share of loan exposure, x-axis: share of banks relative to total bank sample)



Source: ECB calculation based on AnaCredit, Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, and IRENA (2021) data.
Notes: NACE stands for Nomenclature of Economic Activities. Panel a: The shaded areas represent the figures in brackets, which indicate the share of loan volume of significant institutions (SIs). Panel b: Energy-intensive sectors were electricity, gas, steam, wholesale and retail trade, manufacturing, mining and quarrying, and transportation.

Large banks are more exposed to potential losses given that their loan exposures tend to be less collateralised. The average loss given default (LGD) on credit exposures would range from 30% for smaller banks to almost 50% for larger banks (**Chart 28**, panel a). Moreover, the relative share of loans covered by collateral would reduce in line with total bank-level loan volume (**Chart 28**, panel b). The median collateral ratio for the smallest quantile of banks sorted by size would be about 65%, while in the upper quantile of banks only 55% of loans would be collateralised.

Chart 28

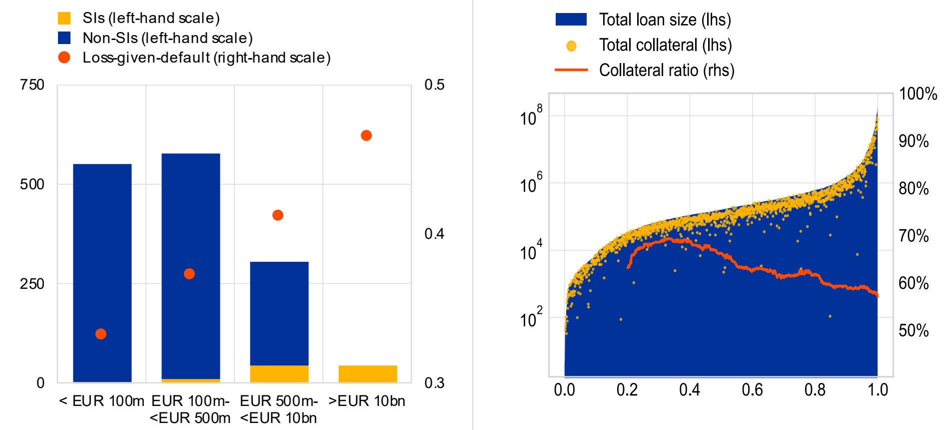
Large banks demand less collateral on their loans and are exposed to higher loss given default

a) Number of banks and the loss-given-default ratio by bank total loan volume

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

b) Total loan volume and collateral value by bank-level total loan volume and the moving-median collateral ratio

(left-hand scale: EUR thousands; right-hand scale: percentages)



Source: ECB calculation based on AnaCredit, Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections and IRENA (2021) data.
Notes: Panel a: Loss-given-default (LGD) ratios were calculated as 1 minus the ratio of total bank-level collateral divided by the total volume of loans. Median LGDs are shown. Panel b: The collateral ratio was calculated as the median of total collateral divided by total loan volume in a moving window of 300 banks. "lhs" stands for "left-hand scale" and "rhs" stands for "right-hand scale".

The transmission of transition risk from households to banks was assessed on the basis of the projected deterioration in the credit quality of banks' household loan portfolios (see Section 5). The projected pathways of the share of banks' loans to households expected to default were used to estimate bank-level expected losses from household loan portfolios under the transition scenarios[47]. A breakdown by households' country of residence was available and was used to derive expected losses at more granular level.

6.1.1 Credit risk

Banks' credit risk would increase with transition risk and banks exposed to more vulnerable firms would be disproportionately more affected. The PDs of corporate loan portfolios (hereinafter, bank-level PDs) would rise higher at the start of the transition period under the accelerated transition scenario but would be outpaced from 2026 onwards under the late-push transition scenario (**Chart 29**, panel a). The increase would be higher for the median SI compared with the median of other banks due the relatively larger share of exposure to energy-intensive sectors of SI portfolios (see **Chart 27**, panel a). Credit risk would start to recover in the second half of the time horizon under the accelerated and late-push transition scenarios given that the peak of the transition would have been reached by then. In contrast, under the delayed transition scenario there would be a continuous increase

[47] For household loans, the expected losses on household loans were calculated for each scenario and year as the total household exposures at the starting point (EAD) multiplied by the projected CQD (defined as projected share of defaulted exposures (proxy PD)) and by the LGD at the starting point.

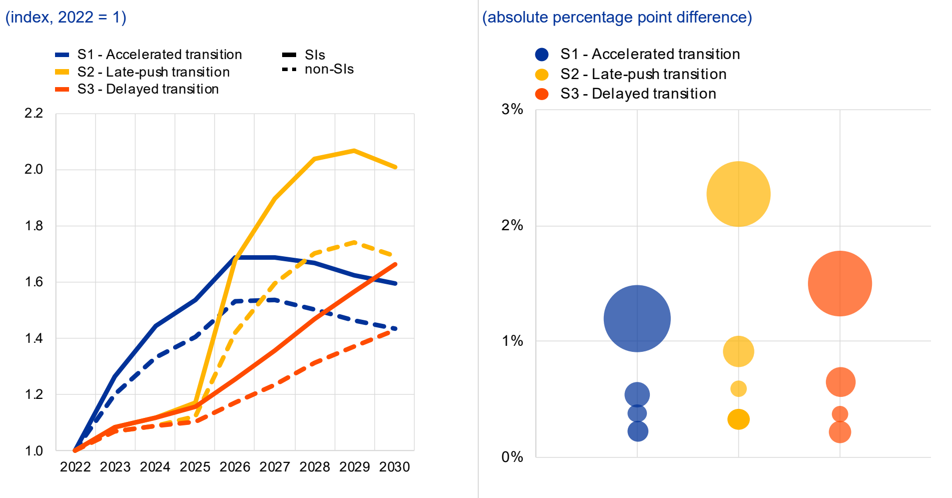
in credit risk until 2030. This would be expected to impose additional credit risk for banks after 2030 given the lower emissions reductions until 2050 under that scenario (as illustrated earlier in **Chart 5**), resulting in higher long-term temperature increases and greater physical risk. In addition, PDs would not yet have started recovering by 2030 under the delayed transition scenario. Transition risk, and thus credit risk, would be expected to continue to increase after 2030. Across scenarios, the average percentage point increase in PDs between 2022 and 2030 would range from 0.2 to 0.9 percentage points for the lower three risk quartiles, while the upper risk quartile would see an average increase of 1.2 percentage points and 1.5 percentage points under the accelerated and delayed transition scenarios and even up to 2.3 percentage points under a late-push transition (**Chart 29**, panel b). Moreover, banks in the highest risk quartile would be larger in terms of loan volumes, indicating that the impact of transition risk on these banks could have systemic importance.

Chart 29

Significant and larger institutions would be exposed to larger credit risk increases

a) Increase in the median corporate loan portfolio PD relative to 2022 for significant and less significant banks across scenarios

b) Quartiles of absolute increases in corporate loan portfolio PDs in 2030 compared with 2022 across scenarios and the corresponding loan exposures



Source: ECB calculations based on AnaCredit, Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections and IRENA (2021) data.
Notes: Panel a: SI stands for significant institution. Panel b: Quartiles of absolute percentage point increases in PDs in 2030 compared with 2022 ae shown. Increases in probabilities of default are average values per quartile and scenario in 2030 in excess of 2020 levels. The size of each bubble corresponds to the total loan volume per quartile.

An accelerated transition would lead to the best trade-off between credit and transition risks given that it would achieve larger emissions reductions and faster PD recovery by 2030. The transition-to-credit-risk intensity (TCI)[48] serves as a metric of transition risk that takes into account banks' exposure to credit risk. It was calculated by combining borrowers' loan-weighted emissions with their PDs and aggregating them over each bank's total corporate loan exposures. While the accelerated and delayed transition scenarios would reach the same level of credit risk in 2030 (see **Chart 29**, panel a), the transition-to-credit risk intensity in 2030

[48] The TCI was calculated at portfolio level and is defined as the average product of borrower level relative Scope 1, 2 & 3 GHG emissions and (projected) PDs weighted by borrowers' loan exposures.

would reduce by around 40% under the accelerated transition scenario compared with only half of that under the late-push and delayed transition scenarios (**Chart 30**, panel b). The strong decrease in TCI under the accelerated and late-push transition scenarios until 2030 further substantiates the fact that the economy would be recovering fast from the green transition by 2030 under the more ambitious scenarios, while the TCI under the delayed transition scenario would be expected to remain at elevated levels after 2030, due to sluggish transition speed, and to potentially increase further as a result of the long-term impact of physical risk on credit risk. Across sectors, the TCI would increase in the most energy-intensive sectors, namely mining, manufacturing and electricity until 2030 (**Chart 30**, panel a). The differences in the pathway for TCI as compared with that for PD show that combining both transition and credit risk dimensions into one metric can serve to reveal information on banks' point-in-time exposure to credit risk as well as their forward-looking exposure to transition risk in terms of outstanding CO2 emissions.

Chart 30

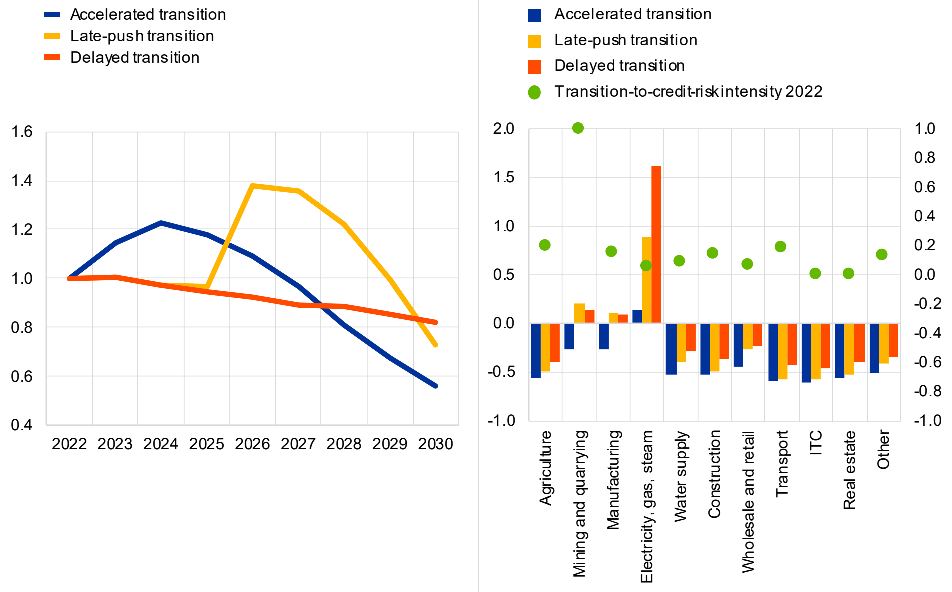
Transition-to-credit-risk intensity across time and sectors

a) Aggregate transition-to-credit-risk intensity relative to 2022

(index, 2022 = 1)

b) Transition-to-credit-risk intensity by sector

(left axis: percentage change, right axis: normalized TCI)



Source: ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021) and IPCC (2022) data.
Notes: The transition-to-credit-risk intensity was calculated at portfolio level and defined as the average product of borrower level (projected) relative Scope 1, 2 & 3 GHG emissions and (projected) probabilities of default, weighted by borrowers' loan exposures.

By 2030, a late-push transition would affect banks' credit risk more severely. However, the long-term transition and physical risk implications would be more acute under a delayed transition scenario. In 2030, the average increase in portfolio-level PD under the late-push transition would amount to 1.0 percentage points, but only 0.6 percentage points under the accelerated and delayed transition scenarios (**Chart 31**). While credit risk would be higher during the first half of the period under the accelerated transition scenario, bank-level PDs would recover by the end of the second half under this scenario (**Chart 29**, panel a), leading to PD levels similar to those under the delayed transition scenario. Moreover, some significant banks would appear to be already worse off in 2030 under a delayed transition as opposed to under the accelerated transition scenario (**Chart 31**, panel b).

Chart 31

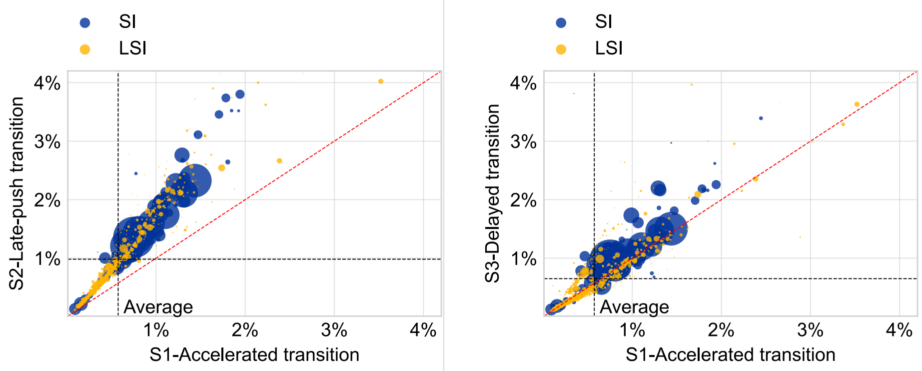
Increases in corporate loan portfolio PDs would be heterogenous across banks and most severe under the late-push transition scenario

Absolute percentage point difference of corporate loan portfolio PDs in 2030 relative to 2022

(absolute percentage point difference)

a) Late-push transition versus accelerated transition

b) Delayed transition versus accelerated transition



Source: ECB calculation based on AnaCredit, Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, and IRENA (2021).
Notes: Dots corresponds to the corporate loan portfolio of individual banks. SI stands for significant institution and LSI stands for less-significant institution. Excess probabilities of default were computed as the difference between projected PD levels in 2030 and the corresponding levels in 2022 across the three scenarios. Dashed black lines correspond to the scenario averages. The red dashed line shows the 45-degree line. The size of each bubble corresponds to the total loan exposure of banks. To reduce outlier distortion, very small banks with a total portfolio size of less than EUR 10 million were excluded from the sample.

Transition risk would be of varying magnitudes across scenarios and time, and banks most exposed to transition risk would face large increases in expected losses until 2030. The late-push transition scenario would generate the highest annual expected losses from transition risk across scenarios and time, peaking at €21 billion in 2029 (**Chart 32**), exacerbated by baseline losses due to macroeconomic developments and current climate policies (green bars in Chart 31)[49]. Under the accelerated transition scenario, annual expected losses would rise sharply in 2023 and peak at €13 billion in 2026, before declining to €6.6 billion by 2030. Under the delayed transition scenario, expected losses would increase by €9 billion until the end of the projection period, due to milder transition efforts, but would be expected to increase further after 2030, due to greater long-term transition and physical risks than under the accelerated and late-push transition scenarios.

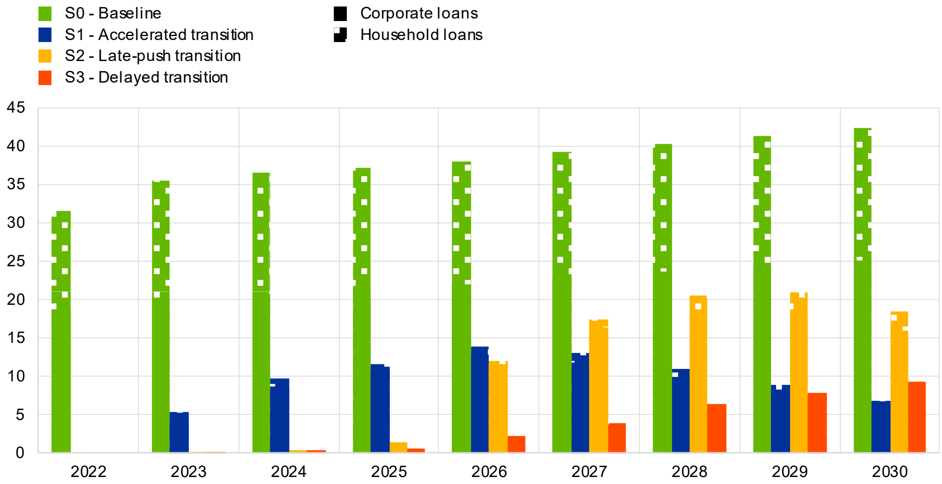
[49] To isolate the impact of transition risk from other macroeconomic developments, expected losses were first calculated for a baseline scenario which comprised NGFS current policies only and no additional transition risk. Expected losses due to transitional risk were defined as annual expected losses under each transition scenario in excess of annual expected losses under the baseline scenario. The sum of baseline and excess transition risk losses equate to the total expected losses per year and scenario.

Chart 32

Expected losses would vary substantially across time and scenarios

Annual expected losses on corporate and household loans by scenario and year

(EUR billions)



Source: ECB calculation based on ECB, AnaCredit, Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections and IRENA (2021) data.
Notes: The shaded areas show the share of expected losses stemming from household exposures. The green bars show the baseline losses stemming from the current policies and macroeconomic effects. The blue, yellow and orange bars show the expected losses due solely to transitional efforts under transition scenarios S1, S2 and S3. Thus, the total sum of expected losses under S1, S2 and S3 is the sum of the green bars and the corresponding blue/yellow/orange bars. Losses from corporate loans represent 80% of total AnaCredit exposures.

The materialisation of transition risk would be conditional on the size of current expected losses. Percentage increases in total annual expected losses between 2022 and 2030 are heterogeneous across banks, and frequently above 100% under the late-push and delayed transition scenarios, as shown by the fat tails of the loss distribution (**Chart 33**, panel a). Under the late-push transition scenario, one out of ten banks would experience an increase in annual expected losses above 190% in 2030 compared with 2022. The same share of banks would be exposed to an increase above 100% and above 135% under the accelerated transition and delayed transition scenarios respectively. Around half of these increases in annual expected losses would stem from macroeconomic developments and current climate policies (i.e. the baseline scenario). Expected losses on bank portfolios are covered by provisions, and the provision coverage for International Financial Reporting Standards (IFRS) stage 1 loans[50] was 0.69% in 2022. Banks' provision coverage would be expected to increase by 25 basis points until 2030 due to macroeconomic and current-policy effects (**Chart 32**, panel b). If the transition scenarios were to materialise, the provision coverage for such loans would increase by an additional 37 basis points and 61 basis points during the peak of the accelerated and late-push transition scenarios in 2027 and 2029 respectively. Given that the reduction in emissions during a delayed transition would be less ambitious, the increase in provision coverage until 2030 due to transition risk would be smaller in this scenario. However, provisions are expected to increase more strongly in the delayed transition

50 Provisions for IFRS stage 1 loans account for one-year expected losses, allowing direct comparison with the expected annual losses considered in this study.

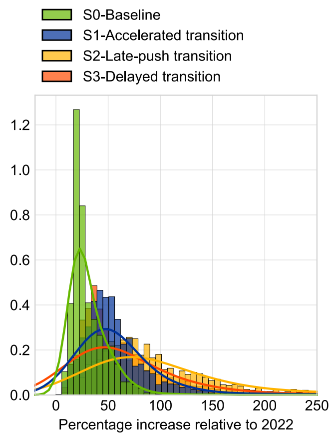
after 2030 due to ongoing transition efforts and the stronger impact of physical risk in the long-term.

Chart 33

Increase in expected losses compared to current loan-loss provisions

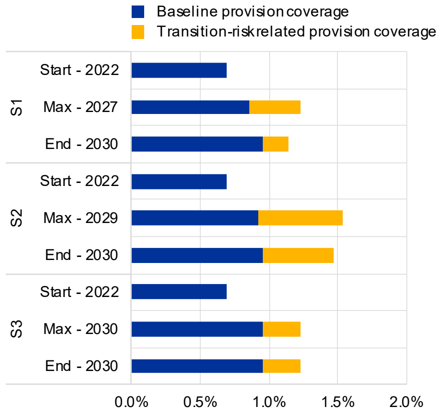
a) Increase in absolute expected losses in 2030 relative to 2022

(density, percentage increase)



b) Provision coverage ratio by scenario and selected years

(percentages)



Source: ECB calculation based on ECB, AnaCredit, Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections and IRENA (2021) data.
Notes: Panel a: The distribution of percentage increases in bank-level expected losses in 2030 relative to 2022 across the scenarios is shown. Panel b: Aggregated provisions and expected losses as a fraction of total outstanding loan volume based on a subsample of IFRS stage 1 loans are shown.

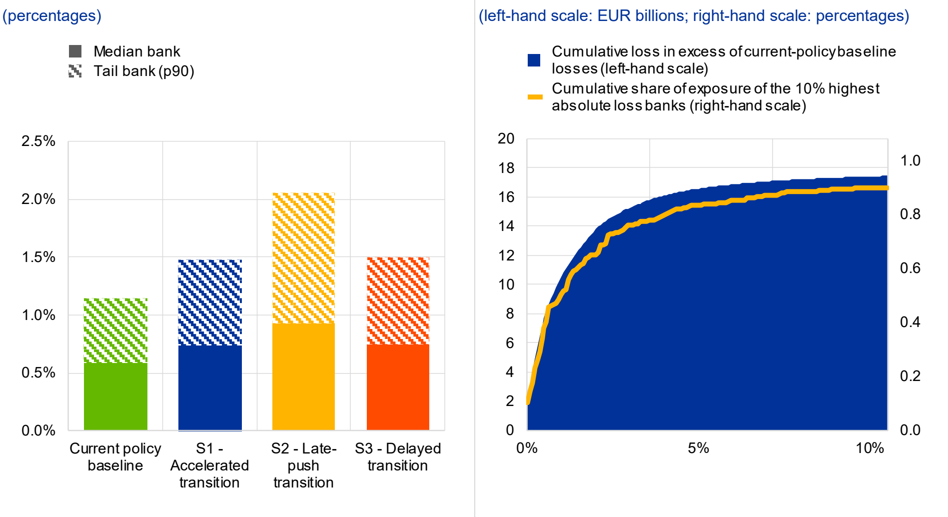
Based on the bank-level distributions, the highest expected losses would be concentrated in a few banks. Focusing on SIs, expected losses in 2030 as a fraction of total loan exposures for the median bank would be around 0.7% under both the accelerated and the delayed transition scenarios, and close to the losses projected for the median bank under a current-policy baseline scenario (**Chart 34**, panel a). The figure would be slightly higher, standing at 0.9%, under the late-push transition scenario. At 2.1%, the 90th percentile of the expected losses' ratio would be double the median under the late-push scenario and also compared with the 90th percentile of the expected losses' ratio under a current-policy scenario. In addition, expected losses would be concentrated in a few banks in absolute terms. Under a late-push transition scenario, 2% of banks with the highest absolute expected losses would already account for 75% of total expected losses by 2030 (**Chart 34**, panel b). At the same time, those banks would account for 65% of total loan exposures.

Chart 34

Expected losses would be considerably higher in the tails and concentrated across banks

a) Expected losses in 2030 as a share of total exposure for euro area significant institutions

b) Expected losses in excess of a current-policy baseline scenario in 2030 under a late-push transition scenario for top 10% banks with the highest absolute losses



Source: ECB calculation based on ECB, AnaCredit, Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections and IRENA (2021) data.
Notes: Tail bank is defined as the 90th percentile bank in terms of expected losses relative to total loan exposures in 2030.

6.1.2 Market risk

The market risk channel acts through a repricing of banks' corporate bond portfolios based on sensitivity to transition risk over time. As in the first ECB economy-wide climate stress test exercise, an internal ECB pricing tool was used to derive potential losses on corporate bond portfolios at the international securities identification number (ISIN) level by capturing the price dynamics for the same risk factors as those that drive firms' credit risk and by using granular data on banks' corporate bond holdings from Securities Holdings Statistics banking group dataset (SHS-G). The impact of the transition was estimated for the entire sample of corporate bonds issued by NFCs as reported in the SHS-G dataset. The subset of bonds held by euro area banks was considered. Overall, the corporate bond portfolios of 78 euro area significant institutions as at the end of 2022 were captured, with a total market value of approximately €30 billion.

To quantify the market risk channel of transition risk, shocked firm PDs were first translated into changes in corporate bond spreads and subsequently to changes in bond prices. Following the approach adopted by Vermeulen et al. (2018) and assuming a linear relationship between corporate bond spreads and PDs,[51] a scaling coefficient was obtained using both a firm-level panel regression

[51] The credit spread of a zero-coupon bond with a residual maturity of one year is equal to the probability of default for that year, assuming 100% LGD (Vermeulen et al., 2018).

and time-series regression for corporate spreads on PDs. Corporate bond spreads were then translated into bond prices using a duration equation.

The results suggested that, over the eight-year horizon, absolute losses on corporate bond portfolios would be limited, but not negligible relative to portfolio size. The average portfolio would experience cumulative losses of around 3% of portfolio fair value and of around 6% to 10% in the tails of the distribution. (**Chart 35**, panel a). The difference in losses between the accelerated and delayed transition scenarios would be small, but the latter would present fatter tails. Nonetheless, relative losses in the tails would materialise mostly in relatively smaller portfolios (**Chart 35**, panel b). Overall, losses would be the highest under the late-push transition scenario.

Chart 35

Market risk impact would be limited but visible relative to portfolio size

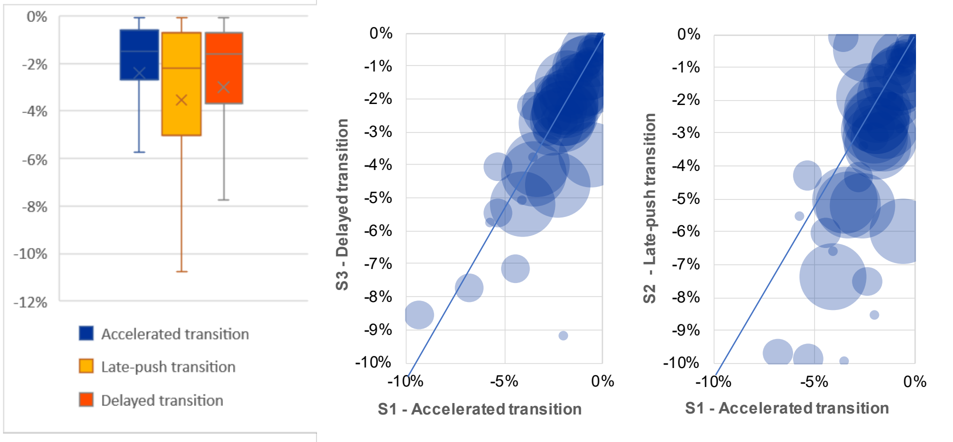
a) Losses relative to portfolio fair value

b) Losses relative to portfolio fair value across scenarios

b.1) Across the accelerated and late-push scenarios

b.2) Across the accelerated and delayed scenarios

(percentages)

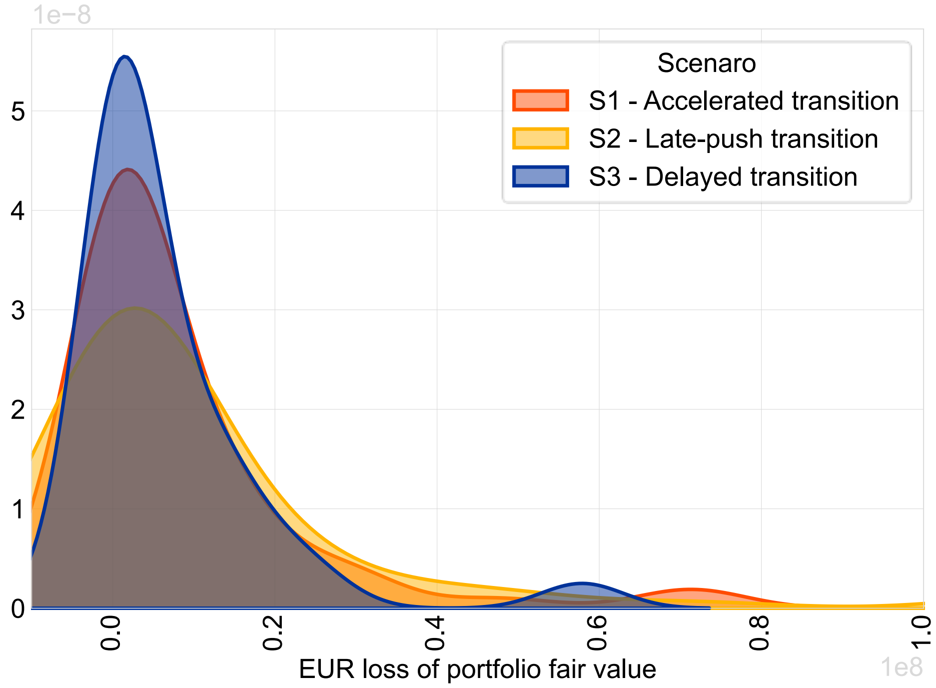


Source: ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021) and IPCC (2022) data.
Note: In panels b.1 and b.2, the size of the bubble was determined by the tercile into which the size of banks' corporate bond portfolios fell.

The late-push and delayed transition scenarios would generate higher risks for banks in the tail of the distribution compared with an accelerate transition. In absolute terms, average losses until 2030 would amount to around €6 million under the accelerated transition scenario, to €11 million under the late-push transition scenario and to € 8 million under the delayed transition scenario. The loss distributions of the late-push and delayed transition scenarios have fatter tails compared with those of the accelerated scenario, suggesting more dispersed and higher market risk losses for banks (**Chart 36**). As with credit risk, market risk losses after 2030 would be larger under the delayed transition scenario compared with the other two scenarios, given that the long-term physical risk implications for firms would be more severe under the delayed transition scenario.

Chart 36
Market risk impact – portfolio fair value losses

(EUR)



Source: ECB calculations based on Orbis, Urgentem, Eurostat, NGFS, BMPE macroeconomic projections, IRENA (2021) and IPCC (2022) data.

6.2 Non-bank financial institutions

Market risk is the main risk channel through which climate-related shocks could affect the securities portfolios of non-bank financial institutions. Such institutions have significant exposure to climate transition risks due to their sizable securities portfolios. The combined corporate bond portfolios of investment funds (IF), insurance corporations (IC) and pension funds (PF) was around €546 billion in the fourth quarter of 2022. Applying the same approach as that used for banks set out above, the potential losses on euro area issued corporate bond portfolios for non-bank financial institutions were obtained at ISIN level for the security holdings of country and non-bank sector combinations derived from the securities holdings statistics sector (SHSS) dataset.

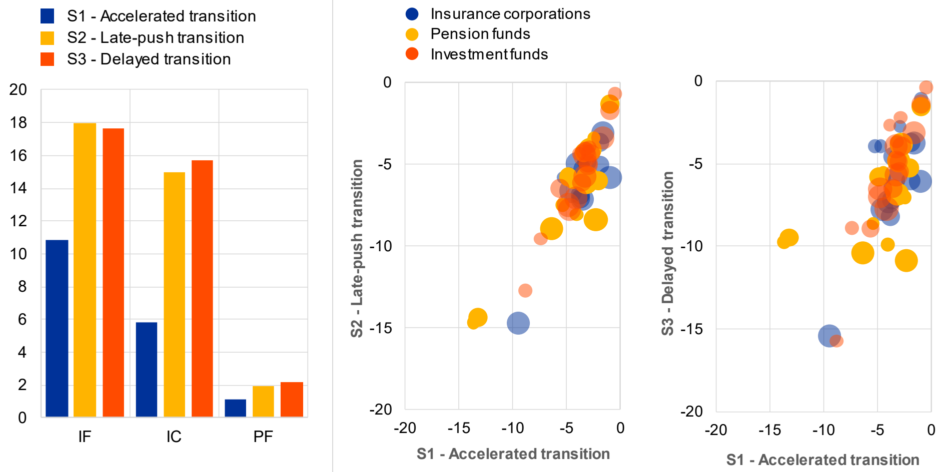
The estimates suggested a substantial market risk impact for non-bank financial institutions, with variation between sectors and countries. Across all three scenarios, the absolute losses of investment funds would range from around 10 to 18 € billion, while the estimates for losses for insurance corporations would amount to around 6 to 16 € billion. The losses of pension funds are estimated to be between 1 and 2 € billion in each scenario (**Chart 37**, panel a). Relative to the size of the respective portfolio the average market risk impact ranges from around 3.5% to 7% across all three scenarios and country-sector combinations. Estimated relative losses reach up to 12%, 15% and 15% for investment funds, insurance corporations and pension funds respectively (**Chart 37**, panel b).

Chart 37

Absolute and relative losses by type of non-bank financial institution in 2030

a) Absolute losses by non-bank financial institution | **b) Relative losses by country, sector and scenario**

(EUR billions) | (percentages)



Source: ECB calculations based on SHSS and CSDB data.
Notes: In panels b.1 and b.2 the size of the bubbles represents the size of the corporate bond portfolio relative to the sector. determine the size of an individual bubble, countries within individual non-bank sectors are separated into three groups based on the size of the corporate bond their portfolios using terciles. The size of the bubble corresponds to the group.

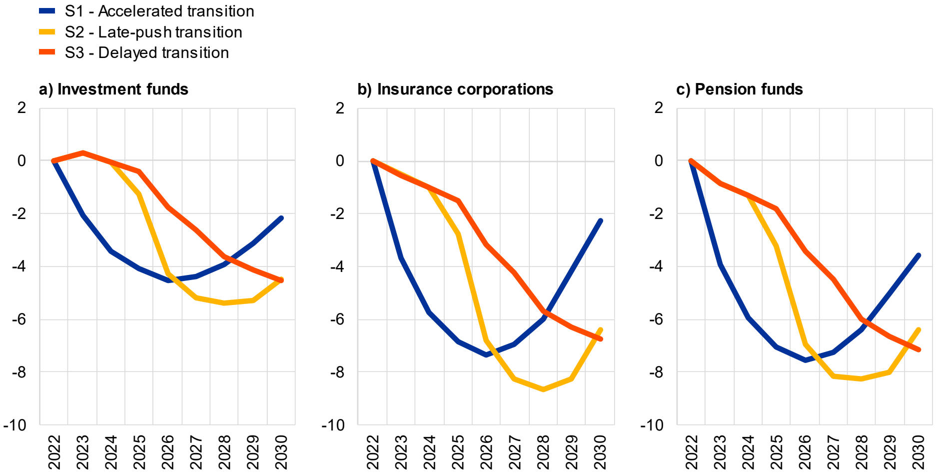
The market risk impact for non-banks would follow similar dynamics over the scenarios but would differ in magnitude across individual non-bank sectors. Estimating the market risk impact in each year of the scenarios reveals that the dynamics would be broadly similar across the three sectors, but that there would also some differences. Investment funds would gain on their corporate bond portfolios in the first year of the late-push and delayed transition scenarios, while insurance corporations and pension funds would experience losses within the first year across all scenarios. Thereafter, the estimated losses would follow similar paths across all three sectors, albeit to a greater magnitude in the case of insurance corporations and pension funds. (**Chart 38**).

Chart 38

Under all the scenarios, different non-bank financial sectors would be affected similarly but with differences in magnitudes

Estimated losses of non-bank financial sectors over the scenario horizon

(percentages relative to 2022)



Source: ECB calculations based on SHSS and CSDB data.

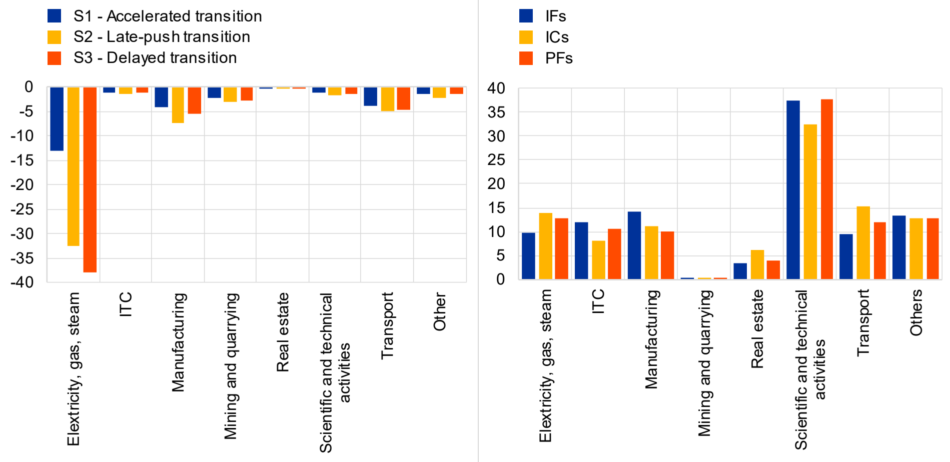
The differences in impact across sectors can be explained by the relative importance of highly affected sectors in the corporate bond portfolios of non-bank financial institutions. Under all three scenarios, the estimated market risk impact on the corporate bond portfolios of pension funds and insurance corporations would be notably higher than the impact for investment funds. This difference can be attributed to the relative size of their exposures to the highly affected electricity, gas and steam sector, which would experience the largest impact. While pension funds' and insurance corporations' average exposure to the electricity, gas and steam sector amount to around 12.7% and 14% of their corporate bond portfolios respectively, that exposure is only 9.7% for investment fund. Another sector to which pension funds and insurance corporations have a relatively higher exposure as compared with investment funds is transport (**Chart 39**).

Chart 39

Insurance corporations and pension funds have a higher share of affected sectors in their portfolios

a) Average estimated losses by scenario for issuing sectors | **b) Average portfolio weights by type of non-bank financial institution and issuing sector**

(percentages) | (percentages)



Source: ECB calculations based on SHSS and CSDB data. ICT stands for the Information and Communication Technology sector.

Future analysis for assessment of the climate-related transition risks for non-banks could be extended in several ways. First, given the diversified international portfolio of non-banks, it is important to extend the analysis to non-euro area firms. Second, sovereign bonds represent a significant share of non-bank portfolios. When better data on sovereign exposures to climate-related transition risks become available and markets start pricing in these risks, non-bank sovereign portfolios might be affected. Third, climate-related risks are very much fat-tail risks, thus the relationship between the increases in PDs and securities prices might become non-linear and need to be modelled differently. Finally, markets are very agile in pricing in all available information, and non-banks might be able to adjust their portfolios relatively quickly to account for the latest information. Therefore, assuming fixed portfolios over the eight year scenario might be somewhat unrealistic.

7 Conclusions

The climate stress test presented in this paper studies the potential vulnerabilities of the euro area economy and financial system to a set of transition pathways towards a net-zero emissions economy. Leveraging the framework developed for the first ECB economy-wide climate stress test, the current exercise is an important step forward in the field of climate stress testing. The original framework was enhanced by i) incorporating current and future euro area macroeconomic and energy-related developments into three plausible short-term transition scenarios, ii) capturing sector-level dynamics as well as more refined and granular modelling of investment needs for the green transition, and iii) assessing the impact of different timings and degrees of transition risk on the euro area real economy and financial institutions by extending the entities covered to include households and non-bank financial institutions. Feedback loops between the financial system and the real economy, as well as the amplification of risks inside the financial system and across financial sectors, were not covered in this work and should be further explored in future exercises.

The scenarios designed for this exercise differ in the timing and ambition of emissions reductions until 2030, combining, for the first time, NGFS transition paths with the latest macroeconomic projections and energy developments. The accelerated transition scenario assumes an immediate start of the transition that is compatible with the NGFS "net-zero by 2050" optimal path. Under the late-push transition scenario, current macroeconomic and geopolitical conditions would lead to a forward-push of the transition, which would start only after 2025 but would be sufficiently intense to reach emissions reductions comparable with the accelerated transition scenario. The delayed transition scenario assumes a late transition timing and milder policy action, which would not be sufficiently ambitious to achieve emission reductions similar to the other scenarios by 2030.

The results of this exercise reveal that an accelerated transition would provide significant benefits for firms, households, and the financial system, compared with a late-push transition scenario. Credit risk would increase during the transition under all scenarios, and particularly in the event of late and abrupt actions as envisaged under the late-push transition scenario. While the accelerated transition would lead to greater costs for households and firms in the short term, due to rapid and severe increases in energy prices, it would lower the financial risks in the medium term thanks to more rapidly reducing energy expenses and to large investments in renewable energy capacity. At the same time, an early start of the transition would allow banks to benefit from both lower credit risk and larger investment needs, thereby improving their income positions.

The accelerated and delayed transition scenarios would lead to similar risk levels in 2030. They would, however, entail substantially different long-term implications for both transition and physical risks. Under the accelerated transition scenario, corporate and households' risk exposure would start to decrease in the second half of the decade, after significant transition progress, while under the delayed transition scenario it would keep increasing until 2030 and potentially further, due to a continuous increase in energy prices and less renewable energy capacity. Moreover, given that the emission reductions by 2030 would not be compatible with the maximum +1.5° temperature target by the end of the century, stronger increases in temperature would be expected to lead to more frequent and severe natural hazards in the long term.[52] Given that temperature increases and physical risk levels would depend on the action taken at global level, these considerations would hold true only on the assumption that all global economies reduced their emissions as envisaged under their respective (front-loaded) NGFS scenario; the risks could be very different otherwise. Thus, assuming global efforts were in line with the assumptions underlying the NGFS framework, in the event of a delayed transition, firms and households might be more vulnerable to physical risk, as well as potentially to the compounding effects of transition and physical risks combined.

The transition impact would be highly heterogeneous across economic sectors, with the largest tail risk for expected losses being experienced if the transition were to happen late and abruptly.[53] Firms in the mining, manufacturing and utility industries would be among those most severely affected by transition risk, and therefore experience the largest impact on their balance sheets and consequently on their financial risk. Due to their strong reliance on brown energy sources, such energy-sensitive sectors would bear the largest costs in the form of higher energy expenditure and the need for major investment in carbon mitigation activities and renewable energy. Transition risk would affect vulnerable firms within sectors disproportionately, especially under the late-push transition scenario. This further illustrates the benefits of an early start to transition in order to mitigate the costs and financial risks.

Both the accelerated and the delayed transition scenarios would increase banks’ expected losses and provisioning needs in the short to medium term, but would not seem to generate financial stability concerns for the euro area. Higher corporate credit risk due to green transition would cause higher expected losses for banks’ corporate loan and households’ portfolios. In 2030, the annual expected losses for the median bank would be 48% higher under both the accelerated and delayed transition scenarios compared with 2022 (also due to a more uncertain macroeconomic environment). In addition, under the accelerated transition scenario, expected losses would reach their peak in 2026 and decline thereafter. At the end of the horizon, annual expected losses relative to portfolio size for the median bank would be below 1% under all scenarios, and more than double

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[52] The NGFS climate scenarios include six scenarios with different temperature targets by the end of the century and provide useful insight into the relationship between temperature pathways and GDP losses over the next 80 years. The most optimistic scenario (net zero 2050: +1.4° temperature target by 2100) reaches the end of the century with a GDP deviation from the baseline of around 3%, while the same figure in the least optimistic scenario (current policies: +3.2° temperature target by 2100) is around 20%. The deviation is due to the combination of chronic and acute physical risks. The GDP deviation for the other four scenarios with temperature targets between +1.4° and +3.2° falls inside the 3%-20% range.

[53] Tail risk (by economic sector) is defined as the 75th percentile of the firm-level distribution of expected losses (for firms in the respective economic sector).

the median only in the tail (i.e. the worst 10% of bank-level distribution). The heterogeneous results across exposures and banks would therefore suggest that a more careful monitoring would be required for some subsets of entities and exposures during the transition process.

Even though the field of climate stress testing is still in its early stages, the findings of other jurisdictions' climate stress tests align with the results of this current exercise. The FSB and NGFS member institutions have already completed 35 exercises on climate scenario analysis; these vary widely in terms of methodology, level of granularity, jurisdictions in scope, horizon and climate risks covered. For abrupt transition scenarios in particular, other exercises have similarly found that climate-related risks would be concentrated within sectors, giving rise to large tail risk (Financial Stability Board, 2022). Other exercises focusing on the impact of transition risks on Italian (Faeilla et al., 2022), Dutch (Caloia et al., 2022), French (Clerc et al., 2021), and Canadian (BoC, OSFI, 2022) financial institutions find effects for credit risks that are of a similar order of magnitude to this current exercise and more pronounced in energy-intensive sectors, such as the petroleum/oil sector.

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Annex

A1 Scenario design

For the first time, the ECB has developed its own set of climate scenarios, specifically designed to assess the impact of different transition pathways on the EU economy and financial system. The complexity of the current environment, characterized by the repercussions of the COVID-19 pandemic and the unusual turbulences in the energy market triggered by the Russian war in Ukraine, required the design of new scenarios to account for all the elements that could impact the green transition process.

Three transition scenarios were obtained by combining BMPE macroeconomic projections with NGFS climate scenarios. The BMPE data reflect the expected macroeconomic developments for the next three years, while the latter made it possible to capture additional shocks triggered by a transition to a greener economy, as well as other climate-related developments. The newly designed climate scenarios of the current analysis cover a time horizon of eight years, from 2023 to 2030. The rationale behind this choice was twofold. First, while standard stress tests usually span a three-year horizon, the green transition is a complex process that is expected to take more than three years. Second, 2030 is the cut-off date for several climate policy targets.

For this exercise, a broad set of climate-related, macroeconomic and financial variables were processed to build the ECB transition scenarios that ultimately fed the ECB climate-sensitive credit risk models used. The granularity selected varied significantly, depending on the nature of the variable and the availability of data. BMPE macroeconomic projections were available only for a subset of macro-financial variables, and only covered the short-term horizon, from 2023 to 2025. NGFS climate scenarios were employed for the projection of climate-related variables, as well as for the macro-financial variables after 2025. Balance-sheet variables were not part of the scenarios since they were iteratively estimated using the climate models discussed in Appendix A2. Table A1.1 provides a comprehensive but non-exhaustive overview of the variables that were included in the analysis.

Table A1.1
Data sources by type of variable

	Variable	Granularity	Source of historical data
Macro-financial variables	Real GDP	Country	ECB Statistical Data Warehouse
	Real GVA	Country-sector	Eurostat FIGARO I/O Tables
	Inflation	Country	ECB Statistical Data Warehouse
	Long-term interest rates	Country	ECB Statistical Data Warehouse
	Real-estate prices	Country	NGFS
	Gas prices	Country	Eurostat
	Oil prices	EU	NGFS
Climate-related variables	GHG emissions	Firm	Urgentem
	Energy mix	Country-sector	Eurostat
	Energy consumption	Country-sector	ECB calculations
	Electricity prices	Country	Eurostat

Source: ECB.

The transition pathways modelled for this exercise implicitly adopt the policy and fiscal assumptions underlying the NGFS scenarios. In particular, the main policy instrument under the NGFS scenarios is an endogenous economy-wide carbon price, iteratively adjusted to ensure that scenario-specific climate targets are met (NGFS, 2022a). Under the NGFS scenarios, the budget surplus generated from implementation of a carbon tax scheme is recycled in different ways, including income tax adjustments and a reduction in government debt. The presence of a carbon tax has a direct inflationary effect on brown energy prices, which, in turn, have a deflationary effect on pre-tax energy prices through a reduction in fossil fuel demand. These complex dynamics are modelled within the NGFS framework and thus indirectly reflected in the scenarios of this climate stress test.

The climate stress test scenarios for this exercise were adjusted to reduce excessively volatile projections, correct data quality issues and cover data gaps. This was especially the case for smaller countries, for which the coverage of high-quality historical data is lower and for which NGFS pathways are not always available. The adjustments mainly included the calculation of averages based on neighbouring or similar countries and the use of regional rather than country projection pathways for some specific variables.

Technical implementation and design of climate scenarios

The accelerated transition scenario (S1) was implemented as a diluted NGFS delayed transition that started in 2023 instead of 2030 and the effects of which overlap with the current energy shock. The baseline macro-financial scenario calibrated for the 2023 EU-wide stress test reflects the current macroeconomic context and was used to project real GVA, inflation, long-term interest rates and oil and gas prices until 2025. These projections were complemented by climate shocks calibrated based on the NGFS delayed transition scenario and calculated by taking the corresponding year-on-year growth rate and adding it to the BMPE projections.

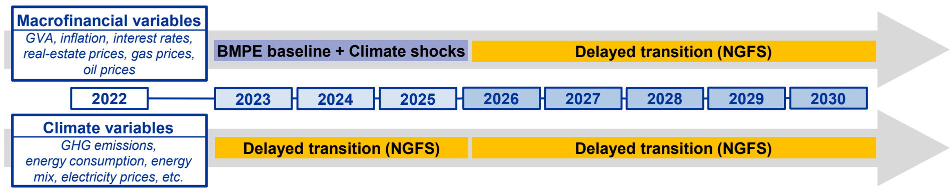
In the NGFS scenario narratives, the delayed transition is a disorderly transition that starts in 2030. To design the climate stress test scenarios, the transition effects were front-loaded on the assumption that a rapid switch to a green economy would already happen in 2023. In addition, the NGFS pathways were diluted through linear interpolation[54] to reflect a transition that was less abrupt than under the late-push scenario and would reach GHG emissions reductions compatible with a +1.5°C temperature change by the end of the century. Table A1.2 and Figure A1.1. summarize some of the features and assumptions relevant to the accelerated transmission scenario (S1).

Table A1.2
Accelerated transition

	Short term (2023-2025)	Medium term (2026-2030)
Relevant scenarios	BMPE macroeconomic projections baseline scenario + Climate shocks* NGFS delayed transition**	NGFS delayed transition
Selected years (NGFS)	Pathways for the period 2030 to 2032, diluted through linear interpolation	Pathways for the period 2033 to 2035, diluted through linear interpolation
Emissions	Compatible with a +1.5°C temperature target by the end of the century	
Investments	High and spread over eight years, with more funding at the beginning	
Energy prices	Very high and increasing further in the first years, providing an incentive for firms to transition rapidly	

* Macro-financial variables: real GDP and GVA, inflation, long-term interest rates, unemployment, real-estate prices and oil and gas prices.
** Climate-related variables: emissions, energy mix, energy consumption, electricity prices, etc.

Figure A1.1
Overview of the accelerated transition scenario (S1)



Source: ECB methodology based on BMPE macroeconomic projections and NGFS climate scenarios.

The late-push transition scenario (S2) would start later than accelerated transition – around 2026 – but would be sufficiently intense to ensure a comparable emissions reduction by 2030. The BMPE projections serving as the basis for the EU-wide stress test pointed to a return to the pre-energy shock macroeconomic conditions towards the end of 2025; this was therefore selected as the cut-off date between the short and medium-term horizons. In the short term, no further policy action was envisaged. The macro-financial variables evolved in line with the BMPE projections, while climate variables evolved in accordance with the NGFS current policies scenario. Starting from 2026, abrupt transition policies were introduced to force the economy to reach the same level of emissions reductions by 2030 as under the accelerated transition scenario. Consequently, the shocks

[54] To create the front-loaded and diluted version of the NGFS delayed transition, projections data for the period 2030 to 2035 were stretched through linear interpolation to cover the entire time horizon of the scenario. In this way, the evolution that was initially expected to occur in five years' time would materialises in eight years.

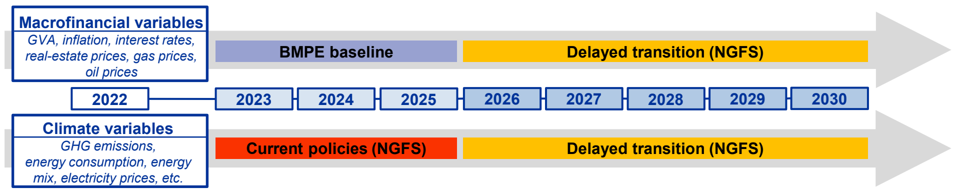
generated by these policies were more acute. To model the transition to a green economy, the NGFS delayed transition scenario was front-loaded to 2026, but not diluted and was therefore more intense.

Table A1.3
Late-push transition

	Short term (2023-2025)	Medium term (2026-2030)
Relevant scenarios	BMPE macroeconomic projections baseline scenario* NGFS current policies**	NGFS delayed transition
Selected years (NGFS)	Pathways for the period 2023 to 2025	Pathways for the period 2030 to 2035
Emissions	Compatible with a +1.5°C temperature target by the end of the century	
Investments	Very high and concentrated in the second part of the horizon	
Energy prices	Fossil fuel prices are constant at a high level before the transition starts and increase thereafter; electricity prices are strongly penalised by the late action in the second part of the horizon	

* Macro-financial variables: real GDP and GVA, inflation, long-term interest rates, unemployment, real-estate prices and oil and gas prices.
** Climate-related variables: emissions, energy mix, energy consumption, electricity prices, etc.

Figure A1.2
Overview of the late-push transition scenario (S2)



Source: ECB methodology based on BMPE macroeconomic projections and NGFS climate scenarios.

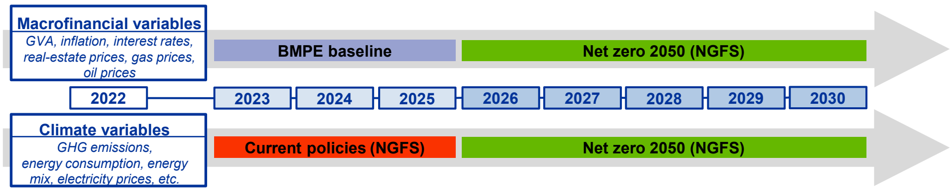
For the delayed transition scenario (S3), new climate policies were introduced from 2026 but were assumed to be milder than under a late-push transition. After three years of limited transition efforts, new climate policies would be smoothly introduced. However, the adoption of green technologies and the shift to renewable sources would be slow and would not make it possible to achieve emissions reductions by 2030 comparable with those under the accelerated and late-push scenarios. When the transition started, it would take the shape of the NGFS net zero scenario, one of the orderly transition scenarios in the NGFS framework. The level of emissions in 2030 would be 55% lower compared with 1990. Such a reduction would be compatible with the NGFS NDCs scenario, which takes into account all pledged policies but is positioned far from the target of a + 1.5°C at the end of the century. It is important to note that the NGFS scenarios do not capture the entire spectrum of emissions pathways compatible with net-zero emissions by 2050 and with the target of +1.5°C. However, given that they are calibrated to optimally reach temperature targets at the end of the century, they were selected as the benchmark for the ECB climate stress test exercise.

Table A1.4
Delayed transition

	Short term (2023-2025)	Medium term (2026-2030)
Relevant scenarios	BMPE macroeconomic projections baseline scenario* NGFS current policies**	NGFS net zero
Selected years (NGFS)	Pathways for the period 2023 to 2025	Pathways for the period 2023 to 2028
Emissions	Compatible with a +2.6°C temperature target by the end of the century	
Investments	Medium, as required to implement an orderly transition	
Energy prices	Constant at a high level before the transition starts and gradually increasing thereafter	

* Macro-financial variables: real GDP and GVA, inflation, long-term interest rates, unemployment, real-estate prices and oil and gas prices.
** Climate-related variables: emissions, energy mix, energy consumption, electricity prices, etc.

Figure A1.3
Overview of the delayed transition scenario (S3)



Source: ECB methodology based on BMPE macroeconomic projections and NGFS climate scenarios.

Downscaling of NGFS emissions pathways

GHG emissions pathways are available at regional level in the NGFS scenarios and were downscaled at country-sector level based on a newly developed ECB methodology. The downscaling process was performed independently from the calibration of the ECB transition scenarios and was based on three long-term NGFS scenarios: current policies, delayed transition and net zero 2050 which cover the period 2020 to 2050. Downscaled, long-term emission pathways were subsequently used to generate short-term pathways, applying the scenario-specific assumptions previously discussed. In a first step, GHG emissions pathways were downscaled at country level using NGFS country-specific GDP pathways. The resulting country-level emissions were then allocated to economic sectors in proportion to their respective projected brown energy consumption, while accounting for future changes in the energy mix.

The following steps were implemented to obtain country-sector emissions pathways:

1. For each scenario, firms' revenues (from Orbis and iBach) were projected until 2050 using the model in equation A.2.1 and equation A.2.4. The projections did not include firm-specific climate shocks but only macro-financial shocks to GDP and inflation stemming from the long-term NGFS scenarios. Revenue growth indices at country-sector level were derived by averaging the projected revenues of firms operating in each respective country-sector couple (at NACE level 2 granularity).

2. Fossil fuels consumption for the year 2020 was estimated,[55] starting from Scope 1 GHG emissions (from Urgentem and aggregated at NACE 2 level), energy-to-emissions conversion factors and information on the country c, sector d and energy consumption by source k (sourced from Eurostat):

$$Fossil\ fuels\ consumption_{t_0}^{c,d} = \frac{Scope\ 1\ emissions_{t_0}^{c,d}}{\sum_k \left(Conversion\ factor_k \cdot Share_k^{c,d}\right)} \tag{A.1.1}$$

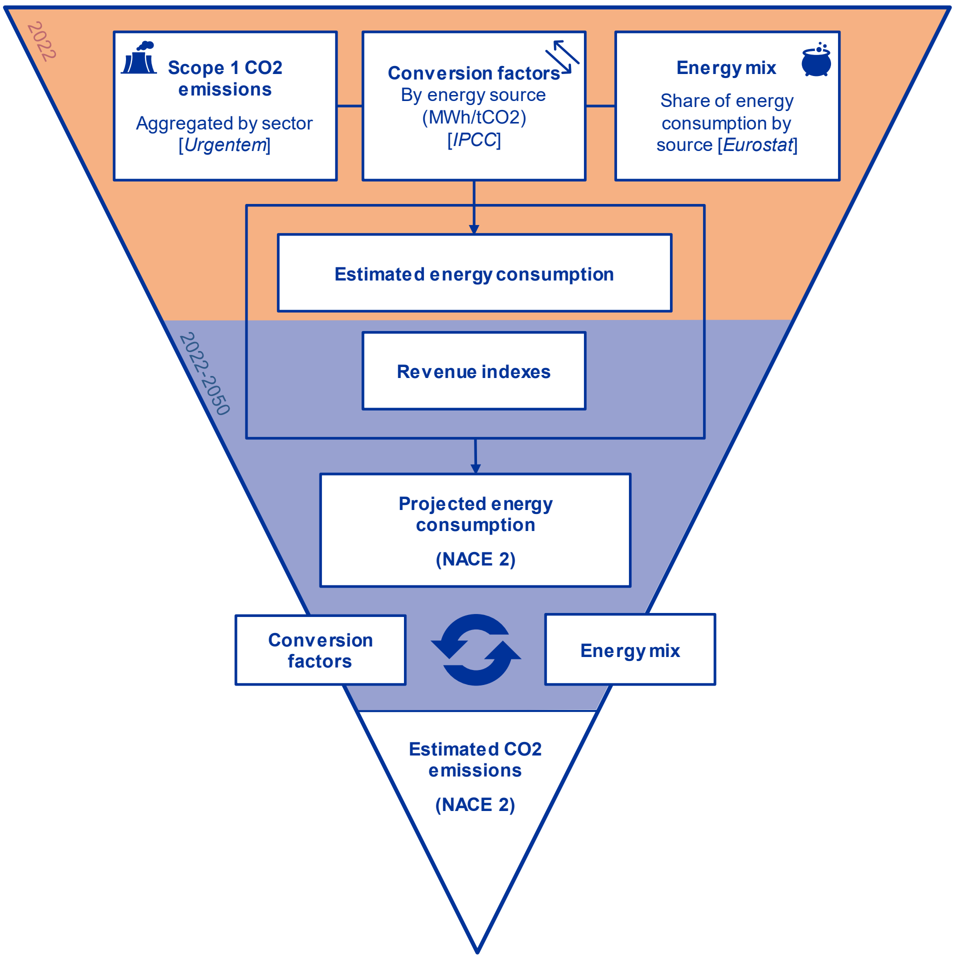
3. Estimated fossil fuels consumption was projected until 2050 using country-sector revenue growth indexes (computed in step 1), assuming that energy needs would grow proportionally to revenues. Country-sector emissions were backward engineered from the estimated energy consumption applying conversion factors, and a forward-looking energy mix was obtained by projecting Eurostat historical data based on NGFS-implied energy consumption pathways by energy source (additional details are given in the next subsection on the estimation of firm-level electricity and brown energy consumption).

4. A forward-looking (scenario-specific) share of emissions by country and by sector was calculated and used to produce the country-sector breakdown of the aggregate GHG emissions available in the NGFS scenarios.

55 Estimation was necessary to obtain a measure of energy consumption at company level.

Figure A1.4

Overview of the ECB emissions downscaling methodology

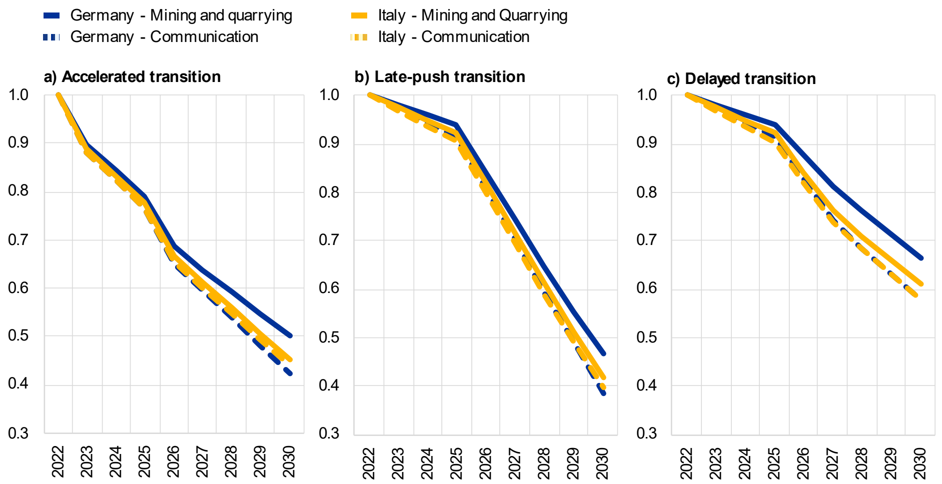


Source: ECB methodology.

Chart A1.1

Downscaled emissions pathways by scenario for selected countries and sectors

(index, 2022 = 1)



Source: ECB methodology based on Urgentem, Eurostat, IPCC and NGFS climate scenarios data.
Notes: GHG emissions pathways were downscaled for standard NGFS long-term scenarios (current policies, delayed transition and net zero 2050). The chart displays the emissions pathways for ECB medium-term transition scenarios, which were derived directly from long-term NGFS climate scenarios.

Firm-level electricity and fossil fuels consumption

The projected energy mix at country-sector level was obtained by combining the latest data from Eurostat and the NGFS climate scenarios. The historical country-sector energy mix was retrieved from the Eurostat energy balances[56] database. By providing a complete statistical accounting of energy products and their flow in the economy, energy balances make it possible to study the overall domestic energy market and monitor the impacts of energy policies. The database includes all statistically significant energy products (fuels) of a given country as well as their production, transformation and consumption by different types of economic players (industry, transport, etc.). Eurostat provides information on energy consumption for 19 “final consumer” sectors and separately for the “energy branch”, which includes all the companies involved in activities related to electricity generation[57]. After matching NGFS-specific primary energy sources with 11 Eurostat energy sources, the energy consumption for each source and each scenario was calculated taking the latest historical values from Eurostat and projecting them based on NGFS-implied energy consumption growth rates. The country-sector energy mix was then calculated directly from the projected energy consumption by taking the share represented by each energy source and dividing it by the total energy consumption of that specific country-sector.

GHG emissions at firm level were estimated using granular data from an external provider (Urgentem) and projected using the downscaled NGFS

56 See the Eurostat energy overview (accessed: November 2022).

57 A complete mapping of Eurostat sectors to the NACE economic activities classification is available in the Eurostat Energy balance guide, setting out the technical details of the Energy Balances dataset.

emissions pathways. Urgentem provides reported emissions for a set of 5,500 global companies for which disclosure data is available from public sources, and infers emissions for the remaining firms based on their sectoral classification and certain financial variables. Urgentem distinguishes between Scope 1, 2 and 3 emissions. This breakdown is crucial for estimating electricity and energy consumption at firm level. Forward-looking firm-level emissions were calculated taking the latest available data from Urgentem and projecting them based on NGFS-implied emissions growth rates obtained after the sectoral downscaling.[58]

The conversion factors for stationary combustion in the energy industry reflect the full carbon content of the fuel concerned. They were sourced from the IPCC 2006 Guidelines for National Greenhouse Gas Inventories and measure the kilograms of carbon dioxide equivalent by terajoules of electricity produced. Conversion factors were used, in combination with firm-level emissions and data on the energy mix at country-sector level previously presented, to estimate the energy and electricity consumption of each company.

Company-level consumption of polluting energy sources[59] was estimated at the starting point ($t_0 = 2022$) and then projected forward using NGFS pathways. For each company i the conversion factor associated with each brown energy source k (i.e., gas, oil, coal, biomass and waste) was weighted by the share of energy source k in country c and sector s, adjusted to account for the proportion of brown energy sources over the total (see Equation A.1.3). This adjustment was necessary to fully allocate Scope 1 emissions to the relevant polluting energy sources and convert them into the energy consumption of these sources. Scope 1 emissions were divided by the energy-to-emissions conversion factor of each source to obtain the company-level consumption of source k at starting point t_0:

$$Energy\ consumption_{k,t_0}^{i} = \frac{Scope\ 1\ emissions_{t_0}^{i}}{Conversion\ factor_k \cdot \widetilde{Share}_{k,t_0}^{c,d}} \qquad (A.1.2)$$

where

$$\widetilde{Share}_{k,t_0}^{c,d} = \frac{Share_{k,t_0}^{i}}{\sum_k \left(Share_{k,t_0}^{c,d}\right)} \qquad (A.1.3)$$

Company-level energy consumption of brown energy sources at time t was obtained by adding together the consumption of each brown energy source k_b, projected using the NGFS-implied pathways for that specific energy source:

---

58 Example: A French company that operates in the mining sector reported emissions in its yearly sustainability report. Data from the 2022 report are collected from Urgentem. The forward-looking emissions pathway associated with France and the mining sector was mapped to the company and used to infer future emissions.

59 For this exercise, primary energy sources were considered to be brown or polluting if they were associated with GHG emissions.

$$Brown\ energy\ consumption_t^i = \sum_{k_b,t} \left(Energy\ consumption_{k_b,t_0}^i \cdot NGFS\ energy\ consumption\ index_{k_b,t}^c \right) \quad (A.1.4)$$

In a similar fashion, company-level electricity consumption was estimated at the starting point ($t_0 = 2022$) and then projected forward using NGFS pathways. A conversion factor for electricity was calculated by applying a weighted average of the conversion factors of the brown sources used to produce it, where the weights were the share of each source in the energy mix of electricity sector e in country c:

$$Conversion\ factor_{t_0}^{c,e} = \sum_k \left(Conversion\ factor_k \cdot \widehat{Share}_{k,t_0}^c \right) \quad (A.1.5)$$

where

$$\widehat{Share}_{k,t_0}^c = \frac{Share_{k,t_0}^{c,e}}{\sum_k \left(Share_{k,t_0}^{c,e} \right)} \quad (A.1.6)$$

The company-level electricity consumption at time t_0 was given by:

$$Electricity\ consumption_{t_0}^i = \frac{Scope\ 2\ emissions_{t_0}^i \cdot Conversion\ factor_{t_0}^{c,e}}{\sum_k \left(Share_{k,t_0}^{c,e} \right)} \quad (A.1.7)$$

where the total share of brown sources in country c and sector e was used in the denominator to account for renewables and nuclear power employed for all electricity generation in country c that are not directly associated with Scope 2 emissions. Finally, the electricity consumption at time t was obtained by multiplying the starting point consumption by the electricity growth index provided as part of the NGFS scenarios:

$$Electricity\ consumption_t^i = Electricity\ consumption_{t_0}^i \cdot NGFS\ electricity\ consumption\ index_t^{c,s} \quad (A.1.8)$$

A2 Corporate model

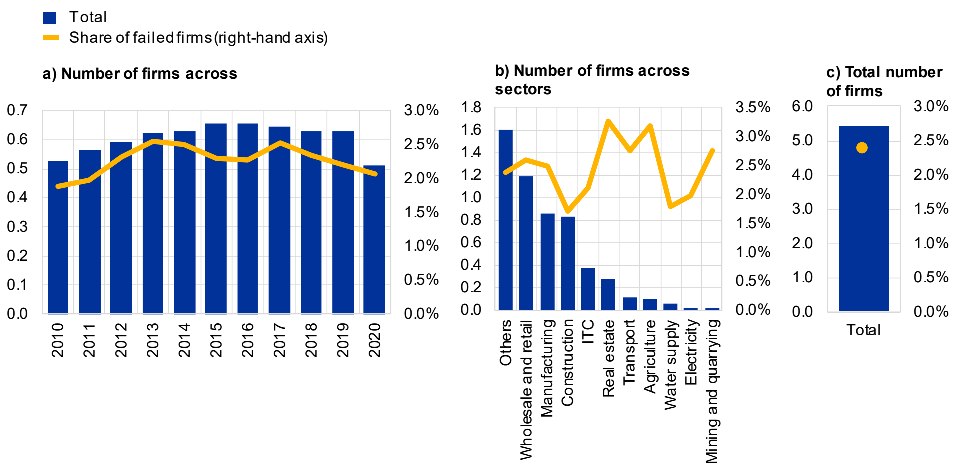
Model calibration stage

For corporates, micro-founded models for firm-level PDs were developed, using firm-level data from the Orbis database. The estimation sample consisted of more than five million firms and spanned from 2010 to 2020. This period encompassed two major Europe-wide economic and financial crises (the European sovereign debt crisis and the COVID-19 pandemic), therefore making it possible to model historically defaulted firms based on their financial information. We identified defaulted firms with a binary variable indicating the "financial failure" of a firm based on two binding criteria: a firm was defined as failed if, for two consecutive years, (a) its cash flow did not cover its financial expenses (cash flow insolvency), and (b) its leverage was above 90% (approximating accounting insolvency; see Cornell Law School (2020) for reference). **Chart A.2.1** provides an overview of the distribution of firms and the share of firms identified as failed across time and sector.

Chart A2.1

Regression sample across time and sector

(left-hand scale: millions, right-hand scale: percentages)



Source: ECB calculations based on Orbis.
Notes: The sample comprised solely those firms for which data on total assets and historical GDP and inflation rates were available.

The two main models developed were for total assets and for PDs. In the following equations the superscript i denotes the firm, t the time (year), c the country and d the sector. For total assets, we used a linear regression model, specified as follows:

$$Total\ assets_t^i = \alpha + \beta_1 Total\ assets_{t-1}^i + \beta_2 GVA\ growth_t^{c,d} + \beta_3 Inflation_t^c + \beta_4\ size\ dummy_t^i + \epsilon_t^i \quad (A.2.1)$$

For estimating firms' PDs, we ran a logistic regression, using the following model specification:

$$PD_t^i = \alpha + \beta_1 leverage_t^i + \beta_2 profitability_t^i + \epsilon_t^i \quad \text{(A.2.2)}$$

Where PD corresponds to the failure rate defined above. In the projection stage, the predicted "failure rate" was a value between 0 and 1, which approximated the PD of a firm in each year. Leverage was defined as total liabilities over total assets, and profitability as net earnings (operating revenues minus operating and financial expenses) before tax over total assets. Equation $A.2.1$ was used to project total assets and other balance-sheet items (revenues, operating expenses and indebtedness), where climate risk drivers entered as exogenous shocks. The projected balance-sheet items were subsequently used to project PDs applying equation $A.2.2$ (more details on the projection stage are provided in the next subsection).

We calibrated each equation for all sectors separately. **Tables A.2.1** and **A.2.2** report the sector-specific regression coefficients of the regression of total assets, while **Tables A.2.3** and **A.2.4** report the sector-specific regression coefficients of the PD regression.

Table A2.1

Regression results for total assets (1/2)

Ln(TA)	Fossil fuels	Energy utilities	Energy-intensive	Buildings
L.ln(TA)	1.004***	1.002***	1.001***	1.0003***
GDP growth	0.033***	0.855***	0.8196***	1.317***
Inflation rate	0.0203***	0.013***	0.003***	0.006***
Observations	5,479	49,149	338,535	988,499
R-squared	0.9995	0.9996	0.9997	0.9996
Size dummies	Yes	Yes	Yes	Yes

Table A2.2

Regression results for total assets (2/2)

Ln(TA)	Transportation	Agriculture	Scientific R&D	Other
L.ln(TA)	1.003***	1.002***	1.006***	1.002***
GDP growth	0.282***	0.727***	0.437***	0.767***
Inflation rate	0.002***	0.009***	0.0105***	0.004***
Observations	187,990	94,249	13,506	3,590,129
R-squared	0.9995	0.9997	0.9993	0.9996
Size dummies	Yes	Yes	Yes	Yes

Source: ECB calculations based on Orbis data. Sectors refer to Climate Policy Relevant Sectors (CPRS) defined in Battiston et al. (2017).
Notes: Standard errors in parentheses. *p<0.1, **p<0.05, *** p<0.01.

Table A2.3

Regression results for probabilities of default (1/2)

PD	Fossil fuels	Energy utilities	Energy-intensive	Buildings
Constant	-7.6***	-7.16***	-7.09***	-6.63***
Profitability	-14.06***	-10.99***	-9.71***	-7.8***
Leverage	3.28***	3.96***	4.11***	3.13***
Observations	1,622	20,037	229,642	261,560

Table A2.4

Regression results for probabilities of default (2/2)

PD	Transportation	Agriculture	Scientific R&D	Other
Constant	-6.27***	-7.08***	-6.2***	-6.44***
Profitability	-9.47***	-12.26***	-10.58***	-7.51***
Leverage	3.004***	3.17***	2.1***	2.98***
Observations	81,223	27,218	3,014	1,159,501

Source: ECB calculations based on Orbis data. Sectors refer to Climate Policy Relevant Sectors (CPRS) defined in Battiston et al. (2017).
Notes: Standard errors in parentheses. *p<0.1, **p<0.05, *** p<0.01.

Projection stage

The starting point input for the projections were firm-level balance-sheet items and macro-variables for year 2021 (for firms where data from 2021 was not available the year 2020 was used), denoted with the subscript t_0. Macro-variables (GVA growth and inflation rates) were projected forward with the macro projections of each short-term scenario based on NGFS. Firms' total assets were first projected forward based on equation A.2.1. The projected total assets were then used to project other balance-sheet items (revenues, operating expenses and indebtedness), where the climate risk drivers entered as exogenous shocks. The following subsections present further details of the projection of other balance-sheet items, the climate shocks and, finally, the projections of firms' PDs. In what follows, the superscript i denotes the firm, t the year $\in [2022, 2030]$, s the scenario, c the country and d the sector.

Earnings

In our framework, baseline operating expenses and revenues were projected based on the growth rate of projected total assets and the relative proportion of operating expenses or revenues to total assets at the starting point. In other words, firms' projected operating expenses and revenues were assumed to follow the same projection pathways as their total assets, keeping constant the initial proportion between operating expenses, or revenues, over total assets. Under each scenario, firms' energy expenses, and consequently operating expenses, would increase with any increase in the prices of coal, gas, oil and electricity. Expenses for brown energy and electricity were derived based on equations A.1.4 and A.1.8, and were added to operating expenses:

$$\text{Operating expenses}_t^{i,s} = \widehat{Total\ assets}_t^{i,s} * \frac{Operating\ expenses_{t_0}}{Total\ assets_{t_0}} + \Delta Brown\ energy\ costs_t^{i,s} + \Delta Electricity\ costs_t^{i,s} \quad \text{(A.2.3)}$$

Operating revenues were calculated as:

$$Revenues_t^{i,s} = \widehat{Total\ assets}_t^{i,s} * \frac{Revenues_{t_0}}{Total\ assets_{t_0}} \quad \text{(A.2.4)}$$

Within the energy sector, firms in the mining and quarrying sector (superscript b) would experience a decrease in their revenues as a result of the green transition and lower brown energy demand. Brown energy demand was measured using the country-level final consumption of coal, gas and oil energy, based on NGFS. The decrease in firms' revenues was referred to as the 'brown deterioration rate' and was assumed to be proportional to the year-on-year percentage change in the consumption of goal, gas and oil:

$$Revenues_t^{b,s} = \widehat{Total\ assets}_t^{b,s} * \frac{Revenues_{t0}^{b}}{Total\ assets_{t_0}^{b}} * (1 - Brown\ deterioration\ rate_t^{c,s}) \quad \text{(A.2.5a)}$$

$$Brown\ deterioration\ rate_t^{c,s} = \%\Delta\ (\text{NGFS brown energy consumption})^{c,s}{}_{\text{t}} \quad \text{(A.2.5a)}$$

Conversely, firms in the electricity sector (superscript e) would experience an increase in their revenues as a result of green transition and higher demand for (renewables-based) electricity. Electricity demand was measured using the country-level final consumption of electricity, based on NGFS. The increase in firms' revenues was referred to as the 'green revenue rate' and was proportional to the year-on-year percentage change in the consumption of electricity:

$$\text{Revenues}_t^{e,s} = \widehat{Total\ assets}_t^{e,s} * \frac{Revenues_{t0}^{e}}{Total\ assets_{t0}^{e}} * (1 - Green\ revenue\ rate_t^{c,s}) \quad \text{(A.2.5b)}$$

$$Green\ revenue\ rate_t^{c,s} = \%\Delta\ (\text{NGFS electricity consumption})_t^{c,s} \quad \text{(A.2.5b)}$$

In the last step, operating earnings were obtained by deducting operating expenses from revenues:

$$Operating\ earnings_t^{i,s} = Revenues_t^{i,s} - \text{Operating expenses}_t^{i,s} \tag{A.2.6}$$

Indebtedness

To project leverage, we needed to project firm's total liabilities, requiring the following steps. In our framework, it was assumed that corporates would maintain the same capital structure over time, meaning that total assets, liabilities and equity would all grow at the same rate (and given that total assets = total equity + total liabilities). Based on this assumption, we projected the growth of liabilities based on the growth of total assets. Under each scenario, firms started to raise funds to invest in (1) carbon mitigation activities and (2) renewable energy generation once the green transition started. Green investments were primarily financed through bank loans, which therefore increased firms' total liabilities. Thus, total liabilities were calculated as:

$$\begin{aligned} Total\ liabilities_t^{i,s} = {} & \widehat{Total\ assets}_t^{i,s} * \frac{Total\ \text{liabilities}_{t_0}}{Total\ assets_{t_0}} \\ & + Green\ investments_t^{i,s} \end{aligned} \tag{A.2.7}$$

For (1), carbon mitigation activities, the amount of green investment that firms would have to raise would depend on their decrease in Scope 1, 2 & 3 emissions from 2022 until 2030, determined by their carbon footprint at the starting point (at firm-level) and the projected emissions pathways for each scenario until 2030 (at sector-level). For the costs of carbon mitigation activities j, we relied on the sector-level prices derived from the IPCC (IPCC, 2022), which calibrated those costs based on the mitigation options and costs of each sector and their potential contribution to net emissions reduction until 2030. Total green investments between 2022 and 2030 for a firm i were therefore calculated as:

$$\begin{aligned} \Delta(Scope\ 1,2\ \&\ 3\ emissions\ in\ tCo2)^{i,s} \\ = Scope\ 1,2\ \&\ 3\ emissions\ in\ tCo2_{2023}^{i,s} \\ - Scope\ 1,2\ \&\ 3\ emissions\ in\ tCo2_{2030}^{i,s} \end{aligned} \tag{A.2.8}$$

$$\begin{aligned} \sum_{t=2023}^{2030} Green\ investments_t^{i,s} \\ = \Delta(Scope\ 1,2\ \&\ 3\ emissions\ in\ tCo2)^{i,s} \\ * Mitigation\ cost_j \left(\frac{EUR}{tCo2}\right) \end{aligned} \tag{A.2.9a}$$

For investments related to (2), renewable energy generation, electricity firms (superscript e) would additionally invest in renewable-based energy capacity. The amount of investment required per electricity firm was determined by the product between (a) the total electricity capacity that each electricity firm would generate between 2022 and 2030 from renewable energy sources ($G_t^{e,s}$) and (b) the costs of investing in renewable energy sources $\mathrm{I_t}$. For (a), the total renewable energy electricity capacity, we derived the amount of green electricity generated by an electricity firm in each year and scenario ($G_t^{e,s}$) from the share of absolute energy consumption stemming from green energy (based on the composition of firms' projected energy mix). For (b), renewable energy investment costs, the costs were modelled using "experience curves", which are explained in more detail in the next subsection. Total green investments between 2020 and 2030 of an electricity firm e were calculated as:

$$\sum_{t=2023}^{2030} Green\ investments_t^{e,s} = \Delta(Scope\ 1, 2\ \&\ 3\ emissions\ in\ tCo2)^{e,s} * mitigation\ cost_j \left(\frac{EUR}{tCo2}\right) + \sum_{t=2023}^{2030} G_t^{e,s} * \mathrm{I_t^s} \quad \text{(A.2.9b)}$$

It is important to note that in equations $A.2.9a$ and $A.2.9b$, the variable $Green\ investments^{e/i,s}$ were first calculated as the total green investments required between 2022 and 2030. In the second step, we assumed that firms frontloaded their green investments and would raise the first 50% in the first three years of transitioning and that the second 50% would be raised in the remaining years. Firms would start to pay back green loans after three years over a maturity period of 15 years.

Finally, green investments would affect firms' net earnings through an increase in amortisation rates and higher financial expenditure (due to interest rate payments on green investments):

$$Net\ earnings\ before\ tax_t^{i,s} = Operating\ earnings_t^{i,s} - Amortisation_t^{i,s} - Financial\ expenses_t^{i,s} \quad \text{(A.2.10)}$$

Costs of investment in renewable energy

We modelled two types of green investment. First, it was assumed that all firms would incur investments in carbon mitigation activities and green technologies proportional to the reduction in their total Scope 1, 2 & 3 emissions. For the costs of carbon mitigation activities, we relied on the IPCC report (IPCC, 2022), which calibrated these costs at sector level, depending on the mitigation options of each sector and their potential contribution to net emission reduction until 2030.

Second, we modelled time and scenario-dependent costs of investment in renewable energy, applying the methodology of 'experience curves'. For investments in renewable energy capacity, we built on Adrian et al. (2022) and model experience curves for renewable energy. The main idea behind those experience curves is that the more renewable energy capacity is generated, the more efficient its production would become through learning and experience (see IRENA, 2022). Consequently, investment costs were expected to decrease over time and scenario as a function of the aggregate cumulative renewable energy capacity, based on NGFS, and a learning factor. We focused on solar and onshore and offshore wind energy as the main renewable energy sources. For each renewable source k_r and scenario, investment costs I in year t were calculated based on cumulative renewable energy capacity G, which comprised the current $(\sum_{t=2022} \mathrm{G}_{\mathrm{k_r,t}})$ and future $(\sum_{t=2023}^{2030} \mathrm{G}_{\mathrm{k_r,t}})$ energy stock and the learning factor $\gamma_{\mathrm{k_r}}$:

$$\mathrm{I}_{\mathrm{k_r,t}} = \alpha_{\mathrm{k_r}} \left(\sum_{t \leq \tau = 2022} \mathrm{G}_{\mathrm{k_r,t}} + \sum_{t=2023}^{2030} \mathrm{G}_{\mathrm{k_r,t}} \right)^{-\gamma_{\mathrm{k_r}}} \quad \text{(A.2.11)}$$

$$\Theta_{\mathrm{k_r}} = 1 - 2^{-\gamma_{\mathrm{k_r}}} \quad \text{(A.2.12)}$$

Historical cumulative renewable energy stock $(\sum_{t=2022} \mathrm{G}_{\mathrm{k_r,t}})$ was obtained from IRENA (2021). The constant $\alpha_{\mathrm{k_r}}$ was a scaling factor and was backward engineered by inserting the values for $\mathrm{I}_{\mathrm{k_r,t}}$ and $\mathrm{G}_{\mathrm{k_r,t}}$ for the year 2022, based on historical information from IRENA (2022). The learning factor determined the speed $\%\Theta_{\mathrm{k_r}}$ of reduction in investment costs $I_{\mathrm{k_r,t}}$ for each doubling of installed energy capacity (i.e. the value in between the brackets in A.2.11). The learning factors were obtained from Adrian et al. (2022) and corresponded to $\gamma_{\mathrm{solar}} = 0.32$, $\gamma_{\mathrm{wind-onshore}} = 0.07$, and $\gamma_{\mathrm{wind-offshore}} = 0.04$. The respective investment cost reduction rates were $\Theta_{\mathrm{solar}} = 20\%$, $\Theta_{\mathrm{wind-onshore}} = 5\%$, and $\Theta_{\mathrm{wind-offshore}} = 3\%$.

Probabilities of default

In the final stage, annual PDs for individual firms were projected based on their projected profitability and leverage. Profitability and leverage were defined as set out below and their projections incorporated the exogenous climate shocks on each individual projected component using the equations given in the above subsections. PD was projected using the model specified in equation $(A.2.2)$.

$$Profitability_{t,s}^{i} = \frac{Net\ earnings\ before\ tax_{t,s}^{i}}{\widehat{Total\ assets}_{t}^{i,s}} \quad \text{(A.2.13)}$$

$$Leverage_{t,s}^{i} = \frac{Total\ liabilities_{t,s}^{i}}{\widehat{Total\ assets}_{t}^{i,s}} \quad \text{(A.2.14)}$$

$$\widehat{PD}_{t}^{i,s} = \alpha + \beta_1 \mathrm{Leverage}_{t}^{i,s} + \beta_2 \mathrm{Profitability}_{t}^{i,s} + \epsilon_{t}^{i} \quad \text{(A.2.15)}$$

A3 Households model

The initial ECB climate stress test was extended to include households in assessment of the impact of climate change on the euro area economic and financial system. The new module leverages the technical infrastructure built for corporates, but has a different level of granularity due to the availability of more aggregate data on households and on banks' exposures to them. The euro area credit register (AnaCredit) currently only includes credit exposures to corporates and other legal entities. Data on credit exposures to households is, however, available at bank-level for the country of the household from ECB supervisory statistics.

PDs for households (HHs) were assumed to correspond to a country-level measure of deterioration in the credit quality of banks' mortgage portfolios. The key variable used to monitor the CQD of country c was defined as follows:

$$CQD^c = \frac{\sum_b new\ defaulted\ to\ HHs_b^c}{\sum_b total\ mortgages\ to\ HHs_b^c} \quad \text{(A.3.1)}$$

which is the share of loans to households defaulted during a pre-defined period divided by the outstanding amount of loans to households, computed at country level.

Model calibration stage

A beta regression model was calibrated and used to project CQD based on macro-variables, such as real-estate prices and long-term interest rates. The model was defined as follows:

$$CQD_t^c = \beta_0 + \beta_1\ Interest\ rate_t^c + \beta_2\ Residential\ real\ estate\ price_t^c + \beta_3 \log(Total\ debt_t^c) + \beta_4 \log(Discretionary\ income_t^c) \quad \text{(A.3.2)}$$

where c denotes the country of residence of households, t the time (quarter) and s the scenario. The input was country-level information on the long-term interest rate, real-estate prices, households' debt and discretionary income, and led to the generation of CQDs at country level.

In order to simplify the text, we used the term "discretionary income" to refer to disposable income net of the energy expenses and debt repayments, defined as follows:

$$Discretionary\ income_t^c \coloneqq Disposable\ income_t^c - Energy\ expenses_t^c - Debt\ repayments_t^c \quad \text{(A.3.3)}$$

The estimation sample included data for all euro area countries and spanned the period from the fourth quarter of 2014 to the third quarter of 2022.

Table A3.1

Estimation of the credit quality deterioration of banks' exposures to households

VARIABLES	CQD
Residential real-estate prices	-1.1453 (***)
Long-term interest rates	0.2340 (***)
Ln(Total debt)	0.3670 (***)
Ln(Discretionary income)	-0.3140 (***)
Constant	-5.6818 (***)
Observations	589
PR-squared	0.329

Notes: the number of observations was 589=19 (countries) x 31 (quarters). For a beta regression, PR-squared is the corresponding measure of R-squared used in usual regressions.

Projection stage

The CQD was projected for each country *c* and scenario *s* for all quarters *t* in time-horizon 2022-2030. All the variables were projected using the approach explained in Annex A1. Total debt and discretionary income were, however, projected in several steps given that households' debt was not included in the NGFS variables and to account for green investments and energy costs.

In a first step, debt was projected using the same pathway as for gross disposable income (the latter being available in the NGFS scenarios) and using the level of debt as at the end of 2022 as the starting point. In a second step, to account for the fact that households would have to finance their green investments, debt was increased by an amount proportional to the decrease in emissions expected by 2030 under each scenario.

$$Green\ investments_t^{c,s} = Scope\ 1\ \&\ 2\ emissions_t^{c,s}[tCO2e] * Mitigation\ cost_j \left[\frac{EUR}{tCO2}\right] \quad (A.3.4)$$

where households' emissions were based on the projected consumption of each energy source k by households in each country c. See Annex 1 for more details.

For the costs of carbon mitigation activities d, we relied on the building-sector prices given in the IPCC report (IPCC, 2022), which calibrated these costs based on the mitigation options of each sector and their potential contribution to net emissions reduction until 2030.

The structure of those investments was modelled in the same fashion as for corporates, in particular:

- Under the accelerated transition scenario, investments would start in 2023 and households would start to repay in 2026;

- Under the late-push and delayed transition scenarios, investments would start slowly in 2023 and intensify after 2025, but would start being repaid only in 2029;
- Repayments would reduce the level of total debt.

Overall,

$$Total\ debt_t^{c,s} = \widehat{Disposable\ income}_t^{c,s} * Total\ debt_{t_0}^{c} + \sum_{\tau=t_0}^{t} (Green\ investments_\tau^{c,s} - Investment\ repayments_\tau^{c,s}) \quad \text{(A.3.5)}$$

where $\widehat{Disposable\ income}_t^{c,s}$ is the gross disposable income pathway derived from the NGFS.

Discretionary income was also projected using the pathway for gross disposable income from NGFS scenarios and using the discretionary income at the end of 2022 as the starting point.

In addition, when projecting discretionary income, the following channels were considered:

(a) The decrease in income levels due to energy costs. This was based on the projected consumption of each energy source j by households in each country c:

$$Energy\ costs_t^{c,s} = \sum_k Energy\ consumption_{k,t}^{c,s} * Energy\ price_{k,t}^{c,s} \quad \text{(A.3.6)}$$

(b) Households were expected to start repaying the debt contracted to finance green investments in line with the schedule given above. As a consequence, total disposable income would reduce.

Overall,

$$Discretionary\ income_t^{c,s} = \widehat{Disposable\ income}_{t,s}^{c} * Discretionary\ income_{t_0}^{c,s} - Energy\ costs_t^{c,s} - Investments\ repayments_t^{c,s} * Interest\ rate_t^{c,s} \quad \text{(A.3.7)}$$

Data sources

The households' module of the climate stress test relied on the following data sources: (i) banks' credit exposures to households, aggregated by country (of households' residence), (ii) country-level information on macro-variables, and (iii) country-level energy mix for the household sector.

Banks' credit exposures by sector and country of residence of the counterparty are reported by all banks subject to European banking supervision as part of the ECB supervisory statistics.[60] Bank-country level information on the LGD of households' exposures[61] is also available in the same data collection, and a weighted average by country was then computed and applied in estimating the losses.

The macro-variables that were used as input for the model were sourced as follows: long-term interest rates from the ECB's "Interest rate statistics", residential real-estate prices from the ECB's "Residential Property Prices" and debt and income from the "Quarterly Sector Accounts" compiled by Eurostat. The data related to energy mix and energy prices were specific for households and came from Eurostat and were projected using the methodology explained in Annex 1.

A4 Market risk model

Market risk: from firm PDs to bond prices

Based on Vermeulen et al. (2018), we computed the change in projected PDs for each bond from one year to the next until maturity in order to obtain the cumulative change in PDs:

$$Cumulative\ \Delta PD(T) = \sum_{t=1}^{T}(1-\Delta PD_{t-1})^{t-1}\,\Delta PD_t \qquad \text{(A.4.1)}$$

Deviating from Vermeulen et al. (2018), we computed the change in spread of a bond as follows:

$$\Delta y = Sensitivity * \ Cumulative\ \Delta PD(T) \qquad \text{(A.4.2)}$$

Where Sensitivity is a parameter that depends on the credit rating of the respective bond. The parameter is derived below.

Finally, we applied the modified duration formula to compute price change:

$$\Delta P = -P * ModD * \Delta y \qquad \text{(A.4.3)}$$

Where ModD is the modified duration and P the price of the bond.

The sensitivity parameter was estimated using two econometric models: a time series model, with a large set of macro-financial controls, and a firm-level panel model. The first model was defined as follows:

$$Corporate\ bond\ spreads_t \ = \alpha_0 + \beta_1 Economic\ indicators_t$$

[60] COREP templates 09.01 (following the "Standard Approach") and 09.02 (following the "Internal Rating Based model").

[61] LGD information is only available in template 09.02 (following the "Internal Rating Based model").

$$+\beta_2 Uncertainty\ indicators_t + \beta_3 Credit\ risk\ indicators_t + \varepsilon_t \quad (A.4.4)$$

The corporate bond spreads used were the asset swap spreads given by the Merrill Lynch global corporate indices for investment-grade and high-yield bonds, which are based on the entire universe of euro-denominated bonds issued by euro area firms. The macroeconomic indicators included GDP growth (12-months ahead forecast), long-term earnings per share (EPS) growth, industrial production and the change in unemployment rate over 6 months. Uncertainty indicators included standard deviation of GDP growth (12-months ahead forecast), the EPS 12 months ahead standard deviation and the EPS long-term standard deviation. Credit risk indicators included the corporate debt to GDP ratio (month-on-month change) and the average PD.

The second model was a large panel regression of individual corporate bond spreads on the median of the expected default frequency. as reported by Moody's (EDF 50), as well as bond-specific ratings, country and sector dummy variables and several bond-specific controls, as established in De Santis (2018) and Gilchrist and Zakrajšek (2012).

The sensitivity parameters were calculated as an average of the coefficients of the two models. For bonds for which no rating could be obtained, an average of the sensitivity parameters for investment grade and the parameter for high yield was used:

Table A4.1

Sensitivity parameters

Credit quality of a corporate bond	Sensitivity
Investment grade	0.9177
High yield	2.1689
Undetermined	1.5433

Acknowledgements
We would like to thank Livio Stracca, Irene Heemskerk, Sujit Kapadia, Costanza Rodriguez D'Acri, Ugo Albertazzi, Katarzyna Budnik, Ivana Baranović, Laura Parisi, Michael Grill, Matthias Sydow and Margherita Giuzio for their helpful comments and suggestions on the paper. We would like to give special thanks to Alberto Grassi for his contributions to the chapter on market risk for banks. We would also like to express our thanks to the members of the ECB/ESRB Project Team on Climate Risk Monitoring, the Financial Stability Committee and the General Council of the ECB for useful comments on the methodology and results. We accept full responsibility for any errors or omissions. The views expressed in this paper are our own and do not necessarily reflect those of the ECB, nor of the people mentioned in these acknowledgements.

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PDF ISBN 978-92-899-6157-8, ISSN 1725-6534, doi:10.2866/49649, QB-AQ-23-019-EN-N