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Sensitivity analysis of climate-related transition risks in the German financial sector

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Non-technical summary

This document describes the methodology, the detailed results and the limitations of the sensitivity analysis of climate-related transition risks in the German financial sector, the results of which were published in the Deutsche Bundesbank's Financial Stability Review 2021. The aim of this analysis is to quantify the potential losses on the balance sheets of German financial intermediaries that could result from an unexpected shift from a climate scenario with lower greenhouse gas reduction targets to a climate scenario with higher ones. This shift affects the real economy initially. In particular, emissions reduction targets and corresponding carbon price increases act as risk factors with varied effects across the economy as a whole. These risk factors also have an impact on the financial system via the usual risk channels, such as credit risk and market risk.

The analysis is based on the climate scenarios devised by the Network for Greening the Financial System (NGFS). These map both the dynamics of climate change and its dependence on greenhouse gas emissions, as well as the global economic processes that lead to these emissions. The scenarios differ in particular with respect to the climate targets to be achieved, each of which require different emissions reduction targets and global carbon pricing paths needed to achieve them. The climate scenarios are broken down into key macroeconomic and financial variables based on the NiGEM macroeconomic model used by the NGFS.

This paper expands upon this by developing a methodology for applying the climate scenarios to individual securities and borrowers. For this purpose, the scenarios are first differentiated by sector using a production network model. This simulates the sectoral interdependencies of the global economy along the relationships determined in the NGFS scenarios, and distributes potential losses across the sectors of the real economy based on the sectors' heterogeneous emissions intensity and position in supply chains. In the next step, market and credit risk models are used to determine historical elasticities between, on the one hand, the variables depicted in the scenarios and, on the other, sectoral credit default rates as well as corporate bond valuations. Lastly, the losses at the level of securities and borrowers are mapped to the balance sheets of German banks, funds and insurers.

Compared to other international studies, and based on the climate-related risks analysed, the results of this analysis suggest similar, moderate potential losses in each financial sector and in the financial system as a whole. However, individual financial institutions may be more heavily affected by potential losses due to a higher exposure to transition-sensitive sectors.

Nichttechnische Zusammenfassung

Dieses Dokument beschreibt die Methodik, die ausführlichen Ergebnisse und die Einschränkungen der Sensitivitätsanalyse klimabezogener Transitionsrisiken des deutschen Finanzsektors, deren Ergebnisse im Finanzstabilitätsbericht 2021 der Deutschen Bundesbank veröffentlicht wurden. Ziel dieser Analyse ist es, die potentiellen Verluste in den Bilanzen deutscher Finanzintermediäre zu quantifizieren, die sich aus einem unerwarteten Übergang von einem Klimaszenario mit geringeren zu einem Klimaszenario mit höheren Einsparzielen von Treibhausgasen ergeben können. Der Übergang hat zunächst Auswirkungen auf die Realwirtschaft. Insbesondere wirken Emissionsreduktionsziele und entsprechende CO_2*-Preisanstiege als Risikofaktoren, die über die gesamte Volkswirtschaft heterogen ihre Wirkungen entfalten. Diese Risikofaktoren wirken über die üblichen Risikokanäle, wie Kredit- und Marktrisiken, ebenfalls auf das Finanzsystem.*

Grundlage der Analyse bilden die Klima-Szenarien des Network for Greening the Financial System (NGFS). Diese bilden sowohl die Dynamik des Klimawandels und dessen Abhängigkeit von Treibhausgasemissionen ab, als auch die globalen wirtschaftlichen Prozesse, welche zu diesen Emissionen führen. Die Szenarien unterscheiden sich insbesondere in den zu erreichenden Klimazielen, welche jeweils unterschiedliche Emissionsreduktionsziele und dazu notwendige globale CO_2*-Bepreisungspfade voraussetzen. Die Klimaszenarien werden durch das vom NGFS verwendete makroökonomische Modell NiGEM entlang wichtiger makro- und finanzwirtschaftlicher Variablen ausdifferenziert.*

Aufbauend darauf entwickelt dieses Papier eine Methodik zur Umlegung der Klimaszenarien auf einzelne Wertpapiere und Kreditnehmer. Dazu werden die Szenarien zunächst sektoral ausdifferenziert mittels eines Produktionsnetzwerkmodells. Dieses bildet die sektoralen Interdependenzen der globalen Weltwirtschaft entlang der in den NGFS-Szenarien ermittelten Zusammenhänge nach und verteilt potentielle Belastungen entsprechend der heterogenen Emissionsintensität sowie der Position in Lieferketten über die Sektoren der Realwirtschaft. Anschließend werden Markt- und Kreditrisikomodelle genutzt. Diese ermitteln historische Elastizitäten zwischen in den Szenarien abgebildeten Größen und sektoralen Kreditausfallraten bzw. Unternehmensanleihebewertungen. Schließlich werden die Verluste auf Ebene der Wertpapiere und Kreditnehmer in die Bilanzen der deutschen Banken, Fonds und Versicherer gespiegelt.

Die Ergebnisse der Analyse legen hinsichtlich der analysierten klimabezogenen Risiken im Vergleich zu anderen internationalen Studien ähnliche, moderate potentielle Verluste je Finanzsektor und im Finanzsystem als Ganzes nahe. Einzelne Finanzinstitute können jedoch stärker von potentiellen Verlusten betroffen sein.

Sensitivity analysis of climate-related transition risks in the German financial sector

Dominik Schober, Tobias Etzel, Alexander Falter, Ivan Frankovic, Christian Gross, Anke Kablau, Pierre Lauscher, Jana Ohls, Lena Strobel, Hannes Wilke[1]

Abstract

Climate-related risks arising from the transition to a low-carbon economy may expose potential vulnerabilities in the financial system. In this article, we develop and describe a set of tools for analysing these risks and apply them to the German financial system. The use of long-term, consistent climate scenarios that have been developed as part of the joint work of the Network for Greening the Financial System (NGFS) allows the effects of the transition to be modelled and then mapped to the financial system. We use a comprehensive dataset in terms of the financial intermediaries and financial instruments reviewed, and demonstrate that the aggregated potential portfolio losses from an unexpected change in climate policy are within the low to medium single-digit percentage range for individual financial sectors. Individual financial intermediaries are more severely affected by transition risks. Uncertainty about the current expectations of market participants leads to results that may deviate by up to 40% from the potential portfolio losses calculated.

Keywords: climate scenarios, climate transition risks, macroeconomic and financial impacts, financial stability analysis, sensitivity test, carbon pricing

JEL-Classification: D53; E27; H23; Q51; Q54

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[1] The opinions expressed in this article are those of the authors and do not necessarily represent the opinions of the Bundesbank or of the Eurosystem. All authors belong to the Bundesbank, Directorate General Financial Stability. The corresponding author is Dominik Schober (dominik.schober@bundesbank.de).

1 Introduction

This document describes the methodology, detailed results and limitations of the sensitivity analysis of climate-related transition risks in the German financial sector, the results of which were published in the Financial Stability Review 2021.[2] The aim of this analysis is to quantify the losses in value on the balance sheets of German financial intermediaries that may occur as a result of different transition scenarios and their effects on the real economy. There is a particular focus on global policy measures that introduce costs for carbon emissions and other greenhouse gas emissions, as implicit drivers of the transition.[3]

In this context, global carbon pricing is regarded as an efficient and effective means of combating climate change. Such pricing has an effect on the real economy in the first instance. The associated costs have an impact on emissions-intensive sectors in particular, but affect almost all areas of the real economy through supply chains, which may reduce the profitability of enterprises. Due to the connections between the financial sector and the real economy via holding company stocks and bonds, and granting of loans and other financial instruments, climate-related transition risks can lead to a reduction in the value of these securities. In order to conduct a sensitivity analysis with respect to climate-related transition risks for the German financial sector, we must use models from different scientific disciplines and combine them with each other. This is the only way that we can fully map the transmission channels of carbon prices as outlined above.

This analysis assumes the introduction of a uniform global carbon pricing system across all sectors and countries. Potential vulnerabilities arising from other carbon price pathways, which vary globally and between sectors, are therefore not examined. This analysis does not look at potential vulnerabilities resulting from the physical effects of climate change, either.

Furthermore, the analysis is limited to policy measures that are associated with the generation of revenue for governments, i.e. carbon pricing revenue from carbon emissions trading or a carbon tax in particular. The analytical framework does not therefore take into account any other conceivable policy measures, such as government investment in carbon-free technologies, efficiency standards or bans, nor is the purpose of this analysis to recommend political climate action measures.

Our analyses are based on integrated assessment models (IAMs), which map the dynamics of climate change and its dependence on greenhouse gas emissions, together with the global economic processes that lead to these emissions. IAMs can describe a wide range of possible

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[2] See Deutsche Bundesbank (2021).
[3] In the following, we talk mainly about carbon emissions, carbon budgets and carbon prices. However, other greenhouse gases that can be translated into CO_2 equivalents using conversion factors are implicitly also always included.

future interdependent developments in the climate and the economy. One notable difference between such climate scenarios is in the climate goals that are achieved by staying within given carbon budgets. Compliance with these carbon budgets imposes some additional (incremental) costs. Activities that seek to avoid carbon emissions are referred to as mitigation. Within the models, the various carbon emissions reduction targets and the costs that are necessary in order to achieve these implicitly give rise to a carbon price. The IAMs that we have used in our methodology are from well-known climate research institutions and have been used within the Network for Greening the Financial System (NGFS) to devise climate scenarios (NGFS 2021a, 2021b).

The IAMs model economic systems in a drastically reduced way. We therefore use complementary economic models that simulate the effects on the real economy traced in the IAMs in the key variables (gross domestic product, energy and emissions intensity, global carbon price pathways) and supplement them with further variables, particularly those relating to the financial sector, such as interest, profits and company valuations.

In addition, the IAM variables are aggregated at only very coarse geographical and sectoral levels and are thus further differentiated in both dimensions and translated into effects on the real economy. International trade links and the indirect effects of carbon prices through imports and exports mean that a global perspective is required here, too. On the one hand, we use the extended macroeconometric model NiGEM, which is also used in the NGFS and translates the economic variables of the IAMs into a range of more detailed macroeconomic and financial variables. On the other hand, we also use a sector model that we have developed internally, which transfers the NiGEM results, which are differentiated only at national level, to 56 sectors of the real economy.

Finally, the financial variables provided by the economic models for each scenario are converted into losses in the value of individual securities with the aid of financial market models. To obtain the broadest possible coverage of all types of securities in our analysis, we estimate historical correlations between the development of gross domestic product, sector sales and sector stock valuations on the one hand and bond and credit default rates on the other. Historical elasticities are then applied to the scenario variables to obtain value adjustments. These are then translated to the balance sheets of German financial intermediaries. The methodology takes into account the specific features of the various financial sectors, i.e. banks, funds and insurers.

With respect to the climate-related risks analysed, the results of the analysis suggest similar, moderate potential losses per financial sector and in the financial system as a whole compared with other international studies. However, individual financial institutions may be severely affected by potential losses.

The results of the analysis are subject to various limitations, however; for example, there is considerable uncertainty with regard to key model parameters. First, changes in the climate cannot be conclusively determined for a given volume of emissions. For instance, it may be that only a much lower emissions budget than the one assumed here would be sufficient to achieve the target of 1.5°C. This would also increase the costs associated with the transition. Second, there is uncertainty as to how exactly the transition will be organised, how the burden will be shared and how effective it will be. Obstacles in the international coordination of climate policy or political changes of course due to elections may significantly increase the cost of the transition. Third, the time dimension for climate change and a transition to a carbon-free economy exceeds the usual time horizon for assets that we look at. Adjustments to the financial system, which may potentially reduce or increase the cost of the transition, are not covered by our analysis.

Sensitivity analyses of climate-related risks have previously been conducted, for example, by DNB, BdF, the ECB/ESRB and EIOPA.[4] These analyses are similar to the one presented here, but focus on subsets of the financial instruments or financial intermediaries examined or of the model chain used to devise scenarios. The analysis presented here includes the financial intermediaries of banks, funds and insurers and, with regard to potential losses on various financial instruments, looks at both credit risk and market risk with almost complete mapping of total assets, including government bonds. In particular, scenarios have been devised in line with a narrative that is consistent within itself, comprising climate scenarios that correspond to the current state of play in climate policy and academic discussions, while many other studies make ad hoc scenario assumptions, such as individual carbon price shocks.[5] These climatic and economic developments, which have been derived on a consistent basis, are successively mapped to the financial system, starting from the real economy, via several sequentially linked models. Regional and sectoral breakdowns are provided for key economic variables, taking into account possible reactions, either sectoral or demand-side. These allow us to derive adjustments to asset values and changes in default rates through value added effects and production effects. This study therefore goes beyond sensitivity analyses conducted previously in terms of the financial instruments examined, the financial intermediaries included and the consistency with which scenarios are devised. Furukawa et al. (2020) and Giglio et al. (2020) offer a comprehensive overview of the academic literature on mutual connections between the financial system and global warming. In particular, the design of scenarios to analyse climate-related risks as part of sensitivity analyses and stress tests is still in its infancy. This study thus contributes to the expansion of existing sensitivity analyses of climate-related risks.

The model framework for the development of climate scenarios is presented in Section 2 below. We describe the design of the individual scenarios and the model chain from the IAMs

[4] See Section 5.4 of this paper.
[5] See NGFS (2021a) and IPCC (2021).

to the derivation of effects on individual financial instruments. Section 3 then outlines the use of these individual climate scenarios to devise shocks to the financial system. Starting from a climate scenario that is assumed to be currently expected by all market participants, a shock to the financial system is generated in which, to the surprise of all market participants, a credible switch takes place to a different climate scenario with higher transition costs. Section 4 describes how the shock to the financial system is mapped to the financial intermediaries' portfolios. Detailed analysis results are shown in Section 5. However, individual model results are presented earlier in order to improve comprehensibility at appropriate points in the development of climate scenarios (Section 2). Section 6 presents the limitations of the analysis in detail. Finally, Section 7 provides a summary of this paper.

2 Development of climate scenarios

The aim of climate scenario-based sensitivity analyses is to quantify potential burdens on financial intermediaries that may arise on the basis of various plausible global warming and climate policy narratives for possible climatic, economic and societal developments. In contrast to these scenarios, forecasts constitute expected developments. Owing to the complexity of possible climatic, economic and societal developments and the significant uncertainty associated with these, it is only possible to devise several plausible pathways for future developments in climate scenarios, rather than forecasts. Within each such scenario, possible consequences for the financial system are differentiated through a model chain. This chain mapping the consequences for the financial system comprises a series of models that are applied successively; see Chart 1.

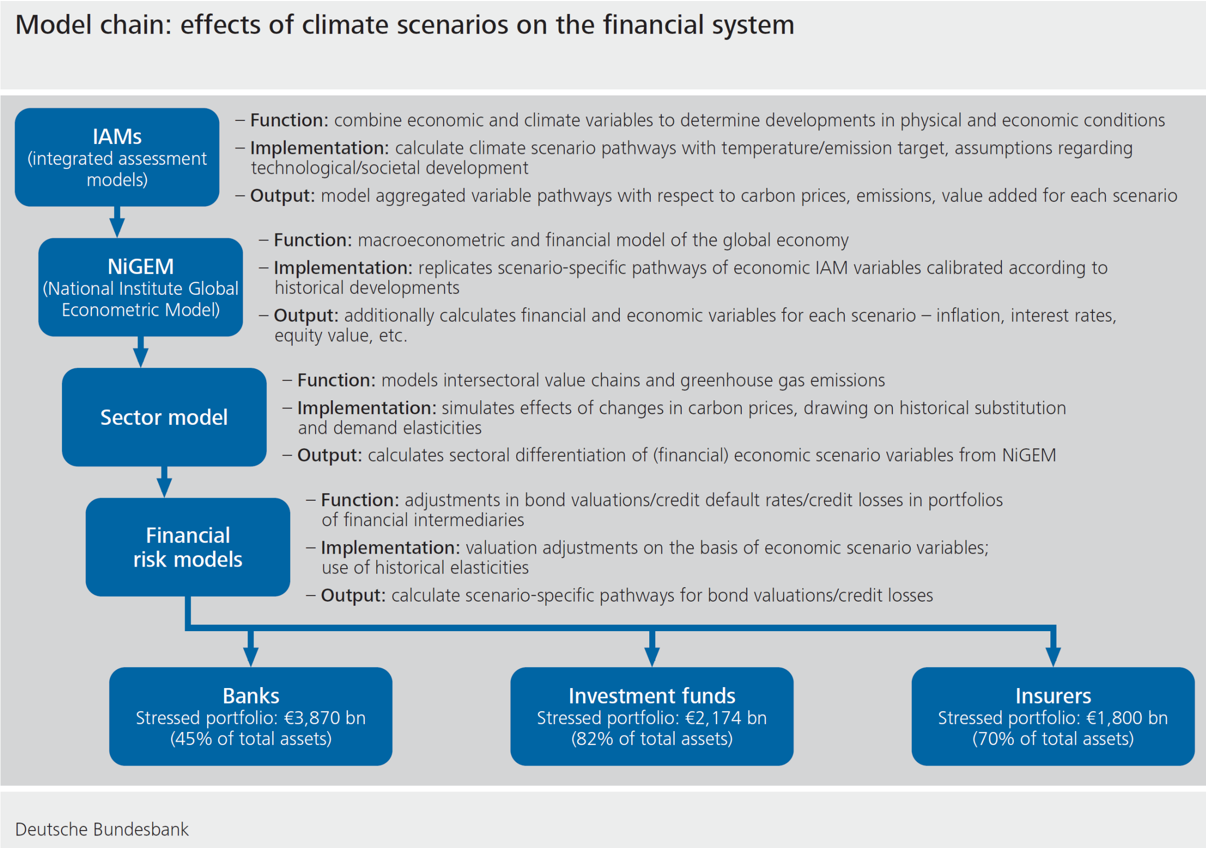

Chart 1: Model chain analysing the effects of climate-related risks on the financial system.

The *Network for Greening the Financial System* (*NGFS*) has played a pioneering role, particularly when it comes to combining *climate models* with macroeconometric and financial econometric models (steps 1 to 2). One of the aims of this is to develop a joint analytical framework for global climate risks for central banks and financial institutions, based on comparability. This is intended to help analyse risks to the real economy and the financial sector that are hidden or unknown and thus not priced in, as well as potential vulnerabilities in the financial system. Using this joint work, which has been coordinated worldwide, the analysis results are fed into Bundesbank models and are mapped to financial intermediaries' portfolios (steps 3, 4 and 5). The model chain is presented in detail below.

2.1 Integrated assessment models (IAMs)

An integrated assessment model (IAM) combines models of economic systems with models of scientific systems in a standardised framework. The economic part of the model mainly comprises a neoclassical growth model. A detailed energy demand and supply model is also incorporated, to quantify the greenhouse gas emissions caused by economic activities. Energy supply includes technologies with varying levels of carbon intensity, their production costs and demand and how their distribution changes dynamically over time. IAMs also include mapping various climate action measures, as well as an implicit societal acceptance and technological development. Emissions pricing, which brings about a transition to low-carbon energy technologies, plays a key role in this. The second part of IAMs involves the modelling of natural systems, particularly the mapping of physical/climatic correlations and the impact of greenhouse gas emissions on temperatures. In addition, IAMs may include models of land use and land management.

The main purpose of climate models is to generate climate scenarios. Climate scenarios may constitute projections, i.e. the simulation of current or assumed trends into the future. One example of this is the “business-as-usual” scenario, in which current climate action measures are extrapolated into the future, leading to high emissions and temperature rises. However, climate scenarios can also be devised as climate pathways. Here, a climate goal is specified, such as the 1.5°C target of the Paris Agreement, while the task of the model is to work out a carbon pricing pathway to achieve this target.

The variation in the assumptions underlying the IAMs (particularly availability and productivity of technology, costs for avoiding carbon emissions, regional variations in climate action measures, population growth, etc.) allows us to devise a range of different climate scenarios that are consistent within themselves. These can be subdivided into simulation and optimisation models, and a basic distinction can also be made with regard to their minimized target function (optimisation of costs vs. optimisation of welfare). The dynamics of the adaptation responses (adaptation of technology on the demand and supply side) are crucial in determining quantitative distinctions between results.

A consortium of world-leading climate research groups and modellers[6] has devised various climate scenarios on behalf of, and in consultation with, the NGFS, based on the latest scientific findings (NGFS 2021a).[7] These scenarios are also used in a similar way in the sixth reporting cycle (2016-22) of the Intergovernmental Panel on Climate Change (IPCC), which includes members of the consortium.[8] In addition, the scenarios have been incorporated into the political process as the basis for the European Commission’s Green Deal. The chart below shows examples of future global warming pathways in different NGFS climate scenarios derived from varying savings targets. The intervals show the climate sensitivities that are assumed.[9]

[6] These include the Potsdam Institute for Climate Impact Research (PIK), the International Institute for Applied Systems Analysis (IIASA), the University of Maryland (UMD), Climate Analytics (CA) and the Eidgenössische Technische Hochschule in Zurich (ETH Zurich).
[7] As agreed between the members of the NGFS and the consortium of climate modellers, the scenarios are limited to the “middle of the road” socioeconomic pathways (“SSP2”). See NGFS Scenarios Portal.
[8] Special report on “1.5°C global warming” (SR1.5): IPCC (2018); Sixth Assessment Report of the IPCC (AR6): IPCC (2021).
[9] See NGFS Scenarios Portal.

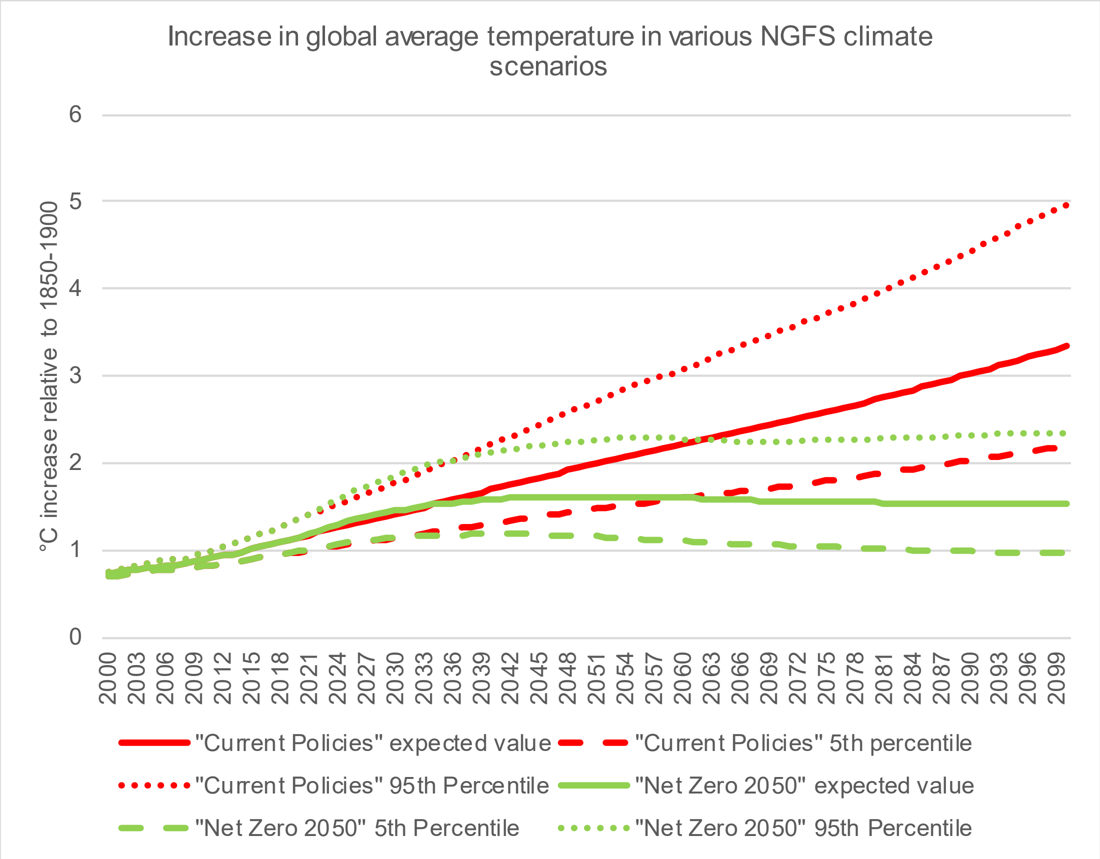

Chart 2: Path of global warming in various NGFS climate scenarios in the MESSAGE model; see NGFS Scenarios Portal.

The defined climate scenarios cover a range of scenarios that are regarded as possible. This includes simultaneous variations in several assumptions, such as climate damage functions (as well as climate tipping points), including assumptions about adaptive behaviour and the costs of adaptation, policy design, technological change including actions to avoid carbon emissions and the costs of these, preference responses (climate prevention/adaptation responses on the demand and the supply side) and general socioeconomic pathways.[10] The IAMs thus generate a wide range of output variables, such as those relating to economic development (GDP, energy costs and intensity, sales) and to the living environment in general (emissions, dissemination of technology, regional climate and weather developments).

The use of different model frameworks allows analyses of robustness to be conducted with regard to the technical assumptions made in the models, which vary between the different approaches. MESSAGE was chosen as the reference model in the analyses presented here,

[10] In the context of the debate about uncertainty, it should be noted here that market participants form expectations of whole climate scenario designs. These each include many essential assumptions about future physical damage to the environment, policy pathways that must be chosen, technological progress and the preferences of producers, consumers and voters, which must consistently be made ex ante in order to ensure that each scenario is credible. The carbon price chosen here is merely the output derived from the respective scenarios, which serves as a key measure of political effects on the real economy and the financial sector and thus makes it possible to quantify potential vulnerabilities in the financial system. Uncertainty is then mapped via a permutation of the scenario selection, as probabilities cannot be used to quantify the risk (in the sense of value at risk, for example) (only *projections, not forecasts*).

so our core calculations are based on the climate scenarios generated by this model. A detailed technical documentation of the IAMs used is available in (NGFS 2021b).

The IAMs used by the NGFS are subdivided into only 11-30 regions worldwide, but subsequently the output variables are scaled down to individual countries based on the country-specific energy demand calculated in the model.

We present the variables used in the MESSAGE model below: development of carbon prices and carbon emissions in Germany in the "Net Zero 2050" scenario. The carbon price rises continuously from 2021 onwards, reaching approximately US$ 400 per tonne in 2030 and US$ 1,000 per tonne in 2050.[11] This leads to a significant reduction in emissions intensity. Although global emissions neutrality is not reached until 2050 in the "Net Zero 2050" scenario, it is achieved in Germany as early as 2045. The product of the pathway of carbon prices and carbon emissions in Germany gives the total cost burden from carbon pricing. This reaches a maximum of about US$ 120 billion around 2030. Negative emissions from the early 2040s onwards turn the cost burden into a subsidy. Emissions fall in the "Net Zero 2050" scenario, due to the transition to a low-emission economy. This is largely driven by the proportion of renewable energies in Germany (solar, hydroelectric and wind power, geothermal energy and biomass), illustrated in Chart 5.

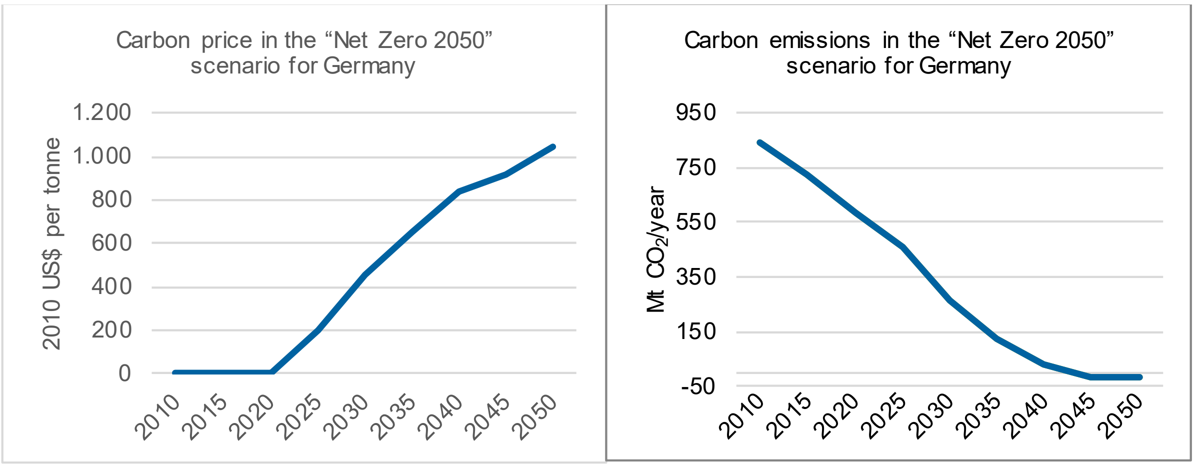

Chart 3: Carbon prices and emissions in Germany in the NGFS "Net Zero 2050" scenario; see NGFS Scenarios Portal.

[11] These are real prices, expressed in 2010 US$ prices.

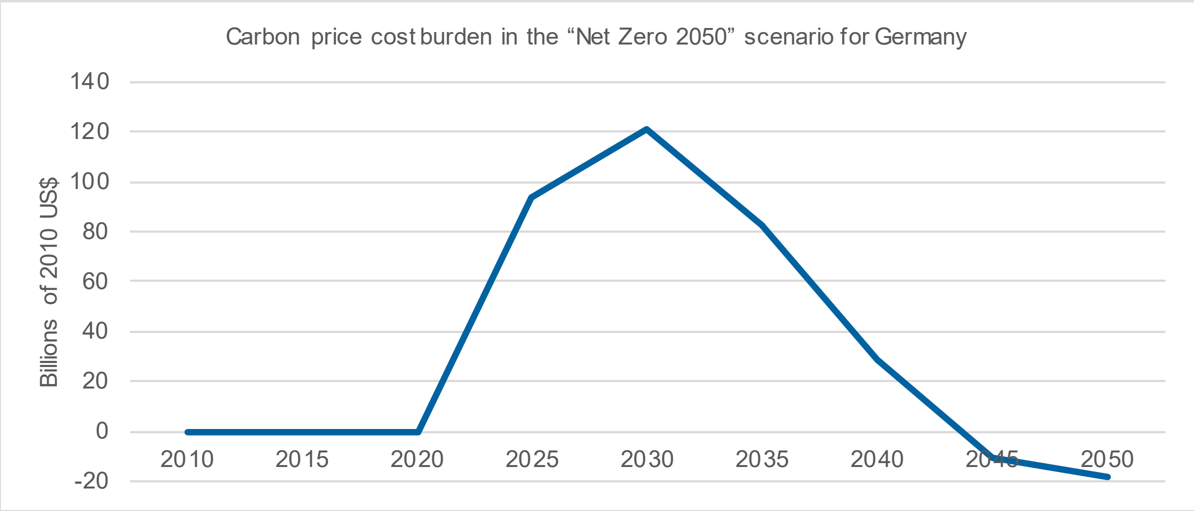

Chart 4: Carbon price cost burden in Germany in the NGFS "Net Zero 2050" scenario, see NGFS Scenarios Portal.

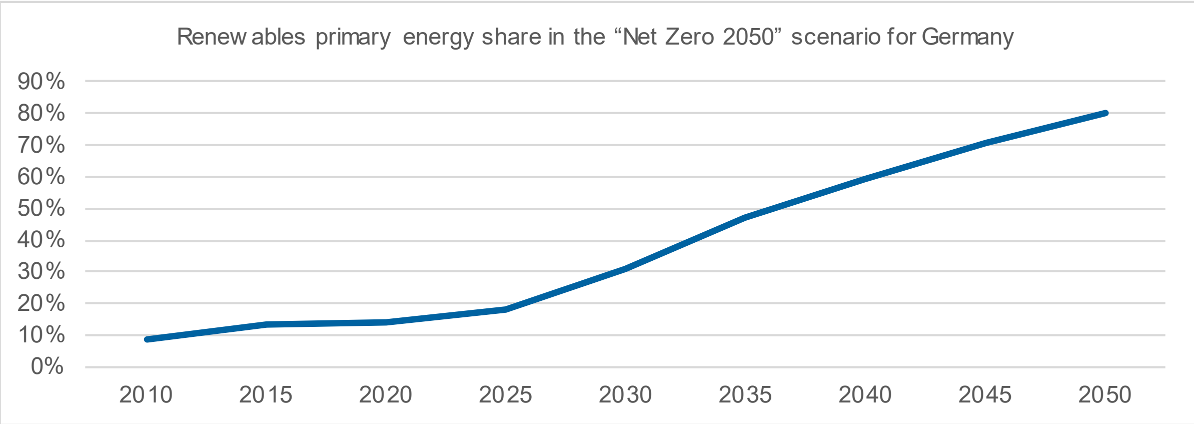

Chart 5: Primary energy share of renewables in Germany in the NGFS "Net Zero 2050" scenario; see NGFS Scenarios Portal.

2.2 Macroeconometric model (NiGEM)

Depending on the purpose of the analysis, IAMs may not adequately map variables relating to the real economy and the financial sector. Particularly in the context of analyses that are relevant to central banks, this makes it difficult to use the climate scenarios directly. To close this gap, another model with a focus on financial/economic parameters was combined with the IAMs in the NGFS work. The National Institute Global Econometric Model (NiGEM) is a macroeconometric model of the global economy and encompasses 60 countries and regions. The model maps over 5,000 variables on a quarterly basis, including with respect to national accounts, trade, the public sector and prices, interest rates and other financial market variables; see Hantzsche et al. (2020) for details. In order to be able to combine the models, NiGEM was expanded in terms of the modelling of connections that are relevant to the climate. Mapping of the carbon price and of the possibility of replacement with less carbon-intensive energy sources, as well as of future economic growth, is key here.

The IAMs and NiGEM are combined using a top-down approach. The evolution of those variables relating to the real economy that are mapped in both the IAMs and NiGEM is replicated in NiGEM through corresponding calibration. This includes regional developments in economic output, investment, consumption of various energy sources and carbon prices. Mappings are carried out for each scenario and each IAM variant. As NiGEM calculates the pathways of all other represented economic variables endogenously, this process significantly expands the range of variables. NiGEM simulates an appropriate set of financial variables on the basis of historically parametrised connections between variables relating to the real economy and to the financial sector. A range of further assumptions are made, relating to, for example, fiscal policy design and in particular the use of revenue from carbon taxes.

In particular, the scenario-specific development of company profits and adjustments to the value of stocks based on this are used in the further calculation steps of the model framework. Changes in government bond premia that are modelled in NiGEM are also used. In NiGEM, these depend on the development of the national debt ratio, which in turn captures the effects on government tax revenue and GDP. Regional trends in inflation and interest rates from NiGEM are also incorporated into further calculations.

Within the scenarios devised by the NGFS, assumptions had to be made regarding the fiscal use of revenue from carbon taxes. In the case of the “Net Zero 2050” scenario, it was assumed in this regard that some of this revenue is used to finance government investment, which has a positive impact on the overall productivity of the economy and thus – ceteris paribus – boosts GDP. To obtain estimates that are as conservative as possible for the impact of carbon pricing on GDP, we have changed the assumptions about fiscal use for the further use of the “Net Zero 2050” scenario within our calculations. To do this, we simulate the development of GDP in NiGEM in the event that revenue from carbon taxes is used to reduce income taxes.[12] In addition, the original NGFS scenarios include negative effects on GDP as a result of physical damage. However, as we want to assess only the effects of transition risks in our downstream analyses, we have excluded the impact of physical damage on GDP in Germany.

Chart 6 below illustrates these scenario changes based on the development of GDP in Germany in the “Net Zero 2050” scenario, expressed relative to the development of GDP in the “Current Policies” scenario. The green line in the middle indicates the original “Net Zero 2050” scenario. If we exclude physical damage, we obtain the light blue line at the top. From the rise in GDP following the initial shock, it is clear that the use of revenue from carbon taxes to fund public finances has strong expansionary effects. However, if we assume that, instead of an increase in government spending, income tax is reduced, the impact on GDP turns negative. In other words, the effects that carbon taxes have in lowering GDP more than offset

[12] Alternatively, we also test its use to increase government transfers to households. However, this results in a very similar trend in GDP compared with the reduction of income taxes.

the positive effects of tax reductions on GDP, leading to a net burden. In all of the calculations below, we use the trends resulting from this fiscal assumption.

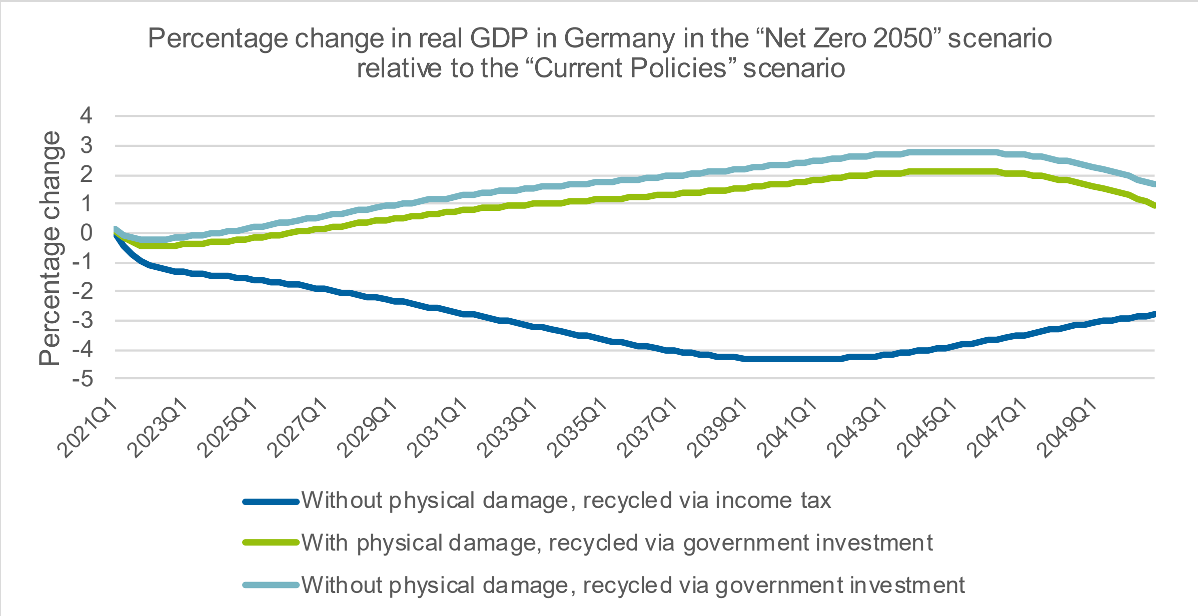

Chart 6: Pathway of real GDP in Germany in the NGFS “Net Zero 2050” scenario relative to the “Current Policies” scenario with and without physical damage and with use as government investment or to reduce income tax.

In the following, we present three further variables in the NiGEM model: development of stock prices, the government bond premium and the GDP deflator in Germany. As part of this, we look at the (percentage) difference between the values of variables in the “Net Zero 2050” scenario compared with the “Current Policies” scenario.

Stock prices fall by about 7% as early as 2021 in the “Net Zero 2050” scenario relative to the “Current Policies” scenario; see Chart 7. Stock prices in NiGEM reflect the discounted future pathway of company profits, based on the assumption of forward-looking expectations. Future profits fall as a result of the cost burden on the real economy from carbon prices. The initial drop in stock valuations thus already takes into account the entire future pathway of carbon prices. As we move forward in time, future cost burdens are less heavily discounted, meaning that losses are larger, reaching a maximum drop of 12% in nominal terms in 2026. However, carbon pricing leads to a strong reduction in the emissions intensity of the German economy over time, so that the rise in the cost burden from carbon prices flattens significantly from 2025 onwards and then falls sharply in the 2030s. This leads to a strong recovery in stock prices, beginning as early as 2026.

A Taylor rule applies in NiGEM, whereby the policy rate is chosen such that the output gap and inflation gap are kept as small as possible. As the cost burden from carbon prices drives up prices as well as reducing production capacity, this rule tolerates moderately higher inflation rates up to the mid-2030s. After the transition is complete, however, price levels in the "Net Zero 2050" scenario are only 4% above those in the "Current Policies" scenario. These higher price levels in the "Net Zero 2050" scenario also explain the significant nominal growth in stock valuations in 2050.

The German government bond premium is only very moderately affected by the increase in carbon prices in the "Net Zero 2050" scenario, falling by a maximum of 8 basis points in the medium term. As the level of debt is kept constant (through the budget-neutral use of carbon tax revenue to reduce income taxes), the development of the debt ratio is the inverse of that of nominal GDP. The latter rises slightly in the "Net Zero 2050" scenario, owing to the somewhat higher inflation in this scenario relative to the "Current Policies" scenario. As the government bond premium depends directly on the debt ratio, we consequently see a drop in premia in the "Net Zero 2050" scenario.

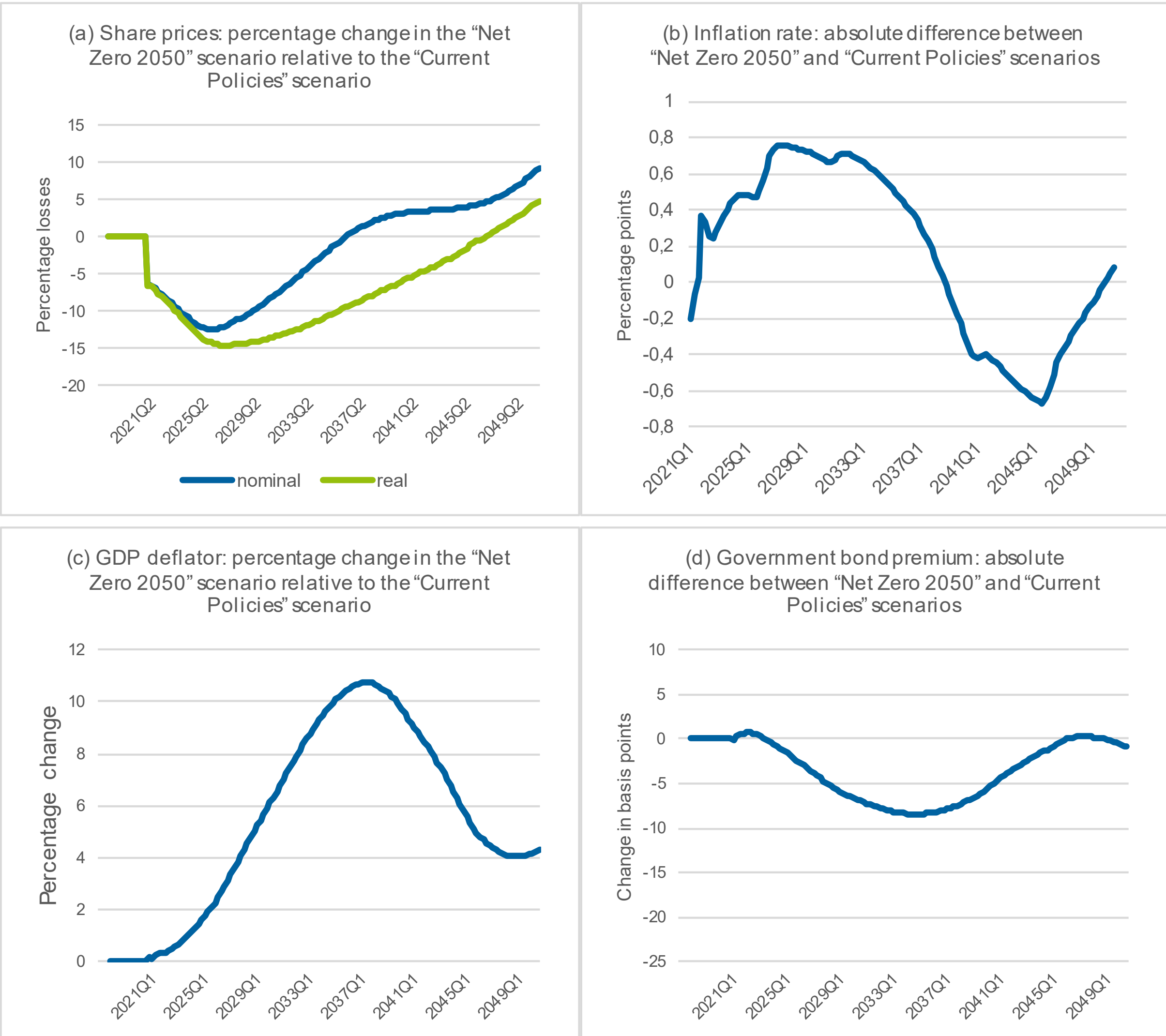

Chart 7: Pathways of share prices, inflation rate, GDP deflator and government bond premium in Germany in the NGFS "Net Zero 2050" scenario relative to the "Current Policies" scenario.

2.3 Sector model

The climate scenarios that are generated in the IAMs and NiGEM are differentiated only in geographical terms and not by sectors of the real economy. Significant heterogeneity and thus asymmetry in the burdens on the real economy requires disaggregation so that the climate scenarios can be applied to the balance sheets of financial intermediaries. Financial institutions with different volumes of investment in sectors with different levels of vulnerability are therefore also exposed to different levels of risk.

To close this gap in sectoral granularity, a production network model (input-output model) has been developed. This maps the intersectoral inputs between economic sectors in various countries. In the model, each sector makes decisions about the extent to which inputs are purchased from other sectors, depending on the price of these inputs. All sectors are subject to a uniform global carbon price in this process. Total emissions costs depend on the volume of carbon emissions (and other greenhouse gases) that accumulate. Particularly carbon-intensive sectors thus have a higher cost burden and will have to raise their prices. There is therefore an incentive for downstream sectors to reduce the volume of inputs from carbon-intensive sectors. This is an effect that extends throughout the entire supply chain of the economy (including demand effects from end consumers), thereby bringing about a structural shift towards less carbon-intensive sectors.

The model maps seven world regions, consisting of four individual countries (Germany, the United States, China and the UK) and three groups of countries (rest of the euro area, other developed countries, rest of the world). Each region comprises 56 sectors of the real economy, which are classified according to NACE Level 2. All (7 x 56) economic units trade with each other, calibrated according to the trade data of the World Input-Output Database (WIOD). The burden of emissions costs per sector in the event of the introduction of a carbon price or an increase in the carbon price is calibrated based on sectoral emissions data from the World Input-Output Database. The model simulates the introduction of a global carbon price and estimates sectoral losses in value added across all the world regions that are captured. These form the basis for sectoral disaggregation of the macroeconomic variables in NiGEM and the IAMs. This allows us to take into account the differences in the degree to which various non-financial sectors are affected by risks relating to climate change in our further calculations. Details of the model and of how it is applied to the climate scenarios are described in a separate technical paper; see Frankovic (2021).

After the NiGEM output is applied through the sector model, the scenarios are expressed in the following variables, amongst others. These variables are used again in the other part of the model framework:

- VA_{iq}: Value added in sector i / quarter q
- EQP_{iq}: Equity prices in sector i / quarter q

The results of the sector model for Germany are briefly outlined below. The scaling factors provide one key result, the scaling factors. These measure the extent to which a sector's value added falls due to the introduction of a carbon price, relative to the overall reduction in value added in Germany. We can see from the chart, for example, that sector C19 (manufacture of coke and refined petroleum products) has a factor of 11.[13] That means that value added in sector C19 falls by 11% for each percentage point by which aggregated value added is reduced. The agricultural sector (A01) and mining (B) also have high scaling factors. Other sectors, especially the services sectors (from code I onwards), have scaling factors of less than 1. That means that the extent to which these sectors are affected by the carbon price is below average.

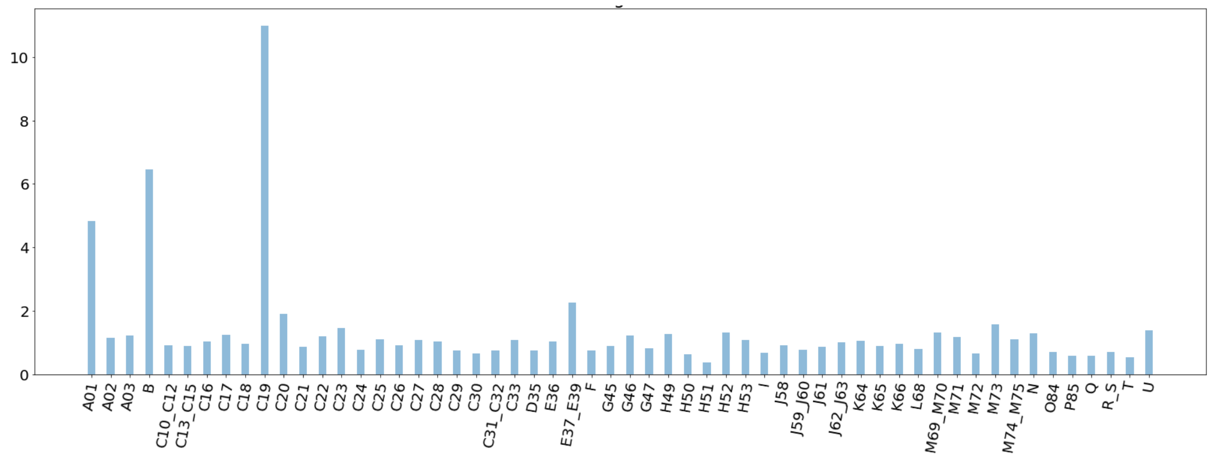

Chart 8: Scaling factors input-output model; see Frankovic (2021).

The scaling factors are now applied to the aggregated trends. The pathway for the total losses in GDP in percentage terms is multiplied by the respective scaling factors in order to obtain the percentage losses in value added in the individual sectors. The losses are thus greatest in the sectors with the highest scaling values. A similar process is applied to stock price valuations, so that sector-specific pathways are generated from the aggregated scenarios.

[13] The sector codes are listed in detail in Table 1.

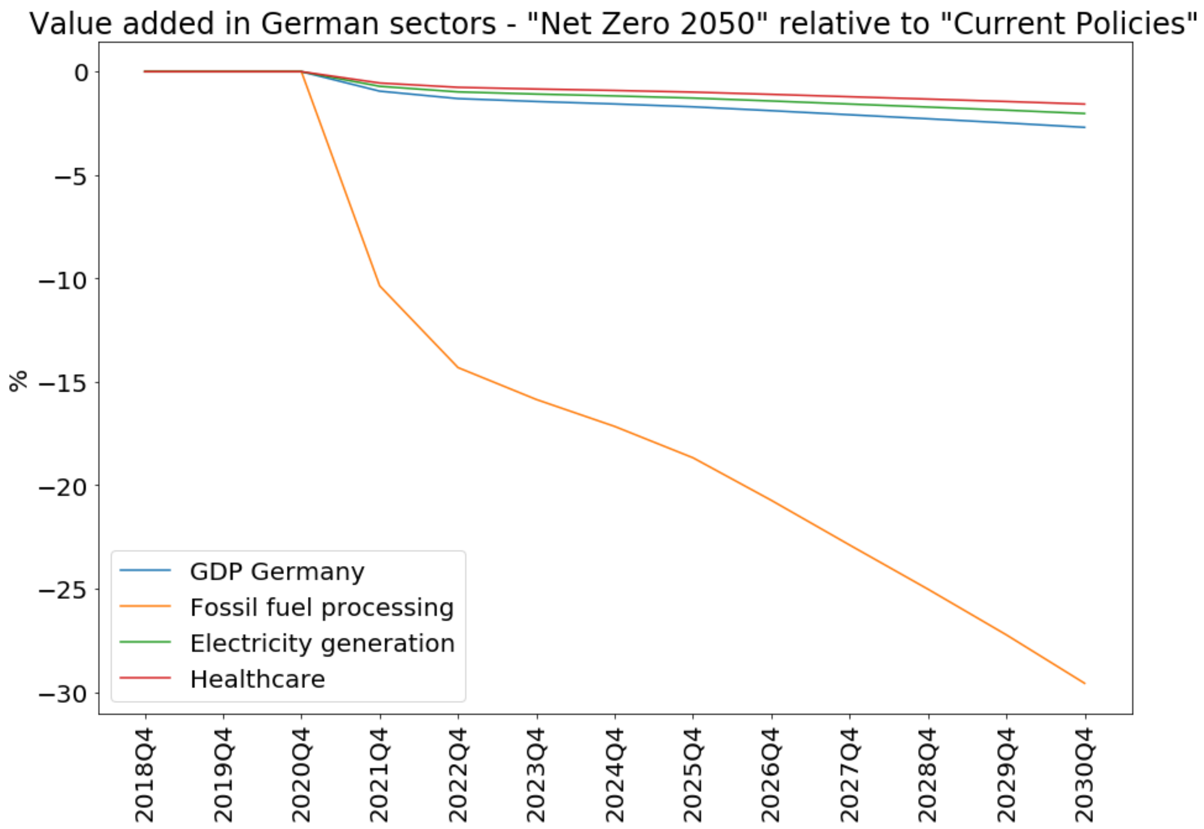

Chart 9: Value added pathways in Germany in the NGFS “Net Zero 2050” scenario relative to the “Current Policies” scenario (percentage change).

Table 1: Overview of the economic sectors taken into account

NACE sector	Name
A01	Crop and animal production, hunting and related service activities
A02	Forestry and logging
A03	Fishing and aquaculture
B:05-09	Mining and quarrying
C10-C12	Manufacture of food products; manufacture of beverages; manufacture of tobacco products
C13-C15	Manufacture of textiles; manufacture of wearing apparel; manufacture of leather and related products
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, trailers and semi-trailers
C30	Manufacture of other transport equipment
C31-C32	Manufacture of furniture; other manufacturing

C33	Repair and installation of machinery and equipment
D35	Electricity, gas, steam and air conditioning supply
E36	Water collection, treatment and supply
E37-E39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
F:41-43	Construction
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles
G46	Wholesale trade, except of motor vehicles and motorcycles
G47	Retail trade, except of motor vehicles and motorcycles
H49	Land transport and transport via pipelines
H50	Water transport
H51	Air transport
H52	Warehousing and support activities for transportation
H53	Postal and courier activities
I:55-56	Accommodation and food service activities
J58	Publishing activities
J59-60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
J61	Telecommunications
J62-J63	Computer programming, consultancy and related activities; information service activities
K64*	Financial service activities, except insurance and pension funding
K66	Activities auxiliary to financial services and insurance activities
L68	Real estate activities
M69-M70	Legal and accounting activities; activities of head offices; management consultancy activities
M71	Architectural and engineering activities; technical testing and analysis
M72	Scientific research and development
M73	Advertising and market research
M74-M75	Other professional, scientific and technical activities; veterinary activities
N:77-82	Administrative and support service activities
P85	Education
Q:86-88	Human health and social work activities
R_S:90-96	Arts, entertainment and recreation; other services activities
T97-98	Activities of households as employers of domestic personnel; undifferentiated goods- and services-producing activities of private households for own use

2.4 Market and credit risk model

Classic financial risk models are used below to map market and credit risk on the basis of historical data. The variables relating to the real economy and the financial sector that have been derived in the model framework to date are applied to developments in securities prices and changes in credit risk. The resulting valuation adjustments from the real economy are thus mapped to the credit and securities instruments that are found in the banking, fund and insurance sector. The financial instruments that we look at are corporate equity (stock prices), corporate and government bonds and corporate loans.

2.4.1 Market risk model

In the sector model (Section 2.3), changes in the market value of the individual sectors are calculated on the basis of the NACE system. This section presents the market risk model, which applies these sectoral changes in value to individual stocks and corporate bonds. This model is also used to calculate changes in the value of government bonds based on changes in a risk premium. The latter variable is modelled in the NiGEM macro-model and is determined by a country's economic development and debt.

2.4.1.1 Calculation of risk premia on corporate bonds

The NiGEM macro-model conveys changes in stock markets but not in corporate bonds. These markets differ considerably in terms of both their primary economic drivers and the extent of liability. For stock markets, future profit expectations play a greater role than short-term credit risk; at the same time, bonds have limited liability. Changes in risk premia on corporate bonds are calculated using a historical percentile approach.

To do this, the historical distributions of appropriate stock and bond indices are combined and, through a calculation of relative rankings, i.e. percentiles, compared with an appropriate spread change for each stock yield calculated in NiGEM. The selected indices are shown in Table 2. Owing to the significant negative correlation of the risk premia on bonds and stock yields, the inverse distribution of the bond spreads is used, i.e. the 90th percentile of the stock yields would be compared with the 10th percentile of the changes in bond spreads.

Table 2: Overview of stock market indices used

Country group	Equity	CDS	$\rho_{\{CDS-EQ\}}$	Kolmogorov-Smirnov test		Mann-Whitney test
				D	P	P(>|z|)
DE	DAX	iTraxx Europe	-0.7607***	0.0632	0.00	0.2566
US	S&P 500	CDX IG	-0.8763***	0.0536	0.00	0.4190
RoEUR	Eurostoxx 50	iTraxx Europe	-0.7371***	0.0645	0.00	0.2336
ODC	MSCI World	CDX IG	-0.8877***	0.0498	0.00	0.4080
EMDC (WD)	MSCI Emerging Markets	iTraxx EM	-0.7786***	0.0980	0.000	0.3619

The underlying assumption is that the inverse relative distribution of bond spreads is similar to the relative distribution of stock market yields. Distribution tests of stock and bond indices suggest that the distributions are similar, even if they are statistically different (see table). That means we cannot reject the null hypothesis of the Kolmogorov-Smirnov test that the distributions are different. However, the distance value (D) is close to zero, which indicates that the differences are only small. The null hypothesis of the Mann-Whitney test, that there are no differences, must be rejected (see last column of table).

Changes in spreads are calculated in 4 steps:

1) Relative changes over 63 trading days (=3 months) in stock market yields and the absolute changes in basis points for CDS spreads are calculated.
2) Stock markets and CDS markets in the same region are combined as shown in Table 2.
3) A relative ranking (=percentile) is calculated for each stock market yield based on the distributions for the stock indices in 1).

4) The associated change in CDS is determined using the inverse distributions for CDS spreads and the percentile from step 3).

A graphical comparison of the changes in risk premia and stock market yields that have been empirically observed and calculated for the various scenarios shows good consistency between the results. Chart 1 shows pairs of changes in bond yields and changes in stock spreads that occur at the same time as orange dots. We can see that there is a negative correlation between the two markets for all regions. The historical average shows that stock markets in Germany rose by 1% over a period of 21 trading days, for example, while investment grade corporate bond spreads declined by 1.6 basis points. The blue dots represent the results for the percentile approach. Here, too, we can see a negative gradient, the magnitude of which is close to the empirically observed gradient.

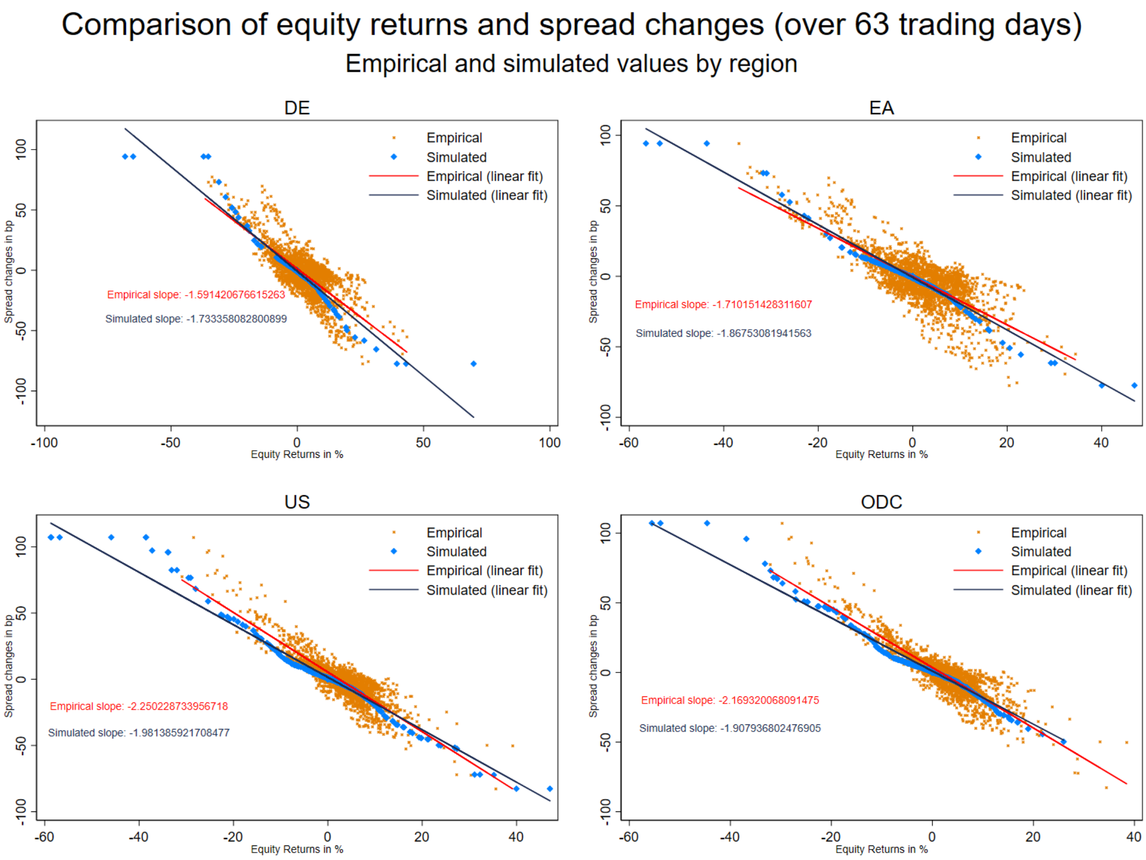

Chart 10: Changes in bond yields and changes in stock spreads.

2.4.1.2 Calculation of losses on securities

The NiGEM macro-model and the sector model show, for each scenario, changes in stock prices for each sector and group of countries and changes in the risk premium for government bonds.

Section 2.4.1.1 above explained how changes in stock prices are translated into changes in risk premia for corporate bonds. The following section will now describe how changes in the value of individual securities are calculated in each scenario, based on these data.

1) From the sector model, the relative changes in stocks in a sector in a group of countries are calculated on a quarterly basis. Using the percentile approach, a corresponding change in risk premia is calculated for each sector loss within a group of countries.
2) In the same way, the market model is used to calculate changes in risk premia on government bonds based on changes in the government premium in NiGEM.
3) Reference data are added from the Central Securities Database for each security that was held by German banks, investment funds or insurers in the first quarter of 2021, with the aid of the ISIN. The reference data can be used to classify stocks and bonds according to the type of security, type of issuers and groups of countries to which they belong, residual maturity/modified duration and credit rating. Funds are classified according to the target region and type of fund, e.g. equity funds with a focus on Europe (an overview of the classifications and CSDB variables used can be found in the annex).
4) For stocks and funds, losses due to changes in the value of equity instruments are used in accordance with the sectors and country groups to which they belong and in line with the results from the NiGEM and sector models. For bonds, losses are determined using the modified duration, the credit rating and the calibrated spread from the percentile method or the risk premia from NiGEM. The spread matrix of EIOPA is used for this; the methodology here is similar to the Bundesbank's macroprudential market risk stress test (see technical paper "stress testing market risk of German financial intermediaries").

The above steps are repeated for each scenario, so that the following asset-level variables are present in each scenario. These variables are used again in the other part of the model framework:

- EQP_{sq}: Equity prices for asset s / time t, whereby $\Delta EQP_s^{scenario,t} = \frac{EQP_s^{scenario,t}}{EQP_s^{2020q4}} - 1$ denotes the change in equity prices from the starting quarter Q4 2020 up to t
- BP_{sq}: Bond prices for asset s / quarter q, whereby $\Delta BP_s^{scenario,t} = \frac{BP_s^{scenario,t}}{BP_s^{2020q4}} - 1$ denotes the change in bond prices from the starting quarter Q4 2020 up to q

- FP_{sq}: Fund prices for asset s / quarter q, whereby $\Delta FP_s^{scenario,t} = \frac{FP_s^{scenario,t}}{FP_s^{2020q4}} - 1$ denotes the change in fund prices from the starting quarter Q4 2020 up to q

2.4.2 Credit risk: Calculation of credit default rates in the German banking sector

In the macroprudential scenario analysis of credit risk, it is customary to proceed in two steps (e.g. ECB 2017, Tente et al. 2019, Memmel and Roling 2021). In the first step, historical elasticities between credit default rates and macro-financial variables are derived from an empirical model. These elasticities and various macroeconomic scenarios are then used to project the development of default rates in the scenario period, which in turn allows downstream calculations of the banks' loan portfolio losses. In principle, we follow this established process in our sensitivity analysis, but we adjust our model to the specific requirements of the scenario analysis of transition risks. An important difference compared with normal scenario analyses concerns the granularity with which the scenarios are designed and applied. Macroprudential scenario analyses are usually based on macro-financial variables at country level, in order to assess the banking system's vulnerability to negative developments. In contrast, our analysis of climate scenarios uses disaggregated pathways for macro-scenarios at the level of individual sectors of the real economy. The aim of this approach is to take into account the heterogeneity with which climate risk shocks are likely to influence the economy. The following section describes the calculation of sector-specific credit default rates for the German banking sector over the scenario horizon.

In order to translate the dynamics of the scenarios at macro and sector level into credit losses in the banking system, an econometric model is used to derive projected pathways for the probabilities of default (PDs) over the entire scenario horizon. We calibrate the projections based on historical data for sector-specific annualised credit default rates (DRs) for domestic corporate borrowers. We devise these using data on specific loss allowances at borrower level, as reported in the Bundesbank's credit register of loans of €1 million or more. In concrete terms, we calculate the proportion of borrowers with specific loss allowances in the respective sector for each quarter, looking at four consecutive quarters in each case:[14]

$$DR_{it} = \sum_{q=1}^{4} \frac{\sum_{k=1}^{d} DB_q}{\sum_{j=1}^{N} B_q} \qquad (1)$$

DB_q denotes the number of borrowers with specific loss allowances (assumed to be borrowers with a credit event) and *B_q* the total number of borrowers in quarter *q*. By adding the numerator and denominator over four quarters in each case in equation (1), we obtain annualised default rates, which are comparable with one-year PDs in their interpretation. To convert the quarterly

[14] See Tente et al. (2019), Memmel et al. (2015) and Memmel and Roling (2021) for similar approaches to deriving annualised default rates for German borrowers using banking supervisory data.

default rates into annual observations, we use the figures from the fourth quarter of each year (i.e. each observation in year *t* covers the default rates from quarters one to four).[15]

The devised variable of annualised default rates is incorporated into our econometric model as a dependent variable. This allows us to determine the magnitude and sign of the historical correlation between default rates and macroeconomic variables that capture the economic dynamics at sector level. Owing to the influence of the economic cycle on default risk in corporate lending business, we take into account gross value added per sector in Germany as an explanatory variable.[16]

Stock prices are the second explanatory variable taken into account in the regression, as stock valuations influence firms' financing conditions and thus implicitly also credit risk (Friewald et al. 2014). We use sector-specific STOXX Europe 600 indices to capture cross-sector heterogeneity.[17]

Data for the period 2008-18 are entered in the regression model on an annual basis, taking into account 54 economic sectors. The period chosen for the underlying historical observations depends on the availability of data. Table 3 shows descriptive statistics drawn from the underlying data.

Table 3: Descriptive statistics

	N	Mean	Median	Std. dev.	5th percentile	95th percentile
Default rate: DR_{it}	594	0.07	0.06	0.0511	0.02	0.15
Gross value added: ΔVA_{it}	594	0.02	0.03	0.0960	-0.14	0.16
Stock returns: ΔEQP_{it}	594	0.04	0.07	0.2410	-0.46	0.36

A panel model approach has been chosen as the econometric framework. Panel regression models for calculating historical elasticities are an established methodological approach in the context of macroprudential scenario analyses (see ECB 2017, Gross et al. 2021). The advantages of a panel model particularly come into play when a limited number of data points means that sector-specific or country-specific regression is not viable.

[15] We use sector-specific default rates for the German share of borrowers, which accounts for the majority of loans in the credit register. We do not devise default rates for foreign credit claims, as exposures abroad are in some cases very limited, which would lead to unreliable estimates of default rates at sector level (see Tente et al. 2019).

[16] The data on gross value added in different economic sectors in Germany come from the national accounts of the statistical office of the European Union (Eurostat). These data are compiled in compliance with the European System of Accounts - ESA 2010, in accordance with Annex B of Regulation (EU) No 549/2013 of the European Parliament and of the Council of 21 May 2013. Eurostat ensures that the data are comparable and consistent between the Member States that are included. Historical time series data on gross value added are available on an annual basis for 64 economic sectors in Germany. The selected economic sectors correspond to the economic sectors in the input-output model for calculating sectoral scenario pathways (see Section 2.3). The only exception is the sectors with NACE codes 65 (insurance, reinsurance and pension funding, except compulsory social security) and 99 (activities of extraterritorial organisations and bodies). No data are available on credit default rates for these sectors, which is why these sectors are not taken into account in the regression.

[17] The STOXX sector indices are devised with reference to the ICB classification of the included companies. We assign the ICB sectors to the NACE Rev. 2 sectors at the most granular aggregation level.

The analysis encompasses variations of the following panel regression model:[18]

$$DR_{it} = c + \beta_0 DR_{it-1} + \beta_1 \Delta VA_{it} + \beta_2 \Delta VA_{it-1} + \beta_3 \Delta EQP_{it-1} + u_i + \varepsilon_{it}, \qquad (2)$$

whereby DR_{it} represents the default rate for sector *i (i = 1,..., 54)* in the year *t (t = 2008, ..., 2018)*, explained by the contemporaneous and lagged rate of change in gross value added ($\Delta VA_{it} = (VA_{it} - VA_{it-1})/VA_{it-1}$), lagged stock returns ($\Delta EQP_{it-1} = (EQP_{it-1} - EQP_{it-2})/EQP_{it-1}$) and a fixed sector-specific effect, u_i.[19] To reduce the effect on the estimated results of autocorrelation with respect to the dependent variable, we also include the lagged values for the default rate as an additional variable on the right side. We compare the results for two different models. First, the fixed effects (FE) model is used as a benchmark in the regression analysis. As an alternative approach, we use the bias-corrected fixed effect estimator (LSDVC) as proposed by Bruno (2005a, b) and Kiviet (1995). The LSDVC corrects the potential bias that arises due to the lagged dependent variable in the estimate where fixed effects are present.[20] Finally, we implement the fractional probit model for panel data (Papke and Wooldridge 2008) as a second alternative estimator to the FE estimator. This approach factors in non-linear correlations between the variables by means of a probit estimate and also takes account of the fact that the dependent variable is limited to between 0 and 1 in terms of its magnitude.

The empirical estimates (Table 4) suggest that both explanatory variables, gross value added and stock returns, have a statistically significant impact on sectoral default rates. As expected, the coefficients are negative. A drop in value added and stock prices is associated with a rise in credit default rates. The results are generally comparable across the three different models. With regard to the quality of the models, the standard model with fixed effects outperforms the LSDVC estimator. This can be seen from the two quality criteria AIC and RMSE, with which lower values show a higher explanatory power for the model. Owing to the non-linear estimation method, the general quality of the fractional probit model is not comparable to that of the FE and the LSDVC estimator. However, the results for this alternative estimator are also listed in order to check the robustness of the results for the linear estimators. We use the parameters of the benchmark model with fixed effects for the following scenario analysis.

[18] Default rates are available on a quarterly basis from 2008 onwards, following the introduction of the Bundesbank's credit register of loans of €1 million or more. The classification by sector of borrowers in the credit register (based on 2-digit NACE codes) allows us to calculate default rates at sector level. This model builds on state-of-the-art methodology. The stress simulated in the climate scenarios are in some cases outside historically observed values for individual sectors that are strongly affected. Research is currently ongoing into how to deal with these extreme values.

[19] To determine the lag structure of the model, contemporaneous values and values lagged by one year were incorporated into the regression model for the explanatory variables. As the contemporaneous stock yields did not have any statistical significance, they were removed from the model in order to ensure economical use of parameters. Consequently, the model in equation (1) should be given preference over alternative specifications, owing to the quality of the model.

[20] In addition, it has been demonstrated that the LSDVC estimator is suited to specifications with a medium-sized number of cross-sectional observations. Previous studies have also shown that the LSDVC estimator outperforms the instrumental variable and GMM estimators (Dang et al. 2015). The GMM estimator is therefore not assessed in this analysis.

Table 4: Empirical estimates of the macro-determinants of credit default rates

Dependent variable: Credit default rate (DR_{it})			
	FE	LSDVC	Fractional probit
DR_{it-1}	0.6640***	0.7530***	
ΔVA_{it}	-0.0509***	-0.0499***	-0.0378***
ΔVA_{it-1}	-0.0267***	-0.0201**	-0.0548***
ΔEQP_{it-1}	-0.0433***	-0.0449***	-0.0287***
N	540	540	540
R^2	0.8153	-	0.1550
AIC	-2,786.441	-	211.3841
RMSE	0.0183	0.0194	-

Notes: FE: fixed-effects model, LSDVC: bias-corrected least square dummy variable estimator proposed by Bruno (2005a, b) and Kiviet (1995), fractional probit: model approach proposed by Papke and Wooldridge (2008). The coefficients stated for the fractional probit model were linearised after estimation, to ensure comparability with the FE and LSDVC estimator.
*, ** and *** denote significance at the 10%, 5% and 1% level. R^2 and AIC cannot be derived for the LSDVC model. For the fractional probit model, it is not possible to derive an RMSE that can be compared with the FE and LSDVC estimators.

3 Development of a shock to the financial system

A shock to the financial system occurs due to an unexpected change from previously expected future developments to a new, unforeseen scenario. Although, as outlined above, many implicit assumptions must be made when defining scenarios, we will distinguish between the scenarios in the following based on the climate policy parameter that is the focus of public debate, the carbon price.[21,22] As in classic stress tests, a baseline scenario is used as the basis; we refer to

[21] The respective carbon price for the scenarios is chosen here as the higher-level, summarised categorisation, as this can be regarded as a key measure of climate-related (transition) risks associated with a particular future scenario pathway. The mitigation that policymakers are seeking aims to avoid carbon emissions. The NGFS scenarios used here each already have specific names that relate to degree values or policy measures that have been taken/will be taken. Strictly speaking, the carbon price is a model result from the IAMs. The main restriction, and thus the climate goal, is a reduction in carbon volumes, which can be translated into carbon prices through carbon avoidance cost curves that are assumed and in some cases (based on technological progress) calculated in the model. In actual economic life, however, they are the main driver of climate-related increases in production costs and thus of both GDP development and development of equity prices – the key financial indicators for subsequent determination of potential vulnerabilities in the financial system.

[22] We use a standardised carbon (equivalent) price as a theoretical economic ideal under specific conditions. With CO_2 a key greenhouse gas, carbon also constitutes the main chemical element responsible for climate change, emissions of which must be documented along with its costs to society. Due to some other market failures, insufficient practicability and some dynamic and other aspects, a variety of differentiated carbon prices in different areas of life are actually optimal. The standardised carbon price that is assumed here should thus be regarded as a degree measure ("thermometer") for the carbon reductions that various political measures are seeking to achieve. In this analysis, they represent a measure of intensity of changes in climate policy. Exceptions to standardised carbon prices are justified in theory and essential in practice. As we have chosen here to focus on presenting the chain of cause and effect in its entirety, showing the effects of climate policy on the financial system, we have dispensed with this depth of detail, which may potentially be relevant to results.

it here as the reference scenario and describe it in concrete terms using a carbon price pathway. This is intended to reflect market expectations for future climate scenarios and the associated carbon prices and is derived from the NGFS climate scenarios with lower carbon price pathways (see Chart 11, Table 5). In terms of an adverse scenario, we assume an increase scenario with a steeper carbon price pathway. In this scenario, an unexpected transition shock is assumed.[23]

The two carbon price pathways, i.e. for the reference scenario and the increase scenario, are assumed to reflect the expectations of market participants within the respective scenario. However, both scenarios and the associated pathways are subject to uncertainty; expectations as to carbon prices can be observed only to a very limited extent and cannot be reliably predicted over a period of 30 years. It is therefore not possible to estimate measures of distribution and thus probabilities of occurrence for the scenarios and the carbon price pathways themselves. Nevertheless, if we wish to carry out an assessment of the bandwidth of possible deviations and their economic consequences resulting from this incomplete information, we can use various reference scenarios as well as various increase scenarios.

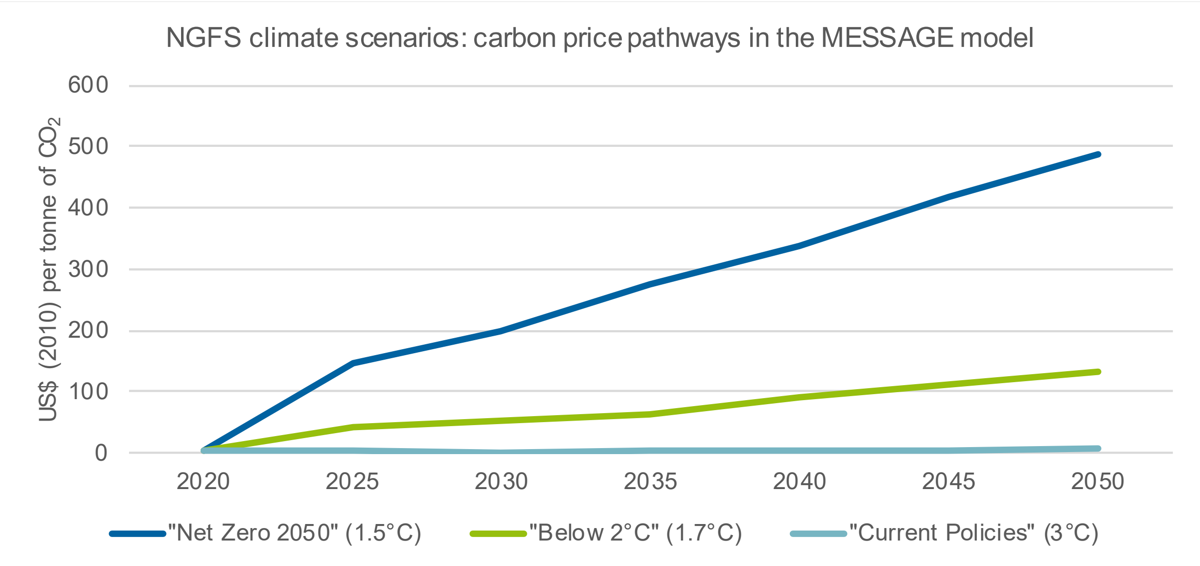

Chart 11: The financial system shock results from an unexpected shock that leads from an uncertain reference scenario to an uncertain increase scenario.

The divergence between the carbon price pathways in the reference and increase scenarios determines the severity of the shock and thus also the potential extent of vulnerabilities in the financial system. It is assumed here that the transition shock, with associated policy changes, occurs in 2021 (Q1) and that future adjustments are thus known after this time.[24] Subsequent

[23] Future political objectives and measures are subject to considerable uncertainty, which is further exacerbated by market participants' mixed expectations regarding these developments.

[24] The analysis also focuses on transition risks. Physical risks have also been examined in sensitivity analyses (in aggregate, at the level of macroeconometric/financial modelling). However, these show only slight deviations in the low single-digit percentage range for Germany. We have therefore dispensed with an explicit discussion of the results, for ease of

unexpected policy changes or new scientific or technological discoveries, which could constitute further shocks, are therefore not taken into account. The divergence in carbon price pathways is accompanied by a divergence in the development of GDP and of equity/securities prices, as calculated in the model chain described above. On the one hand, permanent structural adjustments to production and demand occur in the transition scenarios in accordance with the scenario assumptions; on the other hand, market participants' expectations lead to immediate adjustments to asset values. Based on the assumed expectations of (capital) market participants in the reference scenario, the latter adjust their expectations and revalue their assets when a relevant transition shock occurs.

In the reference scenario "Current Policies" (3°C), given a credible change to an increase scenario "Below 2°C" (1.7°C), the burden on the real economy is relatively low (due to a smaller increase in carbon prices) and the shock to the financial system is correspondingly small. If, instead of this, there is a credible shift to an increase scenario of "Net Zero 2050" (1.5°C), then based on the same reference scenario, the burdens on the real economy will be greater, as the increase in carbon prices will also be larger. The shock to the financial system would thus be classed as strong. A switch from "Below 2°C" (1.7°C) as the reference scenario to the increase scenario of "Net Zero 2050" (1.5°C) triggers a moderate shock to the financial system.[25] Table 5 illustrates these correlations.

Table 5: Scenarios for shocks to the financial system.

NGFS climate scenarios	**Shock to the financial system**		
	Mild	Medium	**Strong**
"Net Zero 2050" **Global climate neutrality by 2050. 1.5°C Paris Climate Agreement goal achieved.**		Increase scenario ⇧	**Increase scenario** ⇧
"Below 2°C" **Minimum goal of Paris Climate Agreement. Rise in temperature kept to below 2°C.**	Increase scenario ⇧	Reference scenario	
"Current Policies" **Continuation of current global climate policy measures. Rise in temperature of around 3°C.**	Reference scenario		**Reference scenario**

presentation. This does not mean that a more detailed analysis, particularly in the light of an increase in extreme weather events, may also reveal significant physical risks for Germany.

[25] The combination "Below 2°C" (1.7°C) X "Below 2°C" (1.7°C) has been omitted. Likewise, the NGFS scenarios "Divergent Net Zero" (1.5°C), "Delayed Transition" (1.8°C) and "Nationally Determined Contributions" (2.5°C) have not been examined. In particular, the scenario "Divergent Net Zero" (1.5°C) is associated with a lower impact on general macroeconomic variables (GDP, losses in asset values) for Germany than "Net Zero 2050" (1.5°C) and is therefore excluded. The main effects occur in the scenario "Delayed Transition" (1.8°C) and become significant after 2030. This is not fully compatible with the limitations of the analysis conducted here (e.g. static portfolios of financial intermediaries). For Germany in particular, which communicated its reduction objectives last year in the context of COP 2015 and the European Green New Deal, the "Nationally Determined Contributions" (2.5°C) scenario largely matches the NGFS scenario "Below 2°C" (1.7°C) and – for Germany – differs only marginally from it. The results have not been presented, as this was considered to be redundant. For a detailed presentation of the scenarios that were included and excluded, see the NGFS Scenarios Portal.

The choice of reference scenario is significant with regard to the permanent structural adjustment costs and in particular the discounted loss allowances. Discounted loss allowances, i.e. “stranded assets”, take into account the divergence of payment flows from carbon price burdens, development of GDP and development of equity/securities prices over several decades, during which the discrepancy between the scenarios also grows increasingly wider.[26]

In summary, it should be emphasised that:

- The **carbon price *reference* scenarios** are intended to reflect the current expectations of market participants.
- The **carbon price *increase* scenarios** are based on NGFS climate policy pathways that deviate from reference scenarios.
- A ***shock to the financial system*** arises for banks, insurers and funds due to an abrupt transition from the reference scenario to an increase scenario. It thus results from the combination (“difference”) between a carbon price *reference* scenario and a carbon price *increase* scenario. This is classified as mild to strong, depending on the choice of reference and increase scenarios (Table 5).

The selection of scenarios is limited to scenarios in which current developments and attitudes continue into the future. These more comprehensive assumptions are referred to as “Shared Socioeconomic Pathway 2: Middle of the Road”.[27] While global socioeconomic developments could conceivably turn out to be more climate-hostile or more climate-friendly, the developments we are analysing here are those that appear most plausible from a present-day perspective. For the potential vulnerabilities in the financial system that are being examined here, the size of the possible shock to the financial system, based on plausible assumptions, is key. In this regard, the choice of a reference scenario with an increase in carbon prices that is as moderate as possible while still remaining plausible, and of an increase scenario with an increase in carbon prices that is as significant as possible while still remaining plausible, ensures that the maximum plausible risks to financial stability are assessed.

4 Mapping of scenario sensitivities for various financial intermediaries

The effects on loans and securities in the German financial sector that were calculated in Section 2.4 are reflected in the portfolios of individual German intermediaries in this section. The intermediaries are modelled as price takers in this process. Explicit (dynamic) expectations and/or portfolio adjustments of German banks, funds and insurers are therefore

[26] In the period of three to ten years that is usually assessed for financial stability, this discrepancy in carbon prices between the scenarios tends to be limited. However, there will be real differences in carbon prices of around €50 to €200 / tCO_2 from 2030, and by 2050 these will actually reach around €500 to €800 / tCO_2 (see Chart 11).

[27] See IPCC (2021).

not modelled. This implies that German intermediaries do not pass on assets that are subject to climate risks to each other or to foreign market participants.

In particular, we also show the original effects of the shock to the real economy due to climate policy over the medium to long term. The aggregated physical/economic effects of climate policy and climate change are mapped in the climate models and, through macroeconometric replication of the model results, supplemented with further economic variables, which are then transferred to individual sectors of the real economy based only on plausible assumptions. The dynamic responses assumed in the climate models are therefore presented realistically. Loss allowances and adjustments to the GDP path due to climate change are mapped accordingly in the part of the model relating to the real economy. Only the balance sheets of the financial intermediaries are assumed to be static. [28]

4.1 Banks

4.1.1 Credit risk

Based on the empirical results presented in Section 2.4.2 for the elasticities between credit default rates and variables relating to economic development in the corporate sector, the next step is to carry out a scenario analysis in order to project the effects of forward-looking climate and policy pathways on the loan portfolios of German banks. The chosen approach involves feeding the long-term climate scenarios into the estimated benchmark model in order to obtain projections of the default rates over the scenario horizon from 2021. The default rates for each region and each sector are projected separately, using sector-specific and region-specific scenario variables for stock prices and value added. In formal notation, the development of the sector-specific default rates in the scenarios, $\widehat{DR}_{it}$, is shown in equation (3):

$$\widehat{DR}_{it} = \hat{c} + \widehat{\beta_0}\widehat{DR}_{it-1} + \widehat{\beta_1}\Delta VA_{it}^{s} + \widehat{\beta_2}\Delta VA_{it-1}^{s} + \widehat{\beta_3}\Delta EQP_{it-1}^{S} + \hat{u}_i, \qquad (3)$$

whereby $\widehat{\beta_0}$, $\widehat{\beta_1}$, $\widehat{\beta_2}$, $\widehat{\beta_3}$ and $\hat{u}_i$ denote the estimated values of the parameters in (2), and ΔVA_{it}^{s} and ΔEQP_{it-1}^{S} describe the rates of change in scenario *s*.

Based on the predicted default rates and changes in these (in percentage growth rates) in each year of the scenario horizon relative to the starting point in Q4 2020, sector-specific scaling factors S_{it}^{s} are derived in each scenario s.[29] These scale the borrower-specific PDs up or down and give us the scenario PDs for each individual borrower *k* in sector *i* at time *t*:

$$PD_{kt}^{s} = PD_{k,i,2020Q4} * S_{it}^{s}. \qquad (4)$$

[28] Only first-round effects are considered at present.

[29] The PDs in the credit register come from the lenders' internal rating systems. For borrowers for which no estimates of PDs are available, we take the median PD for all borrowers in the same sector (German exposures) or the same country/region (foreign exposures).

Next, the expected losses (*EL*) for the loan portfolio of all banks *M*, consisting of *N* borrowers, can be derived for any given point in time in the scenario horizon *t* with the following formula:

$$EL_t = \sum_{i=1}^{N} \sum_{j=1}^{M} PD_{ijt}^{scenario} * LGD_{ijt} * EAD_{ijt}, \quad (5)$$

whereby LGD_{ijt} represents the loss given default and EAD_{ijt} the exposure at default, as reported in the credit register. Borrower-specific LGDs are taken as reported in the credit register.[30] EAD_{ijt} represents the loan exposure on the balance sheet of bank *j* to non-financial corporation *i* in Q4 2020. If a bank has several exposures to one borrower, the exposures have been aggregated.[31] Intragroup loans are excluded from the analysis. Furthermore, the scenario analysis only considers the loan exposure to the non-financial corporate sector and excludes banks and other financial intermediaries (e.g. money market funds and insurers). Public administrations and real estate and consumer loans to households are also excluded from the analysis.[32] In total, we look at 1,336 institutions.

Chart 12 shows a breakdown of the loan exposures of German banks to the five most climate-sensitive economic sectors in terms of transition risks, based on the level of the scaling factors generated by the input-output model. We can see that the share in the entire corporate loan exposure in the German banking system is about 3.5%.

[30] If no information is available about the borrower-specific LGD, we use the sector averages for loans to German borrowers and the respective country averages for loans to borrowers based in all other countries.

[31] The same borrower may receive a different rating from different banks. If several PDs are available for the same borrower, we take the maximum value. If different LGDs have been reported for the same borrower/bank relationship, we use the exposure-weighted average.

[32] The behaviour of credit default rates in the public sector and for banks and other financial intermediaries differs from the other economic sectors analysed, and can be explained only partly with the chosen model framework. Real estate and consumer loans to households are not recorded, or not recorded adequately, in the credit register.

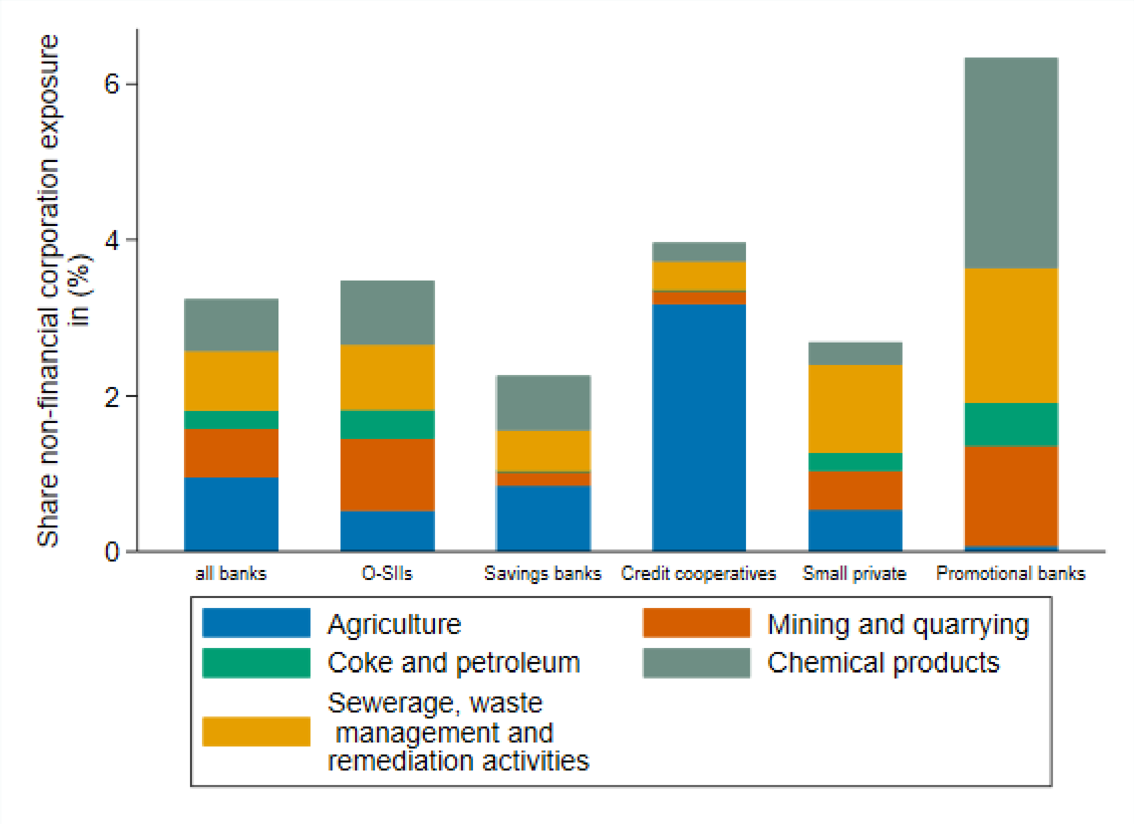

Chart 12: Corporate loan exposures of German banks to economic sectors sensitive to climate risks.

4.1.2 Market risk

The market risk module for the banking sector calculates profits or losses from changes in the market prices of securities held by banks. Profits or losses from changes in market prices are approximated at the level of the individual security (ISIN level). Securities portfolios that are taken into account include equity and debt instruments and fund shares.

Data:

1.) Own safe custody account holdings reported to the Securities Holdings Statistics: The financial institutions report to the securities holding statistics which securities they hold in their own safe custody accounts. The securities holding statistics also contain information about whether securities are held in the banking book or the trading book and about the carrying amounts of securities.

2.) Centralised Securities Database (CSDB): The CSDB contains further information about individual securities and their issuers and price information for debt and equity instruments and fund shares.

According to the securities holding statistics, the banks analysed held securities portfolios worth €1,474 billion as at the end of 2020. Of this figure, 96.2% was included in the analysis.[33]

[33] With some securities it is not possible to approximate a revaluation, owing to the unknown valuation function; this concerns certificates or hybrid instruments, for example.

Scenario leads to revaluation of securities

Banks j hold individual securities s in their securities portfolios, which can be assigned to equity instruments, debt instruments or fund shares. Losses in market value are calculated at the level of the individual security. To do this, for each point in time in scenario horizon t, depending on the type of security, the market value following market price shock $MV_{js}^{scenario,t}$ is calculated by applying the securities losses from Section 2.4.1.2.

a) Revaluation for stocks

$$MV_{js}^{scenario,t} = MV_{js}^{2020q4} * (1 + \Delta EQP_s^{scenario,t})$$

b) Revaluation for bonds

$$MV_{js}^{scenario,t} = MV_{js}^{2020q4} * (1 + \Delta BP_s^{scenario,t})$$

c) Revaluation for fund shares[34]

$$MV_{js}^{scenario,t} = MV_{js}^{2020q4} * (1 + \Delta FP_s^{scenario,t}))$$

Aggregated losses in market value in the banking sector

Losses in market value per security are calculated from the difference between the market value after revaluation $MV_{js}^{scenario,t}$ and the original market value MV_{js}^{2020q4}.

That means that aggregated losses in market value $MV_{loss}^{scenario,t}$ across all securities portfolios P of banks K in the German banking sector can be calculated as follows for any point in time in the scenario horizon t:

$$MV_{loss}^{scenario,t} = \sum_{s=1}^{P} \sum_{j=1}^{K} (MV_{js}^{scenario,t} - MV_{js}^{2020q4})$$

Where impairments are recognised on securities, losses in market value are reflected in balance sheet losses in the income statement or in other comprehensive income (OCI), which can reduce the banks' equity.

Owing to the different accounting treatment options for securities, which depend on the accounting standards applied and the purpose for which securities are held, losses in market value do not always translate into balance sheet losses to the same extent.[35] In view of the

[34] Where possible, fund-specific losses from the market price module are used here for the fund sector (see also Section 2.5.2 b). This calculates losses on securities held by funds in a similar way to the market risk module for the banking sector. However, the necessary transparency ("look-through") is not available for all funds held by the banking sector (particularly not for foreign funds), which means that assumptions are made about drops in prices, depending on the type of fund (equity, mixed or bond fund).

[35] In accordance with the German Commercial Code (*Handelsgesetzbuch*), for example, banks can exercise write-down options in parts of the banking book if it is assumed that the decline in market prices is not permanent. In addition, the German Commercial Code allows securities held in the banking book to be recognised on the balance sheet at less than their market

extended stress horizon, we have dispensed with modelling these specific accounting features, as accounting treatment options in principle entail a time delay in the realisation of profits and losses.

4.2 Funds

The sensitivity analysis in the fund sector simulates the effects of various transition scenarios on the assets managed by German funds. This takes place at aggregate level for the fund sector on the one hand and at the level of the individual fund on the other. The granular portfolios of German funds as at the end of 2020 form the basis for this. The simulation uses scenario-dependent relative changes in securities prices for each individual security, calculated on an annual basis, as a key input. Modelling is always carried out over the 30-year scenario horizon from 2020 to 2050 (year-end figures in each case).

Dataset:

- Investment Funds Statistics (IFS): Comprehensive information about the assets and liabilities of German funds. Granular information about the securities held by each fund (securities level)
- Securities Holdings Statistics (WP Invest): Information about the ownership structure of German funds (fund level)
- Centralised Securities Database (CSDB): Comprehensive information about the securities held by German funds (securities level)

Mechanics of the model:

The underlying model is a modified version of the macroprudential stress test model of Fricke and Wilke (2021).[36] Depending on the relevant transition scenario, annual bond and stock price changes are simulated at the level of individual securities for German funds.

These changes in value imply:

a) direct changes in the portfolio value of the funds (as in Section 2.4.1); and

b) indirect further changes in the value of portfolios, if the analysed funds hold shares of other funds as well as stocks and bonds (crossholdings).

Let's say there are **N** funds and **K** market-traded assets (stocks and bonds) and cash. Let **F** be the (K+1) vector for the asset-specific annual shocks ($EQP_i^{scenario,t}{}_t / EQP_i^{scenario,t-1} - 1$ for stocks, $BP_i^{scenario,t-1} / BP_i^{scenario,t-1} - 1$ for bonds, see Section 2.4.1) and **M** the (NxK+1)

value, which gives rise to hidden reserves, but does not allow them to be recognised at more than the purchase price. The accounting valuation may also differ from the market price at banks that use IFRS accounting standards, if securities are recognised at amortised cost.

[36] For details of the analysis method, see Fricke and Wilke (2021), pp. 10 ff.

matrix for asset-specific portfolio weightings.[37] Let **A, E, D and B** be the respective (NxN) diagonal matrices for the fund assets, equity (= total net assets), debt and the debt/equity ratio (D/E). Let A^{Fund} be the (NxN) crossholdings matrix, whereby $a_{i,j}^{Fund}$ represents the value in euro of the shares that fund i holds of fund j. The value in euro of the fund shares that fund i holds can thus be calculated as A_i^{Fund} = $\sum_j a_{i,j}^{Fund}$. Let the fund assets A comprise the K+1 stocks, bonds and cash held (A^{WP}) and the fund shares held (A^{Fund}): $A = A^{WP} + A^{Fund}$.

With regard to a) Direct changes in the portfolio value of funds:
The annual changes in value of K stocks and bonds and cash, depending on the transition scenario chosen, can be calculated as $R^{WP} = M \cdot F$. The fund assets after the initial shock correspond to $A_0 = A^{WP} \cdot (1 + R^{WP}) + A^{Fund}$, which implies a change in the fund assets of R_0^A = $(A_0 - A)/A$ and a change in the total net assets of R_0^E = $(E_0 - E)/E$ = $(\mathbb{I}_N + B) \cdot R_0^A$.

With regard to b) Additional changes in portfolio value due to fund crossholdings:
Funds may be directly linked to each other through mutual holdings of fund shares (crossholding network). This means that the share value of a fund may (potentially) depend on the value of *all* other shares issued by funds. The crossholding network between German funds is explicitly included in modelling. This ensures that direct spillover effects within the fund sector, resulting from direct links between German funds, are taken into account.

After the changes in value of stocks and bonds have spread throughout the German fund sector due to the crossholding network, we can calculate

- the value in euro of fund shares held by fund i as $A_{1,i}^{Fund} = \sum_j a_{i,j}^{Fund}(1 + R_{1,j}^E)$ and with $A_{1,i}^{Fund} - A_i^{Fund} = \sum_j a_{i,j}^{Fund} R_{1,j}^E$
- the complete change in value of fund share i as $R_{1,i}^E = R_{0,i}^E + \frac{\sum_j a_{i,j}^{Fund} R_{1,j}^E}{E_i}$.

The complete change in value of fund i is thus calculated as the sum of changes in the value of the stocks and bonds held by fund i ($R_{0,i}^E$) and changes in the value of fund shares held by fund i ($\frac{\sum_j a_{i,j}^{Fund} R_{1,j}^E}{E_i}$). Due to the crossholding network, the return on fund i may therefore depend on the returns on all other funds in the network.

In this way, the model generates the changes in value of German fund shares for each year, in addition to annual changes in value of stocks and bonds, which are used as an input. These are incorporated into the simulation model for the banking sector and in future will also be used in the model for the insurance sector. Furthermore, it will also be possible to use these in future for calibration of changes in the value of foreign fund shares.

[37] The cash position of funds is always recorded as asset K+1 and is assumed to be constant, as this position is not subject to fluctuations in market prices. Consequently, the cash position of a fund always has an initial shock value of 0.

In contrast to classic macroprudential fund sector stress test applications, the portfolios of German funds are fixed at one point in time (end of December 2020) and no sales of securities by the fund sector are modelled (the flow performance channel and the leverage targeting channel are excluded). This is consistent with the assumption that German funds cannot systematically pass on assets that are subject to transition risks to other market participants.[38]

Output:

The key output of the simulation, for each of the transition scenarios, is the performance of the portfolios of German funds over time (in each case aggregated across all funds and at the level of the individual fund).

The difference in portfolio value between the respective increase scenario and the reference scenario is shown for

a) the entire fund sector; and

b) each individual fund.

This allows us to analyse heterogeneities between different transition scenarios or different fund types (e.g. equity, bond or mixed funds, funds of funds, retail funds or specialised funds) and to identify potential concentration risks for individual funds.

4.3 Insurers

Brief description of sensitivity analysis for insurers

The sensitivity analysis for the German insurance sector calculates profits or losses arising from changes in market prices of securities held by insurers in various climate scenarios. Profits and losses are approximated on the basis of individual securities.

The total assets of the German insurance sector came to around €2,590 billion in Q4 2020. In the scenario analysis, stocks/participating interests, fund investments, corporate bonds and government bonds are stressed wherever the insurance company directly bears the risks arising from the investments. Unit-linked products are therefore not taken into account in the analysis, as the policyholder typically bears the risk arising from the investment with these products. The stressed investments, i.e. stocks/participating interests, fund shares, corporate bonds and government bonds, account for about 70% of total assets.

The look-through approach is applied to German fund shares, i.e. we look through the fund to the securities that it holds. The losses in value in the scenario analysis are then assigned to the asset classes of the securities held by the funds. Life insurers in particular have institutional

[38] In addition, an ISIN time shock matrix is used as an input instead of an ISIN shock vector, as changes in securities prices fluctuate over time, depending in each case on the transition scenario modelled.

incentives to hold their investments via funds rather than directly on their own balance sheets.[39] As around 80% of German fund investments consist of "single-investor funds", in which one insurance company owns the entire fund, investments through funds and direct investments are treated in the same way in the scenario analysis.[40] Only if a look-through approach is not possible (in the case of foreign fund shares, for example) is the fund share reported separately.

Data:

1.) Solvency II: Solvency II data come from the supervisory reporting system for German insurers and are used at solo level (individual companies). As part of the Solvency II data, the list of assets includes holdings of securities and other investments of insurers at individual level (asset-by-asset) as well as the characteristics of securities. Securities and fund shares with an ISIN are included, as well as all other investments. Data from Solvency II relating to the size of insurance companies, their line of insurance and their capital resources are also used.
2.) Centralised Securities Database (CSDB): The CSDB contains further information about individual securities and their issuers and price information for debt and equity instruments and fund shares. Information is available for securities with an ISIN.
3.) Investment Funds Statistics: This includes information about the asset structure of domestic funds and their inflows and outflows of funds, issue and redemption prices and distribution of income. Granular information is available about the securities held by funds (based on individual securities).

As with banks and funds, it is primarily information from the CSDB (including with regard to NACE sector, rating, issuer region and duration) that is used to measure stress for individual securities. However, the CSDB can include only securities with an ISIN. This covers 66% of corporate bonds and 74% of government bonds, although there is considerable variation between insurers. In a second step, additional information is consulted from the list of assets in Solvency II, so that bonds without an ISIN can also be taken into account.[41] If not all the required variables are populated, the stress factor is imputed based on the information that is available. This allows a total of 97% of the securities portfolio (not including unit-linked products) to be covered.

Model and equations:

Scenario leads to revaluation of securities

Insurers j hold individual securities s in their securities portfolios, which can be assigned to stocks/participating interests and bonds. Losses in market value are calculated at the level of

[39] See Deutsche Bundesbank (2017).

[40] The look-through approach is also used in the Solvency II regulation on insurers, in which investments made through funds are treated in the same way as direct investments by insurers.

[41] As with the procedure for CSDB data, the NACE sector, rating, issuer region and modified duration of the security are used.

the individual investment. Depending on the type of security, the market value following a market price shock at time t, $MV_{js}^{scenario,t}$, is calculated:

a) Revaluation for stocks and participating interests
$MV_{js}^{scenario,t} = MV_{js}^{2020q4} * (1 + \Delta EQP_s^{scenario,t})$
Whereby MV_{js}^{2020q4} is the market value of the stock/participating interest s at time Q4 2020 and $\Delta EQP_s^{scenario,t} = \frac{EQP_s^{scenario,t}}{EQP_s^{2020q4}} - 1$ is the change in stock prices from the starting quarter Q4 2020 to time t (whereby Q4 2020<t<Q1 2050). $EQP_s^{scenario,t}$ and EQP_s^{2020q4} are the stock prices from NiGEM and the I/O model at time t and Q4 2020, which are assigned on the basis of the region and the NACE code for the respective stock/participating interest s.

b) Revaluation for bonds (market price shock defined as decline in market prices as a percentage)
$MV_{js}^{scenario,t} = MV_{js}^{2020q4} * (1 + \Delta BP_s^{scenario,t})$
Whereby $\Delta BP_s^{scenario,t} = \frac{BP_s^{scenario,t}}{BP_s^{2020q4}} - 1$ denotes the change in bond prices from the starting quarter Q4 2020 up to q.

c) Revaluation for fund shares (if look-through approach is not possible)
$MV_{js}^{scenario,t} = MV_{js}^{2020q4} * (1 + \Delta FP_s^{scenario,t}))$
Whereby $\Delta FP_s^{scenario,t} = \frac{FP_s^{scenario,t}}{FP_s^{2020q4}} - 1$ denotes the change in fund share prices from the starting quarter Q4 2020 up to t.

Aggregated losses in market value in the insurance sector

Losses in market value at time t are calculated from the difference between the market value after revaluation $MV_{js}^{scenario,t}$ and the original market value MV_{js}^{2020q4}.

That means that losses in market value $MV_{loss}^{scenario,t}$ across all portfolios P of insurers K in the German insurance sector can be calculated as follows:

$$MV_{loss}^{scenario,t} = \sum_{s=1}^{P} \sum_{j=1}^{K} (MV_{js}^{scenario,t} - MV_{js}^{2020q4})$$

Assessment of losses in market value within the regulatory and commercial law framework

As analysis under Solvency II is based on market values and risk, losses in market value are reflected directly in insurers' regulatory solvency ratios. On the one hand, these losses reduce insurers' available own funds, while at the same time their own funds requirements are reduced, as the losses that have already been realised mean they now have a lower exposure and therefore need to keep fewer own funds available in accordance with regulatory law. The first effect is generally greater, which means that solvency ratios fall in net terms.[42]

As well as the regulatory framework, the treatment of losses in market value under the German Commercial Code (*Handelsgesetzbuch* – HGB) plays an important part in fulfilment of guaranteed returns for life insurers in particular. When losses in market value lead to impairments, these are reflected in balance sheet losses in the income statement, which reduces insurers' own funds in accordance with the German Commercial Code.

As with banks, the provisions of Section 253 HGB apply to insurers. These state that fixed assets must be valued using the less strict lower of cost or market method if impairment is not permanent. The strict lower of cost or market principle applies to current assets. This is not particularly relevant to insurers, which therefore mainly apply the less strict lower of cost or market principle. Impairment due to climate change is likely to be permanent, so impairment is carried out directly.

In accordance with the Minimum Allocation Regulation (*Mindestzuführungsverordnung*), life insurers must give their customers an appropriate share of their income (investment income, risk income, other income) and must provide the guaranteed returns they have promised. Life insurers recognise bonus and rebate provisions inter alia as a technical provision in their annual financial statements in connection with this. These bonus and rebate provisions reflect the value, in accordance with commercial law, of policyholders' rights to premium refunds as at the balance sheet date.

As an accounting instrument, bonus and rebate provisions serve to smooth the profit participation shares of policyholders. Surpluses are not usually distributed directly to policyholders, but instead are initially transferred to bonus and rebate provisions. The profit participation shares payable to policyholders are taken from the bonus and rebate provisions at a later date and paid out. The bonus and rebate provisions thus act as a buffer. This also ensures that customers' profit participation shares can be kept relatively stable even if results fluctuate. Bonus and rebate provisions ebb and flow over time. They are reduced if income goes down (due to low interest rates or climate change, for example) and are built back up if income increases.[43]

The sensitivity analysis of the effects of climate change determines losses in the market value of the portfolios of German insurers. For the time being, we have dispensed with modelling of the development of bonus and rebate provisions through changes in surpluses.

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[42] Rating migrations could also alter own funds requirements. This effect is not investigated in the scenarios.
[43] See Deutsche Bundesbank (2013): Financial Stability Review, p. 73.

5 Detailed results of the sensitivity analysis

5.1 Assets of financial intermediaries that were included

Table 6 shows a summary of the stressed assets that were covered, their asset classes and residual maturities and the proportion of investments in the German financial sector that are in transition-sensitive sectors.

The proportion of total assets of German banks included in the scenario analysis is around 45%. The items that we looked at depended on the market or credit risk in each case. With respect to credit risk, a smaller proportion of the total exposure was included than for market risk (51% vs. 96%). The analysis does not take into account loans to other financial institutions (credit institutions and other financial corporations) or the public sector. Credit claims on central banks, households (loans for house purchase, consumer credit, etc.) and extraterritorial organisations are not included in the analysis, either. The loan portfolio of German banks that is taken into account therefore comprises the loans to German and foreign enterprises reported to the Bundesbank's credit register of loans of €1 million or more (i.e. credit claims of >€1 million). We did not refer to the total securities portfolio when it came to market risk, either. Amongst other things, we disregarded derivatives for which, without detailed knowledge of the product details, it was not possible to determine the reaction to changes in parameters in the carbon price increase scenario. This approach can be regarded as conservative, however, as derivative instruments are generally used for hedging purposes, and not including them thus tends to increase stress.

Total assets of the German fund sector came to €2,641 billion at the end of December 2020. The sensitivity analysis takes into account the securities held by a total of 5,980 equity, bond and mixed funds and funds of funds in the German fund sector with aggregated total assets of €2,174 billion, or 82% of total assets of the German fund sector. Their aggregated securities holdings come to €2,027 billion, or 92% of total securities holdings in the German fund sector (€2,206 billion). This therefore ensures a high level of coverage of the German fund sector overall.

The assets of more than 250 insurers are analysed. In the scenario analysis, stocks/participating interests, fund investments, corporate bonds and government bonds are stressed wherever the insurance company bears the risks arising from the investments directly. Unit-linked products are therefore not taken into account in the analysis, as the policyholder typically bears the risk arising from the investment with these products.

Table 6: Portfolios of German financial intermediaries in the scenario analyses (as at Q4 2020).

Loan portfolios			
Metric	Banks		
Total in € billion	4,789		
Loan portfolios included in the scenario analyses (stressed portfolio), in € billion	2,452		
of which: Percentage share of loans issued to transition-sensitive sectors	18.8		
Ratio of share of loans issued to transition-sensitive sectors to the share in value added of these sectors	66.6		
Stressed portfolio as a percentage share of total loan portfolios	51		
Remaining term to maturity of loans in the stressed portfolio, in years	5 to 7		
Securities portfolios			
Metric	Banks	Funds	Insurers[44]
Total in € billion	1,474	2,206	1,853
Securities portfolios included in the scenario analyses (stressed portfolio), in € billion	1,418	2,027	1,800
Stressed portfolio as a percentage share of the securities portfolios of the respective financial sector	96	92	97
Remaining term to maturity of non-financial bonds in the stressed portfolio, in years	6.0	10.5	12.7
Stressed portfolio by asset class, percentage shares			
Government bonds	28	19	30
Non-financial bonds	3	12	9
of which: Share attributable to transition-sensitive sectors	45	15	8
Ratio of share attributable to transition-sensitive sectors to the share in value added of these sectors	150	53	27
Financial bonds	52	22	31
Stocks and participating interests	3	23	26
of which: Share attributable to transition-sensitive sectors	33	36	9
Ratio of share attributable to transition-sensitive sectors to the share in value added of these sectors	117	126	32
Investment fund shares	14	25	4

[44] Unit-linked products are not taken into account in the analysis because policyholders typically bear the investment risk with such products. Insurers' holdings of shares in German funds are assigned to the asset class of the securities held by the funds. The category of fund shares itself only includes the portion for which this is not possible (e.g. foreign investment fund shares).

The overall level of coverage of total assets can be regarded as high. Coverage of securities portfolios is particularly high, ranging from 92% to 97%. While stocks, government bonds and financial and non-financial bonds are more or less equally represented in the aggregate figures for funds, the proportion of non-financial bonds is lower and the proportion of government bonds and financial bonds is higher for insurers and banks. Financial bonds account for more than half of the securities portfolios of banks.

The effects on the financial system depend on the one hand on the size of the share of transition-sensitive sectors in financial intermediaries' portfolios.[45] The smaller this share is, the lower the potential losses due to transition risks. On the other hand, the impact depends on the residual maturities of financial and financing instruments in the portfolios, as risk premia are in principle higher for longer residual maturities.

Banks' loan and bond portfolios have relatively short residual maturities. However, securities such as stocks, participating interests and fund shares can potentially have an unlimited term. Although the proportion of securities from transition-sensitive sectors among these investment instruments is relatively high, the fact that they account for only a small percentage of the portfolio (3% in each case) means that banks are not very vulnerable to transition risks overall.

German funds hold the largest proportion of stocks, participating interests and fund shares in their portfolios, at about 48%. They also hold non-financial bonds with an average residual maturity of 10.5 years. The bond portfolio of insurers has the longest average residual maturity of 12.7 years. Transition-sensitive sectors are noticeably under-represented among non-financial bonds in the portfolios of both funds and insurers. In the case of stocks, participating interests and fund shares held by insurers, transition-sensitive sectors are also strongly under-represented; with funds, however, they tend to be over-represented.

5.2 Potential vulnerabilities in the financial system

Potential vulnerabilities in the financial system are derived from climate-related risks using the method described in the previous section.

A carbon price reference scenario and a carbon price increase scenario are combined in each case in order to deduce the climate-related shock, realised with all market participants having perfect foresight. This section looks at shocks of varying intensity. The increase scenario is assumed to be "Net Zero 2050" (1.5°C). Only the "Current Policies" (3°C) scenario is used as

[45] Transition sensitivity refers to the severity with which a sector's value added responds to an increase in carbon prices. This transition sensitivity is calculated based on the ratio of sectoral losses in value added to value added of the economy as a whole. The one-third of sectors whose value added reacts most strongly to an increase in carbon prices, i.e. those sectors with the highest scaling factors (see Section 2), are defined as transition-sensitive. The proportion of financial and financing instruments in intermediaries' portfolios that were issued by a transition-sensitive sector is measured. These percentages are then compared with the share of value added of the economy as a whole attributable to transition-sensitive sectors.

the reference scenario here. This allows us to work out the maximum vulnerabilities within a conservative but plausible scenario framework. That means forming a pair of scenarios that are as far apart as possible in terms of their impact on the financial system.

For banks, funds and insurers, the following potential vulnerabilities arise for climate-related market risk, i.e. with respect to changes in market prices that could lead to the depreciation of securities that are valued at the market price. We show accumulated annual portfolio losses for banks, funds and insurers. Losses are always stated in relation to aggregated assets of the respective financial sector.

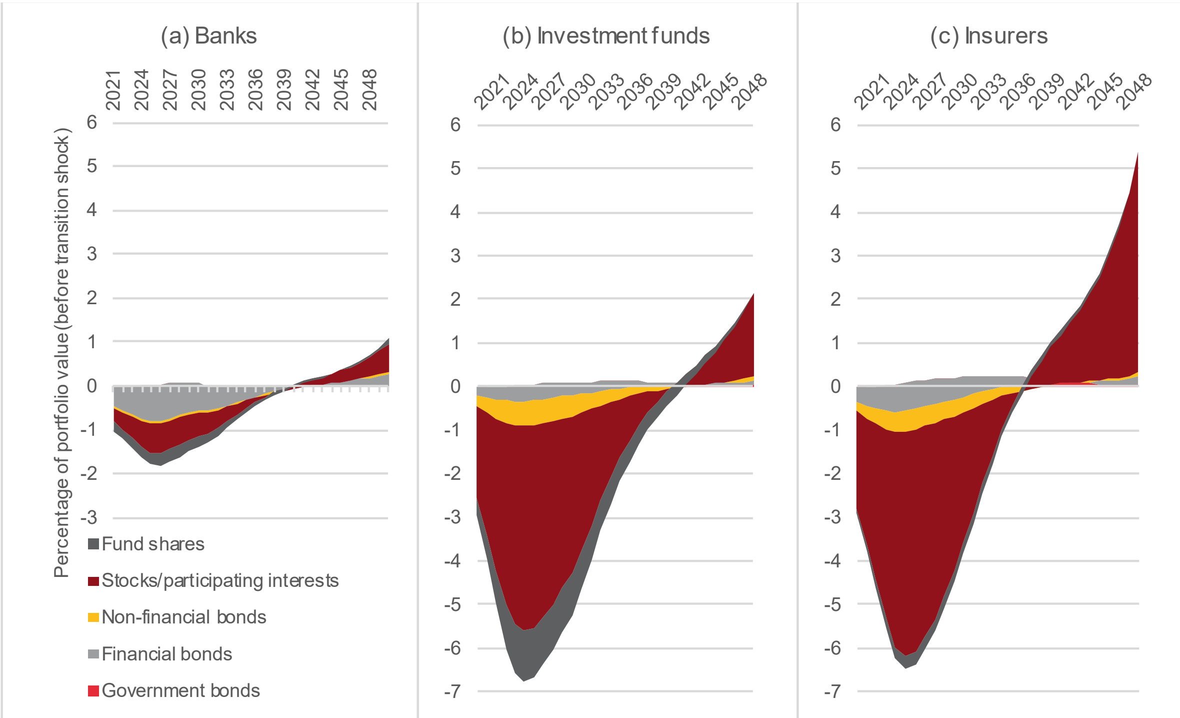

Chart 13: Modelled portfolio losses suffered by German financial intermediaries in a scenario of a strong shock to the financial system, i.e. an unexpected change from the "Current Policies" reference scenario to the "Net Zero 2050" increase scenario, broken down by financial instruments.

In the *combined view*, the unexpected transition from the reference scenario to the more severe "Net Zero 2050" scenario results in moderate portfolio losses for banks of almost 2% of their securities portfolio; for funds and insurers, the losses come to just under 7% of their securities portfolios in each case.

The effect of assumed perfect foresight is very clear: about half of the potential loss is realised directly upon the occurrence of the information shock in 2021.[46] Market participants anticipate future losses and price them into their asset valuations straight away. Subsequent annual changes are each smaller than the initial portfolio loss in 2021. These smaller modelled losses

[46] The shock occurs in Q1 2021. The losses in Q4 2020 thus come to zero.

in asset values are mainly attributable to further structural adjustments after the initial shock in 2021, which also come at the expense of profits (changes in carbon price pathways, changes in value added, etc.). In particular, the economic recovery from the mid-2020s onwards is partly attributable to the restructuring of the economy and increasingly low-carbon production, which also leads to a lower effective cost burden.

The long-term nature of climate-related risks also becomes clear here and manifests itself in the very long horizons for expectations of a transformation to a low-carbon economy. The bulk of the cost burdens on the real economy is incurred in the 2020s and early 2030s. Discounting of these cost burdens, and therefore losses, that are expected in the long term, along with the adjustment processes that are expected to take place in the real economy, will lead to only a moderate initial adjustment of asset values. However, climate-related transition risks will continue to lead to moderate losses in the further course of the next two decades. Although the speed at which the shock initially occurs is therefore high, the extent of the shock itself is not very severe, while the duration can be classed as extremely long. We should qualify this by pointing out that the realisation of potential portfolio losses is highly uncertain, especially from the late 2020s onwards. Although dynamic adjustment processes are to some extent taking place in the real economy, the analyses that have been conducted assume that the behaviour of financial operators remains static. Adjustments to the balance sheet structure are therefore likely, particularly in view of the usual short maturities of the financial instruments analysed here. This could reduce or increase the vulnerabilities calculated here.[47]

Looked at in detail, stocks account for almost half of initial losses at *banks*, despite their small volume (3%). The other main driver of potential losses is financial bonds. This is not due to the large size of specific losses, however, but to the fact that they account for a large proportion of the portfolio, at 52%. This is followed, at some distance, by fund shares (14% of the portfolio). The maximum potential loss is 2.1% in 2026.

Funds, on the other hand, realise significantly larger losses. The aggregated portfolio value of German funds in the “Net Zero 2050” scenario is up to 7% lower than in the “Current Policies” reference scenario by the mid-2020s. By way of comparison (not included in the graphic), when the “Below 2°C” (1.7°C) scenario is assumed as the increase scenario, the aggregated portfolio value of German funds falls by a maximum of 2% compared with the “Current Policies” reference scenario.[48] The effects of a faster transition (with higher carbon prices) are particularly evident in the stock portfolios of German funds and, to a lesser extent, in fund

[47] On one hand, a shift in portfolios towards less transition-sensitive sectors could lead to an ex ante reduction in vulnerabilities, provided that there is sufficient opportunity on the market for corresponding transition-insensitive investments. On the other hand, sales of transition-sensitive investments after the transition shock has occurred could further increase losses, if these sales take place on a broad scale or in an emergency (fire sales).

[48] When the “Below 2°C” (1.7°C) scenario is assumed as the increase scenario, the physical risks would increase, but these are not taken into account at this point in the analysis (see above). However, according to the results of analyses conducted here in Germany based on aggregated national data, these are second-order effects, particularly with regard to the impact on financial stability.

shares as well. Stocks held in the fund sector account for around 4.7 percentage points of the total losses in value modelled for German funds up to 2026 (6.8% in 2026). Price drops for corporate bonds and bank bonds held in the fund sector play less of a part in the performance of portfolios. The government bond portfolio of German funds suffers barely any losses in value due to a faster transition over the entire observation period, but does not record any growth in value, either.

German *insurers* are subject to similar vulnerabilities to German funds. If we compare the “Net Zero 2050” scenario with the “Current Policies” scenario, they record potential relative losses of about 6% in relation to the total portfolio value by the mid-2020s. In the final phase of the transition from 2040, insurers achieve gains in a comparison of the increase and reference scenarios. Compared with the reference scenario, insurers record losses in their portfolios, particularly in the stocks segment. Potential losses come to a maximum of 5% by the mid-2020s. By the end of the observation period, however, they have generated profits of 5% (in nominal terms). The losses in other asset classes are smaller. Only financial and non-financial bonds each contribute about one percentage point to the maximum potential loss in 2026.

While credit risk for German funds and insurers is largely included in the market risk that has already been examined, as a large proportion of their assets are market-traded, German banks have large portfolios of loans that are not market-traded. Credit risk for the German banking sector resulting from these is analysed separately.

Chart 14 shows credit losses in the two climate scenarios of “Below 2°C” and “Net Zero 2050”, in each case in relation to the baseline scenario of “Current Policies”. It is clear that the losses in the “Net Zero 2050” scenario are greater than in the “Below 2°C” scenario. The losses materialise for the most part in the first half of the 2020s and then turn into profits (or smaller losses) relative to the baseline scenario in the early 2030s, once adjustments to the real economy in response to the adverse shock from the climate scenarios have been completed. In 2050, the relative losses in both scenarios are close to zero.

(a) As % relative to baseline scenario (b) As % relative to stressed loan portfolio

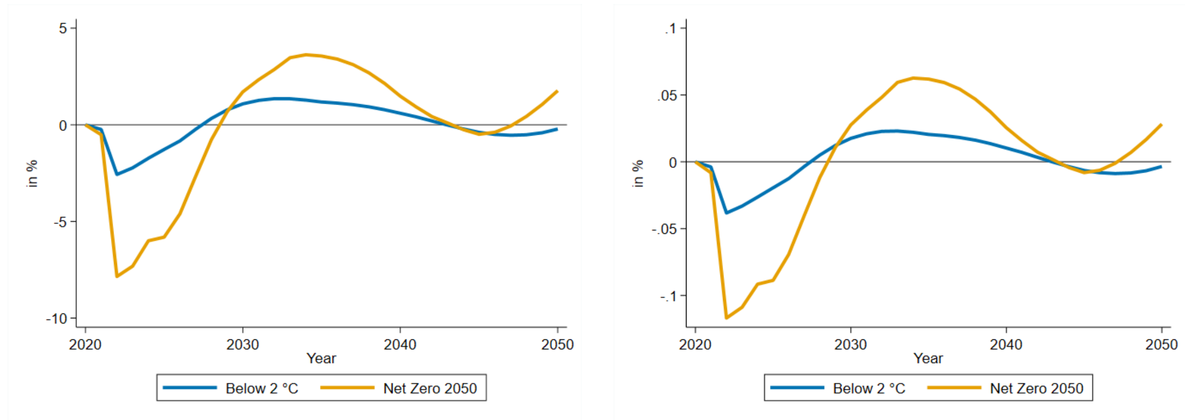

Chart 14: Potential credit losses in the banking system in a scenario of a strong shock to the financial system, i.e. an unexpected change from the “Current Policies” reference scenario to the “Net Zero 2050” increase scenario.

5.3 Concentration effects and potential vulnerabilities in the financial system

The fact that the impact of the transition shock varies between sectors leads to a concentration of climate-related risks, particularly in sectors that emit disproportionately high volumes of carbon. Depending on the ownership structure of financial instruments in these sectors, risks could also be concentrated among financial intermediaries. The transfer of this asymmetric burden to the financial sector may intensify or even create vulnerabilities.

The analyses presented in the previous section should therefore be supplemented by an analysis of the varied impact of climate-related risks. In the following, we outline the expected asset losses resulting from a faster transition based on the extent to which sectors are affected. The respective percentiles for the expected losses are calculated for each year from the assumed occurrence of the shock in 2021 up to 2050. In contrast to the aggregated vulnerabilities for the three financial sectors in the respective years that we looked at above, this allows us to make statements about the vulnerabilities of individual banks, insurers or funds that are affected to a greater or lesser extent. For example, the 5th percentile for the fund sector shows the modelled portfolio losses for the fund whose losses are exceeded by only 5% of funds; for the 95th percentile, only 5% of funds have smaller losses.

With regard to market risk, vulnerabilities can thus be presented as follows, depending on the concentration of risks.

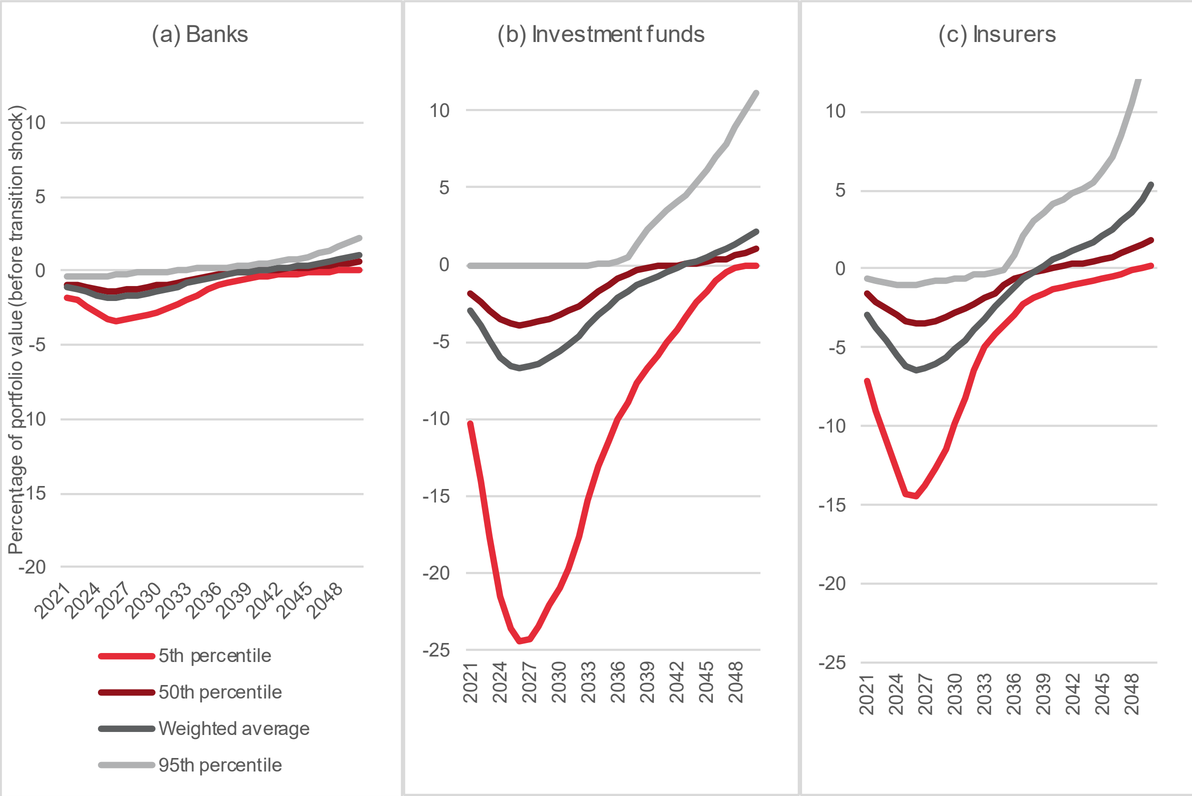

Chart 15: Quantile distribution of potential portfolio losses suffered by German financial intermediaries in a scenario of a transition shock, i.e. an unexpected change from the "Current Policies" reference scenario to the "Net Zero 2050" increase scenario.

The *combined view* of future development across the three sectors shows that, apart from a few deviations, the trends over time are very similar and differ primarily in terms of the intensity with which financial intermediaries are affected. Those financial intermediaries that are initially more strongly affected also suffer heavier losses in asset values in the beginning, up to the maximum expected loss in 2026. The distributions of modelled losses become narrower after that, and the aggregated assets have returned to similarly high levels within the respective sectors by about 2040, when they are also at a comparable level to the "Current Policies" scenario.

Another factor common to all financial sectors is that the weighted average is initially lower in relation to the median, which states the expected potential loss for the financial intermediary that is exactly in the middle for the sector concerned. That means that financial intermediaries with larger portfolios are initially more strongly affected by transition risks and therefore also realise larger portfolio losses than other financial intermediaries. Consequently, the weighted average is reduced relative to the median, which only looks at the number of financial intermediaries when determining losses.[49] Towards the end of the transition phase, from about

[49] The modelled portfolio loss for the financial intermediary that represents the 50th percentile is reported here, i.e. half of the financial intermediaries realise a smaller loss and half realise a larger loss.

2040, the weighted average exceeds the median. That means that financial intermediaries with larger portfolios see a better portfolio performance again in this period. It should be noted that this is always relative to the "Current Policies" scenario. Financial intermediaries with larger portfolios, which initially have more investments in fossil fuel assets, are initially more strongly affected in the unexpected increase scenario "Net Zero 2050" (1.5°C) in 2021 than the rest of the respective financial sector in this increase scenario and than they themselves would be in the "Current Policies" scenario. Once again, it is difficult to interpret medium-term to long-term developments, as the balance sheets of the financial intermediaries are assumed to be static. Performance is also calculated based on nominal values. This means that potential differences in profit from 2040 onwards would be smaller in real terms.

The largest modelled losses for the three financial sectors are recorded in the *fund sector*. In particular, the spread also increases most strongly in relative terms. The portfolio values of funds whose losses are exceeded by only 5% of the funds (5th percentile) fall by about 25% by the mid-2020s. This is higher than the weighted average by a factor of around 3.5, while the banking and insurance sectors each record factors of only about 2.

The losses of around 600 funds are larger than the 5th percentile. In particular, these include equity funds or mixed securities funds that hold stocks and are most strongly affected by an increase in the carbon price. These funds that are most severely affected by a faster transition manage only €65 billion in aggregate terms, or 3% of total net assets of German funds. Nevertheless, this sub-segment accounts for up to 18% of additional potential losses caused by a faster transition. During the 2020s in particular, these funds record average portfolio losses of more than 30% compared with the reference scenario "Current Policies" (3°C). However, these funds also recover in value significantly in relation to the reference scenario in subsequent years.

In the *banking sector*, the difference in potential losses between those banks that are most strongly affected (5th percentile) and those that are least affected (95th percentile) is greatest in the mid-2020s, at 3.1 percentage points.[50] Institutions in the banking sector that are less affected by transition risks record portfolio gains from the mid-2020s.

The portfolio losses that are exceeded by only 5% of insurers (5th percentile) come to about 14% in relation to the reference scenario by the mid-2020s. By the end of the observation period, those insurers that are most strongly affected may end up in a similar potential loss situation as in the reference scenario, while the insurers with the largest gains actually achieve profits in 2050 that are similar in size to the losses recorded by the most severely affected

[50] The climate stress test of De Nederlandsche Bank shows even smaller differences between banks. Losses of between 1% and 3% were recorded here in 2019. See Vermeulen et al. (2019).

insurers in the mid-2020s. Larger insurers also tend to be more strongly affected by a faster transition, initially through larger losses and later through higher gains.

As with market risks in the banking sector, potential losses owing to **credit risk** are approximately twice as high at the 5th percentile compared with the median if we compare the increase scenario and the reference scenario (Chart 16). At the 95th percentile, the relative potential loss in the increase scenario compared with the reference scenario is close to zero. Potential losses are thus unevenly spread across individual banks.

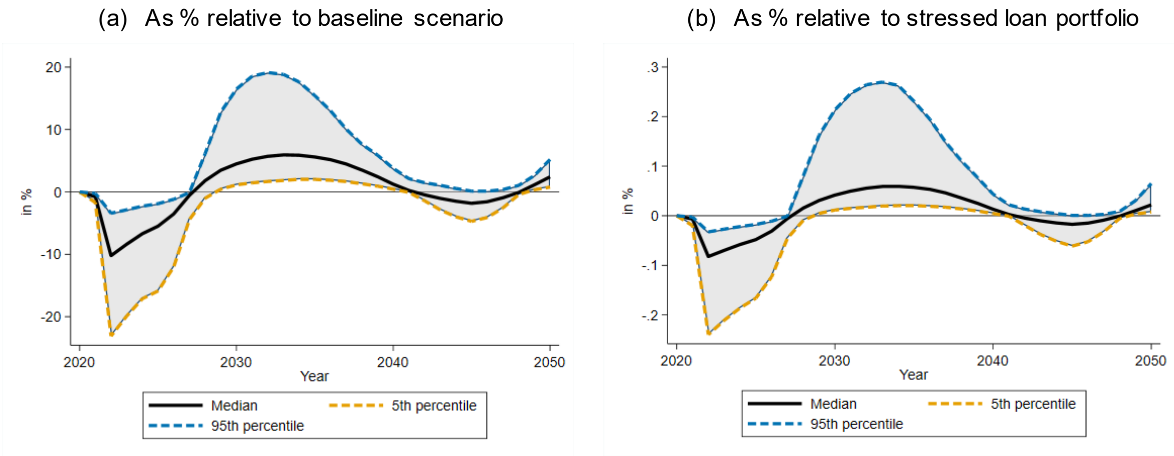

Chart 16: Quantile distribution of potential loan losses in the banking system in a scenario of a strong shock to the financial system, i.e. an unexpected change from the "Current Policies" reference scenario to the "Net Zero 2050" increase scenario.

5.4 Comparability of results with external studies of climate-related risks

The results can be classed as comprehensive in terms of both the breadth of the sectors and the financial instruments covered in each case, including in comparison with other studies. With regard to market risk, the moderate losses for the *German banking sector* are in line with the climate stress test conducted by De Nederlandsche Bank, for example, which in 2019 calculated a similarly low level of stress for banks under comparable general conditions.[51] This ranges from 1% to 3% of total assets.

The quality of the results obtained for the *German fund sector* in these analyses is consistent with studies by the European Systemic Risk Board (ESRB), the European Securities and Markets Authority (ESMA) and the European Central Bank (ECB). In climate analyses by the ESRB, the portfolio of European investment funds was also found to be slightly more

[51] See Vermeulen et al. (2019). The stress test can also be considered to be comparable due to the fact that the methodology is similar. Although it is much shorter, with a time horizon of five years, the maximum potential losses occur within a similar time structure, after about three to four years. The shorter horizon of the Dutch stress test is offset by the fact that the carbon price shock occurs immediately and is therefore initially greater, while the banks' exposure to the real fossil fuel economy is slightly higher. Furthermore, only transitory risks are analysed, and the scenario has been devised based on the NiGEM macroeconometric/financial model and distribution of the severity of the shock in line with carbon intensity within a sectoral model. Overall, we can therefore assume that the results are highly comparable.

vulnerable than the portfolios of European insurers and banks.[52] The ESRB estimates that around 7-8% of securities investments of European investment funds are climate-sensitive. However, these results are based on an exposure analysis that uses simpler methodology, involving a list of vulnerable NACE sectors. The ESMA estimates that around 5% of fund investments would be affected by an abrupt tightening of climate policy; see ESMA (2021). Studies by the ECB also conclude that European funds have a significant exposure to climate-sensitive sectors.[53] About 22% of assets held by European funds are subject to transition risks. In keeping with our results, the vulnerability of European funds to transition risks also varies widely in cross-sectional analyses. However, these figures are only exposures and are not comparable to the figures discussed in this paper in quantitative terms.

Studies by other institutions in the insurance sector are generally consistent with the results obtained in the analyses conducted here. EIOPA estimates that the portfolios of German insurers would lose just over 6% in value in a scenario comparable to the increase scenario used here.[54] EIOPA also finds that the largest losses occur on stocks. These come to 16.7% in aggregate terms for all insurers examined, measured against the entire portfolio. The potential losses calculated in the analysis conducted in this report are comparatively low for stocks, at up to 5%.

In contrast, De Nederlandsche Bank has calculated that total potential losses for Dutch insurers in a “double shock” scenario would come to 11%.[55] This scenario comprises a political shock and a technological shock. The carbon price increases to US$ 100 per tonne of CO_2, while at the same time there are breakthroughs in technologies that reduce carbon consumption.[56] It becomes apparent that the interest rate effect that occurs is very important when it comes to losses in the value of Dutch insurers’ assets. Of the losses of 11% measured for the entire portfolio in a double shock scenario, 9 percentage points can be attributed to the interest rate effect. Only the remaining 2 percentage points are due to the effects of exposures. In the context of the analysis of credit risk in the banking sector, the results of the stress test conducted by the ECB/ESRB group with regard to climate risks for the entire EU offer a suitable basis for comparison.[57] The potential losses calculated in the credit risk analysis carried out here are significantly smaller. While the calculated credit losses could grow to around 0.1% of the stressed loan portfolio, the losses in the ECB/ESRB stress test, in a comparison of the two scenarios “Hot house world” and “Disorderly”, are similarly low, at about -0.15% of risk-

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[52] See ESRB (2020).
[53] See ESRB (2021).
[54] See EIOPA (2020). The methodology used by EIOPA is different from that used here. For stocks and corporate bonds, for example, the PACTA tool is used to estimate the carbon intensity of listed securities. That means that coverage is lower than in the analysis presented here. For Germany, only about 45% of corporate bonds are examined, while for stocks the figure is actually just under 5%, as the bulk of investments are participating interests, which are not included in PACTA.
[55] See DNB (2018).
[56] The scenarios are designed to cover five years. De Nederlandsche Bank also uses NiGEM. It converts the carbon price pathway into equivalent price pathways for fossil fuels in advance and then carries out endogenous simulations of developments in GDP, the Harmonised Index of Consumer Prices and the 10-year interest rate.
[57] See ESRB (2021), p. 74-74.

weighted assets – but are positive rather than negative and therefore constitute relative gains. This is because the stress test has a different focus and compares only the assets in 2050 with those in 2019, explicitly including physical climate risks. These are higher due to the different geographical coverage in the ECB/ESRB stress test. The choice of scenarios is also different. In addition, exposures to sectors that are directly and indirectly affected by transition risks are very low in the German banking sector, which means that only limited comparison is possible. Comparing financial intermediaries' balance sheets over a 30-year period without explicitly taking into account adjustments to balance sheet structures can also reduce the validity of the results.

In summary, the potential vulnerabilities that have been calculated can be classed as relatively moderate by international standards.

5.5 Discussion of the possible effects of uncertainty

Owing to the complexity involved in forecasting climatic and economic developments, there is considerable uncertainty as to which climate scenarios will occur in future. This presents major challenges when it comes to selecting scenarios and specifying a reference scenario and an increase scenario. Even with regard to the assessment of market participants' current expectations, i.e. the choice of a reference scenario, there is significant uncertainty. In order to assess which reference scenario is plausible, we need, for example, information about which future losses ("stranded assets") are already priced into assets today. We would also need to know of any structural adjustments that have already been implemented (anticipated) owing to expected changes in climate policy. Based on this information, we would be able to define a reference scenario.[58]

However, it is possible to estimate the extent of this uncertainty in an initial approximation. When defining the financial shock, the reference scenario is replaced in each case. While the "Current Policies" scenario served as the reference scenario in previous analyses, this is subsequently replaced by the "Below 2°C" scenario, which pursues more stringent climate action goals. The additional shock to the financial system caused by a faster, unexpected transition is thus smaller if we assume a reference scenario with more ambitious climate action goals, i.e. more stringent emissions reduction targets. This is because, if we start from a scenario in which the climate action targets are already higher, the additional climate-related risks and the costs that these could potentially give rise to in order to achieve a "Net Zero 2050" scenario, associated with very ambitious climate action goals, are smaller.

It is particularly interesting to note here how large the gap is between the two potential loss curves for the "Net Zero 2050" scenarios and the associated shock to the financial system (see

[58] The same problems arise in a similar form with respect to the increase scenario. However, the increase scenario should be left unchanged at this point, as it is the scenario that can reveal the largest potential vulnerabilities in financial stability within the context of the SSP2 scenarios.

Chart 17). The lower curve maps the strong shock to the financial system that was already known and the resulting potential vulnerabilities shown in previous analyses. The climate scenarios "Net Zero 2050" (1.5°C) and "Current Policies" (3°C) were used for this purpose to generate a shock to the financial system. The upper curve maps the potential vulnerabilities if we choose a reference scenario in which climate action goals are already more ambitious and carbon price pathways are higher, in line with this ("Below 2°C").

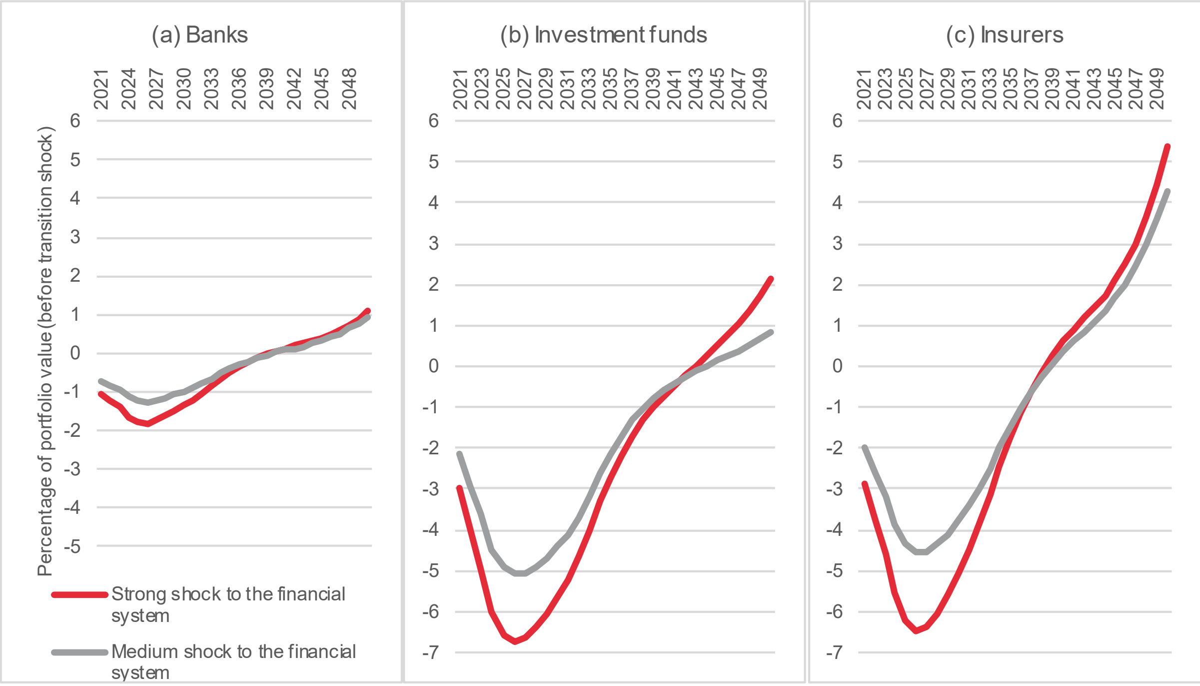

Chart 17: Potential portfolio losses suffered by German financial intermediaries given uncertainty surrounding the reference scenario in a scenario of a strong and medium shock to the financial system.

In the combined view of market risk results, it becomes clear that the losses that may potentially arise in the financial system due to climate-related transition risks are considerably smaller if a reference scenario with more stringent climate action targets has already been assumed. Potential vulnerabilities are reduced by about one-quarter to one-third across all financial sectors. Nevertheless, even in the event of a moderate shock to the financial system, i.e. with a reference scenario with more stringent climate action targets, the "Below 2°C" scenario, there are still losses, albeit at a lower level.

The trend in the deviations is very similar across all financial sectors. The deviations also increase as the potential vulnerabilities become larger. This makes sense: in all scenarios, the deviations depend directly on the carbon price pathways that drive the modelled losses, and therefore increase or decrease in proportion to these.

Analysis of the credit risk of German banks confirms the findings obtained. Here, too, the prevailing uncertainty can lead to deviations in calculated losses (Chart 18).

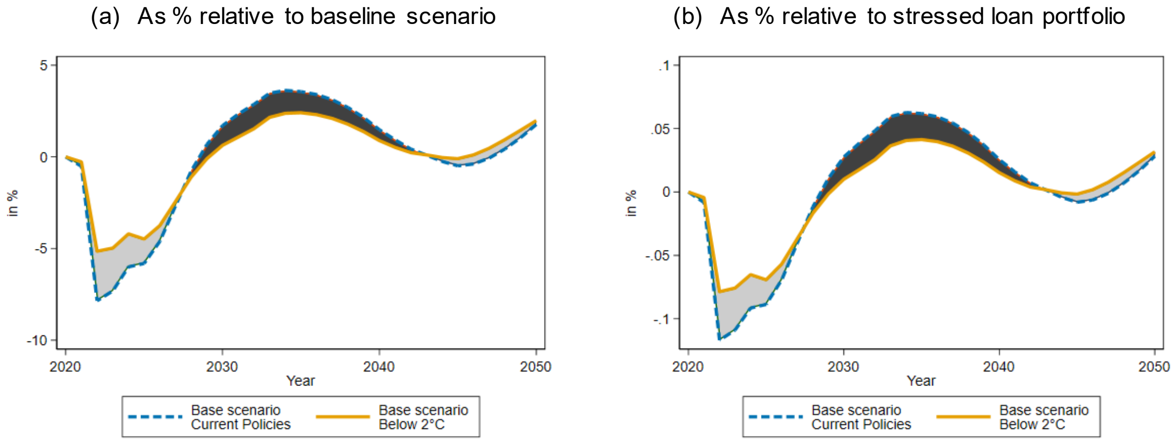

Chart 18: Potential loan losses in the banking system given uncertainty surrounding the reference scenario in a scenario of a strong and medium shock to the financial system.

We should qualify this by pointing out that the effects of uncertainty quantified here do not constitute an upper or a lower limit. The specific characteristic of uncertainty is that no information is available about the distribution, and thus the probability, of future developments. That means not only that we cannot determine a credible upper or lower limit, but also that it is impossible to make a forecast in the sense of the most probable development. In addition to the quantification of uncertainty carried out here by way of example, many other parameters that have been used in devising scenarios can be responsible for even greater uncertainty regarding climate-related risks and can thus cause greater deviations in the quantification of potential vulnerabilities. These may also increase the maximum potential vulnerabilities estimated here.

6 Challenges in devising climate scenarios and shocks to the financial system

The methodology presented here involves the use of a series of sequential models. This begins with integrated assessment models (IAMs), which generate carbon price pathways that are consistent with various climate goals based on a range of assumptions regarding global socioeconomic development. The carbon price pathways are then translated into adjustments to the values of securities held by the German financial sector, using macro-models and financial market models. These are aggregated across various intermediaries and sectors in order to determine the sensitivity of the German financial sector to plausible carbon price pathways.

Even if this methodology plays a significant part in enabling us to describe and quantify the implications of carbon prices for the German financial system, this analysis has various limitations that we must mention.

Due to its design, our analysis of risks arising from possible carbon price pathways does not cover the full bandwidth of possible transition scenarios and risks. As well as pricing of greenhouse gas emissions, other factors such as technological breakthroughs and changes in consumer preferences can also trigger transition shocks and lead to the revaluation of financial assets.

With regard to risks arising from carbon prices, the NGFS scenarios used only cover price trends that rise monotonically. Possible changes in policy course that reverse announced carbon price pathways, scale back green subsidies or result in an important redistribution of sectoral burdens, can lead to significant additional burdens and thus to financial distortions, such as the bursting of “green bubbles”. The relevance of this point is underlined by the repeated changes in Germany’s nuclear policy over the last 20 years.

Unlike with local environmental pollution, climate change is also a global phenomenon that depends to a large extent on total worldwide emissions. Those who cause it and those who are the victims of it are often located in different geographical states with different jurisdictions. However, international negotiations are often hampered by “free riders”, which makes it difficult to agree on effective and credible climate action measures. This can lead to uncertain transition pathways and associated financial risks. In our analysis, we abstract from this uncertainty and assume a uniform global climate policy.

This analysis is therefore limited to the risks resulting from monotonically increasing global carbon price trends. However, there are also considerable uncertainties in connection with this, due to the models used and their calibration. The integrated assessment models translate prescribed climate goals into global carbon price scenarios, but use assumptions with regard to climate sensitivity and the costs that will be incurred in the economy for avoiding carbon emissions. Neither of these aspects can be determined with sufficient accuracy, and they are both therefore subject to significant uncertainty. By using various integrated assessment models, however, we can to some extent reflect this uncertainty in our analysis. The macro-model that is used, NiGEM, the sector model and the financial market models also involve uncertainties with respect to parameterisation. NiGEM and the market and credit risk model are estimated based on historical connections between the modelled variables. Key parameters in the sector model, the elasticities of substitution between fossil and non-fossil energy sources, are also based on estimates of historical data. The evaluation of forward-looking scenarios using historically estimated models therefore constitutes a limitation of the analytical framework. It should be noted that each additional model in the model chain heightens the uncertainty of the overall analysis, as the results of one model build on the results and inaccuracies of the model preceding it.

Furthermore, only a very limited sensitivity analysis is possible with respect to individual parameters that are of interest. This would generally require simultaneous re-simulation and re-calibration of all models used in the analytical framework and runs counter to the idea of the global standardisation of climate scenarios and integrated assessment models pursued by the NGFS. At the same time, it is not possible to present feedback effects from downstream models to upstream models. One particular consequence of this is that potential reactions in the economic sphere arising from the interplay of economic agents, which are more complex than is presented in climate models, cannot have any feedback effects on the climate models themselves. Furthermore, only limited variation of the implicit assumptions in the climate models about reactions at later stages is possible. A major interaction with variables that are also used in upstream models would then lead to a reduction in consistency in these upstream models, and would ultimately also adversely affect the consistency of the devised scenarios. Even in the context of the short-term analysis horizons that we are focusing on here, this must be taken into account when interpreting the results. With longer-term analysis horizons, factors such as innovation incentives with variable structures (irrespective of general economic development), differences in acceptance, the structure and dynamic responses of the financial system or the exceeding of tipping points in global warming and extreme weather events and associated responses in society can have significant feedback effects on assumptions in climate models, and thus on the results of climate models. This is not included in the model framework we have chosen.

Finally, we should point out that the assumption that the financial intermediaries examined have static balance sheets is a limitation of this analysis. Two aspects are relevant here.

First, the losses in value calculated in the scenarios are reflected directly on the balance sheets and thus only constitute first-round effects. Second-round effects that may potentially be relevant to financial stability are thus not taken into account. These can be caused by connections between the financial agents examined (through contagion) or their systemic importance (size, substitutability) or by similarities in the exposures of financial agents, which can lead to fire sales. These second-round effects may therefore further amplify the direct losses calculated in our analytical framework.

Second, and especially in view of the long time horizon in this analysis, the assumption of static balance sheets implies that there will not be any radical changes in the positions of financial agents. Banks may reduce or stop lending to transition-sensitive sectors as soon as carbon prices are actually increased substantially, for example. This would tend to reduce actual losses relative to the results presented here. On the other hand, it will not be possible in the event of a sudden correction of market expectations to sell assets in good time and on a large scale without losses. Only the systematic restructuring of the portfolio in good time before the transition shock can therefore reduce the losses.

7 Summarised assessment

This document describes the methodology, dataset and results of the Bundesbank's analysis of climate-related transition risks for the Financial Stability Review 2021.

Its key contribution lies in the calculation of financial intermediaries' potential portfolio losses resulting from climate scenarios that are based on consistent assumptions and that have been developed in global collaboration within the framework of the NGFS. The downstream use of quantitative models supplements this with a richer landscape of economic variables and enables climate model effects to be disaggregated along geographical borders and based on sectors of the real economy. Only the disaggregation of these global climate model effects allows differentiated derivation of the effects on financial instruments and financial intermediaries' portfolios.

The comprehensive dataset opens up the opportunity to calculate representative effects on the German financial system. This includes the derivation of effects on the real economy and macroeconomic effects within a global framework on the one hand, and comprehensive consideration of the portfolios of German financial intermediaries on the other. In aggregate terms, the portfolio losses are within the low to medium single-digit percentage range, although individual financial intermediaries are much more severely affected. The uncertainty examined with respect to the baseline scenario has a significant impact on the potential losses of financial intermediaries.

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