OeNB climate risk stress test – modeling a carbon price shock for the Austrian banking sector

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The climate crisis is one of the most pressing global issues of our time. Policymakers across the field are challenged with the trade-offs of either taking insufficient action to tackle climate change and keeping the current economy humming or decisively addressing global warming and sending the economy into a tailspin. The introduction of a carbon pricing mechanism, one of the main policy instruments in the transition to a more climate-friendly economy, has been intensively discussed. In Austria, the government presented a tax reform package in September 2021, which also includes a carbon pricing scheme.

In this article, we assess the impact of carbon pricing on the Austrian banking system in a forward-looking framework. We evaluate three scenarios over a horizon of five years: The baseline scenario is consistent with the current OeNB top-down solvency stress test and serves as a reference point. One transition scenario assumes an orderly increase of carbon emission costs for the economy, the other one envisages a disorderly increase. These two scenarios provide the empirical basis for our policy conclusions. Our stress test focuses on the transmission channels and the potential impact of transition risks on the banking system and should not be interpreted as a forecast of the development of the Austrian economy.

We expand the OeNB's top-down stress testing infrastructure with two additional models. First, we develop an enhanced multiregional input-output model to calculate cost and turnover changes for different economic sectors following the introduction of carbon pricing schemes. Second, we expand the OeNB's corporate insolvency model introduced in 2020 to assess the impact of the COVID-19 pandemic to include shocks such as a carbon emissions-based shock. This allows us to assess the impact of the aforementioned policy measures on sectoral insolvency rates, which is then used as an approximation for stressed credit risk default probabilities. In addition, we use these stressed default rates to derive valuation losses in Austrian banks' bond portfolios. Both inputs feed into the OeNB's top-down stress testing framework ARNIE, making it possible to assess the impact on the Austrian banking system.

Our results imply that especially the disorderly transition scenario can have a sizable impact on certain economic sectors, most importantly agriculture and transport, where default rates would rise sharply, affecting banks exposed to these sectors. The aggregate CET1 ratio for the Austrian banking system would decrease by 2.7 percentage points in the disorderly scenario and by 0.7 percentage points in the orderly scenario. Given initial capitalization levels, this seems manageable. Hence, while the introduction of a carbon pricing mechanism will certainly create additional costs for the Austrian banking system, our results indicate that the banks are well placed to withstand the indirect effects of measures to counter the climate crisis.

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Climate change has been intensively discussed in the scientific community for several decades. For central banks, it is a fairly new topic by comparison, which is gaining traction as the implications of climate change for monetary policy and financial stability are becoming more and more tangible. Since 2017, several supervisory authorities and central banks have conducted climate risk stress tests and sensitivity analyses, either on their own by using reporting data (i.e. top-down) or together with banks (i.e. bottom-up).[2] Broadly speaking, there are two main types of climate risk: transition risk[3] and physical risk[4]. When analyzing transition risk, the carbon intensity of economic sectors is the key factor as energy- and emissions-intensive sectors are sensitive to climate policy measures. When looking at physical risks, the geographical location of production facilities and assets pledged as collateral are of particular importance.

The dual challenge of traditional banking sector stress tests – model and scenario uncertainty – is particularly pronounced in the analysis of climate risks. Especially with regard to physical risk, extended time horizons play a crucial role. Climate change and its impact will be unfolding over decades, and the global economy will likely undergo an unforeseeable transformation. Unfortunately, traditional financial sector stress tests usually cover a period of no more than three to five years and employ a static balance sheet assumption[5]. To counter this shortcoming, more dynamic models could be employed, however, at the cost of a substantial increase in modeling risks.

Still, the quantification of climate risks – even if fraught with uncertainty – can support decision-makers in assessing the magnitude and urgency of these risks for the banking sector as well as the potential impact of policy measures. Having a long history of conducting stress tests and scenario analyses, the OeNB decided in 2020 to run a pilot exercise to assess the potential impact of climate policy measures on the Austrian banking system. Like most other central banks, we expanded the time horizon of our analysis by two years compared to our regular banking sector stress tests and focused exclusively on transition risks to alleviate some of the above concerns.

This paper is structured as follows: In section 1, we provide an overview of the scope of this paper, followed by a description of the underlying scenarios of our climate risk assessment in section 2. Section 3 provides details regarding the components of our modeling framework, and in section 4, we present results, again for each component. Finally, we close with a discussion of our findings in section 5.

[2] *For a comprehensive overview of climate risk stress testing activities across different institutions, see ECB (2021). Most notably, De Nederlandsche Bank conducted the very first top-down stress test in 2018 (Vermeulen et al., 2021), and the Bank of England (2019) and the Banque de France (Allen et al., 2020) conducted the two subsequent bottom-up exercises. Although similar in their nature of addressing climate-related risks, the stress tests are difficult to compare as the methodologies and underlying assumptions diverge significantly between institutions.*

[3] *Transition risks refer to the risks associated with the transition to a low-carbon economy. The risks arise due to disruptive processes triggered by the need to reduce carbon emissions, such as policy, legal and technology shocks (IPCC, 2020).*

[4] *Physical risks refer to the risks associated with the potential damage to infrastructure, buildings, raw materials and supply chains by weather and climate. These risks are often grouped into risks from short-term events (e.g. increased insurance costs) and long-term events (e.g. flooding of coastal areas) (IPCC, 2020).*

[5] *The static balance sheet assumption serves as a simplification for the stress test; it implies that banks do not take any management action or change their business model over the projection period. Hence, the size, composition and risk profile of a bank's balance sheet is kept constant (EBA, 2018).*

1 Overview: scope of analysis and modeling approach

Our objective in this paper is the assessment of how the introduction of a new carbon emission pricing scheme could impact the Austrian banking sector over a short- to medium-term horizon. We focus on this aspect as emission pricing is a central element of the provisions established in the 2015 Paris Agreement to disincentivize climate-damaging behavior in the economy. Consequently, the evolution of the carbon price is the main risk driver in our analysis. This section provides an overview of our modeling setup.

The general idea behind our approach is that a carbon tax will increase production costs and reduce demand for carbon-intensive goods. As producers cannot fully pass on these additional costs, the combined impact of higher costs and reduced turnover will have a negative impact on profitability and will result in the insolvency of some firms, especially those with weak equity positions or cost structures. This effect will be larger for firms in carbon-intensive sectors. Within our framework, we do not make assumptions on firms' capability to adapt within the observation period.

Banks will be affected through credit losses from defaulted loans. At the same time, a changed market perception of the riskiness of bonds issued by carbon-intensive firms will lead to valuation losses for banks holding such bonds. Both effects will weaken banks' capital positions, with banks more exposed to carbon-intensive sectors facing a higher impact as measured by their decreasing capital ratio.

We run our analysis for two carbon price transition scenarios: One assumes a moderate and gradual price path, while the other one assumes a larger and sudden shift in carbon prices. The development of carbon prices is based on the current version of the scenarios constructed by the Central Banks and Supervisors Network for Greening the Financial System (NGFS, 2021). The underlying macroeconomic variables for both transition scenarios are based on the current baseline scenario for the 2021 stress test of the European Banking Authority (EBA), which we also use as our reference scenario where no additional carbon pricing takes place. A more detailed discussion of our scenarios can be found in section 2.

Our analysis covers all Austrian credit institutions to which the Capital Requirements Regulation (CRR) applies. In total, the sample includes 379 banks at the highest level of consolidation as of end-2020, which we segment into 7 significant institutions (SIs), 1 material foreign SI subsidiary and 371 less significant institutions (LSIs).

We perform a top-down assessment using a multitude of data sources available to bank supervisors under European and national reporting requirements[6], but also public data, most importantly the most recent available input-output and emission data by Eurostat as the basis for the sectoral carbon price model and the BACH database as the basis for the insolvency model.

We choose a time horizon of five years, which we view as consistent with (1) the assumptions ingrained in input-output analysis, (2) the static balance sheet assumptions implemented in both, our corporate insolvency model and our stress

[6] *This includes multiple proprietary, nonpublic data sources available at the OeNB, such as EBA's EU-wide supervisory reporting standards and national reports for balance sheet data, the OeNB's microdata reporting regime for the NII models, credit risk exposures are based on ECB's AnaCredit, national reporting and international banking supervision statistics.*

test framework ARNIE, and (3) our use of the current baseline scenario for the 2021 EBA stress test, which we extend to five years and combine with carbon price paths. The calculation steps are performed for each quarter of our simulation horizon.

These choices are also consistent with our objective of providing an assessment of how a sudden increase in carbon prices could impact the banking sector while limiting model uncertainty. Consequently, we explicitly exclude the longer-term impact of physical risk and the large-scale and unforeseeable transformation our economy will undergo if climate change continues unchecked. It is important to keep these limitations in mind when interpreting the results.

Our model builds on the following four components, as illustrated in figure 1.

A newly developed sectoral carbon price model links additional carbon charges to economic sectors' costs and output. Specifically, we employ an input-output analysis which captures differences as well as interlinkages between economic sectors on a granular level (Owen, 2017). In contrast to traditional applications, we do not assume that costs can be fully passed on to other customers, but restrict this ability based on a sector's trade and emissions intensity.

The OeNB's corporate insolvency model, a microdata-founded structural approach developed in 2020 to assess sectoral vulnerabilities in the COVID-19 environment (Puhr and Schneider, 2021), will translate higher costs and lower turnover into increased insolvency rates for Austrian corporates based on their sector-specific balance sheets and profitability characteristics. The increases in insolvency rates are later used as sector-specific shocks to probabilities of default (PDs).

A set of linking equations translates sector-specific PD shocks for the Austrian economy into shocks for other countries. This step is necessary as our corporate insolvency model is only available for Austrian firms. Moreover, the Austrian insolvency rates are further used as an input to the market risk module, which calculates valuations losses as an additional shock factor.

Finally, ARNIE, the OeNB's well-proven top-down stress testing framework (Feldkircher et al., 2013), is used to calculate the impact of carbon price-induced credit risk and market risk shocks on individual banks. Each box depicted in figure 1 will be explained in more detail in section 3.

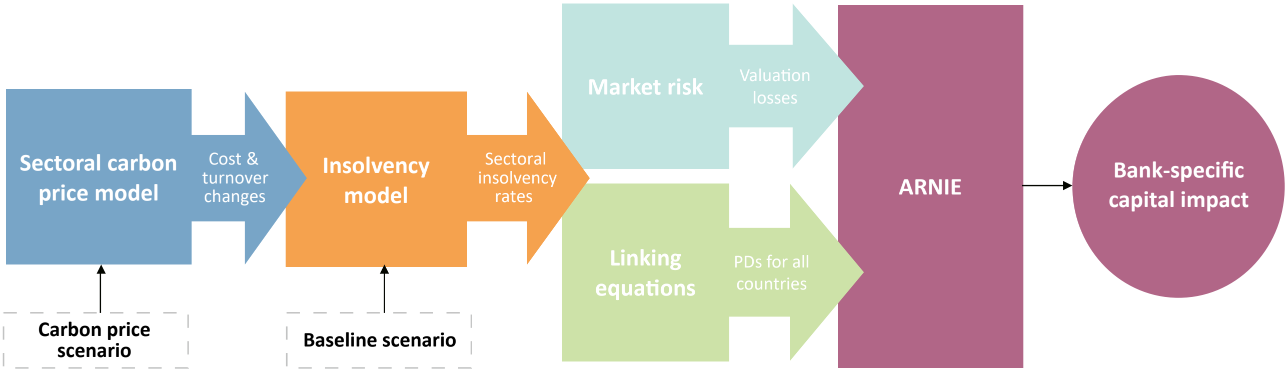
2 Scenario definition

The scenario narratives published by the NGFS since 2020 serve as the starting point for most recent climate risk assessments. Covering the periods 2020 to 2050 and 2050 to 2100, respectively, these scenarios provide a range of macroeconomic variables such as GDP and carbon price paths for an orderly and a disorderly transition to a carbon-neutral economy (NGFS, 2021). Given our short- to medium-term time horizon and our focus on carbon pricing, we follow a slightly different approach.

A five-year baseline scenario serves as the reference scenario to which we add two sets of carbon price paths inspired by the NGFS scenarios. For the baseline scenario, the forecast of the broader economy is based on the current baseline scenario for the EBA EU-wide stress test, which we also use for the OeNB's regular top-down banking stress test also published in this

Figure 1

Stylized overview of the OeNB's climate risk stress test framework



Source: Authors' compilation.

report.[7] The scenario of the EBA stress test is enriched by the current OeNB forecast (June 2021) to enable its decomposition into granular economic sectors.

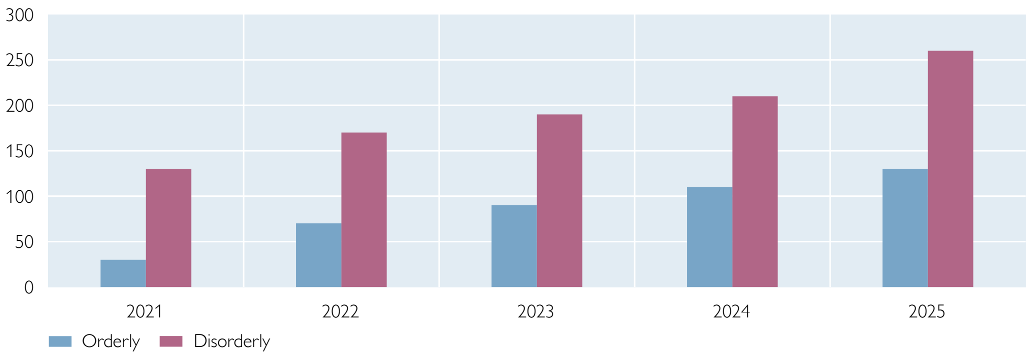
In the first transition scenario, carbon pricing is implemented in an orderly fashion, where the additional cost of emitting greenhouse gases rises steadily from EUR 30 per ton CO_2 equivalent in 2021 to EUR 130 per ton in 2025. The second scenario assumes a disorderly transition such that the cost of emitting greenhouse gases jumps immediately to EUR 130 in 2021 and rises to EUR 260 in 2025 (see chart 1).

Importantly, we model the carbon price as an additional impact on existing direct and indirect emission pricing schemes such as fuel taxes, the European Emission Trading System (ETS) and national pricing regimes. In both scenarios, carbon pricing applies to all economic sectors and includes all important greenhouse gases.[8]

Chart 1

Carbon price paths in the orderly and disorderly scenarios

EUR per ton of CO_2 equivalent



Source: OeNB.

[7] *See the "Recent developments" section in this publication.*

[8] *The main greenhouse gases – carbon dioxide (CO_2), methane (CH_4), nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride – are measured in CO_2 equivalents in our analysis.*

Carbon pricing is assumed to be implemented in all EU countries and includes a carbon border adjustment mechanism ("border tax"), which we apply to all imported goods.[9] We do not consider the possibility of channeling the tax income to other uses, such as a reduction of income taxes or lump sum payments to households. The estimated impact on demand is thus higher than in practice, where tax recycling is a major factor to reduce the regressive nature of a carbon tax and greatly reduces the overall impact on GDP (Kirchner et al., 2018).

3 Modeling framework

As mentioned above (see also figure 1), our modeling framework is based on four main components to assess the impact of carbon price scenarios on the Austrian banking system. The first model is an input-output model to assess the direct and indirect impact of these industry-specific tax increases on final goods prices (see section 3.1). Its output – sectoral cost and turnover changes – are then fed into the second model. Using the OeNB's insolvency model, we derive the impact of the materialization of climates risks in our scenarios on sectoral insolvency rates (see section 3.2). These insolvency rates are put to three-fold use in the third step: (1) they are translated into PDs for Austrian exposures; (2) a set of linking equations is applied to extrapolate the Austrian PDs to the rest of the world to bridge data gaps; (3) the PDs are further used to calculate valuations losses as an additional risk factor for Austrian banks (see section 3.3 for further details). The final set of PDs and valuations losses are subsequently fed into ARNIE, the OeNB's top-down stress testing module to calculate a bank-specific capital impact (see section 3.4).

3.1 The sectoral carbon price model

In our framework we employ a multiregional input-output analysis for all EU countries to determine the impact of an additional carbon pricing mechanism on production costs and output (i.e. corporate turnover). Input-output models are well established for analyzing the impact of carbon prices and other environmental policies (Owen, 2017; Miller and Blair, 2009; Perese, 2010; Gonne, 2016). Examples include central banks' climate risk exercises as well as numerous academic studies that examine economic impacts of carbon pricing mechanisms.[10] Here, the need for sectoral models is especially pronounced since sectors differ substantially in their carbon intensity and are therefore affected differently by an increase in the cost of emitting greenhouse gases. Input-output models can describe these differences and demand interlinkages between economic sectors on a granular level. Therefore, they can capture the transmission of the cost shock caused by a carbon tax on all industries and final demand components (i.e. private and government consumption, investment, exports). At the same time, input-output models are static in that they assume fixed production functions. This means there is no technological change or

[9] *In contrast to the current carbon border adjustment mechanism proposal by the European Commission, we apply the border tax not to specific products such as fossil fuels and cement but to all sectors. In accordance with the Commission proposal, we follow the approach to price imported goods as if they would have been produced in the EU (European Commission, 2021). Hence, we calculate the border tax for imports from outside the EU based on the average emissions intensity of the respective European economic sectors.*

[10] *Most notably De Nederlandsche Bank and the National Bank of Romania have conducted climate risk exercises based on input-output analyses (Hebbink, 2018; Vermeulen et al., 2021; National Bank of Romania, 2019). For a comprehensive overview of carbon tax literature including input-output analyses, see Timilsinas (2018).*

substitution of inputs. Firms are assumed to continue producing with the same mix of input materials, they only react to carbon price-driven changes in demand by producing more or less of the same goods. The databases used for our input-output model are the latest FIGARO[11] multiregional input-output tables for 2019.

Figure 2 provides an overview of our approach.

We perform our calculations in five steps:

1. Based on the carbon price scenarios described in section 2 and sectoral emission intensities, we calculate sector-specific carbon price shocks.
2. The price model provides consistent price changes for the goods each sector produces. Input-output analysis generally assumes a full pass-through of costs to consumers. To capture not only output effects (i.e. reductions in turnover), but also cost effects, we extend this framework by including incomplete pass-through rates. The ability of firms to pass through additional costs to consumers depends on (1) the competitive situation of the firm and (2) the size of the cost shock. We approximate the first component by its trade intensity, i.e. firms in more competitive markets are less able to pass on costs. The second determinant accounts for the empirical observation that higher cost shocks are more difficult to pass on to consumers than lower ones. We combine both effects and classify sectors into three groups, with pass-through rates ranging from 90% to 99% (for more details, see the online supplement to this study).[12] The part of the cost shock that is passed on results in higher prices. The remainder of the shock is our first input for the insolvency model (profit reduction, production cost increase).
3. The final demand model translates higher prices into demand reductions for 21 sectors. This is done separately for private consumption and for exports, using own price elasticities for all goods (for more details, see the online supplement to this study).
4. Based on these demand changes, the input-output quantity model yields sectoral output reductions, which capture the direct effects per industry and the indirect effects by intermediate demand linkages between industries, i.e. first-round effects.
5. Finally, we account for second-round effects. In traditional input-output analysis, second-round effects via a reduction in employment and wages are usually not captured. As analyzing these effects in detail would require integrating the input-output framework into a fully-fledged dynamic macroeconomic model, we simulate the impact of wage losses via a reduction of private consumption, which in turn reduces output, employment and, ultimately, wages. We use a Keynesian multiplier based on the intrayear dynamic responses of the OeNB's macroeconomic model[13]. These second-round effects are added to the first-round effects to obtain the total carbon

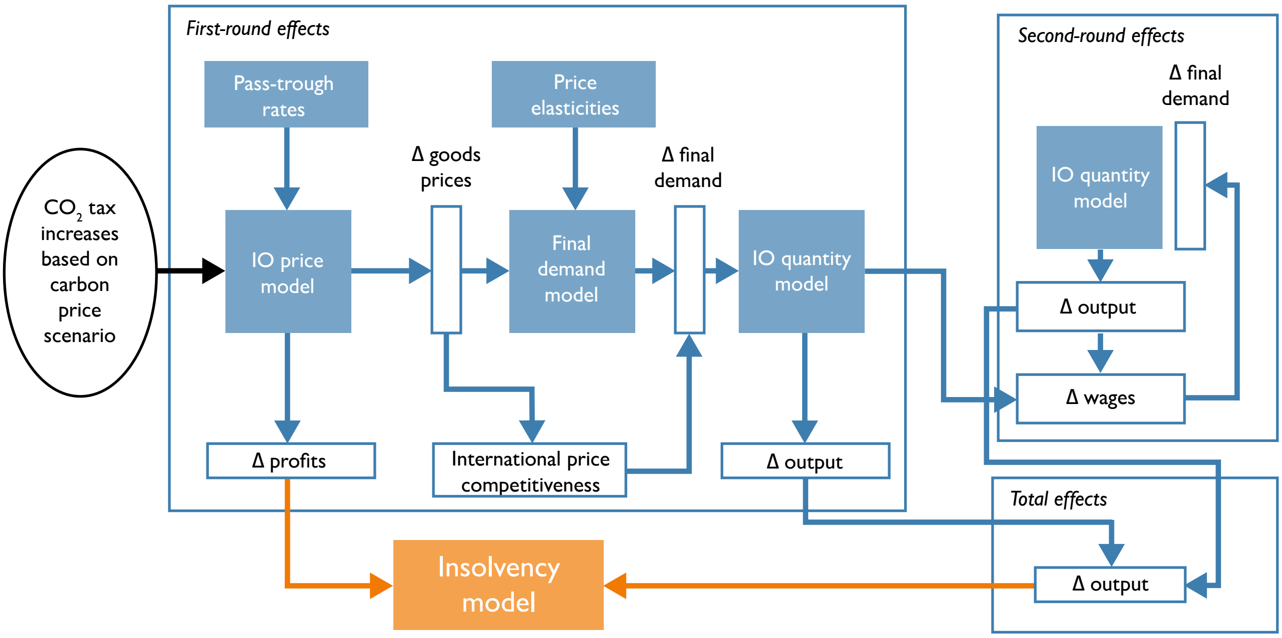
[11] *FIGARO stands for "full international and global accounts for research in input-output analysis," latest version published by Eurostat in May 2021.*

[12] *This approach is derived from the EU's Emission Trading System methodology to calculate a sector's carbon leakage indicator to determine the number of free certificates a sector receives (for formulae, see the online supplement to this study).*

[13] *See Fenz and Spitzer (2005) and Leibrecht and Schneider (2006).*

Figure 2

Stylized overview of the input-output (IO) model



Source: OeNB.

price impact on output. This output reduction (a shock to firms' turnover) is the second input which feeds into the insolvency model.

3.2 The OeNB's corporate insolvency model for Austrian firms

Originally implemented to assess the impact of COVID-19 and the associated mitigating measures on the Austrian economy, the OeNB's insolvency model allows us to estimate the effect of an additional carbon price tax on sectoral insolvency rates in Austria. Adapting the original model,[14] we (1) extend the observation horizon by two years to a five-year period and (2) cover not only shocks to turnover but also shocks to production costs.

The model is based on simulated firm-level microdata for nonfinancial firms in 17 NACE 1 sectors. We generate 100,000 hypothetical firms per sector by performing a Monte Carlo simulation. The required marginal distributions of and dependence structures between financial core variables are modeled on distribution parameters sourced from the BACH database[15] and firm-level data from the SABINA database[16]. Our granular firm dataset allows us to simulate firms' profits, cash flows and balance sheets. Over time, shocks to turnover and

[14] *See Puhr and Schneider (2021) for a detailed description.*

[15] *BACH is a database of aggregated and harmonized accounting data of nonfinancial incorporated enterprises from 13 European countries. It contains over 100 variables for 17 NACE sections, about 80 NACE divisions and 4 firm size classes (https://www.bach.banque-france.fr/?lang=en). Besides the weighted mean, data for the quartiles of the distribution for each variable are available.*

[16] *The SABINA database contains firm-level accounting data for more than 130,000 Austrian firms compiled by Bureau van Dijk.*

production costs (see previous section) result in lower profits and cash flows. As the baseline scenario is based on the current EBA stress test and given the current economic environment, the insolvency model allows firms to make use of the ongoing mitigating measure schemes initiated for the containment the COVID-19 pandemic's economic impact (cutoff date: June 2021). Under stress, firms are partially able to reduce their expenses; however, once they fall below certain equity or liquidity thresholds, they default and sectoral insolvency rates rise.

Quarterly turnover changes derived from the sectoral carbon price model are implemented as an additional shock to turnover on top of the baseline scenario. Higher production costs resulting from a carbon tax are assumed to be normally distributed within each sector to reflect intrasector heterogeneity and to allow for a more realistic impact on the simulated firms. Whenever the cost pass-through is incomplete, this results in higher total expenses, which, just like lower turnover, reduces profits and cash flows and, eventually, leads to higher insolvency rates.

At the time of writing, BACH data were not yet available for year-end 2020. As the economic impact of COVID-19 in 2020 rules out a simple forecast based on historical trends, we opt to also model the year 2020, i.e. the year leading up to our observation horizon, based on realized macroeconomic data and firms' use of mitigating measures; so technically, the insolvency model simulates a six-year period.

3.3 From Austrian insolvency rates to global default probabilities

The Austrian insolvency rates calculated in the previous section require some transformation to serve as input for our bank stress testing model ARNIE as described in the next section.

To generate the required relative PD shifts for Austrian exposures, we follow the approach of the regular OeNB top-down stress test. The resulting relative PD shifts are an input to increase reported (and estimated) PDs of banks' portfolios in line with the respective scenarios. This relative shift marks the increase in reported (and estimated) PDs of banks' portfolios. We apply similar shifts as the ones for corporate exposures to the retail exposure of banks, yet with a one- to two-period time lag to capture the delayed impact of firm defaults on household finances. Finally, for the two carbon price scenarios, we add the absolute difference of the relative insolvency rate shifts based on the corporate insolvency model to the PD shifts of the baseline scenario.

To generate relative PD shifts for non-Austrian exposures, which is essential for an assessment of the Austrian banking system given that Austria's larger banks hold significant cross-border exposures, we follow a similar approach as Guth et al. (2020). We use three scaling factors to extrapolate Austrian PD shifts to all other countries. The first two factors are derived from the sectoral carbon price model and reflect the change of the cost and turnover shocks per sector in each country relative to Austria. These two factors are essential to scale the accurately modeled Austrian PDs to the rest of the world, thereby circumventing the lack of firm-level data needed for the insolvency model. The third factor is the relative distance between each country and Austria in terms of annual GDP growth in 2020. This factor captures the underlying macroeconomic outlook and has a stabilizing effect on the extrapolation. To derive consistent estimates, an additional outlier adjustment is introduced to smooth the extreme values on each side of the PD shock spectrum.

Finally, these PD shifts are also used to estimate the market price impact on Austrian banks via valuation losses on bond holdings and equity stakes. To this end, we focus on the impact of widened credit spreads in the different economic sectors and leave other market risk factors (such as the risk-free yield curve) constant. Using the stressed sectoral five-year PD paths as a starting point, we take the maximum yearly relative PD increase, which we interpret as a severe but plausible credit spread shock. A bond's resulting valuation loss is calculated as the difference between its actual and its stressed expected discounted cash flows. Our calculation uses instrument-level data for domestic banks, including coupon payments, residual maturity, economic sector and current PDs. We only include mark-to-market portfolios, i.e. those sensitive to credit spread-driven valuation losses, in our analysis. We follow a similar approach for material equity stakes in nonfinancial firms. For the material equity stakes in nonfinancial firms, we employ a bucketing approach based on the incurred costs at NACE sector level to apply haircuts. These haircuts reflect the severity of the cost component of the sectoral carbon price model, ranging from 0% to 40% for the orderly scenario and from 0% to 70% for the disorderly scenario. The haircuts are applied to the book value of the equity holdings to derive additional losses.

3.4 Using ARNIE to analyze the impact on the banking sector

We utilize the OeNB's well-proven and well-documented top-down stress testing framework ARNIE, a MATLAB-based software used for micro- and macroprudential stress testing and scenario analyses, to investigate the impact of additional carbon pricing on the solvency of Austrian banks, both at the individual and the aggregate banking sector level. ARNIE implements the stress test methodology developed by the EBA for the EU-wide stress test exercise (EBA, 2020) and considers additional risks specific to the Austrian banking sector, such as banks' equity stakes in other banks, which can amplify shocks.[17]

4 Results

In the subsequent section, we describe the individual results of each component of our climate risk stress testing framework. First, we discuss the economic impact of the two carbon price scenarios on Austria's economic sectors (see section 4.1). Second, we present the impact on sectoral insolvency rates for Austrian firms (see section 4.2). Third, we discuss how these elevated Austrian insolvency rates translate into higher default probabilities and valuation losses (see section 4.3). Finally, we show the impact of carbon pricing on the Austrian banking system (see section 4.4). An interactive presentation of the results is available on the OeNB's website.[18]

4.1 The impact of carbon pricing on sectoral turnover and costs

Using the input-output model described in section 3.1, we determine the impact of the carbon price scenarios on sectoral price levels, output and production costs.

[17] *For more details see Feldkircher et al. (2013), OeNB (2019, box 1) and Guth et al. (2021).*

[18] *https://www.oenb.at/en/financial-market/banking-supervision/stress-tests.html.*

Table 1

Price, turnover and cost changes derived from the sectoral carbon price model

Sector	Direct GHG/ EUR[1]		Price changes (%)[2]		Turnover changes (%)[2]		Cost changes (%)[2]	
	AT	EU	AT	EU	AT	EU	AT	EU
Agriculture, forestry and fishing (A)	0.9	0.95	15.78	15.51	–7.18	–8.70	0.16	0.57
Mining and quarrying (B)	0.4	0.68	8.84	11.85	–3.01	–3.88	0.09	0.36
Manufacturing (C)	0.1	0.12	4.21	4.36	–3.00	–3.27	0.04	0.16
Electricity, gas, steam and air conditioning supply (D)	0.3	1.30	13.75	22.20	–2.50	–3.18	0.14	0.86
Water supply; sewerage; waste management and remediation activities (E)	0.3	0.52	6.54	9.24	–2.14	–2.34	0.07	0.33
Construction (F)	0.0	0.03	1.58	2.05	–2.16	–2.72	0.02	0.07
Wholesale and retail trade; repair of motor vehicles and motorcycles (G)	0.0	0.03	1.11	1.70	–1.81	–2.20	0.01	0.06
Transporting and storage (H)	0.2	0.29	3.71	5.80	–4.66	–7.03	0.04	0.22
Accommodation and food service activities (I)	0.0	0.02	1.18	2.04	–3.36	–4.76	0.01	0.07
Information and communication (J)	0.0	0.0	0.75	0.89	–1.56	–1.79	0.01	0.03
Real estate activities (L)	0.0	0.0	0.76	0.65	–1.95	–1.95	0.01	0.02
Professional, scientific and technical activities (M)	0.0	0.0	0.72	0.92	–1.85	–2.07	0.01	0.03
Administrative and support service activities (N)	0.0	0.0	0.71	1.15	–2.14	–2.56	0.01	0.04
Education (P)	0.0	0.0	0.64	0.79	–0.27	–0.42	0.01	0.03
Human health and social work activities (Q)	0.0	0.0	0.78	1.05	–0.31	–0.38	0.01	0.04
Arts, entertainment and recreation (R)	0.0	0.0	1.04	1.43	–1.93	–2.07	0.01	0.05
Other services activities (S)	0.0	0.0	0.89	1.48	–1.03	–1.69	0.01	0.05

Source: OeNB.

[1] *Emissions coefficient: a sector's direct greenhouse gas emissions (GHG) in thousand tons divided by its total output (in EUR million).*

[2] *At a carbon price of EUR 130 per ton using incomplete pass-through rates.*

Table 1 presents these results across 17 NACE 1 sectors for Austria and the EU aggregate at a carbon price of EUR 130 per ton – the end point of the orderly price scenario and the starting point of our disorderly scenario. Since our input-output modeling framework relies on linear assumptions, the results shown in table 1 can easily be scaled to different carbon prices.

Not surprisingly, the sectors hit hardest are generally those with the highest emissions per unit of output and/or elastic demand. In Austria, sector A (agriculture), currently the most emissions intensive, sees a price increase of about 16%, which would reduce output by 7%. In the second hardest-hit sector, H (transporting and storage), prices increase by less than 4% but demand decreases by almost 5%. Sector I (accommodation and food service activities) faces the third-highest turnover losses – almost 3.5% – while prices increase by about 2%.

The size of the cost shock is determined by a sector's direct emissions and its ability to pass on additional costs. In our model, pass-through rates are high (99%) for most sectors, hence the relative cost increase is low, amounting to 0.57%, 0.22% and 0.07% for the sectors A, H and I, respectively, in Austria. Still, this can have a substantial impact on insolvencies, depending on individual sector profitability.

Generally, and within the confines of the modeling framework, the results of our input-output analysis can be interpreted as the upper bound of a carbon price impact since neither tax recycling nor technological change are included. Especially in industries such as electricity production, transport and agriculture, carbon-neutral technologies already exist, which could reduce emissions intensity and thus the tax burden if they were to be adopted at a large scale.

4.2 The impact of carbon pricing on corporate insolvencies

The impact of the carbon price shocks on the Austrian economy discussed in the previous section is used as input to the OeNB's corporate insolvency model described in section 3.2. On aggregate, the insolvency model suggests that insolvency rates increase by 0.6 percentage points by end-2025 in our orderly transition scenario relative to the baseline scenario without carbon pricing. In the disorderly transition scenario, the aggregate insolvency rate is markedly higher, increasing by 2.5 percentage points by 2025 relative to the baseline. Put differently, additional average insolvencies would rise by 0.5 percentage points per year as a result of carbon pricing. Table 2 displays the cumulative annual insolvency rates expressed as the difference from the baseline scenario for all Austrian nonfinancial corporates in 17 NACE 1 sectors. For the purpose of comparison, the first column shows the percentage shares of firms' individual exposure in the Austrian banking system at year-end 2020. The table shows that the impact of carbon pricing to be greatest for sectors A (agriculture) and H (transporting and storage), where insolvency rates would rise by an additional 15.9 and 12.9 percentage points, respectively, in the disorderly scenario when compared to the baseline. At the same time, however, Austrian banks' exposure to these sectors is limited, amounting to 0.8 and 3.3 percentage points, respectively. While sectors I (accommodation and food service activities) and R (arts, entertainment and recreation) show higher insolvency rates, these are caused by already elevated insolvencies in the baseline scenario and to a lesser extent by carbon pricing. When interpreting these results,

Table 2

Cumulative annual insolvency rates for Austrian nonfinancial corporate sectors

	Share of exposure at default	Average[1]	Orderly (delta to baseline)					Disorderly (delta to baseline)				
	2020	2017–2019	2021	2022	2023	2024	2025	2021	2022	2023	2024	2025
	%	*Percentage points*										
Agriculture, forestry and fishing (A)	0.8	0.2	0.0	0.3	0.5	0.9	1.4	0.0	2.5	5.8	10.0	15.9
Mining and quarrying (B)	0.6	0.5	0.0	0.1	0.1	0.2	0.2	0.1	0.2	0.3	0.4	0.6
Manufacturing (C)	15.4	0.7	0.0	0.1	0.2	0.3	0.5	0.0	0.4	0.8	1.4	2.1
Electricity, gas, steam and air conditioning supply (D)	2.8	0.3	0.0	0.0	0.1	0.1	0.2	0.0	0.1	0.3	0.7	1.2
Water supply; sewerage; waste management and remediation activities (E)	1.0	0.7	0.0	0.3	0.7	1.1	1.6	0.2	1.3	2.6	3.9	5.2
Construction (F)	8.7	2.0	0.0	0.1	0.3	0.5	0.7	0.0	0.4	0.8	1.2	1.7
Wholesale and retail trade; repair of motor vehicles and motorcycles (G)	10.1	1.0	0.0	0.3	0.3	0.4	0.4	0.0	1.1	1.4	1.5	1.7
Transporting and storage (H)	3.3	2.6	0.3	0.9	1.6	2.3	2.9	1.7	4.5	7.6	10.3	12.9
Accomondation and food service activities (I)	4.3	2.0	0.0	0.3	0.5	0.7	0.9	0.0	1.2	1.8	2.5	3.2
Information and comunication (J)	1.9	0.6	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.3	0.3	0.4
Real estate activities (L)	29.9	0.3	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.2	0.2
Professional, scientific and technical activities (M)	14.9	0.5	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.2	0.3
Administrative and support service activities (N)	3.0	1.6	0.1	0.2	0.3	0.3	0.4	0.3	0.7	0.8	0.9	1.0
Education (P)	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Human health and social work acitivities (Q)	1.7	0.4	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.4
Arts, entertainment and recreation (R)	0.4	0.6	0.1	0.4	0.8	1.2	1.6	0.5	1.3	2.2	2.9	3.7
Other services acitivities (S)	0.9	0.7	0.0	0.2	0.4	0.5	0.8	0.2	0.6	1.0	1.3	1.8
Total	100.0	0.9	0.0	0.2	0.3	0.4	0.6	0.0	0.8	1.3	1.8	2.5

Source: KSV 1870, OeNB, authors' calculations.

[1] *According to KSV 1870 data.*

it is important to note that our modeling approach does not allow firms to switch to less carbon-intensive means of production and that no new, potentially more innovative firms enter the market.

4.3 The impact of carbon pricing on default probabilities and valuation losses

As described in section 3.3, the main factors for extrapolating the relative shifts of Austrian PDs are the cost and turnover shocks per sector in each country relative to Austria. In general, Austria's economy has a lower emissions intensity than the countries Austrian banks are exposed to, which can be largely attributed to the high share of renewable energy in the electricity sector (E-Control, 2020). Moreover, the geographical breakdown of the results from the input-output model reveals that Eastern Europe is hit harder by a carbon price shock than Western European countries and the EU on average. This is an important factor when analyzing the impact on the Austrian banking system due to the aforementioned significant cross-border holdings of the largest Austrian banks in harder-hit regions.

The impact of the scenarios on bond and equity valuations is rather muted. At system level, valuation losses amount to roughly EUR 150 million in the orderly and EUR 200 million in the disorderly transition scenario. This is not surprising, however, given that only one-third of bonds are marked to market. Of those, almost two-thirds are issued by financials, which typically possess high credit ratings (i.e. low PDs) while being faced with a lower direct CO_2 impact. The revaluation of material equity stakes shows a similar picture, with losses of roughly EUR 189 million in the orderly and EUR 540 million in the disorderly transition scenario. However, these losses stem from a handful of large industry stakes concentrated in a couple of banks, thereby putting significant strain on the capitalization of these banks.

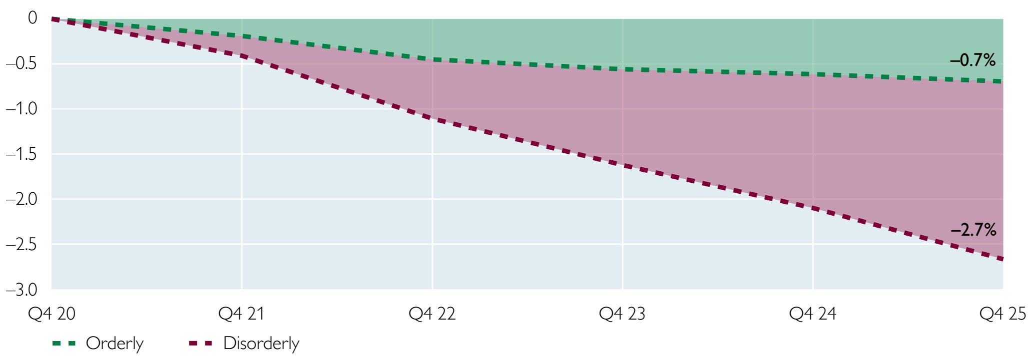
4.4 Results for the Austrian banking system

In this section, we present the impact of the baseline, the orderly and the disorderly carbon price transition scenarios on the consolidated Austrian banking system as calculated with ARNIE (see section 3.4). For the purpose of this paper, we are less interested in absolute CET1 ratios; rather, we look into the additional impact of

Chart 2

CET1 ratio of the Austrian banking system in the OeNB climate risk stress test

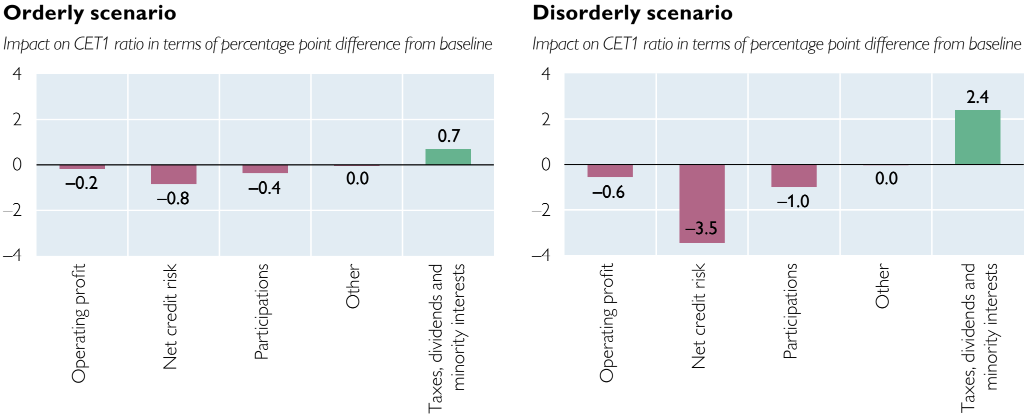
Difference from baseline in percentage points



Source: OeNB.

Chart 3

Risk drivers for the Austrian banking system



Source: OeNB.

carbon pricing and therefore focus on the deviation of banks' capitalization in both transition scenarios from the baseline (chart 2).

Our results indicate that carbon pricing has a manageable impact on the capitalization of Austrian banks in both transition scenarios. In the orderly scenario, the aggregate CET1 ratio for the Austrian banking sector would be 0.7 percentage points lower compared to the baseline over the five-year observation horizon. Under the harsher disorderly scenario, the impact amounts to 2.7 percentage points.

Chart 3 shows how different risk drivers contribute to the change in the CET1 ratio; the green and red bars denote components contributing to capital buildup or depletion, respectively.

We see that credit risk is the main contributor to the deviation of both carbon price scenarios from the baseline. This is not surprising given our modeling framework. In the orderly and disorderly scenarios, net credit risk is 1.9 percentage points and 4.5 percentage points, respectively, higher than in the baseline. Credit risk reflects provisioning needs for newly defaulted and increased provision coverage of "old" defaulted assets as well as the impact on risk-weighted assets. Over five years, credit risk losses amount to 0.8% and 1.8%, respectively, of total exposure in the orderly and the disorderly scenario. This significant difference is partly driven by the results of the insolvency model. Higher carbon prices and their speedier introduction lead to more defaults. Another important driver is a methodological assumption concerning cure rates. Under the orderly scenario, cure rates remain at historical levels, i.e. a share of the nonperforming portfolio is assumed to perform again. The disorderly scenario does not permit cures, which leads to significantly higher net credit risk costs.[19]

[19] *This follows the approach prescribed by the EBA in its methodology for the EU-wide stress test, see EBA (2020).*

Higher default numbers in turn reduce operating profits. Nonperforming exposures do not pay interest, thereby reducing net interest income. This effect reduces the CET1 ratio by 0.2 percentage points in the orderly scenario and by 0.6 percentage points in the disorderly scenario, each compared with the baseline.

The participation risk channel remains significant, also in the carbon transition scenarios. Cooperative ownership structures are an important feature of the Austrian banking sector, especially within the three-tiered Raiffeisen sector. The small local Raiffeisen banks ("primary banks") own the Landesbanken, which again hold a substantial share in Raiffeisen Bank International. In good times, the lower tier benefits from profits made at the higher tiers through dividend distributions and potential revaluation surpluses of their equity stakes. In bad times, the reverse holds true. Income from equity stakes falls, and revaluation losses mount. The combined impact of both results in a drop in the CET1 ratio by 0.3 percentage points in the orderly and 1.0 percentage point in the disorderly scenario compared with the baseline.

Taxes, dividends and minority interest (TDM) have a stabilizing effect, as all three components are calculated as a fraction of profits. In our two transition scenarios, losses are higher, depleting capital, but at the same time tax payments and profit distribution are lower, supporting capitalization compared to the baseline.

Differences across banking sectors emerge but remain limited. Chart 4 breaks down the CET1 impact of the baseline as well as both transition scenarios by different sectors of the Austrian banking system. Joint stock banks, Raiffeisen banks and special purpose banks show the highest impact. For the small Raiffeisen banks, this impact is also an indirect one resulting from losses trickling down from second-tier Landesbanken and, ultimately, Raiffeisen Bank International (RBI).

In general, the impact of carbon pricing on banks reflects their portfolio mix. At the industry-sector level and in line with the sectoral carbon price model and the OeNB insolvency model, Austrian banks with a disproportionately higher exposure to the hardest-hit NACE 1 sectors H (transporting and storage) and A (agriculture) are more affected in the transition scenarios relative to their exposure shares. In the disorderly scenario, this difference is more pronounced than in the orderly scenario. However, as has been noted in section 3.2, banks' exposure to these most affected sectors is rather limited across the entire Austrian banking sector.

Furthermore, banks active in cross-border lending to Central, Eastern and Southeastern Europe (CESEE) also see a higher impact. In relative terms, banks' Austrian exposure is affected less than their foreign exposures; especially in CESEE countries, the PD impact is higher in the relevant economic sectors due to the higher impact of carbon pricing in the respective economies in our model.

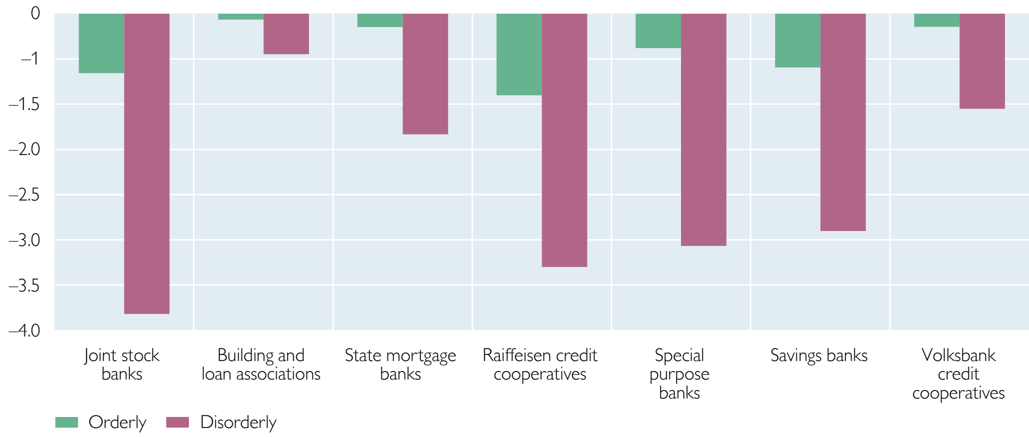
Overall, our results indicate that transition costs stemming from carbon pricing have a limited impact on the capitalization of Austrian banks. In line with other exercises[20] that quantify transitional risks, we find that the impact is mainly driven by credit risk and only to a smaller extent by market

[20] *Also, Vermeulen et al. (2021) and (Alogoskoufis et al., 2021) see credit risk as the main driver of bank losses induced by climate risk.*

Chart 4

Stressed CET1 ratio by business models

Difference from baseline in percentage points



Source: OeNB.

Note: "Stressed CET1 ratio" refers to the ratio taken from the fifth year of the stress test horizon.

risk (through valuation losses). However, the magnitude of the overall effect of transition risk scenarios is fairly limited in both transition scenarios, as we show in table 3.

Our results for banking sector losses caused by transition risks are broadly in line with other exercises. For instance, Vermeulen et al. (2021) find that Dutch banks' CET1 ratio decreases by 1.8 percentage points to 4.3 percentage points according to the chosen transition risk scenario. Also, Alogoskoufis et al. (2021) conclude that transition risks account for a relatively moderate increase in PDs and that the negative effects of physical risks by far outweigh transition costs.

5 Discussion and conclusion

The Intergovernmental Panel on Climate Change urges in its latest report that immediate and large-scale reductions in greenhouse gas emissions are needed to reduce the global increase in temperature and the catastrophic fallout that could follow if climate change is left unchecked (IPCC, 2021). The implications for the financial system are enormous too. The climate crisis will significantly reduce the value of some financial assets, which in turn affects financial intermediaries that hold these assets. As a consequence, central banks, tasked with safeguarding financial stability, are focusing more and more on the potential implications of the climate crisis for banks and financial markets. Like all other policymakers, central bankers are struggling with the trade-offs of reacting either too slowly, i.e., preserving short-term financial stability but not setting enough incentives for change to counter global

Table 3

Results overview

	Price path	Increase in insolvencies[1]	Change in CET1 ratios[1]
Scenario	*EUR*	*Percentage points*	
Orderly	30–130	0.6	–70
Disorderly	130–260	2.5	–267

Source: OeNB.

[1] *Cumulated, relative to baseline.*

warming or too fast, i.e., addressing global warming but putting undue strain on banks' balance sheets and capitalization levels.

The OeNB was one of the first central banks to contribute to this research area by assessing the share of Austrian banks' exposure to economic sectors that are particularly affected by climate transition risks (Battiston et al., 2020). In the current paper, we assess the impact of carbon pricing – one of the main policy instruments to counter global warming – on the Austrian banking system. To this end, we extend our previous work with a simple and consistent approach to quantify transitional risk costs for the Austrian banking system in two five-year scenarios, one assuming an orderly and the other a disorderly introduction of carbon pricing. By extending the framework of the OeNB's top-down stress testing infrastructure ARNIE, we are able to calculate the impact stemming mainly from credit risk losses on the aggregate banking system as well as on 379 individual banks.

It should be noted that our modeling approach rests on a set of simplifying assumptions. First, the chosen input-output analysis framework implies that certain aspects have a substantial impact on the results. Most prominently, our results indicate that the insolvency rates are more sensitive to cost changes than to turnover changes. Furthermore, the results of the input-output model are sensitive to price elasticity assumptions. Therefore, a careful calibration of the pass-through rates and elasticities in the sectoral carbon price model is key for producing meaningful results.

Second, the deployed models operate in a static environment – the sectoral carbon price model implies a static economy and both, the OeNB's insolvency model as well as ARNIE, are based on static balance sheet assumptions. This implies that our results exclude potential mitigating realignments of the economy and behavioral reactions of banks over the stress horizon. Introducing dynamic components will be a key part of future advancements in the field of stress testing in general and for climate-related stress tests in particular, as they allow us to produce more realistic results and study the impact of potential feedback effects.

Third, given the restriction of the time horizon owing to the static nature of our framework, physical risks are entirely disregarded in this exercise. Given the current state of climate research, such risks will materialize in the medium to long term if the climate crisis remains unaddressed. Hence, if such risks should be modelled, the dynamic interactions between climate scenarios, underlying macroeconomic assumptions and banks' balance sheets must be included. Moreover, granular information on climate-relevant data (e.g. emissions intensity) is not available in a consistent manner. Therefore, we conduct a sectoral rather than a firm-by-firm analysis, which, by design, may distort results when mapped to individual bank portfolios. Data gaps also drive the assumptions regarding the linking equations that map Austrian default probabilities to other countries. Our fairly simplistic extrapolation implies that the inherent dynamics driving the default probabilities in Austria are replicated for other countries.

These caveats notwithstanding, our results indicate that the impact of both the orderly and the disorderly introduction of a carbon pricing scheme is manageable for the Austrian banking system. While the impact is heterogeneous across economic sectors, it is most pronounced for the sectors H (transporting and storage) and A (agriculture), and the share of the most impacted sectors is relatively small compared to Austrian banks' overall exposure. Hence, policy measures such as a carbon emissions tax to guide the transition of the Austrian economy toward an ecologically sustainable trajectory will certainly create additional costs for the banking system.

However, our results suggest that the Austrian financial system is well placed to withstand the indirect effects of measures to fight the climate crisis thanks to banks' favorable initial capitalization levels. Despite diverging approaches and scenarios, other exercises that have been conducted lately come to similar conclusions. Less intrusive policies than the one modeled in our scenarios obviously entail lower costs in the short term, but continued inaction might eventually result in an even higher impact than anticipated now in the medium to long term.

To conclude, we strongly believe that in light of the climate crisis, a granular, micro-founded analysis of climate risks is warranted. Addressing the caveats above by including more granular data and the introduction of more dynamic elements in exercises such as this will hopefully provide further certainty on the impact of climate risks on the Austrian financial system in the future and confirm that Austrian banks are in a position to support the greening of the economy.

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