Credit Risk Where It's Due: An Analysis of Carbon Pricing-Induced Credit Risk of European Firms

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Abstract

This study investigates carbon pricing-induced credit risk, the potential negative impact of carbon pricing on firms' ability to meet their financial obligations. Applying a well-established credit assessment model to a novel dataset combining financial statements and emissions data, we subject over 750 European firms with EUR 2 trillion of outstanding debt to two carbon pricing stress scenarios. Our findings reveal notable variation in impacts between and within sectors. However, even under the conservative scenario, many firms experience only a minimal increase in their probabilities of default. In the more realistic scenario, the aggregate impact on firms' creditworthiness is negligible. What's more, the analysis shows that the euro area banking system's capitalization would not be dramatically affected by the carbon pricing-induced increase in corporate credit risk. Higher global carbon prices are needed to achieve the goals of the Paris Agreement. This study indicates that these higher carbon prices are not likely to trigger widespread firm defaults and jeopardize financial stability. It thereby offers valuable insights for informed climate policy design.

Keywords: Credit Risk, Climate Change, Transition Risk, Carbon Pricing.

JEL classification: G32, Q54, Q58

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1 Introduction

By pledging to limit the global temperature increase to well below 2°C above pre-industrial levels (UNFCCC, 2015), countries worldwide committed to fundamentally transform their economies towards carbon neutrality. This transition of the world economy away from greenhouse gas emissions comes with tight deadlines: to achieve the Paris Agreement's safer and more ambitious goal of limiting global warming to 1.5°C, yearly greenhouse gas emissions have to peak before 2025 and decline by more than 40% before 2030 (UNFCCC, 2023).

Given the scale and speed of the necessary transformation, designing the right policies amounts to a difficult balancing act: delayed action exposes humanity to the fallout of an ever hotter climate (IPCC, 2022), while badly designed, drastic or unanticipated policies might unduly damage the economy and negatively affect livelihoods. In the business and finance literature, these two sources of risk have been labelled *physical risk* and *transition risk* respectively (IPCC, 2020).

Transition risk, which is the subject of this paper, is driven by the "societal changes arising from a transition to a low-carbon economy" (BCBS, 2021): public-sector policies, technological change, consumer preferences and investor sentiment. Among public sector policies aimed at reducing greenhouse gas emissions, *carbon pricing* takes a central role. It it widely considered the most effective climate change mitigation policy (Hepburn et al., 2020; Climate Leadership Council, 2019) and plays a crucial role in many countries' climate policy package (World Bank, 2023). Risks from badly designed carbon pricing schemes are referred to as *carbon transition risks*.

The financial sector has a critical role to play in in the transition by financing the vast required investments (IEA, 2021). But financial firms – and banks in particular – do not just *affect* the climate via their lending decisions, they are also *affected by* climate-related risks, in particular by carbon transition risk. Newly introduced or tightened carbon pricing schemes might increase the traditional financial risks: credit risk, market risk and operational risk (BCBS 2021).

Carbon pricing-driven credit risk, arises when firms or households find it more difficult to meet their financial obligations because of the additional burden of a carbon price. This could come from a direct carbon tax they need to pay or indirectly, from a tax-induced increase in prices of purchased goods and services. Given that credit risk is the biggest risk on bank balance sheets (ECB, 2023a) and banks play a predominant role in many countries' financial systems (FSB, 2022), a badly designed carbon pricing scheme could in theory trigger an increase in credit losses and cause significant financial stability risks. It is therefore essential to quantify carbon pricing-induced credit risk to inform climate policy design.

In the literature, the relationship of firm credit risk and carbon emissions on one hand (Carbone et al., 2021; Zhang & Zhao, 2022; Capasso et al., 2020; Safiullah et al., 2021) and carbon-related ESG scores on the other hand (Dumrose & Höck, 2023; Ramos-García et al., 2023) has been studied extensively. These analyses demonstrate that, even without any increase in carbon prices, markets and credit rating agencies consider firms with higher emissions less creditworthy, all else equal. Another strand of the literature considers the impact of a "carbon pricing shock" on credit risk as one of the building blocks of central banks' climate stress tests (Vermeulen et al., 2018; Alogoskoufis et al., 2021; Guth et al., 2021; Mora et al., 2022; Jung et al., 2023; Emambakhsh et al., 2023). However, these analyses consider a number of climate-related stress factors in their scenarios – including macroeconomic shocks – and do not explicitly report on banks' pure carbon pricing-induced credit risk. Finally, Faiella et al. (2022) and Aiello & Angelico (2023) estimate the financial impact of a carbon pricing shock on Italian firms and households and subsequently on banks and Nguyen et al. (2023) present a similar exercise in the United States. Belloni et al. (2022) study the impact of rising carbon prices on banks by relying on a simple Merton-style model of firm asset dynamics and do not report firm- or sector-level impacts.

We are not aware of a systematic analysis focusing on carbon pricing-induced credit risk of both European firms and banks using a tried and tested credit risk model – and our study aims to fill that gap. Using a novel dataset of financial statements and emission data in combination with the long-established credit assessment model developed by the Oesterreichische Nationalbank and the Deutsche Bundesbank (Leitner & Mayer, 2015), we apply a carbon pricing stress to firm balance sheets and quantify the carbon pricing-induced credit risk of more than 750 European non-financial firms with more than EUR 2 trillion of outstanding debt under two scenarios.

We show that, under the first – very conservative – scenario, there is significant cross-sector variability in carbon pricing-induced credit risk, but a sizeable proportion of firms' probabilities of default remains practically unaffected. In the second – more realistic – scenario, the aggregate impact on firms' creditworthiness is virtually negligible and some of the cleaner firms actually *benefit* from a rise in carbon pricing. Accordingly, the effect of the carbon pricing shock on the capitalization ratio of the euro area banking system, although substantial under the conservative scenario, does not pose a systemic threat to the stability of the banking system.

These results inform the design of carbon pricing and indicate that higher carbon prices, which would be warranted to achieve the goals of the Paris Agreement, seem to have only a limited impact on corporate credit risk and financial stability in Europe. From that perspective, there is scope for more ambitious carbon pricing schemes that would speed up the transition and avert the fallout of unmitigated climate change.

The remainder of the paper is structured as follows. Section 2 describes the data sources and the sample. Section 3 outlines the employed methods and metrics. Section 4 presents the results. Finally, section 5 discusses the findings and concludes.

2 Data

In our research, we use consolidated financial statement data of listed European, non-financial firms as well as a unique dataset of corporate greenhouse gas emission data.

2.1 Financial statement data

Financial statement data are taken from the ERICA (European Records of IFRS Consolidated Accounts) database European Records of IFRS Consolidated Accounts (2023) which is run under the aegis of the European Committee of Central Balance Sheet Data Offices (2023)[1]. The data is supplied by member institutions who collect and submit consolidated International Financial Reporting Standards (IFRS)[2] financial statements from listed, non-financial firms in a harmonized format based on the IFRS taxonomy. For the fiscal year 2021, we obtain consolidated financial statements for 881 groups listed in one of the participating countries (Austria, Belgium, France, Italy, Germany, Greece, Portugal, and Spain) from the ERICA database.[3]

2.2 Emission data

Global emissions

Emission data is retrieved from the ERICA database and from third-party data providers (ISS ESG and Carbon 4 Finance). Starting from the accounting period 2019, the ERICA database also holds information on climate risk relevant data, including CO_2 emissions. This data is taken from the groups' IFRS reports or from separate sustainability reports, and refers to the global CO_2 emissions of the firm and all its fully consolidated subsidiaries in a given

[1]The ECCBSO is formed by a group of European National Central Banks who voluntarily join forces in analysing non-financial firms' financial statement data and making the data set available to the general public.

[2]Accounting standard that must be followed by publicly traded parent companies in the EU when preparing consolidated financial statements and is issued by the International Accounting Standards Board (IASB).

[3]Micro data are currently only available to participating institutions while access to aggregated data is described in European Records of IFRS Consolidated Accounts (2023).

year. The publication of emission data remains a voluntary reporting under the current legal framework (European Parliament and Council, 2014). Hence, emission data are not available for all groups and, when available, are not based on a harmonized methodology. For the analysis we do not distinguish between groups reporting only CO_2 emissions and groups reporting all greenhouse gases in CO_2 equivalents

In addition, we use two additional data sources (ISS ESG and Carbon 4 Finance) providing a large set of variables related to companies' climate risk, including Scope 1 and Scope 2 emissions.[4] Regarding data from ISS ESG and Carbon 4 Finance, we consider both modeled and reported information.[5]

When available, we utilize reported information instead of modeled data. If emission data are available from two or more sources for an entity, we use the source closest to the peer-group[6] median. Also, we check whether Scope 1 emissions are lower than those reported under the European Union Emissions Trading System (EU ETS) as European emissions are a subset of global Scope 1 emissions.

In our study, we focus on direct (Scope 1) and indirect (Scope 2) emissions. Direct emissions are potentially subject to carbon pricing (like the EU ETS or CO_2 taxation) depending on the economic sector and the jurisdiction. Including indirect emissions allows us to approximate indirect costs due to higher energy prices from carbon pricing.

Scope 3 emissions, finally, were reported less frequently, proved most challenging in their calculation, and were often assumption-based. Hence, at the time of the study, they were not seen as sufficiently comparable and suitable.

EU ETS emissions and costs

The European Union Emissions Trading System (EU ETS) is the world's largest carbon pricing scheme,[7] and covers electricity and heat generation, energy-intensive industries, and parts of the aviation sector. Every year, installations from these sectors need to surrender allowances for the greenhouse gases they emit. A fraction of these allowances is allocated to the installations for free,[8] while the residual needs to be covered with allowances purchased

[4]Scope 1 includes all direct greenhouse gas (GHG) emissions caused by a company itself. Scope 2 includes the indirect GHG emissions caused by a company's energy suppliers from generating electricity, heating, cooling and steam. Scope 3 includes all other indirect GHG emissions from the upstream and downstream value chain.

[5]The data providers estimate emissions for companies where information is not available based on other variables. Also, they run internal validations of emission information reported by companies.

[6]We define 19 peer-groups based on NACE codes.

[7]1.36 billion tons of CO_2 equivalent were covered by the EU ETS in 2021, see European Environmental Agency (2023)

[8]This fraction varies from sector to sector and typically increases with the risk of "carbon leakage", that is firms moving emissive production to other jurisdictions in order to circumvent carbon pricing policies.

in public auctions or on the secondary market.

In order to gauge (a) what fraction of the emissions of the firms on our sample were covered by the EU ETS and (b) how much firms needed to pay for those emissions, we follow the standard aggregation methodology of Millischer et al. (2023). Installations in the EU ETS database, for which yearly emissions and free allowance allocations are known, are matched with the ORBIS firm database. Using the ORBIS ownership structure, we determine whether a firm in the ERICA sample owns a controlling share in that installation, then sum over all controlled installations to obtain a firm's emissions and free allowance allocation.

2.3 Stylized facts

This study estimates the impact of carbon pricing on firms' creditworthiness. In this section, we describe the baseline situation before applying the carbon pricing shock: firms' initial creditworthiness and emission intensity.

The sample contains data for the fiscal year 2021. As presented in Table 1, emission data is available for most companies included in our sample (776 out of the 881 firms for which financial statements are available).

Firm size	corp. publication	modeled	Total
Small	47	205	252
Medium	169	79	248
Large	257	19	276
Total	473	303	776

Table 1: Emission data by source and firm size: Small if revenue $<$ EUR 250 Mio., Medium if EUR 250 Mio. $\geq$ revenue $<$ EUR 1,500 Mio., Large if revenue $>$ EUR 1,500 Mio.

The sample is further structured in climate policy relevant sectors (CPRS) and non-CPRS. CPRS refers to sectors that could be affected both positively and negatively by climate policy measures. The CPRS scheme was developed by Battiston et al. (2017) and considers the classification of activities at the NACE Rev2, 4-digit level. Sectors 1 to 6 of the scheme are classified as CPRS whereas sectors 7, 8 and 9 are non-CPRS. Table 2 shows the distribution of the data sample according to the CPRS scheme: 469 companies belong to CPRS whereas 317 companies are classified as non-CPRS.[9]

Since 2013 the fraction is very low for the electricity sector.

[9]Given the low number of reporting entities in sector 6 and 8, we exclude sector 6 and collapse sectors 8 and 9 into Non-CPRS for the remainder of the analysis.

Creditworthiness

Table 2 shows the baseline (pre-carbon pricing shock) predictions of our rating model (see section 3.2) with 469 of 776 entities reaching investment grade. The share of investment grade companies is higher in the fossil-fuel, utility and energy-intensive industries sector. Figure 1 presents the distribution of PDs measured on a rating scale associated with historical default rates from Standard & Poor's (S&P) used as PDs. [10]

CPRS sector	N	Investment-grade
1-fossil-fuel	16	81%
2-utility	45	76%
3-energy-intensive	236	67%
4-buildings	80	53%
5-transportation	92	59%
6-agriculture	-	-
7-finance	-	-
8-scientific R&D	11	-
9-other	296	56%
Total	776	60%

Table 2: Distribution of sample companies and rating class by CPRS classification

Emission intensity

Figure 2 presents the distribution of Scope 1 and Scope 1+2 emission intensities – firms' emissions normalized by revenue. Scope 1 and Scope 1+2 emission intensities are generally well aligned (Kendall's tau = 0.75). The fossil fuels and utilities sector are associated with pollution levels multiple times higher than other sectors on average. We record a median total intensity of 231 and 434 tCO_2/Mio EUR of revenue for fossil fuels and utilities respectively. Further, our sample of the third sector of energy-intensive manufacturing is characterized by relatively low emission intensities, reporting a median value of 34 tCO_2/Mio EUR of revenue. However, there are several observations with significantly larger intensities, suggesting that the energy-intensive sector is very heterogenous. The transportation sector shows a slightly higher median intensity of 39 tCO_2/Mio EUR. Buildings report a median intensity of 25 tCO_2/Mio EUR. Non-CPRS businesses record a median intensity of 17 tCO_2/Mio EUR, also showing some heterogeneity. As demonstrated by the graph, direct (Scope 1) emissions make up for the bulk of carbon intensity in the fossil fuel and utility sector. The Transportation

[10] The output of the rating model is a one-year probability of default, which is associated with the S&P rating scale based on the historical default rates observed by S&P.

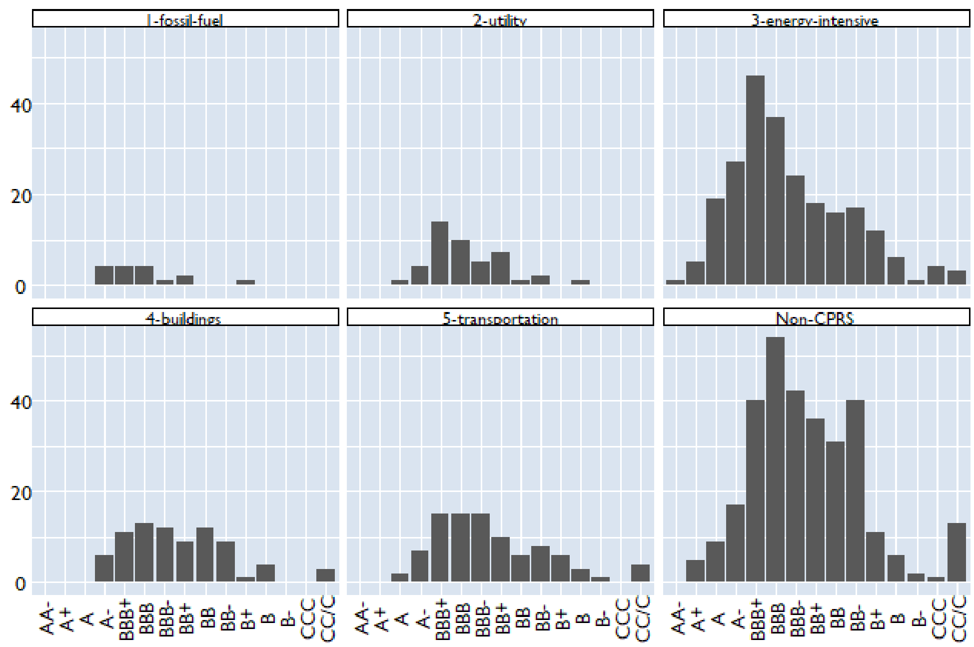

Figure 1: Distribution of base ratings on the S&P scale

sector reports a median Scope 1 share[11] of 58%. All other sectors report higher Scope 2 emissions for the median company.

Table 3 presents the relation between global direct (Scope 1) emissions and emissions covered through the EU ETS (in the third column) and the share of global emissions for which free allowances are handed out under the EU ETS (forth column). In total, we record 770 $MtCO_2$ emitted through direct emissions in 2021. As already mentioned, some direct emissions are already priced in Europe through the EU ETS. With 373 $MtCO_2$ covered through the EU ETS, roughly half of the companies' emissions are already priced. As the EU ETS regime is not yet implemented across all industries, the share of emissions recognized in the EU ETS varies largely across sectors. Also, the EU ETS share depends on the geographical distribution of the production processes. Roughly two-thirds of the overall emissions in fossil-fuel industries and utilities are already covered through the EU ETS, with utilities having to pay for nearly all of the EU ETS allowances (only 2% of allowances are allocated for free). The energy-intensive sector is associated with a coverage of 37%. The transportation sector records a coverage of 20%. In general, the emissions from the most polluting sectors and companies are at least partly managed through the EU ETS.

[11] Scope 1 to total emissions (Scope 1+2)

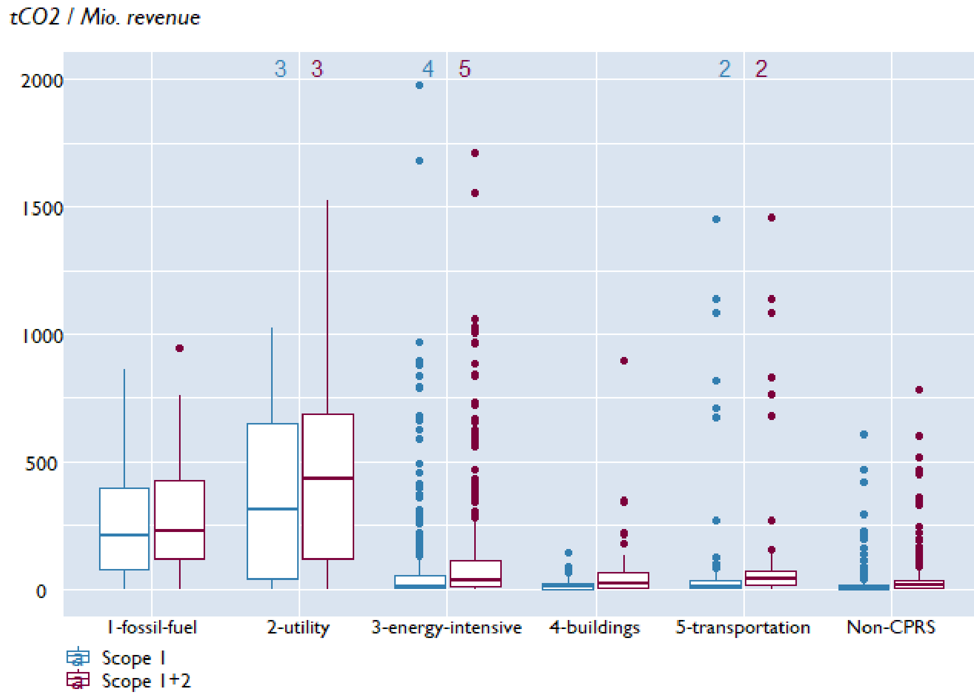

Figure 2: Emission intensity by sector. The boxes show the 25^{th}, 50^{th}, and 75^{th} percentiles of the distribution, and the whiskers correspond either to the min or max, or to $1.5\times$ interquartile range. The number of observations above the cut-off is indicated at the top.

CPRS sector	Scope 1 emissions	EU ETS share	Free share
1-fossil-fuel	86	67%	40%
2-utility	346	60%	2%
3-energy-intensive	246	37%	30%
4-buildings	5	5%	3%
5-transportation	70	20%	12%
Non-CPRS	16	10%	7%
Total	770	48%	16%

Table 3: Global direct (Scope 1) emissions [in $mtCO_2$] of firms in our sample by sector and share covered through the EU ETS. The last column presents the share of global emissions that are covered by free EU ETS allowances.

To get an intuition for the size of the carbon cost on firms' income statements, Figure 3 shows a boxplot of the carbon cost as a share of the revenue assuming a price of EUR 60 per tCO_2 (average EU ETS price for the year 2021). We present three different pricing schemes: current EU ETS implementation with free certificates (blue), EU ETS implementation without free certificates (red), and global pricing for Scope 1 emissions (green).

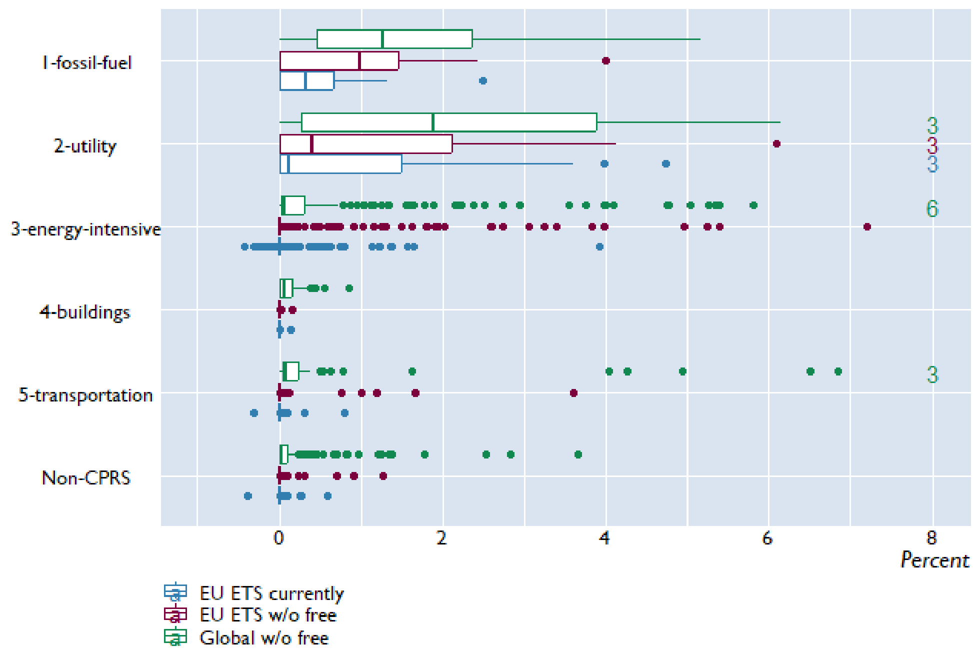

Figure 3: Carbon cost as a share of revenue, assuming a price of EUR 60 per tCO_2 for different pricing schemes. The boxes show the 25^{th}, 50^{th}, and 75^{th} percentiles of the distribution, and the whiskers correspond either to the min or max, or to 1.5× interquartile range. The number of observations above the cut-off is indicated at the top. See Table 7 in the Annex for a detailed summary table.

In the current scenario with free allocations (blue boxes), emission costs as a share of revenue are no higher than 1% except for 26 firms.[12] Only three entities from the utilities sector are associated with costs higher than 5% of their revenue, estimated costs range between 16-18% for these companies. Some companies even recorded a profit (negative cost share) as they were allocated more free permits than needed to cover their European emissions for the year 2021. In a scenario without free allocations, eight companies[13] exceed a cost share of 5%, with a maximum of 18%. The median cost share increases from 0.3% (with free allocation) to 1% (without free allocations) in the fossil-fuel sector and from 0.1% (with free allocation) to 0.4% (without free allocation) in the utility sector. Note that only a subsample of 173 companies is covered by the EU ETS and therefore records non-zero cost in these two scenarios. Applying a price of EUR 60 per tCO_2 on the global direct (Scope 1) emissions yields a different picture: 25 entities are associated with a cost share above 5%.

[12] Two observations in fossil-fuel, 16 in utility sector, and eight companies in the energy-intensive sector.
[13] Four utilities and four energy-intensive producers.

The median cost share increases to 1.3% in the fossil-fuel sector and 1.9% in the utility sector. Energy-intensive industries are associated with a median cost share of 0.1%, but the sector shows strong heterogeneity.

3 Methods

We use the OeNB's In-house Credit Assessment System (ICAS) model to compute stressed probabilities of default (PD) in order to gauge the impact of a carbon pricing shock on the creditworthiness of firms. This section first presents the two stress scenarios (section 3.1), then gives details on how the model is used (section 3.2) and describes the metrics used for quantifying the impact (section 3.3). The results of the scenario analysis are presented in section 4.

3.1 Scenarios

We model a carbon pricing shock corresponding to an increase in the global price of carbon to EUR 100 per ton of CO_2. This price has been chosen as it is projected to be a suitable price to reach a 40% reduction of GHG emissions until 2030 and allows a smooth price increase to reach CO_2 prices sufficient to reach the "Fit-for-55" plan proposed by the European Green Deal (Pietzcker et al., 2021). We consider a setting where the carbon price applies universally across firms' worldwide Scope 1 and Scope 2 emissions. Note that this could be achieved by either local pricing schemes or by carbon border adjustment mechanisms, where the carbon pricing is added as an import tariff (European Commission, 2021; IMF, 2019). IMF simulations suggest that a uniform global carbon price of USD 50-80 per tCO_2 by 2030 could achieve the necessary emission reductions to align global greenhouse gas emissions with the 2° goal of the Paris Agreement (Parry et al., 2021; Chateau et al., 2022). However, according to Chateau et al. (2022), high-income countries would need carbon prices up to USD 225 per tCO_2 to achieve national reduction goals. As of 2021, the global carbon price was about EUR 3 per tCO_2 (Parry, 2021) and the effective price in the EU was less than EUR 20 per tCO_2[14] (Parry et al., 2022). Assuming a price of EUR 100 per tCO_2 can be considered a severe but plausible carbon pricing shock.

Taking the increase of the global carbon price to EUR 100 as an input, we will consider two scenarios: a raw and an enhanced stress scenario, which differ in the sophistication of their assumptions and are described in more detail in the following.

[14] The price of an EU ETS allowance was EUR 60 per tCO_2 in 2021 but the EU ETS only covers about half of EU emissions and half of the allowances were allocated for free. However, other carbon pricing schemes do exist in the EU at national level Parry et al. (2022) have computed an average price of about EUR 45 per tCO_2 as of 2022 (the prices in 2021 were lower) applying to less than half of emissions, hence the effective price of less than EUR 20 per tCO_2

Raw stress scenario

The raw stress scenario is designed to be simple and conservative. It does not rely on estimations of already paid carbon taxes (set to 0) or on models of the pass-through rate of carbon costs to consumers (also set to 0). These simple assumptions are relaxed in the "enhanced stress scenario" described further down.

In the raw stress scenario, firms need to pay EUR 100 per ton of global Scope 1 and Scope 2 emissions. Existing carbon costs (whether in the EU ETS, national carbon taxes, or other worldwide carbon pricing schemes) are not subtracted from that figure, meaning the raw stress scenario simulates an increase of the global carbon price *by* EUR 100 rather than *to* EUR 100.

Including Scope 2 emissions in the calculation of carbon costs corresponds to the assumption that firms need to pay for their direct (Scope 1) emissions and their energy costs rise in proportion to the embedded indirect energy emission (Scope 2).

In the raw stress scenario, the additional carbon costs are simply computed according to equation (1):

$$\Delta\text{costs} = 100 \times \text{global Scope 1 and 2 emissions} \tag{1}$$

While this scenario is designed to be simple, it has a number of shortcomings:

- First, the scenario does not consider that firms can offset some of their carbon costs by **raising costs for consumers** and generating higher revenues. Furthermore, while all firms see their (Scope 2) energy costs rise, energy-producing firms do not see a commensurate increase in revenues. While this assumption is inconsistent, it is conservative at the level of individual firms.

- Second, the raw stress scenario does not take into account that **firms face rising costs** of intermediate goods and services *other* than energy, nor does it try to model that energy costs might rise by more than their embedded emissions (a mechanism discussed in the "enhanced stress scenario").

- Third, the raw stress scenario includes no macroeconomic impact related to the sudden impact of a EUR 100 carbon price. Estimating that impact and breaking it down by sectors and firms is an arduous task. Depending on cyclical components and revenue recycling, that impact could well be positive (Schoder, 2021).

- Finally, in this scenario, firms make **no changes to their production processes** or business model and implement no energy efficiency measures. Similarly, their balance sheet and income statement are assumed to remain unchanged beyond the increased carbon costs. This "business-as-usual assumption" is conservative, as firms' reaction to an increase in carbon prices would certainly aim at improving their financial position. This is why bank stress tests often make an analogous "static balance sheet assumption" (see e.g., Ong, 2014 and Alogoskoufis et al., 2021, Emambakhsh et al., 2023). As a robustness check, we investigate whether different balance sheet representations of the carbon costs impact the PD increase in section 4.3.

Enhanced stress scenario

The enhanced stress scenario was designed to address some shortcomings of the raw stress scenario, which comes at the expense of simplicity. In this scenario, we account for (a) the pass-through of carbon costs to consumers and (b) carbon costs firms already paid under the EU ETS. These features make the enhanced stress scenario more realistic and less conservative than the raw stress scenario, yet also more sensitive to a number of modeling assumptions.

Carbon cost pass-through In the raw stress scenario, firms face increased carbon costs, which weaken their balance sheets via reduced profits and are not offset by any positive cash-flow. In reality, firms would aim to raise their prices in order to pass on some of the carbon costs they face to consumers.

Since the introduction of the ETS in Europe, several studies have estimated cost pass-through for CO_2 pricing. These studies document significant and almost complete pass-through rates for the power sector (Sijm et al., 2006; Fabra & Reguant, 2014; Dagoumas & Polemis, 2020). Evidence for full carbon cost pass-through is also found for the petroleum sector (Alexeeva-Talebi, 2011; Cludius et al., 2020). Significant pass-through rates are also found for energy-intensive industries (cement, glass, iron and steel, chemicals), but these are associated with higher variation (from 20-100%, see Cludius et al., 2020). To the extent that energy price increases are informative proxies for carbon price increases, Ganapati et al. (2020) find varying results for different industries too. According to Ganapati et al. (2020), empirically, one can observe higher pass-through for industries with lower demand elasticity and higher mark-ups. In this line, Neuhoff & Ritz (2019) state that market structure and international competition are key determinants.

It should be noted that the EU ETS currently allows for exemptions from carbon pricing via a system of free allocations, primarily for energy-intensive industries. These industries claim that they are unable to pass on costs to customers because of international competition. Hence, to prevent "carbon leakage", i.e. the shifting of greenhouse gas emissions from the

EU to countries with lower carbon costs, they receive free allowances. The introduction of the Carbon Border Adjustment Mechanism (CBAM)[15] aims to prevent carbon leakage. CBAM thus helps to reduce emissions from the production of imported goods and should allow more cost pass-through for producers within the EU.

In general, cost pass-through is difficult to model, as it requires detailed information on a firm's cost structure and competition. Think of a retailer: accounting for cost pass-through ultimately leads to a change in costs and product prices at every step in the value chain, from purchased goods to transport and storage. Thus, a realistic model would need to consider upstream Scope 3 emissions as well, to incorporate the indirect effect due to the price increase of input factors (raw materials and intermediate goods).

For the purpose of the enhanced stress scenario, we apply the simplifying assumption for utilities that they behave like electricity companies. The most carbon-intensive firm is assumed to be the marginal producer and can pass on 90% of its additional carbon costs, i.e., their revenue increases by 90% of additional carbon costs. All other firms benefit from raising prices, i.e. they receive the same proportional increase in revenue as the marginal producer. For companies in all other sectors, we simply assume that they are able to pass on 50% of their costs to customers, i.e., their revenue increases by 50% of said additional carbon costs. Equation (2) summarizes how cost pass-through is modeled for different firms.

$$\Delta\text{revenue} = \begin{cases} 90\% \times \Delta\text{carbon costs} & \text{most carbon intensive utility} \\ F^{marginal} \times \text{revenue} & \text{other energy firms} \\ 50\% \times \Delta\text{carbon costs} & \text{all other firms} \end{cases} \tag{2}$$

where $F^{marginal}$ is defined as Δrevenue/revenue for the most carbon intensive energy firm.

Paid EU ETS carbon costs As explained in section 3.1, we want to simulate the increase of the global carbon price *to* EUR 100 and therefore have to take into account that firms already pay a price on some of their emissions. Following Millischer et al. (2023), we compile the emissions and free allowances of firms under the EU ETS which is the biggest and most expensive pricing scheme.[16] The carbon costs that firms paid under the EU ETS are estimated as the total emissions covered minus the free allowances received multiplied by the average price of EUR 60 per tCO_2.

By considering the already paid carbon costs, we are now much closer to the impact of an

[15] CBAM sets a level playing field for domestic European production and foreign production by adding the embedded emissions as a tariff for imported goods and will enter into force in 2026 with reporting already compulsory (see European Commission (2021)).

[16] In 2021 the UK was still part of the EU ETS

increase of carbon prices *to* EUR 100 rather than an increase *by* EUR 100 as in the raw stress scenario. It should be noted, however, that the globally operating groups in our sample are subject to a number of carbon pricing schemes other than the EU ETS (see World Bank, 2023 for a comprehensive list of schemes) and, for lack of available firm-level data, we do not consider the costs they incur under those smaller schemes.

Implementation To summarize, firms' additional carbon costs in the enhanced stress scenario are computed according to equation (3)

$$\begin{aligned} \Delta\text{carbon costs} &= 100 \times \text{global Scope 1 and 2 emissions} \\ &\quad - \underbrace{60 \times (\text{EU ETS emissions - EU ETS free allowances})}_{\text{EU ETS costs}} \end{aligned} \tag{3}$$

and the overall costs (considering the pass through to consumers) according to equation (4)

$$\Delta\text{costs} = \Delta\text{carbon costs} - \underbrace{\Delta\text{revenue}}_{\text{cost pass-through}} \tag{4}$$

where Δrevenue is given by equation (2).

3.2 Credit risk model

At the core of this study's analysis lies the OeNB's credit risk model. The model is operated as part of the OeNB's in-house credit assessment system for the purpose of accepting bank loans as collateral for monetary operations in the euro area.[17] The model is built with consolidated financial statements, credit register data and default information from the entire universe of Austrian, Germany and Greek IFRS companies. The model is calibrated on the ICAS default definition which builds upon the Basel III default definition, i.e. it considers unlikeliness to pay and 90-days past due as default events.[18] It features six financial ratios (see Table 4) which are weighted to obtain a credit score. This score is transformed to obtain an issuer-specific, point-in-the time, probability of default estimate for a one-year horizon.

In the past the model has been successfully applied to also rate Belgian, Spanish and Portuguese firms, using their IFRS financial statements. Since its first introduction in 2011, the model has consistently shown excellent performance regarding discriminatory power and calibration quality in the Eurosystem's annual performance monitoring.[19]

[17]See Auria et al. (2021) for an overview over in-house credit assessments in the euro area.

[18]For more details on the calibration methodology see Leitner & Mayer (2015).

[19]The Eurosystem accepts collateral assessed by various rating sources as part of the Eurosystem Credit

Ratio	Stressed
EBIT, adjusted	Yes
Self-financing ability	Yes
Net indebtedness ratio	Yes
Capital interest burden	No[20]
Return on cash flow	Yes
EBITDA – ROI	Yes

Table 4: Financial ratios of OeNB's IFRS model.

Carbon stress

In our carbon stress model, we simulate the impact of a hypothetical CO_2 price increase on the creditworthiness of firms by following four steps:

1. We determine the Scope 1 and Scope 2 emissions for each company.

2. We then compute additional costs stemming from a higher CO_2 price. For the raw stress scenario, these costs come on top of the already existing expenses (increase *by* 100 EUR), as in equation (1). In the enhanced stress scenario, we recognize already paid expenses under the EU ETS (increase *to* 100 EUR) and allow firms to pass on costs to consumers, as in equation (4).

3. We run the financial projection based on the stressed financial statement. When calculating the financial projections, we refer to the EU ETS scheme and accounting rules guided by IFRS standards.[21] For our financial projections, we assume that carbon costs are paid via the "cash and deposits" balance sheet item. If these accounts are insufficient, companies borrow, i.e., they increase their indebtedness.

4. We then use stressed positions as basis for stressed credit risk rating assuming an otherwise static balance sheet, i.e., no additional investments are undertaken, and profits and loss are affected only by the additional costs for CO_2 emissions.

Figure 4 depicts the impact of this stress on the financial statement.

Assessment Framework. For more details see ECB (2023c)

[20] The capital interest burden is defined as total interest payments divided by total debt. By not stressing this model variable, we assume the average interest rate of a firm is not impacted by the carbon price shock.

[21] Therefore, we assume that the emission cost is incurred via the obligation to purchase permits for every tCO_2 emitted during the production process in the respective fiscal year (t). The allowances for the expected emissions are bought and paid via cash and deposits within the same period (t). Certificates are kept in stock and submitted in the year after (t+1).

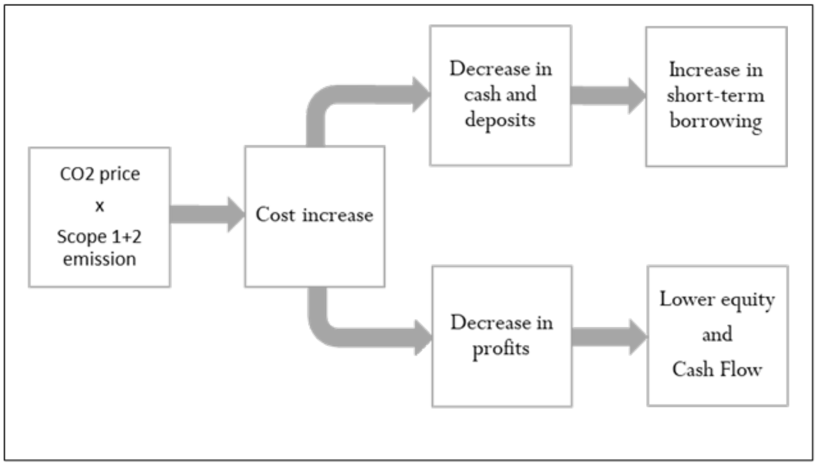

Figure 4: Sketch of the base stress model

3.3 Metrics

Firm-level metrics

The stressed PD factor (F^*_{PD}) is defined as the ratio of the stressed PD to the unstressed PD prediction and measures the relative increase:

$$F^*_{PD} = \frac{PD_{stressed}}{PD} \tag{5}$$

Credit rating scales typically show an exponential link between rating grades and probabilities of default. The stressed PD factor can thus be interpreted similarly to a rating migration but without the discretization effect induced by using rating grades.

The stressed PD difference (ΔPD^*) is defined as the difference between the stressed PD and the unstressed PD prediction and is measured on an absolute scale.

$$\Delta PD^* = PD_{stressed} - PD \tag{6}$$

Once multiplied with the exposure, the stressed PD difference is a measure of the change in the expected loss incurred by the stress scenario.

The increase in PDs translates into rating migrations, which are measured on a rating scale equivalent to the Standard & Poor's (S&P) rating scale. The investment grade is determined from this equivalent mapping to the S&P scale.

Stressed bank capitalization ratio

In order to gauge the relevance for financial stability of the deterioration of firms' creditworthiness, we also translate the PD increases into decreases of the aggregate capitalization of the euro area banking sector. Starting from the core equity tier 1 ratio ($CET1r$) which is defined as follows:

$$CET1r = \frac{CET1}{RWA} = \frac{CET1}{RWA_{CRC} + RWA_{other}} \tag{7}$$

where CET1 is the amount of core equity tier 1 capital of the euro area banking system and RWA its risk-weighted assets, both in billion Euro. We further split RWA in the part related to the credit risk of corporate exposures (RWA_{CRC}) and the remaining risk-weighted assets (RWA_{other}) – the part related to other risks (market risk, operational risk) as well as credit risk of non-corporate exposures.

Assuming that the 776 firms in our sample are representative of the corporate exposure of euro area banks, we can compute a simplified estimate of the CET1 ratio impact of the carbon price-induced deterioration in creditworthiness. The CET1 ratio is impacted via two channels:

- First, increased PDs lead to higher expected losses for banks (ΔEL), which need to be covered by provisions, thereby reducing own funds ($CET1$).

$$\Delta EL = \sum_f \Delta PD_f^* \times EAD_f \times LGD_f \tag{8}$$

  where ΔPD_f^* is the change in PD for firm f and EAD_f is the exposure amount for firm f approximated by the size of its outstanding debt[22]. For the sake of this estimation, having no information about the firm- and exposure-specific loss given default (LGD), we assume the flat value of 40%.[23]

- Second, increased PDs lead to higher risk-weights. We can compute the stressed risk-weighted assets as:

$$RWA_{CRC}^* = \sum_f RW(PD_f + \Delta PD_f^*, LGD_f) \times EAD_f \tag{9}$$

[22] Borrowings from financial institutions and bonds derived from the firm balance sheet.

[23] Treatment of unsecured corporate claims under the foundational internal-ratings based (F-IRB) approach (Basel Comittee on Banking Supervision, 2023b). This assumption is conservative as observed average LGD rates for corporates in the range of 20-30% (see EBA, 2023 and series `SUP.Q.B01.BE._Z.EL002._T.SII._Z._Z._Z.PCT.C` on ECB, 2023a)

where, as in equation (8), PD_f and ΔPD_f^* are respectively the PD and change in PD of firm f, EAD_f is the exposure amount for firm f approximated by the size of its outstanding debt and LGD_f is set to 40% in line with the F-IRB approach. $RW(\cdot)$ is the Basel IRB risk-weight formula (Basel Comittee on Banking Supervision, 2023a).

Finally, the stressed CET1 ratio ($CET1r^*$) is computed as follows:

$$CET1r^* = \frac{CET1 - \Delta EL}{RWA_{other} + RWA^*_{CRC}} \tag{10}$$

where the additional provisions ΔEL are derived in equation (8) and the stressed corporate credit risk RWA (RWA^*_{CRC}) in equation (9).

4 Results

This section presents the result of the carbon price shock, first in terms of increased firm PDs (section 4.1) and then in terms of capitalization ratios of the European banking sector (section 4.2). For each of the two metrics, both the outcome of the raw stress scenario and the enhanced stress scenario are presented.

4.1 Impact on firm probabilities of default

Raw stress scenario

Figure 5 presents boxplots of the stressed PD factor, i.e. the ratio of stressed to baseline PDs, across sectors. Panel A confirms that the sectors fossil fuel and utility are most affected under the raw stress scenario, with a median stressed PD factor of 1.17 and 1.23 respectively. Third-quartile results indicate a Stressed-PD-Factor of 1.80 for the fossil-fuel industry and 2.13 for utilities. All other sectors show no widespread shift, but a significant impact on individual companies.

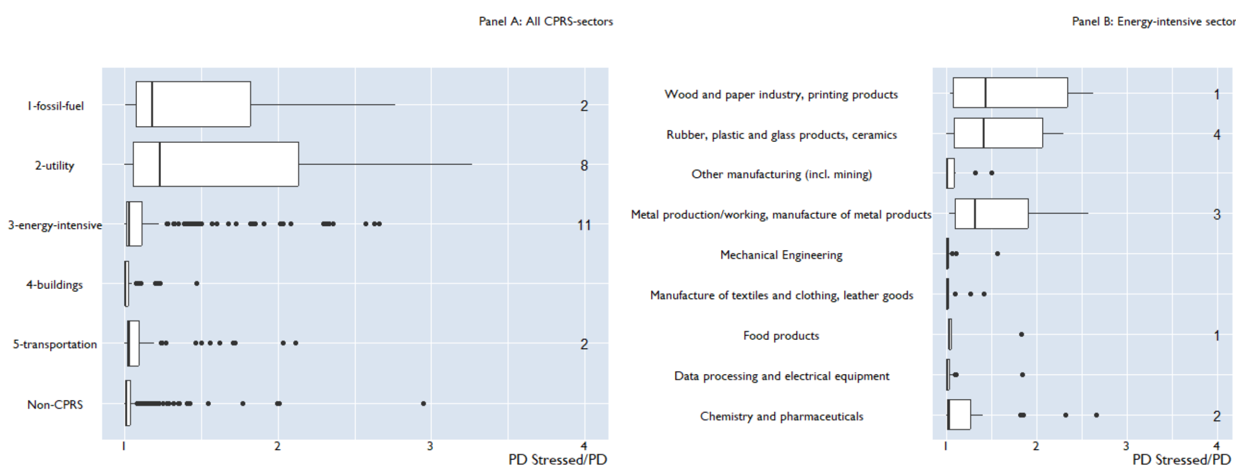

Figure 5: Impact, in terms of **stressed PD factor**, of the carbon shock in the **raw stress scenario** on firm creditworthiness, by sector. The boxes show the 25^{th}, 50^{th}, and 75^{th} percentiles of the distribution, and the whiskers correspond either to the min or max, or to 1.5× interquartile range. The number of observations above the cut-off is indicated at the edge. See table 8 in the Annex for a summary table. Note: the four outliers in the "Rubber, plastic and glass products, ceramics" category on Panel B are cement companies.

A more granular subsector classification highlights the heterogeneity within the energy-intensive sector[24] (Figure 5, Panel B). The sectors "metallic manufacturing and metal pro-

[24] 236 firms in our sample belong to the energy-intensive sector.

duction", "wood and paper industry" as well as "rubber, plastic and glass production, ceramics" record a strong increase due to the stress, comparable to the fossil fuel and utility sector. Also, the chemical industry is associated with strong adverse effects for the upper quartile. On aggregate, the debt weighted sample PD[25] increases from 0.41% to 0.63%, i.e. by a factor of 1.55. A summary table is provided in the Annex (see table 8).

Measured on an absolute scale as shown in Figure 6, PD increases are rather small: below 1 percentage point (pp) increase for almost all firms and below 0.1 pp for most firms in all but the utility sector. Only in the "metal production and manufacturing of metal products" subsector are PD increases relatively high, with more than half of the 25 firms experiencing an increase of 0.3 pp or more. It should be noted, however, that baseline PDs in that sector are among the highest (see Figure 7, which shows baseline and stressed PDs). A summary table is provided in the Annex (see table 9).

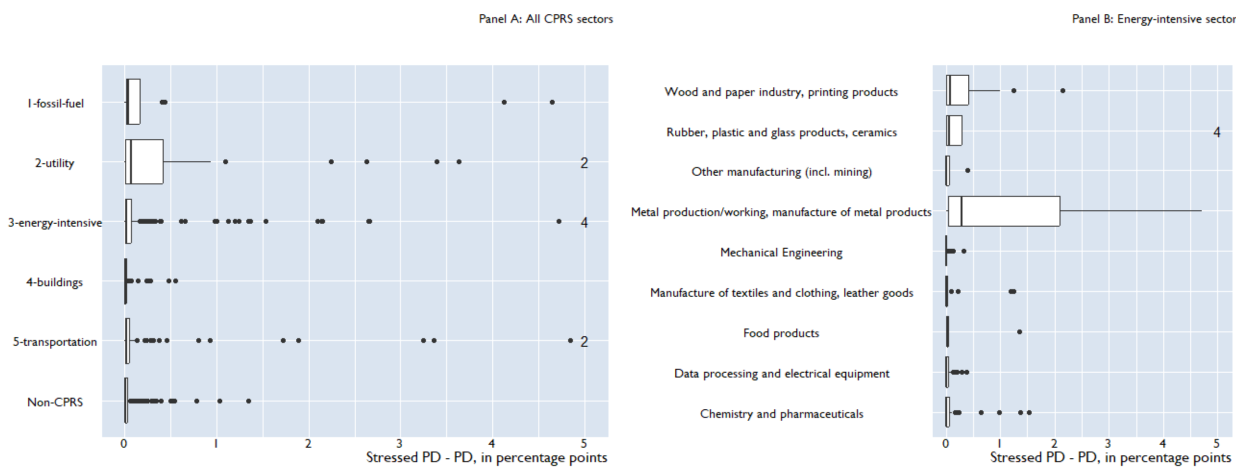

Figure 6: Impact, in terms of **stressed PD difference**, of the carbon shock in the **raw stress scenario** on firm creditworthiness, by sector. The boxes show the 25^{th}, 50^{th}, and 75^{th} percentiles of the distribution, and the whiskers correspond either to the min or max, or to 1.5× interquartile range. The number of observations above the cut-off is indicated at the top. See table 9 in the Annex for a summary table.

Rating migrations The increase in PDs described above also translates into rating migrations. Table 5 indicates that under the raw stress scenario, 82% of firms would *not* be downgraded by one notch or more. In the utility sector, where emission intensities are highest, more than half of the 45 firms would be downgraded by at least one notch. Likewise, in the fossil fuel sector, 8 of 16 companies would be associated with a downgrade and approximately one-fourth of companies in the energy-intensive industries. Downgrades by three or

[25] PD weighted by firm debt on the balance sheet.

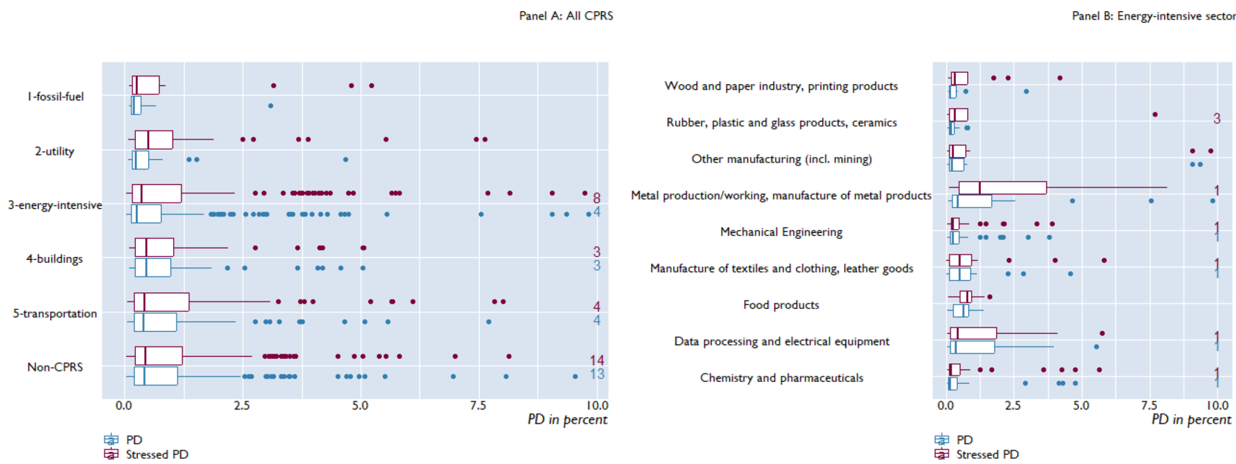

Figure 7: **Baseline and stressed PDs** in the **raw stress scenario**. The boxes show the 25^{th}, 50^{th}, and 75^{th} percentiles of the distribution, and the whiskers correspond either to the min or max, or to 1.5× interquartile range. The number of observations above the cut-off is indicated at the top.

more notches are most common in the utilities sector (20% of the sample companies). As is shown, the stress simulation indicates a drop in credit quality below investment grade for only 5% of the sample companies (from an initial 60% with investment grade), again particularly among utilities but also for energy-intensive manufacturers and fossil-fuel industries. Measured in terms of debt, this translates into 5% of total volume migrating to a non-investment grade. 16% of the debt volume is associated with a downgrade by at least one notch.

		Downgrade		
CPRS sector	N	>= one notch	>= three notches	to non-investment grade
1-fossil-fuel	16	50%	13%	15%
2-utility	45	53%	20%	35%
3-energy-intensive	236	27%	5%	11%
4-buildings	80	5%	-	-
5-transportation	92	12%	2%	4%
Non-CPRS	307	8%	0,3%	3%
Total	776	18%	3%	8%

Table 5: Downgrades per CPRS sector in the raw stress scenario: downgrade by at least one notch, downgrade by three or more notches, and downgrade from investment grade to non-investment grade as a share of the sample size. The last column is computed as a share of firms starting with an investment-grade rating.

These are the results for the rather conservative raw stress scenario. Next, we present the impact on PDs under the enhanced stress scenario, in which we account for already incurred carbon costs and allow for (partial) cost pass-through.

Enhanced stress scenario

Figure 8 presents the impact on firm PDs under the enhanced scenario: allowing for pass-through and accounting for existing carbon costs reduces stress significantly. As can be seen in Table 6, in the enhanced scenario, only 68 out of 776 companies are associated with a downgrade of at least one notch and 12 companies are downgraded to a non-investment grade rating class (vs. 137 and 38 in the raw stress scenario): 91% of firms see their rating unchanged or upgraded.

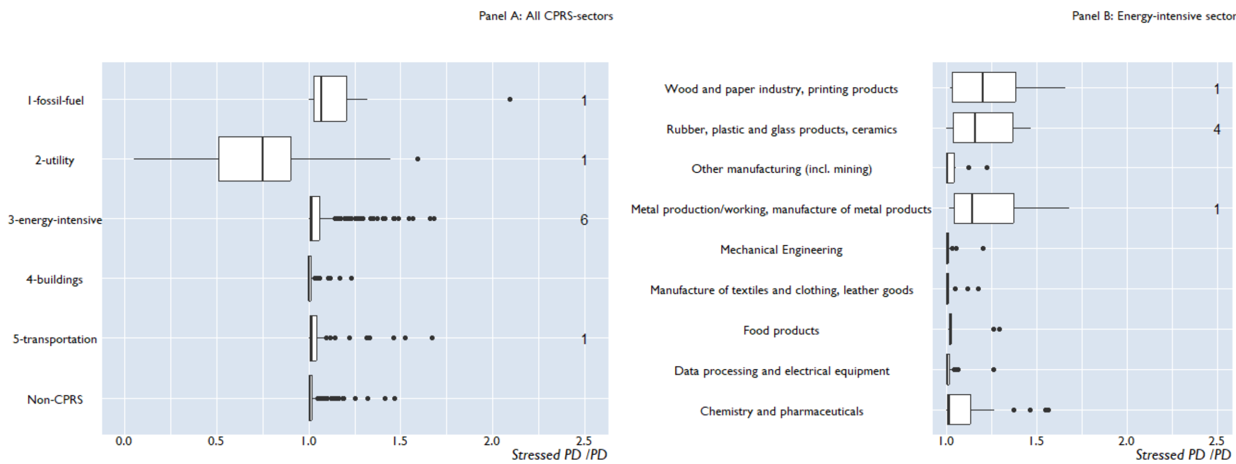

Figure 8: Impact, in terms of **stressed PD factor**, of the carbon shock in the **enhanced stress scenario** on firm creditworthiness, by sector. The boxes show the 25^{th}, 50^{th} and 75^{th} percentile of the distribution, and the whiskers correspond either to the min or max, or to 1.5× interquartile range. The number of observations above the cut-off is indicated at the edge.

The results for the utilities sector suggest that creditworthiness significantly improves on average, driven by companies with more carbon-efficient technologies. This is because sub-marginal producers gain from higher carbon prices due to the mechanism of price formation in the electricity market (Keppler & Cruciani, 2010; Hobbie et al., 2019). Our simplified model yields a revenue boost of 18.5% across the board for energy producers, whereas total additional carbon costs sum up to 3.6% of total revenue. As evidenced by the European energy crisis in 2022, suppliers of renewable power see no increase in marginal costs while prices go up, driven by more polluting technologies. Our modeling of the pass-through mechanism is rather simple. Indeed, marginal cost pass-through and effective prices in the electricity market are highly dependent on the fundamental demand and supply structure (Chernyavs'ka & Gullì, 2008; Hobbie et al., 2019). Also, as shown in a report of the IEA

(2022), companies' business models vary as firms may operate different technologies at the same time and engage in different contracts, which yields further complexity.

		Downgrade		Upgrade
CPRS sector	N	>= one notch	to non-investment grade	>= one notch
1-fossil-fuel	16	25%	13%	-
2-utility	45	9%	2%	71%
3-energy-intensive	236	16%	3%	-
4-buildings	80	3%	-	-
5-transportation	92	9%	1%	-
Non-CPRS	307	4%	0,3%	-
Total	776	9%	5%	4%

Table 6: Downgrades per CPRS Sector in the enhanced stress scenario. The "downgrade to non-investment grade" column is computed as a share of firms starting with an investment-grade rating.

However, while the modeling remains simple to allow for an easy understanding of the quantitative impacts, it allows highlighting an interesting and somewhat counter-intuitive result, namely that carbon pricing can be *financially beneficial* for carbon-efficient firms giving rise to *transition opportunities*. While the mechanism can be easily observed in the electricity sector, it could also occur in other sectors where technologies with different carbon intensities exist.

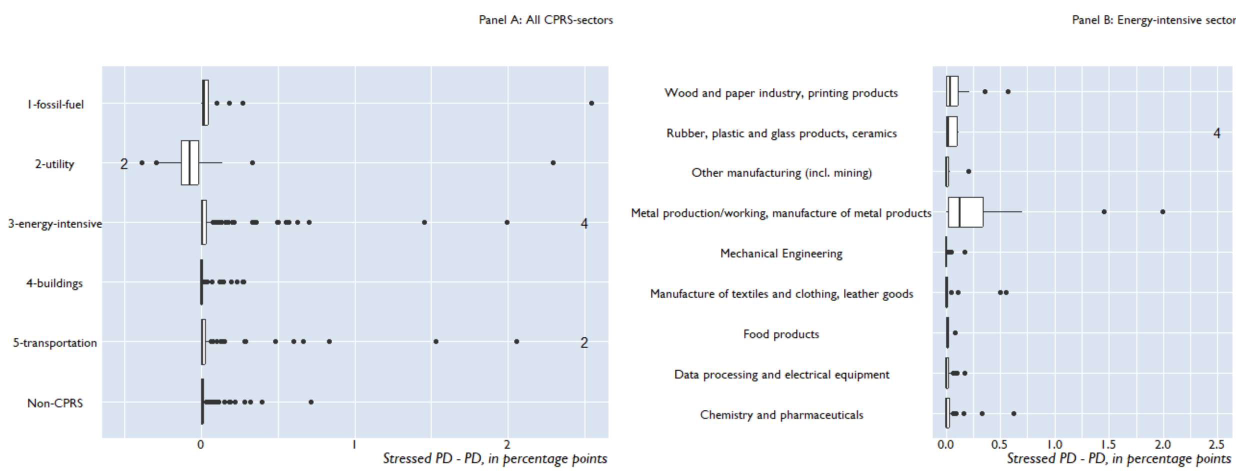

Figure 9: Impact, in terms of **stressed PD difference**, of the carbon shock in the **enhanced stress scenario** on firm creditworthiness, by sector. The boxes show the 25^{th}, 50^{th} and 75^{th} percentile of the distribution, and the whiskers correspond either to the min or max, or to 1.5× interquartile range. The number of observations above the cut-off is indicated at the top.

4.2 Impact on bank capitalization ratios

In order to gauge the relevance for financial stability of the deterioration of firms' creditworthiness, this section translates the PD increases into decreases of the aggregate capitalization of the euro area banking sector, for both the raw and enhanced stress scenario, according to equation (10):

$$CET1r^* = \frac{CET1 - \Delta EL}{RWA_{other} + RWA^*_{CRC}} \tag{10}$$

where $CET1r^*$ is the stressed CET1 ratio, $CET1$ the baseline CET1 capital (in bn EUR), and RWA_{other} the risk-weighted assets covering risks other than corporate credit risk.[26] The additional provisions to cover increased credit risk, ΔEL, are derived in equation (8) and the stressed risk weighted assets for corporate credit risk, RWA^*_{CRC}, in equation (9).

In 2021, the CET1 capitalization ratio of the aggregate euro area banking system[27] was 15.6%, corresponding to a total amount of available CET1 capital of EUR 1,306 bn and a total RWA of EUR 8,373 bn, covering all kinds of risks. Risk-weighted assets for corporate credit risk made up roughly 40% of all RWA, i.e. EUR 3,338 bn.

We can compute the impact on $CET1r$ of the carbon pricing shock of the raw and enhanced stress scenarios by making two assumptions: first, that the outstanding debt of the 776 firms in our sample is representative of the corporate credit risk exposure of the euro area banking system,[28] and second, that banks compute risk-weighted assets on the corporate exposure using the foundation IRB approach.[29] In order to estimate the $CET1r$ impact, we first compute the RWA of each of the 776 firms' outstanding debt (a total of EUR 888 bn) and scale it up to the total corporate credit risk RWA, i.e. EUR 3,338 bn. We then compute ΔEL and RWA^*_{CRC} under the raw and enhanced scenarios and derive $CET1r^*$ using equation (10).

Figure 10 presents the composition of the corporate credit risk portfolio, both in terms of exposure[30] and risk-weighted exposure. The transportation sector records the largest share of the bank exposure with 32%, followed by the aggregate non-CPRS sector with 23%. Taken together, the fossil-fuel, utility and energy-intensive manufacturing sectors account for 37% of the bank portfolio. The composition of risk-weighted assets depicts an equivalent picture, although the current credit exposure to the fossil-fuel, utility, and energy-intensive

[26] RWA_{other} covers market and operational risk as well as credit risk of non-corporate exposures.

[27] All figures in this paragraph cover significant institutions in the European Banking Union, which, as of 2023, comprises the euro area plus Bulgaria. Figures were retrieved from ECB (2023a)

[28] A more detailed investigation to support this assumption is currently carried out.

[29] In the foundation IRB approach, the Basel IRB RWA formula from Basel Comittee on Banking Supervision (2023a) is used with an internally derived PD (we will be using the ICAS model PDs) and a constant LGD of 40%. See footnote 23.

[30] Outstanding amounts

manufacturing sectors are deemed less risky and exhibit a slightly lower share in terms of RWA.

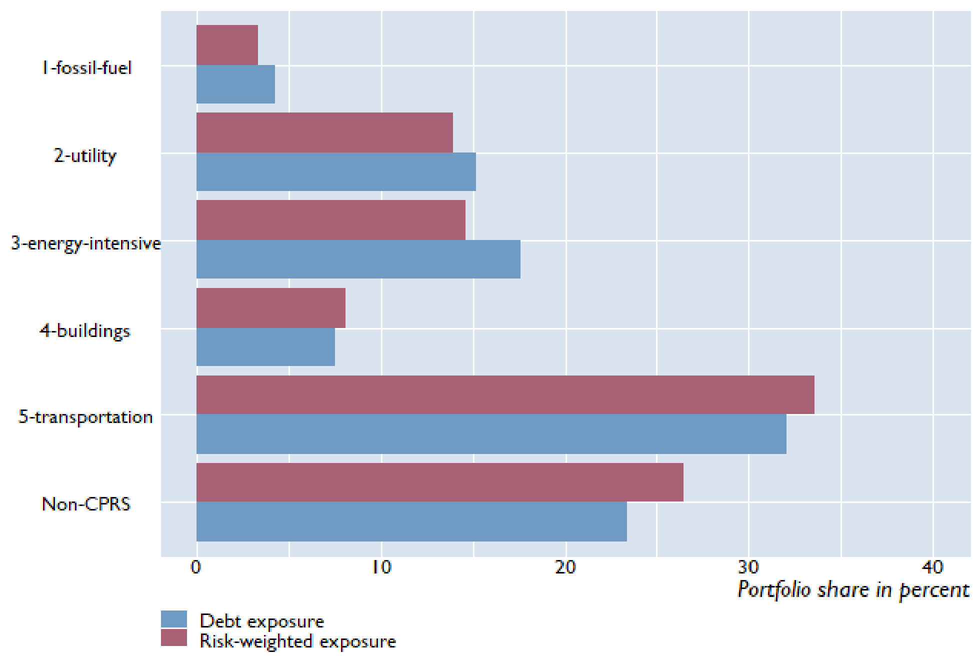

Figure 10: Composition of the bank portfolio in terms of exposures and risk-weighted assets.

Raw stress scenario

Figure 11 presents the stress results under the raw scenario. Panel A shows the weighted sector PD before and after the stress for the raw scenario. It appears that the stress is most pronounced in the utility sector. Energy-intensive manufacturing shows the second largest increase. Also, the sectors fossil-fuel and transportation show relatively large absolute increases. As expected, the impact on non-CPRS sectors is limited. The exposure weighted PD increases from 0.41% to 0.63% for the total portfolio. The increase in PD also directly reflects the increase in expected loss and thus the numerator effect with respect to $CET1r^*$. Panel B demonstrates the denominator effect: due to the increase in PDs risk-weights for bank assets increase. Overall, the exposure weighted risk-weight increases from 43.2% to 48.1% with increases most pronounced in the utility sector.

As a result of the stress, the CET1 ratio decreases by 75 bp in the raw scenario. This shock is comparable to the impact of the COVID-19 shock where the CET1-ratio decreased from 15.6% in Q4 2019 to 15.0% in Q2 of 2020. CET1-capital depletes by 0.5% due to

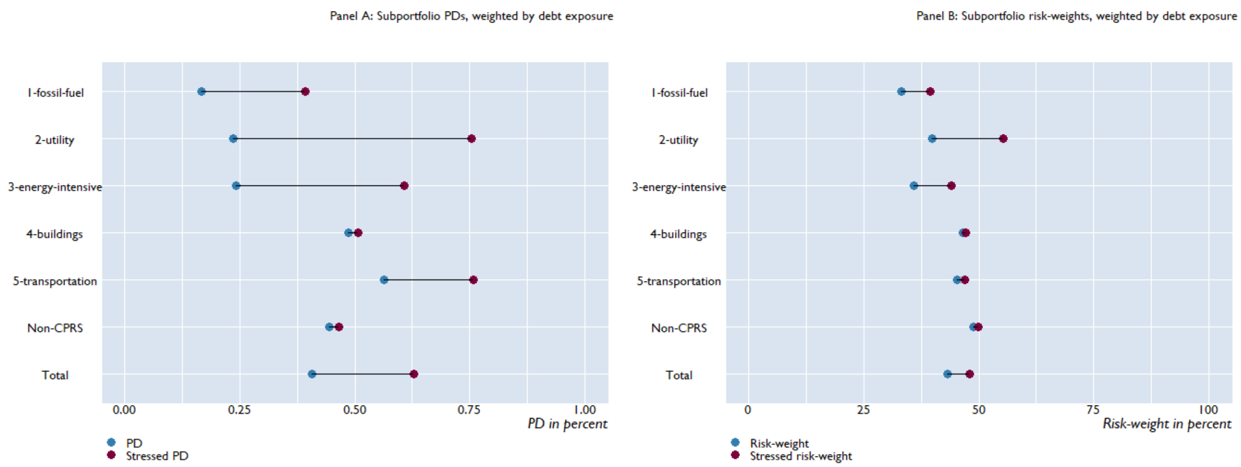

Figure 11: Baseline and stressed PDs as well as risk-weights in the **raw stress scenario**.

additional provisions for expected loss and corporate credit risk-weighted assets increase by 11.2%.[31]

We find that the impact on banks' capitalization is largely from the most polluting producers: measured by the emission intensity, the top 25 producers comprise 71% of the additional expected loss and 52% of the increase in RWA. In terms of absolute emissions, the top 25 producers account for 75% of additional provisions for expected loss and 67% of the risk increase. This suggests that the banking system is also dealing with a concentration of risk.

Enhanced stress scenario

In the enhanced scenario, the aggregate portfolio PD increases from 0.41% to 0.48%, which marks a 15 bp lower stressed PD compared to the raw stress scenario. As shown in Figure 12, the enhanced scenario reduces stress, particularly in the utility sector, where the weighted sub-portfolio PD increases only marginally from 0.24% to 0.26% and the debt-weighted risk-weight shrinks from 39.8% to 33.8%. We record that CET1 capital decreases by 0.2% and corporate credit risk-weighted assets increase by 0.8% in the enhanced stress scenario. This yields a reduction in the CET1 ratio of 8 bp, which is nearly negligible.

[31] RWAs for corporate credit risk only account for 40% of total RWA in equation (10).

Figure 12: Baseline and stressed PDs as well as risk-weights in the **enhanced stress scenario**.

4.3 Sensitivity analyses and robustness checks

This section investigates how the modeling assumptions affect final results in order to gauge our conclusions' robustness. It considers: the assumed carbon price, the pass-through modeling, the financing method, and a toy model to compute the PD impact.

Sensitivity: Carbon price

We compute the sensitivity of the stressed PD to the assumed carbon price by using scenarios in the range from EUR 100 to EUR 200 per tCO_2. Figure 13 shows the distribution of the Stressed-PD-Difference across sectors for three different price scenarios. Unsurprisingly, the results suggest that higher prices lead to both more widespread downgrades across all sectors and steeper increases, particularly for the most vulnerable companies. At a price of EUR 200 per tCO_2, 199 companies (26%) are associated with a downgrade, compared to 137 for a price of EUR 100 in the raw scenario. The rate of downgrades to non-investment grade rating classes increases from 38 to 71 companies. Enhanced scenario results record a downgrade rate of 119 firms (15%) at a price of EUR 200 compared to 68 (9%) downgrades at a price of EUR 100. With respect to banks, a doubling of the scenario price to EUR 200 yields a 160 bps decrease of the CET1 ratio in the raw scenario (compared to 75 bps) and a 19 bps decrease in the enhanced scenario (compared to 8 bps for a global carbon price of EUR 100).

In summary, when assuming a higher increase in global carbon prices, the worsening of creditworthiness (PDs and downgrades) and bank capitalization metrics scale roughly with the carbon price increase. Still, in particular, in the enhanced stress scenario, the aggregate impacts seem manageable from a financial stability point of view. It should be

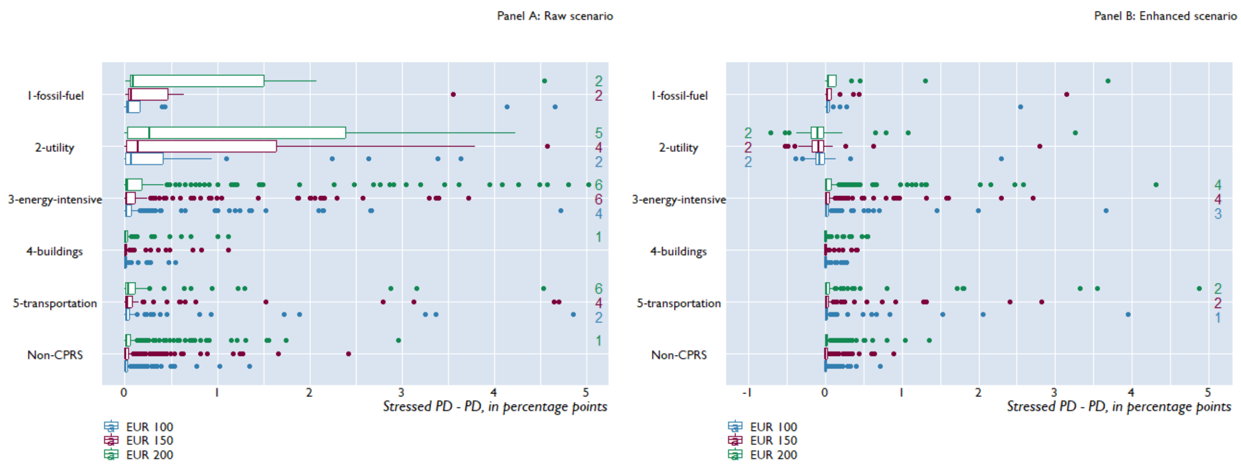

Figure 13: Impact on the PD in the raw stress scenario (Panel A) and the enhanced stress scenario (Panel B) for different CO_2 prices, by sector.

noted, however, that moving from a global carbon price of EUR 3 per tCO_2 (Parry, 2021) to EUR 200 is highly unlikely and that under such an increase, the underlying assumptions such as a static balance sheet structure and the lack of macroeconomic impact become more unrealistic.

Sensitivity: Pass-through assumption

We know that the impact on creditworthiness critically depends on the possibility for firms to pass-through some of their additional carbon costs to customers. As discussed in section 3.1, modeling the pass-through is arduous and introduces some uncertainty in the final results.

While Cludius et al. (2020) find significant and above zero pass-through estimates for some industries (cement, steel, petrochemicals, etc.), they emphasize the uncertainty around estimates. Also, Neuhoff & Ritz (2019) argue that, even if available, carbon pass-through rates – for sectors other than the power sector – are associated with high degrees of uncertainty with relatively large confidence intervals and there is still much work to do for research to guide policy. The power sector is an exception, where estimates provide significant evidence for high pass-through rates (Neuhoff & Ritz, 2019). However, even if cost pass-through could be perfectly modeled, one would need to account for demand reduction to project realistic revenue numbers – since cost pass-through implies a change in prices to which consumers respond – which we have not specifically modeled so far. Indeed, in the enhanced stress scenario, we make an assumption about the increase in revenues but do not specify how the changed revenues are driven by higher prices and/or lower volumes.

Elasticity[32] estimates suggest that demand is relatively inelastic in utilities sectors, at least in the short run (Labandeira et al., 2017; Csereklyei, 2020). In their meta-analysis Labandeira et al. (2017) report average short-run elasticities in the in range of -0,15 to -0,20, for different energy goods (electricity, natural gas, gasoline, diesel, etc.). Long-run estimates are somewhat higher in the range of -0,37 to -0,57. Guided by these estimates, we run another simulation for the utilities sector accounting for demand reduction due to higher prices. For simplicity, we assume that the price change is equivalent to the revenue change given by equation (2).[33]

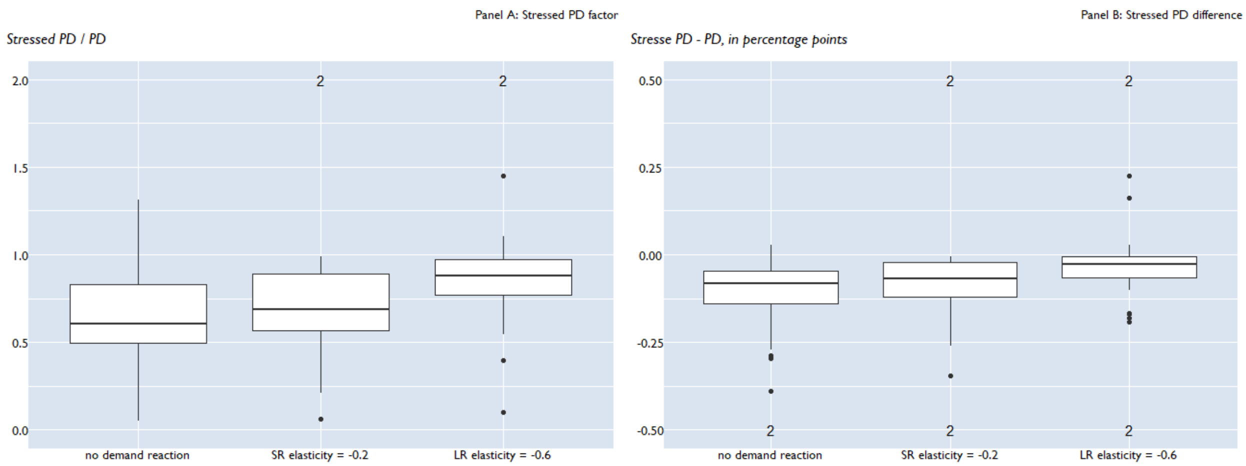

Figure 14: Impact on the PD of firms in the utility sector in the **enhanced scenario** for different elasticities.

Figure 14 presents the results for the simulation in the enhanced scenario under the assumption of a short-run (-0,20) and long-run (-0,60) elasticity of demand for energy goods[34]
. Under the assumption of no demand reaction, 32 entities are associated with an upgrade by at least one notch. Accounting for a short-run demand reaction leads to 26 upgrades and two downgrades. Under the simulation of a higher long-run demand reaction, results suggest 13 upgrades and four downgrades. These results confirm that pass-through assumptions are essential determinants of the carbon pricing-induced credit risk stress but do not call the overall conclusions into question.

[32]The elasticity of demand is defined as $\eta = \frac{\Delta Q/Q}{\Delta P/P}$ with Q signifying the volume and P the price respectively.

[33]That is $\frac{\Delta P}{P} = \frac{\Delta revenue}{revenue}$

[34] $\frac{\Delta Q}{Q} = \eta \times \frac{\Delta P}{P}$

Robustness: Financing method

Given the cost shock, companies face the decision of how to finance the purchase of CO_2 allowances. In our base model, we assume that businesses first use cash and deposits and draw on short-term credit lines only if liquid reserves are insufficient to pay the receipt. In practice, companies would most likely mix between cash and additional credit or even borrow the entire amount. This decision has implications for the expected stressed PD, as it affects the size and composition of firms' balance sheets.[35] In turn, running down cash corresponds to an asset swap, which has no impact on total assets. As depicted in Figure 15, switching the model to full short-term bank financing (bank model) shows that stressed PDs change only slightly depending on the financing method. The deviation corresponds to a negligible factor of 0.99 and 1.01 for the 5^{th} and 95^{th} percentile. We conclude that technical assumptions concerning the financing methodology do not impact our results.

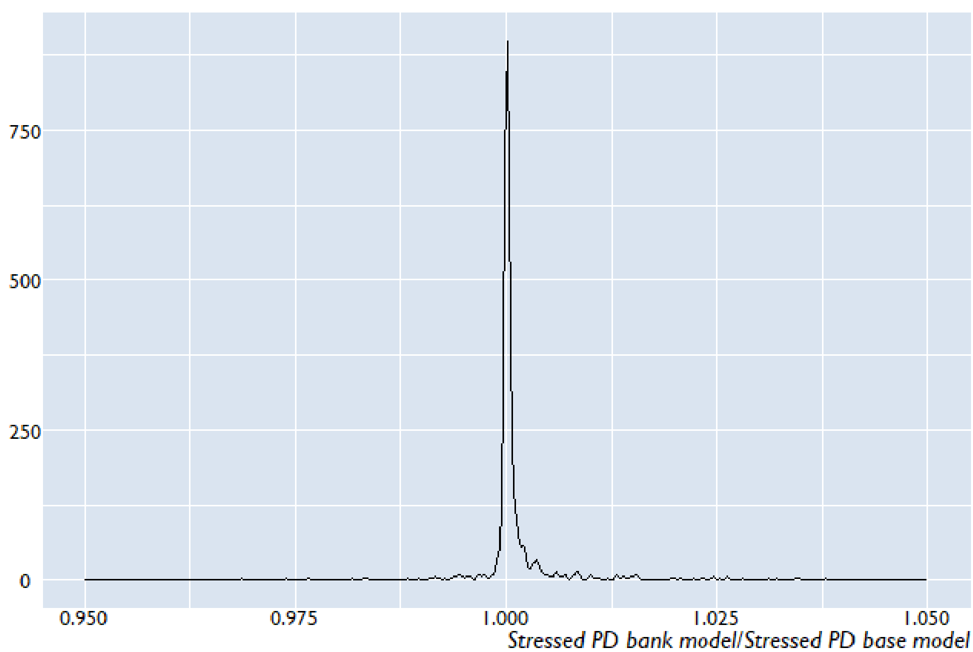

Figure 15: Density plot of the deviation of the stressed PD factor F_{PD}^{*} between full bank financing and cash first financing.

[35] Additional borrowing results in an extension of the balance sheet, leading, for example, to a lower equity ratio.

Robustness: Emission intensity as driver of stress

When comparing the stressed ratings in the raw scenario with the emission intensity for each company (see Figure 16) we find a strong correlation of 0.70 (Kendall's tau) for CPRS and non-CPRS with 0.63 (Kendall's tau). The strong correlation of the relatively simple emission intensity and our Stressed-PD-factor is not surprising, as the CO_2 intensity essentially maps to the model stress factor.

However, as the vertical dispersion of the scatter plot on Figure 16 demonstrates, the emission intensity is not the only driver of a company's carbon pricing-induced credit risk.

It is therefore essential to use a credit assessment model that takes the initial financial situation of companies into account and thereby captures the non-linear relationship between a firm's exposure to the carbon price shock and its creditworthiness as measured by the PD. A highly solvent company may well be able to deal with the one-off stress, whereas a leveraged business find it difficult to repay its loans despite having a relatively low intensity. Hence, carbon pricing-induced credit risk also depends on the ex-ante creditworthiness of a borrower (Nguyen et al., 2023).

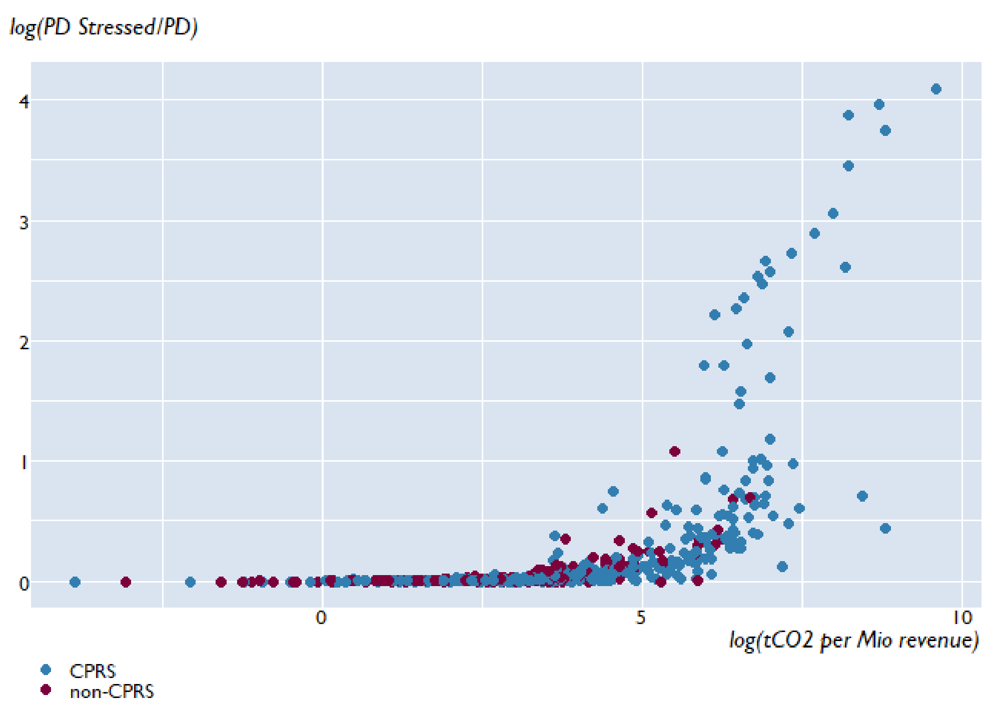

Figure 16: Log of the Stressed PD factor F^*_{PD} versus log carbon intensity in the raw stress scenario.

5 Discussion

Carbon pricing is widely advocated as the most effective climate change mitigation policy. By affecting prices of intermediate and final goods according to their carbon content, it leads economic agents all along value chains to bear the costs of the emissions they trigger and thereby provides an incentive to reduce emissions.

The financial sector is part of most value chains and the incentives of carbon pricing apply to investors and borrowers alike. On one hand, carbon pricing alters the risk-return profile of potential investments – by reducing the relative profitability of highly emissive projects – and thereby creates an incentive for investors to lend to cleaner firms. On the other hand, faced with higher interest rates or the outright loss of financing if they fail to decarbonize, companies have an incentive to reduce emissions. This financial-market incentive applies above and beyond firms' incentive to avoid paying the carbon tax itself.

While there is broad agreement on the efficacy of carbon pricing, its negative fallout is often discussed, subsumed under the term "carbon transition risk". If implemented too abruptly, the argument goes, carbon pricing would wreak havoc in the economy, lead to widespread company bankruptcies, unemployment, and financial losses for investors. In this scenario, instead of improving welfare, carbon pricing would achieve the opposite. Quantifying the various transmission channels of carbon transition risk is therefore an essential ingredient for calibrating carbon pricing at a level that drives decarbonization while not endangering economic stability.

One kind of carbon transition risk is carbon pricing-induced credit risk, the potential negative impact of carbon pricing on firms' and households' ability to repay loans. In this research paper, we estimate carbon pricing-induced credit risk for a sample of 776 European non-financial firms with a total outstanding debt of more than EUR 2 trillion. Using a well-established probability of default (PD) model, we quantify the carbon pricing-induced increase in the likelihood of default under two scenarios.

Aggregate impact

We show that, even under the first – very conservative – scenario, in which the costs of global direct and energy-related emissions increase *by* EUR 100 per tCO_2 and firms are unable to pass on any costs associated with carbon pricing, a significant proportion of firms' PDs remains relatively unaffected. Indeed, 82% of firms are not downgraded, even by one notch. While some firms see a significant deterioration in their creditworthiness, the exposure-weighted PD of the sample of 776 firms increases from 0.41% to 0.63%.

In the second, more realistic, scenario, the costs of global emissions increase from EUR 3 *to* EUR 100 per tCO_2 and firms are assumed to pass on some of the carbon costs. Under that scenario, the impact on firms' creditworthiness is virtually negligible: the exposure-weighed PD of the sample increases from 0.41% to 0.48%. Some of the cleaner firms actually *benefit* from a rise in carbon pricing and see their creditworthiness improve. Indeed, these firms face only very small additional carbon costs but earn a windfall profit from rising market prices. This underscores the existence of both transition risks and *transition opportunities* from carbon pricing.

In order to examine the broader financial stability implications, we quantify the effects of the carbon pricing shock on the capitalization ratio of the euro area banking system, by assuming the 776 firms in our sample are representative of the overall corporate credit portfolio. In the conservative scenario where firms are assumed incapable of passing on carbon costs, the Common Equity Tier 1 capital ratio (CET1r) is projected to experience a decline of 75 basis points, from 15.60% to 14.85%. This reduction, although material, is not expected to pose a systemic threat to the stability of the banking system. When considering a more realistic scenario where cost pass-through is feasible, the impact on CET1r is negligible (8 basis points).

Comparison with other studies on carbon-pricing induced credit risk

A number of recent research papers have also studied carbon-pricing induced credit risk of firms, although using different methodologies and coverage. The overarching conclusion across these analyses resonates with our own findings: the impact of carbon pricing varies by sector, yet its overall effect on both firms and financial institutions is expected to be manageable.

Vermeulen et al. (2018) specifically investigate the Dutch financial sector, employing the De Nederlandsche Bank's top-down stress test model to estimate the impact of carbon pricing on corporate loans, bonds and equity under a "policy shock" scenario in which the global carbon price rises by USD 100 per ton of CO_2. Unlike our study, the authors do not delve into firm-level balance sheet data but rely on sector-level information. They conclude that even in the event of a disruptive energy transition, banks could face sizeable but manageable losses can further reduce vulnerability by including transition risks in their risk management.

The ECB's first top-down climate stress test (Alogoskoufis et al., 2021) focuses on the European financial system, covering 2.3 million European corporate counterparties. Under its "orderly transition scenario", with rising carbon prices compatible with meeting the targets of the Paris Agreement, and using a simple, ad-hoc PD model, the authors find that transition costs only lead to short-term adverse effects on specific sectors like utilities and mining. The impact on bank capitalization is not quantified.

Guth et al. (2021) specifically focus on the Austrian banking sector, and study transition risks under an orderly scenario and a disorderly scenario, in which the carbon prices increase by about EUR 100 within five and one year respectively. Unlike our study, the authors do not consider firm-level data but a sample of representative firms and sector-level average emissions. They also assume governments do not recycle the carbon tax revenue, leading to a overly pessimistic decrease in GDP and firm turnover. Their methodology includes a pass-through model, where firms can pass on most of the carbon costs, and uses product-specific demand elasticities to forecast reduced demand. Despite these conservative assumptions, the paper finds that the CET1 ratio of the Austrian banking system only decreases by 50 to 70 basis points because of the carbon price increase.

Belloni et al. (2022) investigate the European banking system via a banking sector contagion model where firms are negatively impacted by an increase in carbon prices. In terms of methodology, they operate a Merton framework distance-to-default to compute stressed PDs. The paper does not present firm-level effects but does discuss the aggregate impact on banks: an increase in carbon tax of EUR 200 per ton would lead to an increase of banking system losses only 10%, compared to the baseline. It concludes that the banking system may face substantial risks only with high and abrupt changes in the carbon price.

Aiello & Angelico (2023) focus solely on Italian firms, employing a unique methodology that primarily considers firm energy demand and associated costs. Unlike our study, they do not model cost pass-through. To compute PD increases, they estimate the energy demand of Italian firms and simulate the impact of a carbon tax. The paper finds that the credit risk from the introduction of a carbon tax are modest for banks, even with a carbon price of EUR 800 per ton. The sectoral impact varies, with PD factors ranging from 1.1 in real estate to 1.6 in services. They do not estimate the impacts on bank capitalization rates.

Finally, the ECB's secong top-down climate stress test (Emambakhsh et al., 2023) employs an internal ECB model to project PDs based on firm leverage and profitability, without explicitly considering cost-pass through. It finds that high-emitting firms would experience a short-term PD increase of 2% compared to 0.5% for median firms. While the paper does not quantify the impact on banks' capital ratios, it finds that expected losses would increase by about a factor of 1.5 under the "accelerated transition scenario" compatible with reaching the goals of the Paris Agreement. This is broadly in line with our findings.

Policy implications

Our study suggests that the overall impact of a significant increase in global carbon pricing on European non-financial firms' creditworthiness and, consequently, on the capitalization of the euro area banking system, is anticipated be manageable. This observation indicates there is scope for higher carbon prices – this is the first policy implication – which would serve as drivers of an accelerated decarbonization and contribute to achieving the goals of the Paris Agreement, without endangering financial stability via the corporate credit risk channel. When discussing the possible negative fallout of carbon pricing, we should see credit risk only where it's due.

While we find the aggregate impact of a carbon-pricing shock to be manageable, this average conceals significant variation in impact between and within sectors. This differential impact is part and parcel of carbon pricing policies, which aim at affecting firms differently, contingent on their greenhouse gas emissions. Using the "Climate Policy Relevant Sectors" classification, we find that fossil fuel companies and utilities are much more affected on average than firms from the energy-intensive manufacturing, buildings, transportation and "non-climate policy relevant" sectors. Within the "energy-intensive manufacturing" sector, three sub sectors (wood and paper; rubber, plastic, glass, ceramics; metal) are most affected. Overall, there are 22 firms from nearly all sectors whose probability of default would increase by more than 2 percentage points in the conservative "raw stress scenario", illustrating a high within-sector variation in impacts. The sectoral impacts are similar in the more realistic "enhanced stress scenario" with one notable difference: many utilities see their creditworthiness increase via windfall profits.

These important differences in impact between firms should not be ignored by banks and their regulators – this is the second policy recommendation. Indeed, many of the credit risk assessment methodologies – whether they rely on credit rating agencies or on models calibrated with historical time series – are backward-looking and might not differentiate between firms with varying emission intensities. In order to avoid losses, banks should therefore assess the forward-looking transition risk of their borrowers and include it in their risk management, including pricing policies and origination standards. What's more, while the aggregate impact of a carbon-pricing shock on European corporates might be manageable, a bank whose loan portfolio is very concentrated in the most affected sectors and firms, might be hurt by rising carbon prices. Supervisory authorities should investigate such concentration risk and react appropriately.

Finally, we have shown in our study that firms' capacity to pass on carbon costs further down the value chain is a crucial determinant of carbon pricing-induced credit risk. Further research is needed to capture the transmission of carbon-pricing signals all along the value chains, including demand elasticities, in order to better understand which firms will benefit and which will suffer from an increase in carbon pricing.

Declaration of Competing Interest

The authors report no potential conflict of interest.

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Annex A: Detailed firm level statistics

CPRS sector	N	above0	above1	above5	min	p10	p25	p50	p75	p90	max
Current EU ETS with free allocation											
1-fossil-fuel	16	11	2	0	0.00	0.00	0.00	0.33	0.67	1.09	2.49
2-utility	45	26	16	3	0.00	0.00	0.00	0.12	1.50	3.83	17.97
3-energy-intensive	236	55	8	0	-0.43	0.00	0.00	0.00	0.00	0.20	3.92
4-buildings	80	3	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.14
5-transportation	92	27	0	0	-0.31	0.00	0.00	0.00	0.00	0.03	0.80
Non-CPRS	307	18	0	0	-0.38	0.00	0.00	0.00	0.00	0.00	0.58
EU ETS without free allocation											
1-fossil-fuel	16	11	7	0	0.00	0.00	0.00	0.98	1.46	2.12	3.99
2-utility	45	26	17	4	0.00	0.00	0.00	0.40	2.11	3.93	18.00
3-energy-intensive	236	68	25	4	0.00	0.00	0.00	0.00	0.01	1.09	7.19
4-buildings	80	3	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.15
5-transportation	92	28	4	0	0.00	0.00	0.00	0.00	0.00	0.04	3.61
Non-CPRS	307	19	1	0	0.00	0.00	0.00	0.00	0.00	0.00	1.28
Global pricing without free allocation											
1-fossil-fuel	16	16	11	1	0.00	0.14	0.46	1.27	2.37	3.27	5.17
2-utility	45	45	27	7	0.00	0.03	0.26	1.88	3.89	5.83	21.26
3-energy-intensive	236	236	42	12	0.00	0.01	0.03	0.07	0.32	2.20	83.36
4-buildings	80	80	0	0	0.00	0.01	0.01	0.06	0.16	0.31	0.86
5-transportation	92	92	9	5	0.01	0.03	0.05	0.09	0.23	0.76	39.03
Non-CPRS	307	303	8	0	0.00	0.00	0.01	0.03	0.10	0.25	3.66

Table 7: Distribution of the estimated carbon cost share as percent of revenue across sectors with three different pricing schemes.

	N	min	p10	p25	p50	p75	p90	max
Total	776	1.00	1.00	1.01	1.02	1.08	1.42	60.31
CPRS sectors								
1-fossil-fuel	16	1.01	1.01	1.07	1.18	1.82	4.99	9.21
2-utility	45	1.00	1.01	1.06	1.23	2.13	11.72	31.83
3-energy-intensive	236	1.00	1.00	1.01	1.03	1.11	1.83	60.31
4-buildings	80	1.00	1.00	1.00	1.01	1.02	1.08	1.47
5-transportation	92	1.00	1.00	1.01	1.03	1.09	1.44	5.47
Non-CPRS	307	1.00	1.00	1.00	1.01	1.03	1.13	2.95
Energy-intensive subsectors								
Chemistry and pharmaceuticals	42	1.00	1.00	1.01	1.04	1.27	1.85	11.78
Data processing and electrical equipment	54	1.00	1.00	1.01	1.01	1.04	1.08	1.84
Food products	9	1.02	1.03	1.04	1.04	1.05	2.66	6.00
Manufacture of textiles and clothing, leather goods	25	1.00	1.00	1.00	1.01	1.02	1.08	1.42
Mechanical Engineering	45	1.00	1.01	1.01	1.02	1.03	1.05	1.57
Metal production/working, manufacture of metal products	17	1.04	1.06	1.10	1.32	1.91	11.37	14.28
Other manufacturing (incl. mining)	10	1.00	1.00	1.01	1.02	1.09	1.34	1.50
Rubber, plastic and glass products, ceramics	22	1.00	1.01	1.09	1.42	2.07	47.87	60.31
Wood and paper industry, printing products	12	1.04	1.05	1.07	1.44	2.34	2.60	17.95

Table 8: Distribution of the stressed PD factor across different subsamples in the raw scenario

	N	min	p10	p25	p50	p75	p90	max
Total	776	0.00	0.00	0.00	0.01	0.05	0.26	18.29
CPRS sectors								
1-fossil-fuel	16	0.00	0.00	0.02	0.04	0.16	2.28	4.65
2-utility	45	0.00	0.00	0.01	0.07	0.41	2.48	7.27
3-energy-intensive	236	0.00	0.00	0.00	0.01	0.07	0.36	18.29
4-buildings	80	0.00	0.00	0.00	0.00	0.01	0.07	0.55
5-transportation	92	0.00	0.00	0.00	0.01	0.05	0.44	7.34
Non-CPRS	307	0.00	0.00	0.00	0.01	0.03	0.11	1.35
Energy-intensive subsectors								
Chemistry and pharmaceuticals	42	0.00	0.00	0.00	0.01	0.05	0.23	1.53
Data processing and electrical equipment	54	0.00	0.00	0.00	0.01	0.05	0.15	0.38
Food products	9	0.01	0.02	0.02	0.03	0.04	0.31	1.35
Manufacture of textiles and clothing, leather goods	25	0.00	0.00	0.00	0.01	0.02	0.17	1.24
Mechanical Engineering	45	0.00	0.00	0.00	0.00	0.01	0.06	0.33
Metal production/working, manufacture of metal products	17	0.01	0.03	0.05	0.29	2.10	2.66	4.72
Other manufacturing (incl. mining)	10	0.00	0.00	0.00	0.00	0.05	0.11	0.39
Rubber, plastic and glass products, ceramics	22	0.00	0.00	0.02	0.06	0.29	11.55	18.29
Wood and paper industry, printing products	12	0.01	0.01	0.01	0.08	0.42	1.21	2.14

Table 9: Distribution of the stressed PD difference (in percentage points) across different subsamples in the raw scenario

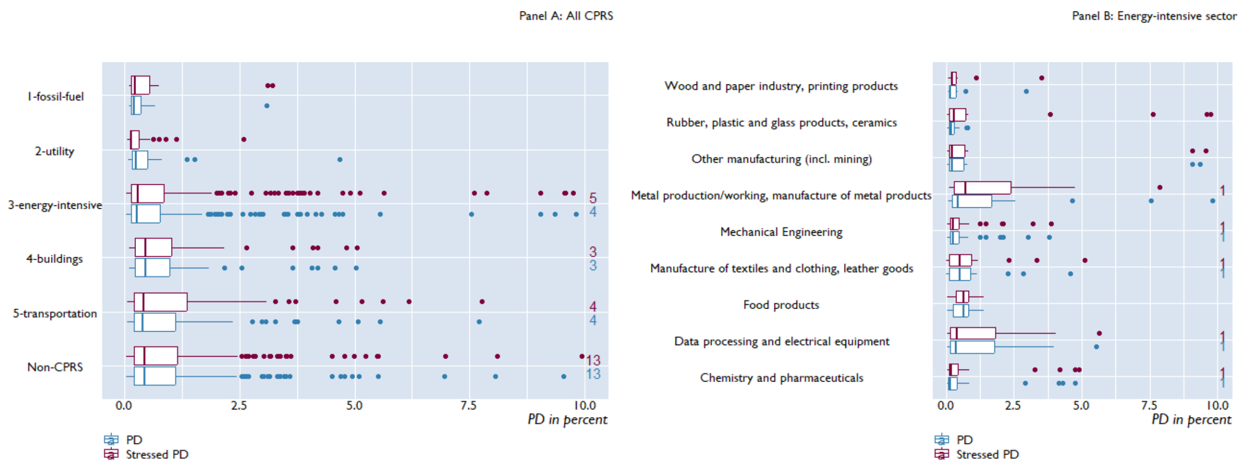

Figure 17: **Baseline and stressed PDs** in the enhanced stress scenario. The boxes show the 25^{th}, 50^{th} and 75^{th} percentile of the distribution, the whiskers correspond either to the min or max, or to 1.5× interquartile range. The number of observations above the cut-off is indicated at the top.

Annex B: Conservative sample

Figure 18 presents the total emission intensity across the EU 27 economies. As can be seen, except for Greece, production in economies within our sample (AT, BE, DE, ES, FR, GR, IT, PT) is less emission-intensive compared to Eastern European economies. Table 10 reports the EU 27 (column two) and our sample companies (column three) emission intensity by NACE activity. Across sectors, our sample companies report higher intensities in six out of 15 activities that are covered by our sample. We do not cover agricultural activities, which are very emission-intensive. Also, important sectors such as the 'mining and quarrying' and energy supply are less emission-intensive compared to the EU 27 average. We explain this by the fact that Eastern European companies are not included, which shows particularly large emission intensities in these sectors. However, on aggregate, table 10 shows that our sample companies are more emission-intensive compared to the EU 27 aggregate. This is because our sample population is dominated by manufacturing companies, as demonstrated by the large share of revenue. Compared to the EU 27 total emission intensity, our sample companies report a 1.7 times higher intensity.

What's more is that our sample portfolio is largely concentrated in the emission-intensive sectors: 'manufacturing' (C), 'energy, waste and water' (D+E), and 'transport and storage' (H). In total, more than 70% of our sample portfolio exposure is comprised of these sectors, compared to 28% of the Euro area loan portfolio (see table 11). Indeed, bank portfolios are largely dominated by real estate loans, which are less exposed to transition risk but more to physical risk (see figure 19). Thus, we conclude that while our sample is not representative for different reasons, it represents a conservative sample with respect to the exposure to a carbon price shock exactly because it is concentrated in emission-intensive sectors. However, it should be noted that there are remaining caveats as companies not included in our sample might be associated with worse "fundamentals" which would lead to higher base PDs.

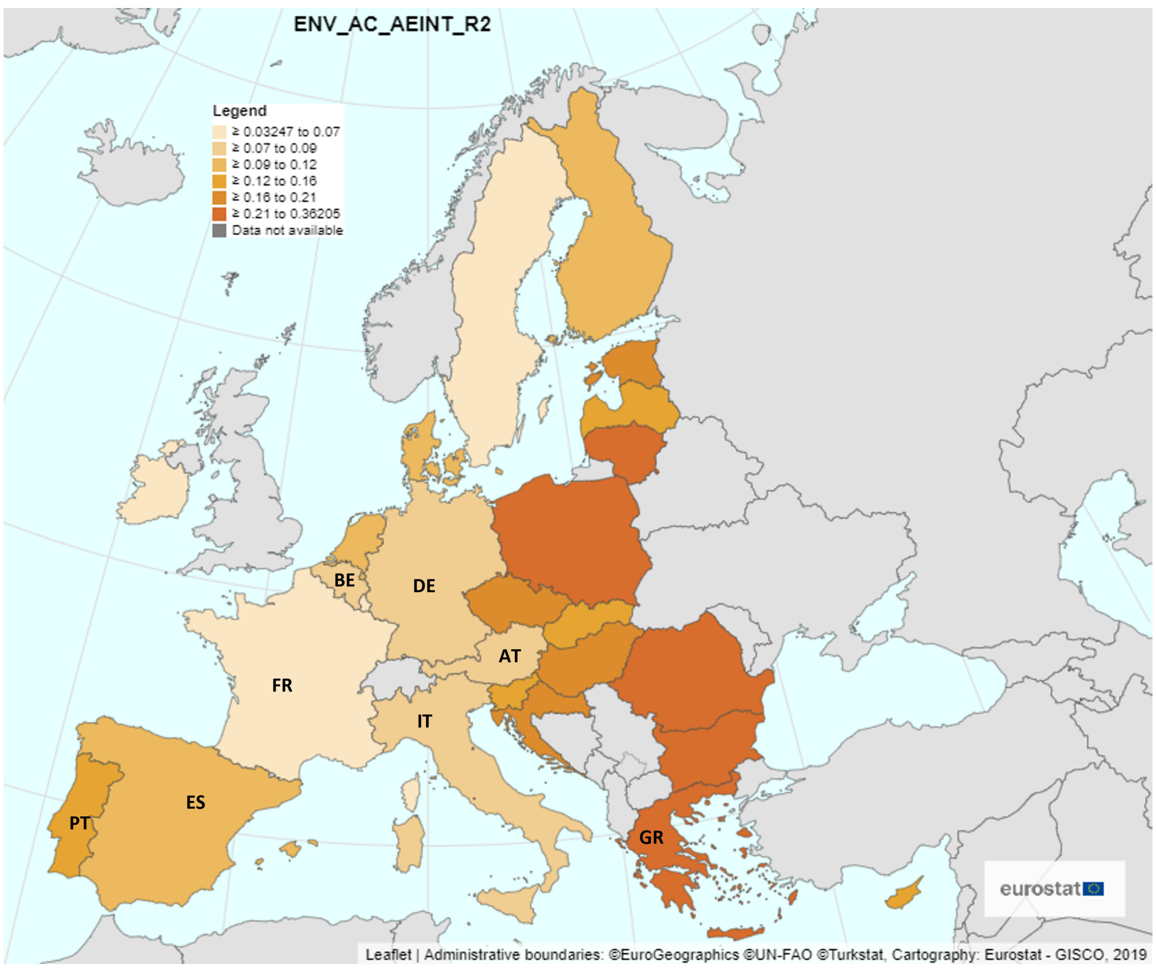

Figure 18: GHG emission intensity of the EU27 countries in $kgCO_2$ per EUR output (total activity). Data source: Eurostat (2022).

NACE activity	Section	EU 27	Sample	Revenue share
Agriculture, forestry and fishing	A	0.8917	-	0
Mining and quarrying	B	0.5675	0.4045	0.9%
Manufacturing	C	0.1117	0.1428	53.7%
Electricity, gas, steam and air conditioning supply	D	0.9481	0.5096	14.2%
Water supply; sewerage, waste management and remediation activities	E	0.4605	0.8500	0.9%
Construction	F	0.0277	0.0466	5.5%
Wholesale and retail trade; repair of motor vehicles and motorcycles	G	0.0343	0.0118	9.1%
Transportation and storage	H	0.2229	0.3073	4.1%
Accommodation and food service activities	I	0.0275	0.0273	0.7%
Information and communication	J	0.0055	0.0038	7.7%
Real estate activities	L	0.0031	0.0063	0.5%
Professional, scientific and technical activities	M	0.0094	0.0062	1.0%
Administrative and support service activities	N	0.0251	0.0129	0.4%
Public administration and defence; compulsory social security	O	0.0223	-	0
Education	P	0.0150	-	0
Human health and social work activities	Q	0.0176	0.0160	0.6%
Arts, entertainment and recreation	R	0.0228	0.0024	0.5%
Other service activities	S	0.0347	0.1357	0.1%
Total		0.1043	0.1780	100%

Table 10: GHG emission intensity by NACE activity for the EU 27 and for the sample companies. Column two reports direct emissions in $kgCO_2$ per EUR output for the EU 27 and column three reports direct emissions in $kgCO_2$ per EUR revenue for the sample companies. Column four reports the share of sample companies' revenue per sector. Data source: Eurostat (2022)

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Section	Euro area	Sample
A	4.0%	0
B	0.5%	0.6%
C	14.0%	45.9%
D+E	5.3%	16.0%
F	6.6%	4.7%
G	12.9%	2.6%
H+J	8.6%	22.2%
I	3.8%	0.7%
L+M+N	39.1%	6.7%
Other	6.6%	1.2%

Table 11: Portfolio distribution of Euro area banks loan portfolio and sample portfolio by NACE sections. Data source: ECB (2023b)

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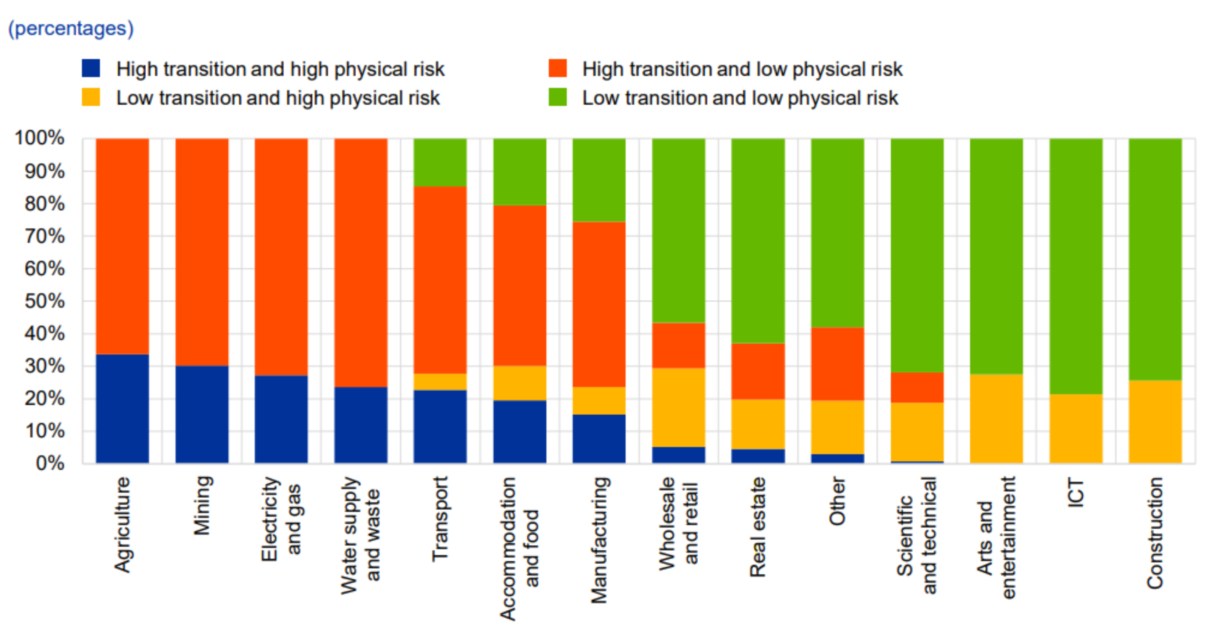

Figure 19: Share of firms subject to climate risks by sector. Source: Alogoskoufis et al. (2021), Chart 16.