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Credit Risk Sensitivity to Carbon Price

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Abstract

In order to meet the objectives set by the Paris Climate Agreement, global greenhouse gas emissions must be drastically reduced. One way to achieve this goal is to set an effective carbon price. Although beneficial for the climate, a rapid increase in this price can have a significant financial impact on corporate firms. Based on the 2018 Intergovernmental Panel on Climate Change (IPCC) scenarios, we study the credit risk sensitivity of 795 international companies. We develop a bottom-up approach and analyze how probabilities of default within each sector might evolve in both the medium (2023) and long term (2060). We find that energy, materials and utilities sectors would be the most affected. Moreover, the risk materializes earlier and is more heterogeneous for utilities. From a policy perspective, the prices associated with a scenario limiting global warming to 2°C have a limited impact on global credit risk. Such a scenario therefore seems achievable without generating substantial financial losses. From these results, we propose a new indicator, the *carbon price threshold*, that takes the economic and capital structure of the firm into account in measuring carbon risk.

Keywords: ESG, Climate change, Carbon price, Credit risk, Scenario analysis.

JEL classification: G17, G33, Q48, Q54

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Graduated from IAE Grenoble Graduate school of Management in corporate and market finance, Vincent Bouchet started a PhD in Management and Economics at École Polytechnique in 2018, under the direction of Nicolas Mottis and Patricia Crifo. In partnership with the Caisse des Dépôts Group, his research focuses on how asset-management and risk-management practices are impacted by climate issues. He is a member of the Energy and Prosperity Chair.

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1 Introduction

Climate change impacts the functioning of human societies and global economic activity (Pachauri *et al.*, 2014; Tol, 2018). To prevent its unfavorable consequences, the international community has committed to reduce its global greenhouse gas (GHG) emissions[1] to keep global average warming below 2℃, along with a more ambitious objective of 1.5℃. These international agreements include nationally determined contributions (NDC), which set targets at a national level. NDCs can be achieved through different mechanisms. Currently, 81 countries have committed to implement a carbon price in their NDC. Figure 1 shows that the number of carbon pricing initiatives has increased in recent years and now covers 20% of global GHG emissions (World Bank, 2019).

This transition towards a low-carbon economy generates a *transition risk* for the financial system. This risk has already been flagged by regulators and financial institutions (Campiglio *et al.*, 2018). Following the warning of Carney (2015), various regulators have first estimated market exposure to the transition risk and the related potential systemic risk. Although more research is needed in this area, these studies highlight significant financial losses for *climate-relevant* sectors and the need to focus on credit risk (Monnin, 2018; NGFS, 2018).

Financial institutions have to develop methodologies applicable to their balance sheets and portfolios in order to manage transition risk. According to the Financial Stability Board Task force on Climate-related Financial Disclosures (TCFD, 2017), transition risk can come from changes in policy and regulation, markets, technology or consumer behavior. As pointed by Campiglio *et al.* (2018), the assessment of climate-related financial risks is hampered by various challenges. First, the data required is often deficient or is provided with excessively low granularity. In addition, the evaluation of climate-related financial risks requires modeling the dynamic interactions between the macroeconomy, the financial system, climate change and environmental policies. These models are subject to deep uncertainty. In this study, we focus on a rise of the carbon price. This is one of the main regulatory risks and its assessment requires that data be available with acceptable coverage.

The issue of carbon pricing has been tackled by two branches of literature through two distinct research questions. On the one hand, some investigated what the optimal price of carbon would be. Many economists have estimated a *social cost* of carbon (SCC), i.e. the optimal cost of additional emissions, minimizing both future damages and the impact on current economy. They generally rely on cost-benefit or cost-efficiency approaches, using integrated assessment models and underlying damage functions[2]. While most researchers agree on the need for a carbon price, the results vary widely, depending on models, discount rates and countries (Tol, 2018).

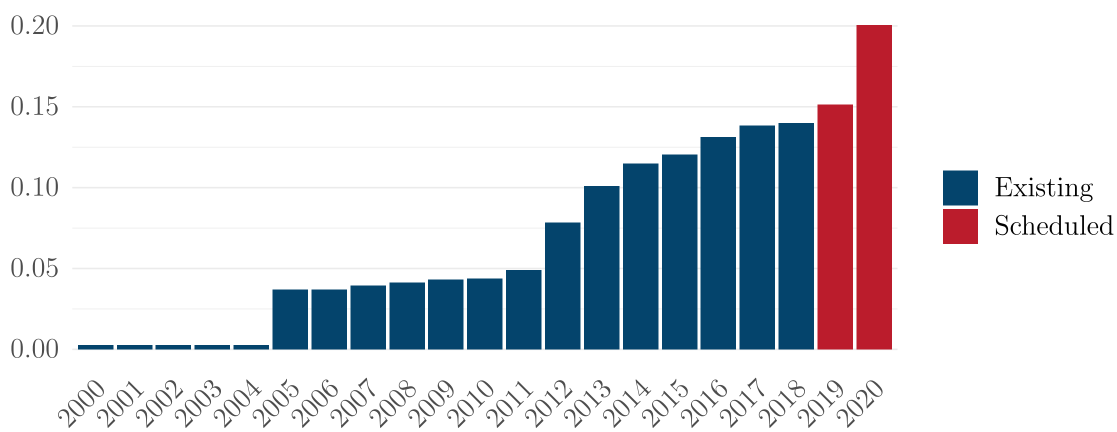
On the other hand, an emerging field of research in finance aims to answer the following question: what are the financial risks associated with a carbon price rise? Indeed, regardless of the optimal value of the price over time, it is observable that an increasing share of GHG emissions is subject to an effective carbon price (see Figure 1). It is therefore possible to study the financial consequences of this trend. Some studies have measured the impact of the observed carbon price on financial performance (Oestreich & Tsiakas, 2015; Scholtens & van der Goot, 2014). However, multi-variate regressions or variance decomposition methods used in finance seem to have limits in forecasting the impact of a potential carbon price on credit risk. The observed carbon price on

[1] First with the Kyoto protocol (1997) and more recently with the Paris agreement (2016).

[2] For a review of methodologies, see Le Guenedal (2019).

which they rely are not comparable with the projections of carbon price from transition scenarios (UNEP, 2018). A second series of research has investigated the extent to which market prices already integrate carbon risk, approximated by the carbon emissions of issuers (Andersson *et al.*, 2016; Görgen *et al.*, 2019; Ilhan *et al.*, 2019; Jung *et al.*, 2018). Heterogeneous results enforce the need to better understand the financial risks associated with carbon price rise.

Figure 1: Share of GHG emissions covered by an effective carbon price



Source: World Bank (2019)

Less research has studied the credit risk associated with future carbon prices from a bottom-up perspective (Howard & Patrascu, 2017; Monnin, 2018; UNEP, 2019). Our study aims to answer the following research question: how does carbon price variation impact sectoral credit risk across scenarios and time? Our contribution to literature is threefold. First, we conduct a bottom-up analysis of a global reference portfolio, based on corporate emissions by countries. Secondly, we address the tragedy of the horizon by using both medium-term (five-year) and long-term (40-year) scenarios. Medium-term analyses are based on current effective carbon prices for each sector in each country (OECD, 2018; World Bank, 2019). Long-term scenarios are based on the social carbon price scenarios of IPCC (2018). Finally, we propose a new indicator, the *carbon price threshold*, which takes the economic and capital structure of the firm into account to measure carbon risk.

The remainder of this paper is structured as follows. Section 2 is dedicated to the literature review. Section 3 presents the two main mechanisms for implementing a carbon price and how they can impact the credit risk of a portfolio. Section 4 develops the theoretical model and describe the data. Section 5 presents the main results, which are discussed in Section 6.

2 Literature review

Although the subject of climate-related financial risk is relatively recent, much research has been published since 2015. Our literature review is structured around three questions. First, what amount of financial assets are exposed to transition risk? Recent central bank reports offer an overview of the proportion of financial assets that can be considered as *climate-relevant* (Battiston *et al.*, 2017). This overall picture is necessary to specify the scope for our study. Second, what are the potential losses in the future? We review the methodologies seeking to estimate future financial losses from existing energy transition scenarios. We present how both bottom-up and top-down approaches are currently used to model the transmission of economic effects into financial losses. And, third, do market prices already integrate transition risk? We review the findings from econometric and financial research focusing on the impact of transition risk on market prices.

2.1 Financial assets exposed to transition risk

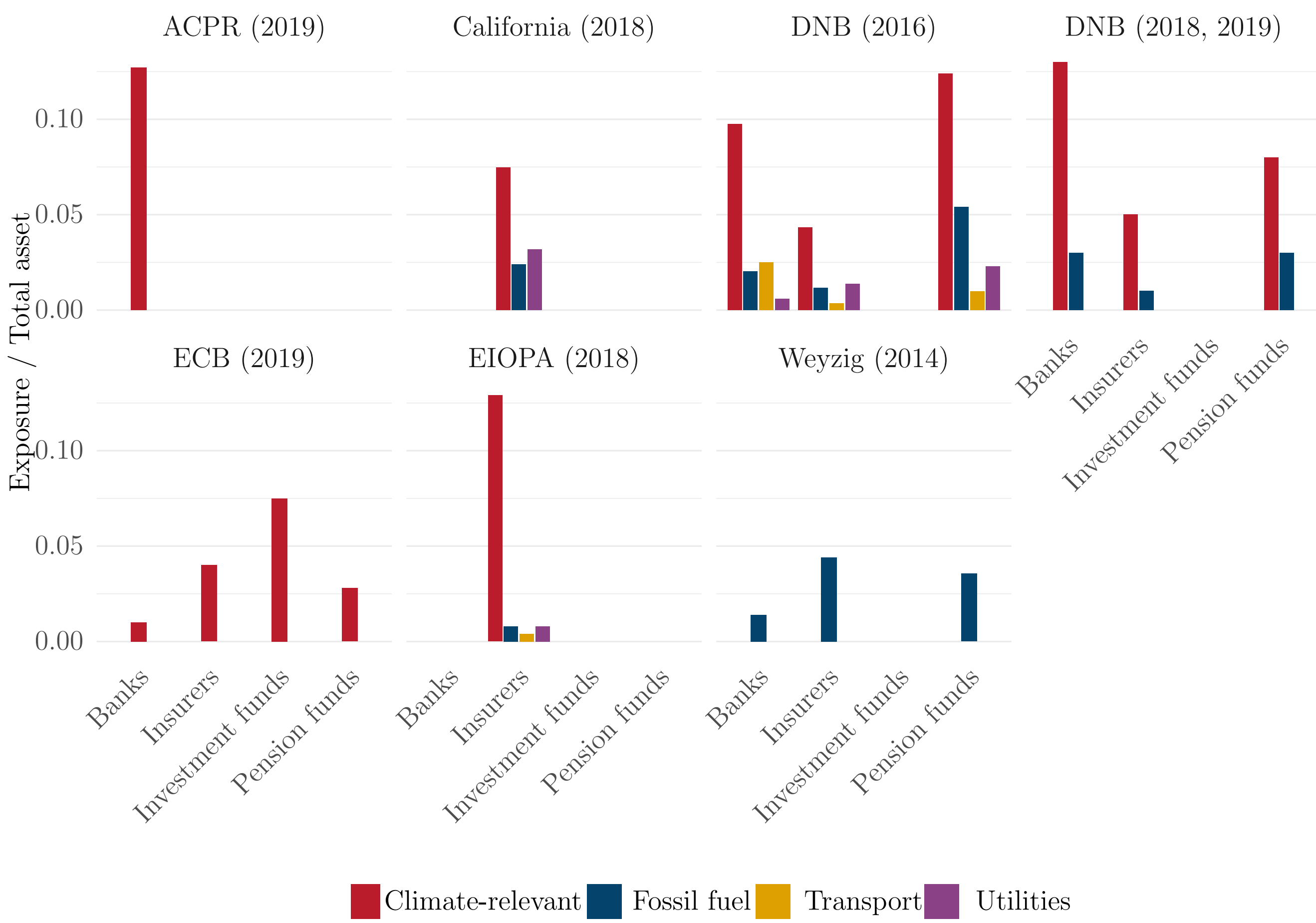
In order to manage climate-related financial risks, many studies estimate the proportion of financial assets exposed to transition risk (see Figure 2 on page 10). Weyzig *et al.* (2014) conduct a first analysis of the exposure of EU financial institutions to fossil fuel companies and commodities. The exposures (as a percentage of total assets) stand between 1.3% for banks and 5% for pension funds. Giuzio *et al.* (2019) update these results by extending the scope to climate-relevant sectors, as defined by Battiston *et al.* (2017). Between 2014 and 2019, pension funds have reduced their exposure to transition risk while banks and insurers have kept it constant[3].

Supervisors also measure the financial system's exposure to transition risk at a national level. In Sweden, Bowen and Dietz (2016) conclude that while there is an aggregate climate-related financial risk, Sweden's economy is probably less vulnerable to climate change than the rest of Europe, thanks to its geographical location. In France, banks' exposure to GHG-intensive sectors reached 12.7% of total credit risk exposure in 2015 and decreased slightly in 2017 (Aubert *et al.*, 2019). The fossil fuel sector accounted for approximately 20% of major risk exposures in 2013 and 16.5% in 2018, suggesting that the risk is taken into consideration by banks. Bank of England (2015, 2017) and Batten *et al.* (2016) consider two types of climate-related assets: securities of companies that may be directly impacted by regulatory limits to produce or use fossil fuels (10% of assets) and securities of GHG-intensive sectors (20% of assets). In the Netherlands, Schotten *et al.* (2016) estimate that the exposure of banks, pension funds and insurers to fossil fuel companies is between 2% (banks) and 5% (pension funds). They also conduct an exposure review to carbon-intensive sectors, which is between 12.4% and 4.4%. While most studies focus on the EU financial system, 2°C Investing Initiative (2018) conduct an analysis on Californian insurers' portfolios (USD 4 000 billion). Exposure to the energy sector is 2%, while exposure to utilities is 3%.

We can draw two main conclusions from these studies. First, the scope of these reports differs in three dimensions: the global assets covered by the study (geographical area and type of institutions), the asset class (equity, bond, loan, commodity), and the definition of climate-relevant

[3]EIOPA (2018) also measures the transition risk exposure of insurers. Climate-relevant sectors account for 13% of insurance investment portfolios.

Figure 2: A comparison of exposure to climate-related assets



sectors. With regard to the latter issue, the technical expert group on sustainable finance, set up by the European Commission, published in June 2019 a technical report on EU taxonomy and a proposal for a classification system for sustainable activities. In the future, this taxonomy could lead to more homogeneity. Secondly, financial institutions' average exposure to climate-relevant sectors is around 10% (see Figure 2).

2.2 Scenario analysis

In this section we present forward-looking approaches that seek to quantify potential losses related to transition risk. First, we synthesize the theoretical channels of transition risk transmission to financial risks. Then, we distinguish two methodological approaches. Top-down analyses are characterized by estimating financial losses at the level of portfolios, sectors or institutions. No distinction is made between assets or issuers within the same sector. These are generally the approaches taken by the regulator to obtain a global picture of transition risk. Bottom-up analyses are based on asset- or issuer-specific data.

2.2.1 From transition risk to credit risk

Many studies analyze the theoretical channels through which transition risk may have an impact on financial risk and more specifically on credit risk (Colas *et al.*, 2018; Monnin, 2018; TCFD, 2017; Thomae & Ralite, 2019). This theoretical framework is the common basis for top-down and bottom-up approaches. Transition risk may affect the economic and financial statements of a company (counterparty) at different levels:

- Cash flows:
  - Revenue: reduced demand for carbon-intensive products and services.
  - Operating expenditure: direct emission costs (carbon price), incremental indirect emissions costs from the supply chain.
  - Capital expenditure: adjustement to production units, and research and development expenditures to develop new technologies.
- Balance sheet:
  - Reserves: devaluation of fossil-fuel reserves.
  - Production capital: devaluation of production tools due to a loss of competitiveness.
  - Equity and liability: difficulties in refinancing due to the risks perceived by financial institutions.

The interactions between these different channels are complex. For example, an increase in research and development expenditure may reduce available cash flows at a given time but either increase revenue of reduce operating expenditure in the future. Moreover, the data required to determine issuer exposure to these channels is generally not disclosed. The present study focuses on the direct operating expenditure from a higher carbon price on cash flows[4]. The link between the counterparty's cash flows and the credit risk carried by the financial institution can be modeled by a conventional credit risk model. Our methodology relies on the Merton model, which is used by Colas *et al.* (2018) and Monnin (2018).

[4] This model can easily be extended to other transmission channels if the data to assess the respective costs is available in the universe of interest.

2.2.2 Top-down analysis

Direct financial valuation shocks A first approach to dealing with the complexity of the transmission channels mentioned above is to assume a shock in the valuation or credit risk at a sectoral level[5]. This approach is appropriate to address the issue of systemic risk by focusing on the propagation of these losses in a financial system.

Weyzig *et al.* (2014) consider a shock, called "*low-carbon breakthrough*", which consists of a quick and definite transition to a low-carbon economy. The underlying assumptions such scenario are that the value of equity investments in oil, gas and coal businesses falls by 60%, the value of fossil fuel commodity investments by 50%, and the value of long-term bonds of oil, gas and coal businesses by 30%. This scenario causes average losses of EUR 350-400 billion for all EU financial institutions. Battiston *et al.* (2017) adopt a similar approach to address a potential systemic risk across EU banks. In their first scenario, 100% of the market capitalization of listed fossil fuel and utilities companies is suddenly valued at zero. Based on a network model, they focus on the indirect losses in banking portfolios due to the devaluation of counterpart debt obligations on the interbank credit market. Taking into account financial actors' exposure to the financial sector (13–25%), they estimate potential losses at less than 1% of the total banks' capital, suggesting that the stability of the financial system would not be affected. This direct valuation shock approach is relevant to addressing transition risk at a macro level. However, it does not make it possible to understand the dynamics of transition risk across sectors. A second approach, based on economic variables computed by integrated assessment models, is more appropriate to tackling this issue.

Top-down transmission of economic shocks Integrated assessment models (IAM) integrate climate modules into traditional economic modeling frameworks. While most of them were designed to answer policy questions, such as the optimal carbon price, their outputs can be used to assess climate-related financial risk. Dietz *et al.* (2016) use the global gross domestic product (GDP), computed by an IAM that covers physical and transition risks. The value of global financial assets is computed as the discounted cash flow arising from holding these assets. These cash flows are assumed to grow at the same rate as global GDP. The climate value at risk (VaR), i.e., the difference of global financial assets value with and without climate change, is 1.8% for a business-as-usual scenario (USD 2.5 trillion). Cutting emissions to keep global warming below 2℃ reduces this VaR to 1.2%. In their second scenario, Battiston *et al.* (2017) shock fossil-fuel and utilities sectors based on the trend of production levels for each sector. For example, they consider that the fossil fuel sector market capitalization will change proportionally to the primary energy production from fossil fuel[6]. As this variable differs across transition scenarios and models, they use the distribution of the values from the 2014 IPCC database. Thomae and Ralite (2019) discount the sectoral added values from an integrated model to project future share prices. In a delayed climate action scenario, losses are estimated between 20% and 60% (compared to base line) by 2025 for carbon-intensive sectors[7].

Focusing on risks associated with a quick transition, Vermeulen *et al.* (2018), Vermeulen *et al.* (2019) designed a stress test framework and applied it to the Dutch financial sector. They consider

[5]The shock is the same for all companies in the sector.

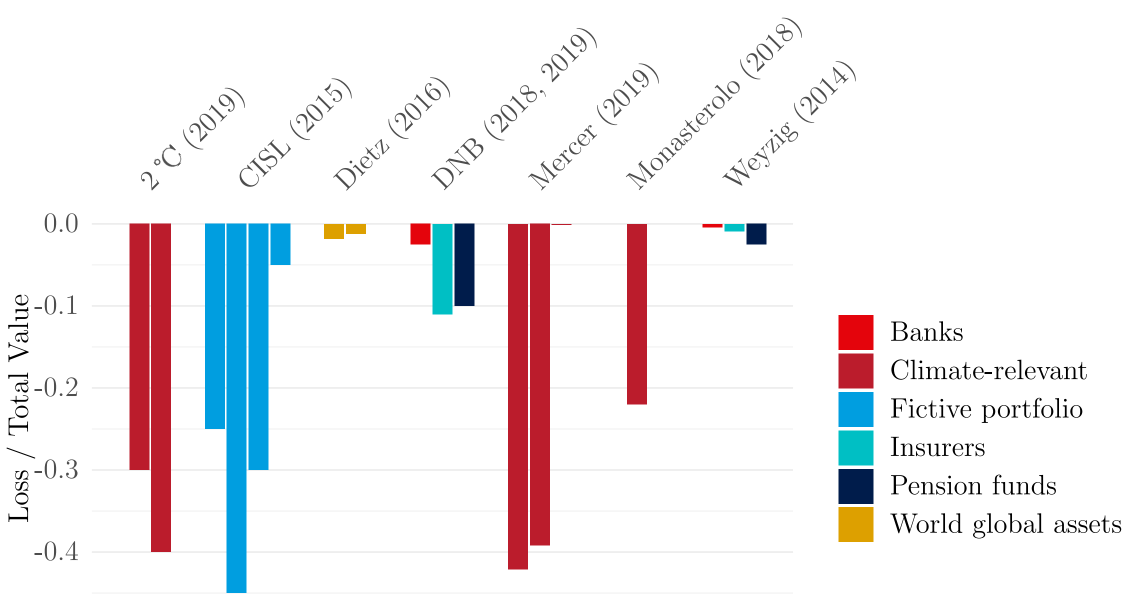
[6]For more details, see Battiston *et al.* (2017) supplement p.13.

[7]A similar approach has been developed by Mercer (2019), combining the results of an IAM that takes into consideration transition and physical risks with sectorial vulnerability factors developed by experts.

a policy shock that leads to a carbon price of USD 100 and a technological shock. The scenario assumptions are translated into existing variables of a conventional macro-econometric model[8]. For example, the carbon price rise is translated into a fossil fuel rise. Sector sensitivity is assessed through the carbon intensity of each sector. The different sectors' valuations are obtained by multiplying aggregate equity index generated by the model with specific vulnerability factors. In the case of a combined technology and policy shock, losses range between 2.5% and 11% over the next five years.

Market confidence shocks These approaches assume a smooth reaction of financial markets to transition risk. What would happen if market sentiment on transition risk shifted more rapidly? CISL (2015) consider that financial climate-related risk will probably be seen in the long term. However, financial markets could be affected in the short term by the projection of these effects. Therefore, they introduce three *sentiment* scenarios. First, they estimate the physical risk financial impact for each sector. This impact is translated in terms of sentiment for the different economic agents. For example, higher risk may lead to an increase of the cost of capital. Finally, they compute the financial impacts of sentiment scenarios using a general equilibrium model[9]. Sector sensitivity is assessed using past correlations between sector financial performances and global asset prices. They conclude that a fictional portfolio with 40% of equities could suffer losses of more than 25% within the next five years.

Figure 3: Losses (as percentage of total asset value) under different transition scenarios



What can we learn from these estimates of global or sectoral financial losses? While scopes vary widely across studies, we summarize the main estimated losses in Figure 3. The systemic

[8]The model used is NiGEM, developed by the UK National Institute of Economic and Social Research.
[9]Oxford economics' general equilibrium model.

risk related to transition risk seems limited, but climate-relevant sectors may suffer losses up to 40%. Therefore, the next relevant level of analysis is the financial statement of a bank, pension fund, insurance company or some of their portfolios. Such levels of analysis require bottom-up approaches.

2.2.3 Bottom-up analysis

Stranded assets Academic research on stranded assets has grown since 2011 (Caldecott, 2017). This concept may be defined as:

> "*assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities*" (Caldecott *et al.*, 2013, p. 7).

Regarding this definition, any transition, including societal and technological transitions, can lead to stranded assets. We focus here on the literature dedicated to climate-related stranded assets (Caldecott, Harnett, *et al.*, 2016). For example, Caldecott, Kruitwagen, *et al.* (2016) explore the risks for coal-fired power stations and thermal coal mines located in the major producing markets. Using a bottom-up approach with asset-level information[10], they identify various criteria that can lead to stranded assets. This study goes beyond carbon-related risks[11]. As the coal sector already faced large losses due to the energy transition, it gives an overview of the potential speed and magnitude of such a devaluation.

Another part of research on stranded assets focuses on stranded fossil fuel reserves. According to scenarios of keeping global warming under 2℃, oil and gas consumption should slow down dramatically. Capex on new oil projects should remain 83% lower in a 1.6℃ scenario and 60% lower in a 1.7-1.8℃ scenario compared to the current policy scenario[12] (IEA, 2018). Carbon Tracker (2019) conduct an economic analysis of the projected investments of major oil and gas companies in regard to projected oil and gas demand for each scenario. They find that around USD 2.2 trillion of capital expenditure planned between 2019 and 2030 may be stranded, with some companies having more than 90% of their capital expenditure at risk in a 1.6℃ scenario.

Studies on stranded assets are relevant for specific sectors (e.g. utilities and energy), but require asset-level data and can hardly be generalized at a portfolio level. Our study focuses on the impacts on cash flows, but it is essential to keep in mind that stranded assets may also have consequences on credit risk, by impacting companies' balance sheets.

Bottom-up transmission of economic shocks Based on Battiston *et al.* (2017), Monasterolo *et al.* (2018) develop a climate stress-test methodology to assess the credit risk of fossil fuel and renewable energy project portfolios of two Chinese development banks. Using the energy mix outputs from four IAMs[13] under five scenarios, they consider that a relative change in the market share of the borrower sector within a region implies an equal relative change in net company value. The authors find that the negative shocks are concentrated on coal and oil projects and vary across regions between 4.2% and 22% of total loan value. Given the current leverage of the

[10] For example, the age, obsolescence and type of technology.
[11] They consider wider environmental factors such as water stress, pollution regulation and societal pressure.
[12] Associated with 2.7℃ global warming.
[13] They used the LIMITS database.

banks, these losses are not negligible in comparison to banks' capital. This approach is relevant for specific sectors such as fossil-fuel or utilities companies. However, it is difficult to apply to a multi-sector portfolio.

Bottom-up transmission of carbon price shocks Among the transition risk transmission channels, the impact of the carbon price has the advantage of being a comparable factor across sectors. Howard and Patrascu (2017) study the impact of a rise in the global carbon price up to USD 100 per tCO2 emitted. Companies' costs will increase in proportion to the total emissions generated by themselves and suppliers. The assumption is that companies will increase their prices to offset cost increases, so returns on capital remain stable. Then, demand should fall in proportion to the price elasticity of each market. This micro approach offers intermediate results comparable to ours. For example, they find a 14% decrease in the aggregate EBITDA of the MSCI World Index. A potential limitation of this study is that they apply one global carbon price (USD 100) and that this price is the same for all regions.

UNEP (2019) and Monnin (2018) rely on a methodology developed by Carbon Delta[14]. Their transition scenarios are based on countries' emission-reduction targets. The carbon price in each country that is necessary to reach the targets is estimated through an IAM[15]. This national carbon targets are first broken down by sectors based on the strategy of each country, and then broken down by production facilities, based on their emissions. The present value of the future cost related to carbon emissions is subtracted from the current enterprise value. The theoretical probability of default of a firm within five years is estimated through Merton model. Monnin (2018) applies this approach to the corporate bond portfolio of the European Central Bank (ECB). He finds that 4.8% of the issuers analyzed would fall out of the investment grade category, meaning that they would not be eligible for ECB portfolios. This methodology seems to be the closest to ours, but relies on a private expertise.

2.3 Transition risk integration in market prices

Another stream of research is related to the measurable effect of transition risk on financial markets. Scholtens and van der Goot (2014) investigate the impact of the emissions trading system price in the European Union (EU-ETS) on the value of individual firms in several countries and industries[16]. Surprisingly, carbon price changes are positively associated with stock returns. The underlying assumption is that energy-intensive industries are able to pass through costs to the demand side. Oestreich and Tsiakas (2015) confirm these results and suggest that this outperformance is explained by higher cash flows due to the free allocation of carbon emission allowances. But these results should be considered with precaution regarding the specific context of phase 1 of the EU-ETS[17].

Most econometric studies do not rely on the ETS or carbon tax price as an explanatory variable, but on the carbon intensity of firms. Andersson *et al.* (2016) find that between 2010 and 2016,

[14] Source: https://www.carbon-delta.com.

[15] REMIND model.

[16] 136 companies in the four largest industries covered by the EU-ETS during the second phase.

[17] Due to the financial crisis and the global economy downturn, companies had excessive carbon emission allowances.

a low-carbon index with a carbon footprint 50% lower than its benchmark had a comparable financial performance, then providing a free hedge against transition risk. The possibility to hedge a risk for free suggests that investors do not integrate transition risk into their investment decisions. This result is in line with Görgen *et al.* (2019), who find that financial institutions can achieve higher performance by including a carbon risk factor in their investment strategies. Similarly, In *et al.* (2019) show that the construction of an efficient-minus-inefficient[18] portfolio would generate abnormal returns of 3.5-5.4% per year. On the other hand, Ilhan *et al.* (2019) find that policy uncertainty delaying the energy transition is already priced into the options market. They observe higher prices of options that hedge against carbon-intensive firms.

These research papers focus on equities. To our knowledge, little research has been done on bonds or loans. While equity valuation is correlated with credit-risk, debt instruments differ in several ways. First of all, debt instruments have a maturity, unlike equities. Second, debt holders are interested in the extreme and irreversible risk that is the default of an issuer, while equity holders will be more sensitive to changes in the company's performance. On the Australian market, firms failing to disclose GHG information to the carbon disclosure project (CDP) observe a positive association between their cost of debt and their carbon intensity (Jung *et al.*, 2018). These results suggest that debt holders take the transition risk into consideration as the concern of their counterparts regarding this risk. These findings are in line with previous research on the relation between the larger environmental performance (Bauer & Hann, 2010) or corporate social responsibility (CSR) performance and credit risk (Ge & Liu, 2015; Oikonomou *et al.*, 2014). Ben Slimane *et al.* (2019) also shows that, in general, high ESG rated companies benefit from lower cost of capital. For example, the average difference between best and worst-in-class ESG corporate firms is equal to 31 basis points in the case of investment grade bonds issued in euros.

All in all, as for CSR or ESG performance[19] (Friede *et al.*, 2015), there is still no absolute consensus on whether or not market prices already integrate transition risk[20]. It is therefore appropriate to adopt a forward-looking approach, in order to provide financial institutions with a new source of information on transition risk.

[18] Carbon efficiency being defined as revenue-adjusted greenhouse gas emissions.

[19] Friede *et al.* (2015) shows that ESG-related studies mostly produce positive results. However, the underlying ESG scores remain controverted and biased in multiple ways (Berg *et al.*, 2019). Additionally, we account for cultural bias in the rating process (Eccles & Stroehle, 2018). The uncertainty related to ESG performance therefore mostly lies on the non-consensual construction of the scores.

[20] For a systemic review of environmental and climate-related risk management in the financial sector, see Breitenstein *et al.* (2019).

Figure 4: Overview of the literature

Scenario definition

Baseline scenario:
(RCP6.0/SSP2) [1]
2.5°C [2]
4°C [10]

1.5°C [9]/ 2°C [1,2,5,8]
3°C [10]/4°C/6°C [8]
No mitigation (RCP8/SSP5) [1]
Policy and/or energy shock [4,7]
Distribution of scenarios [3,6]
Market confidence shock [1]

Time horizon

5 years [1,2,4,5]
15 years [10]
20 years [7,9]
30 years [6,8]
100 years [2]

Scenario variable

Transition specific
Global carbon price [1,7]
NDC [5]
Investments in energy sectors [1]
Energy demand and prices [1,4]
Food prices [1]

Conventional
Housing price index [1]
Market confidence shock [1]
Complete loss of equity value [2]
Production function parameters [4]

Economic model

Integrated assessment model
Nordhaus DICE model [2]
LIMITS model [3,6]
Remind [5,10]
E3M [11]
World energy model [7]

Conventional macro-economic model
Oxford economics GEM [1]
NIGEM [4]
Price elasticity [8]

Economic variables

Climate specific:
Carbon price(s) [5]
Energy mix [3,6]
Eletricity demand by source [9]
Energy prices [9]
Investments in energy sectors [9]

Conventional:
Interest rates [1]
Global credit spreads [1]
Global equity value [1,4]
Global GDP [2]
Sectoral GDP [7]

Financial model

Bottom-up Model
Economic
Revenues change [7,8]
Increased cost of emitting C02 [5,7,8]
Increased cost of goods [7]
Depreciation of assets [7]

Financial
Discounted cash flows [5,7]
Merton model [5]

Top-down model
Duration model [1]
Sectorial CAPM [1]
Present value of future global GDP [2]
Equity valuation variations proportional to energy mix variation [3,6]
Risk factors based on sector GHG emissions [4,7]

Sectors

GICS [1]
Climate-relevant [3]
NACE (56) [4]
IPCC sectors (8) [6]
Other [8,5]

Asset class

Corporate bonds [1,5,11]
Government bonds [1]
Equities [1,2,3,4,7,8,11]
Commodities [1]
Loans [6]

Risk measurement

EBITDA variation [8]
Value at risk [2,3,4,6]
Ratings [5,10]
Expected loss [5]

Scope of analysis

Fictive portfolios [1,7,8,9,10,11]
World financial assets [2]
Eurozone banks [3]
Dutch institutions [4]
ECB portfolio [5]
Chinese banks [6]
Indices [8,10]

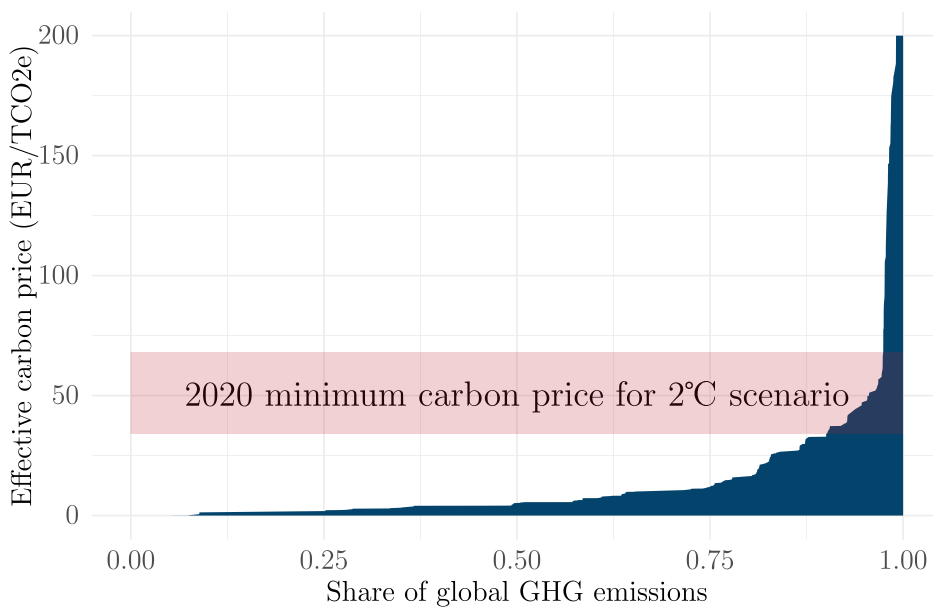
1: CISL, 2015
2: Dietz et al., 2016
3: Battiston et al., 2017
4: DNB, 2018-2019
5: Monnin, 2018
6: Monasterolo, 2018
7: 2degrees, 2019
8: Schroders, 2017
9: UnepFI, 2018
10: UNEP FI, 2019
11: Mercer, 2019

3 Social cost vs. effective carbon price

3.1 Why a carbon price?

Global GHG emissions increased in 2017 after three years of stagnation[21] and are expected to keep rising (by 2.7% in 2018, Le Quéré *et al.* (2018)). Pathways reflecting current NDCs estimate GHG emissions in 2030 at around 60 GtCO2e, leading to global warming of about 3℃ by 2100. It is still possible to bridge the gap to ensure global warming stays well below 2℃ and 1.5℃, but NDC ambitions, including carbon price, need to increase sharply before 2030 (UNEP, 2018). Indeed, Figure 5 shows that the minimum carbon price range should be, on average, EUR 50 per ton emitted while more than 80% of the emissions are still considerably underpriced.

Figure 5: Carbon price gap



Source: UNEP, 2018

From a financial perspective, carbon price is associated with a policy transition risk. It is therefore important to clarify the different meanings of *carbon price*. First, a distinction must be made between the *social* cost of GHG emissions and the *effective* cost. The social cost of carbon (SCC) may be defined as:

> "*The incremental impact of emitting an additional ton of carbon dioxide, or the benefit of slightly reducing emissions. When evaluated along an optimal emissions trajectory,*

[21] Total annual GHG emissions, including from land-use change, reached a record high of 53.5 GtCO2e in 2017, an increase of 0.7 GtCO2e compared with 2016. For more information about GHG emissions by gas, sectors and countries, see "CO2 and Greenhouse Gas Emission" (2017).

the social cost of carbon is [...] the amount GHG emissions should be taxed in order to maximize welfare"(Tol, 2018, p. 13).

There are two approaches to compute the SCC:

- The *cost-benefit* approach seeks to optimize the price such that *"the marginal damage inflicted on the planet by the emission of an additional unit is worth the marginal cost of reducing emissions"* (Montialoux, 2009, p. 133). This is the approach used by Stern (2007).

- The *cost-efficiency* approach is based on the announced reduction objectives and studies the optimal price to achieve them. This is the approach adopted by the Quinet report, which is at the origin of the current carbon tax price in France.

These prices are theoretical but serve as references for evaluating the environmental cost of public projects, for orienting firms' strategic choices such as R&D investments, and finally for calibrating emissions regulation mechanisms. The carbon price used in our long-term scenario is the SCC computed by IAM from the IPCC for the special report 1.5°C. While SCC may be the optimal cost of GHG emissions to reduce future damage and current economic losses, it is not always applied by governments. In practice, this price depends on the countries (Ricke *et al.*, 2018), the abatement costs of each sector and political will. As a result, the *effective* carbon price may substantially differ from the SCC. In order to take this discrepancy into consideration, our medium-term scenario analysis is built on specific carbon prices for each sector in each country, based on current policies.

Different mechanisms can be implemented to limit GHG emissions. Reducing support for fossil fuels, setting emission standards, or supporting low-carbon innovation can be consider as an *implicit* carbon pricing and may have an effect on the financial situation of companies. In our study, we focus on the two main mechanisms to set an *explicit* or *effective* carbon price: emissions trading systems (ETS, or cap-and-trade) and carbon taxes. In 2018, these two mechanisms accounted for 51 initiatives, covering 20% of global GHG emissions (World Bank, 2019) and generating USD 44 billion revenues for governments in 2018 (USD 33 billion in 2017).

3.2 Carbon tax

Mechanism and implementation Carbon tax is a price-based policy instrument. In addition to the dissuasive aspect of the price, the tax aims to invest its receipts towards climate-related projects. It is usually added to the sale price of a good, based on the quantity of GHGs emitted during its production and / or use. Some taxes may apply directly to the emissions of a company or sector. For example, the carbon tax in Chile targets CO2 emissions from intensive actors[22] in the power and industrial sectors. Other taxes will materialize as an extra cost for the consumer. The carbon tax is paid by households and businesses at the time of fossil fuel or electricity production. From a company perspective, the carbon tax will impact the price of commodities[23], increasing

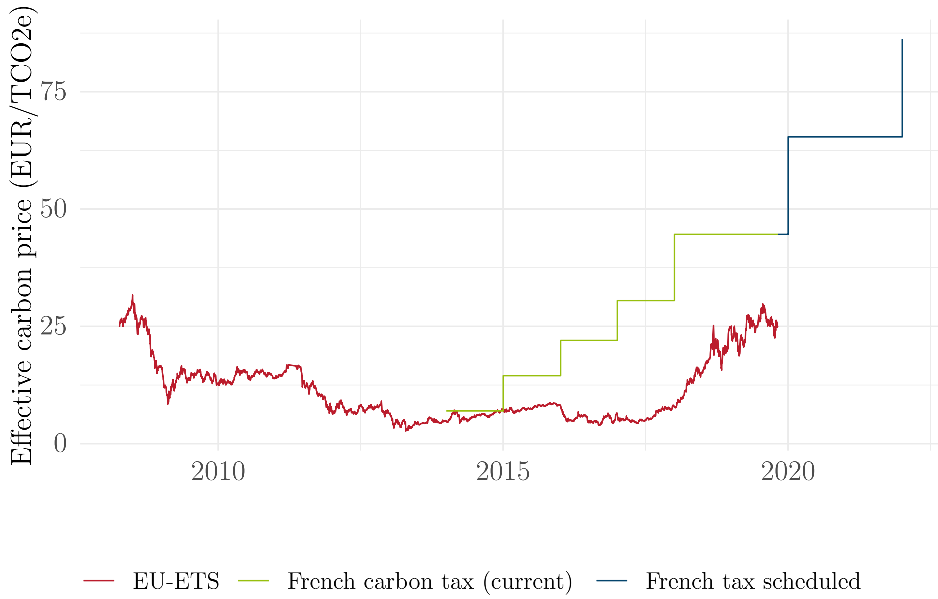
[22] Stationary emission sources over 50MW are subject to a carbon tax of USD 5 per ton of CO2 equivalent emitted.

[23] This assumption is based on the French accountability system. According to the Article 213–31 (Autorité des normes comptables, entreprises industrielles et commerciales, dispositions générales), the acquisition cost of inventories consists of purchase price, including customs duties and other non-recoverable taxes. We then consider the carbon tax as a non-recoverable tax.

the cost of goods sold (see Table 1). Two major phases of carbon-related taxation have emerged in Europe: in the 1990s in the Nordic countries and then since 2008 in Central Europe.

The case of the French carbon tax In 2014, France introduced a carbon component integrated into domestic taxes on the consumption of energy products (TICPE) and the domestic consumption tax on natural gas and coal. Initially at EUR 7/tCO2e, it reached EUR 44.62 in 2018 (see Figure 6). The revenue from this carbon tax, or climate energy contribution, rose from EUR 0.3 billion in 2014 to more than EUR 6.4 billion in 2017[24] (Rogissart *et al.*, 2018). Since 2017, the tax has partly funded a "*special allocation account for the energy transition*", which will finance renewable energy projects. Certain sectors are exempt from the tax. In particular, the carbon tax does not apply to industries already subject to the European Union emissions trading system (EU-ETS). Although the trajectory of the French tax is determined in advance (see Figure 6), the "*yellow vest*" movement is a good example of the uncertainties associated with the social acceptance of such a mechanism.

Figure 6: Evolution of the carbon tax in France



3.3 Emissions trading system (ETS)

Mechanism and implementation A carbon price may also be implemented via a quantity-based instrument. Based on a GHG emissions reduction-target, a certain amount of emission allowances is available each year. At the end of the year, companies must provide the authorities

[24]For comparison, receipts from the value added tax (TVA) amounts to EUR 152.8 billion and the domestic tax on energy products (TICPE), EUR 31.8 billion.

with the number of allowances equivalent to their annual GHG emissions. The carbon price observed on the market will depend only on the demand-side variation.

From a company perspective, there is no consensus on how these quotas should be taken into account in the financial statements[25]. Thus, we follow the recommendations of the French accounting standards authority[26] and consider quotas as commodities. Like taxes, acquired emission allowances will contribute to the cost of goods sold[27].

Following the Kyoto Protocol, regional carbon allowance markets were set up in order to trade surplus allowances. Unlike traditional financial markets (in equities and bonds), carbon markets generate neither income nor direct utility, they are only valuable because of the existence of public regulation. The number of carbon markets in the world is increasing, with national or regional markets in Canada, China, Japan, New Zealand, South Korea, Switzerland and the United States (in California). The major challenge of the coming years will obviously be the Chinese market, which officially launched in December 2017. For the moment, it only covers the electricity production sector, but it still covers more than 3.5 gigatons of annual emissions. In the regional Chinese markets currently in place covering 1.4 gigatons of CO2, the price varies between USD 3 and USD 10.

The case of the European emissions trading system (EU-ETS) The EU-ETS, launched in 2005, is the world's biggest emissions trading system, accounting for over 75% of international carbon trading. It was created to support the EU long-term climate strategy. It covers approximately 11,000 power stations and manufacturing plants, as well as aviation, accounting for 45% of total EU GHG emissions. The next phase (2021-2030) aims to reduce EU-ETS emissions by 43% compared to 2005[28]. Between 2021 and 2030, the number of emission allowances will decline at an annual rate of 2.2%, compared to 1.74% currently (see Figure 6). The European environment agency interactive online reports can be used to follow mechanisms and sectoral emissions[29].

3.4 Direct and indirect effects of the carbon price

We previously introduced the theoretical channel of transition risk transmission. The effective carbon price is part of policy transition risk and can have an impact on a company's financial situation through different channels. In our model, we will only consider the direct impact of a carbon price rise on the cost of goods sold (which is part of opex). It should be noted that this opex rise may be passed through in a higher sales price and have an indirect impact on demand (Howard & Patrascu, 2017). Moreover, a high carbon price will reduce the competitiveness of some production assets, leading to a risk of stranded assets with an impact on the balance sheet.

[25] Source: https://www.accaglobal.com/content/dam/acca/global/PDF-technical/climate-change/rr-122-001.pdf.

[26] Source: http://www.anc.gouv.fr/files/live/sites/anc/files/contributed/ANC/3.%20Recherche/D_Propositions/2012/Livre%20de%20proposition_Comptabilisation%20des%20quotas%20CO2_FRANCAIS.pdf.

[27] In our model, we do not consider the possibility for companies to store quotas, while in reality, they can. In 2013, companies had accumulated the equivalent of more than one year of emission allowances.

[28] Source: https://ec.europa.eu/clima/sites/clima/files/factsheet_ets_en.pdf.

[29] Source: https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-6/assessment-3.

4 Methodology and data

4.1 Structural transmission model

From carbon price to total asset value shock The carbon price transmission channel in income statements is described in Table 1. In practice, there are many ways a change in carbon price can affect firms; this methodology covers one of them. We reiterate that quotas are considered as commodities and then are included in cost of goods sold. On the other hand, carbon taxes are mostly associated with the cost of fuels. The acquisition cost of fuels consists of the purchase price, including customs duties and other non-recoverable taxes[30]. We consider the carbon tax as a non-recoverable tax.

Table 1: Transmission channel of the carbon price

Variable	Step	Calculus
Revenue*	(1)	
Cost of goods sold – **quotas or carbon tax**	(2)	
Gross profit	(3)	(1)-(2)
Operating expense excluding deprec. and amort.	(4)	
EBITDA	(5)	(3)-(4)
Depreciation and amortization**	(6)	
EBIT	(7)	(5)-(6)
Interest expense	(8)	
Tax expense	(9)	
Net income	(10)	(7)-(8)-(9)

Notes:
* Reduced demand effect would affect revenues
** Asset stranding effects would imply depreciations

Let $\text{Scope}_1(i,j,t)$ be the emissions in tons of CO2 equivalent emitted by the company i in a given region j at date t. Each region j has a representative carbon price CP for each date t in each scenario k[31]. This price is based on the mechanisms in region j. The reference scenario $k=0$, is the baseline where current carbon prices remain unchanged:

$$\text{CP}(j,k=0,t)=\text{CP}(j,k=0,t=0)$$

Each year, each company has carbon cost CC derived from the company activity in each region j in the set $\mathcal{M}$ regions where the company has reported direct emissions:

$$\text{CC}(i,k,t)=\sum_{j\in\mathcal{M}}\text{Scope}_1(i,j,t)\times\text{CP}(j,k,t)$$

[30] According to Article 213–31 from Autorité des normes comptables, entreprises industrielles et commerciales, Dispositions générales.

[31] The notations are summarized in Appendix A on page 39.

Integrating this carbon cost leads to a shock to EBITDA defined as[32]:

$$\xi(i,k,t) = \frac{\mathrm{CC}(i,k,t)}{\mathrm{EBITDA}(i,k=0,t=0)}$$

The impact of the variation of EBITDA on total asset value V can be computed through two approaches. The first option is to compute, for each year, the new asset value as the discounted future cash flows. This approach requires defining the discount rate for each company and therefore adds parameters to our model. As our study focuses on the comparability of different companies, we used a second approach that relies on the assumption that the financial ratio between the enterprise value and the EBITDA remains constant over time[33]. In this case, the shock is directly transmitted to the enterprise value. The economic shock transmission to the financial valuation of each company i, in each scenario k and at each date t is:

$$V(i,k,t) = (1 - \xi(i,k,t)) \times V(i,k=0,t=0)$$

From total asset value shock to probability of default The probability of default is derived from total asset value shock through the framework developed by Merton (1974)[34]. The initial total asset value $V(i,k=0,t=0)$ of the company i and total asset volatility $\sigma_V(i)$, which are not observable, are determined by resolving System[35] (1). In this paper, this system is resolved solely to determine initial values for $V(i,k=0,t=0)$ and $\sigma_V(i)$ and is independent of scenario k and future date t:

$$\begin{cases} E(i) = V(i)\Phi(\mathrm{d}_1) - D(i)e^{-rT}\Phi(\mathrm{d}_2) \\ \\ E(i) = \dfrac{\sigma_V(i)}{\sigma_E(i)}\Phi(\mathrm{d}_1)V(i) \end{cases} \tag{1}$$

where σ_E is the observable equity volatility, D is the total debt, Φ is the cumulative normal distribution function and:

$$\begin{aligned} d_1 &= \frac{\ln\left(\dfrac{V(i)}{D(i)}\right) + (r + \frac{1}{2}(\sigma_V(i))^2) \times T}{\sigma_V(i)\sqrt{T}} \\ d_2 &= d_1 - \sigma_V(i)\sqrt{T} \end{aligned}$$

where r is the risk-free rate and T the maturity. Once the initial total asset value and total asset volatility are determined, we can compute the distance to default DD by incorporating the shock

[32] Reinders *et al.* (2020) presented a similar stress-test methodology at the Global Research Alliance for Sustainable Finance (2019). However, there are multiple differences in the two methodologies: the definition of the shock (EBITDA and not discounted cash flows), the bottom-up configuration and multiple scenario and horizons in this paper.

[33] In this case, we can write $V(i,t) = \mathcal{R}_i \times \mathrm{EBITDA}(i,t)$ where $\mathcal{R}_i$ is a constant financial ratio neutral in this study. The assumption is that $\mathcal{R}_i$ is *stable* over time for each company, which is verified in this study.

[34] The validity of this theoretical model is discussed in Appendix D on page 44.

[35] Note that companies' value is also disclosed by providers and we used several values for robustness check. This system is solved using Newton's method.

($\xi \in [0,1]$). Then, the distance to default is given by:

$$\text{DD}(i,k,t) = \frac{\ln\left(\frac{(1-\xi(i,k,t)) \times V(i,k=0,t=0)}{D(i)}\right) + \left(r + \frac{1}{2}(\sigma_V(i))^2\right)T}{\sigma_V(i)\sqrt{T}}$$

and the theoretical probability of default PD of an issuer is:

$$\text{PD}(i,k,t) = \Phi(-\text{DD}(i,k,t))$$

These two metrics are defined for each issuer i in each scenario k at each date t. In a situation where parameters such as asset volatility, risk-free rate, total debt or financial ratio, are not assumed to be fixed, the System (1) would have to be solved at each date in each scenario.

4.2 Scenario definition

One of the limits pointed out by Carney (2019) to address climate-related financial risk is the long-term horizon of climate change compared to the short-term horizon of finance, theorized as the *tragedy of the horizon*. In order to address this issue, our study includes a medium-term (five-year) and long-term (40-year) analysis.

Medium-term scenarios The medium-term analysis focuses on the period from 2019 to 2023 and relies on current carbon prices in four regions. We distinguish the countries belonging to the EU-ETS, Japan, United States and the rest of the world. To estimate the average effective prices in each region, we compute the carbon revenues in 2018 and divide them by the GHG emissions in the corresponding region[36]. This estimation is based on following data:

- The World Bank publishes an annual report on the state and trends of carbon pricing mechanisms (World Bank, 2019). Moreover, since May 2017, it has provided an interactive online platform, the *carbon pricing dashboards*, with open access to the underlying data. This database covers 57 carbon-pricing initiatives, covering 11 gigatons of CO2 emissions accounting for 20.1% of global GHG emissions and provides information on GHG coverage, prices and global value from 1990[37].

- The International Carbon Action Partnership (ICAP) is an international forum for more than 35 jurisdictions that have implemented, or are planning to implement, emissions trading systems (ETS). The ICAP ETS map, an interactive tool with open data, provides factsheets on ETS initiatives[38].

- The Institute for Climate Economics (I4CE) Postic and Métivier (2019) provides a synthesis of carbon price mechanisms by region around the world.

Our first scenario (*trend*) extends the current linear trajectory in the evolution of revenues from carbon price mechanisms. The second (*acceleration*) considers a 30% increase of the carbon price each year over the next five years.

[36] We discuss this approximation in Appendix D.
[37] Source: https://carbonpricingdashboard.worldbank.org/map_data, data extracted on September 16th, 2019.
[38] Source: https://icapcarbonaction.com/en/ets-map, data extracted on September 16th, 2019.

Long-term scenarios For the long-term analysis, carbon prices are retrieved from the Intergovernmental Panel on Climate Change (IPCC) database[39]. This database provides 598 variables associated with 177 scenarios generated by 25 models. Data is generally available until 2100 with a 5- or 10-year step (Huppmann *et al.*, 2018). The carbon prices provided by these models are global. Figure 7 shows that future trajectories for carbon prices widely vary depending on scenarios and models. We therefore selected three scenarios that cover the range of carbon prices in the database (see Figure 7 and Appendix C for the scenarios selection process).

Table 2: Scenario selection

IPCC ref	Mean Temperature 2081-2100
SSP2-19	1.5°C with approximately 66% probability
SSP2-26	1.8°C
SSP2-34	2.2°C
SSP2-Baseline	3.8°C

4.3 Companies data

The medium- and long-term analysis are performed on the MSCI World Index, composed of 1 644 large and mid cap companies across 23 developed markets countries. In order to calculate the impact of each scenario on EBITDA and probability of default, we need the GHG emissions as well as the financial data of each company.

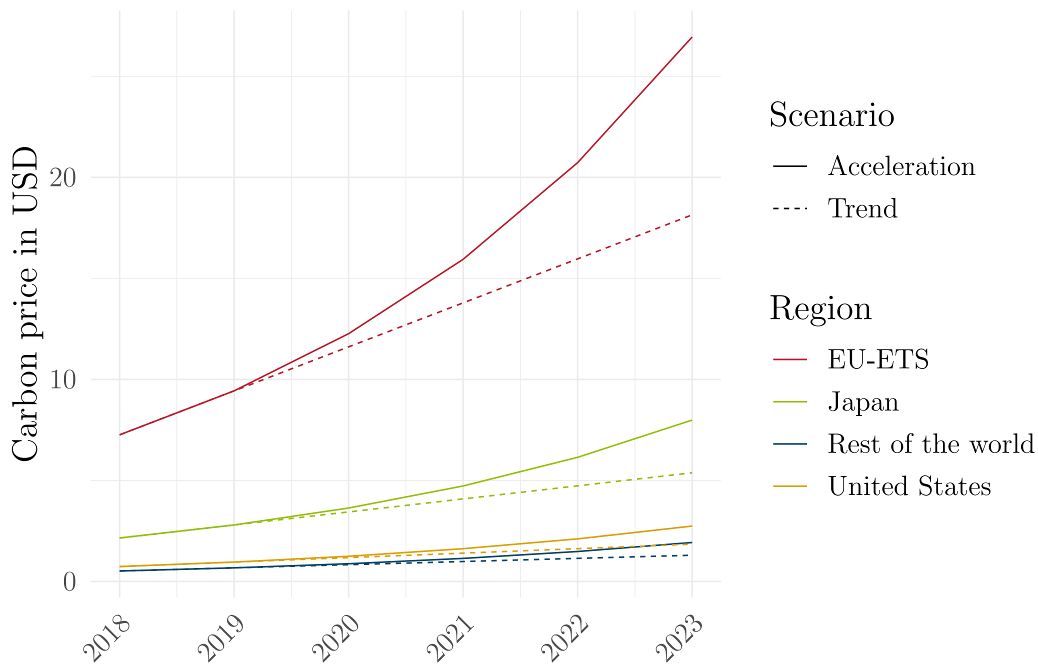
GHG Emissions Scope 1 emissions[40] are provided by the carbon disclosure project (CDP) database. CDP is a not-for-profit organization running the global disclosure system for financial institutions, companies, cities, states and regions to manage their environmental impacts. Over 7 000 companies responded to their questionnaire in 2018. One of the strengths of this database is to provide, for each company, the repartition of scope 1 emissions by country[41]. We also use Trucost (part of S&P Dow Jones Indices) to test the robustness of our results. The Trucost database covers over 14 000 companies in 2018, with an history until 2005 for 3 500 companies.

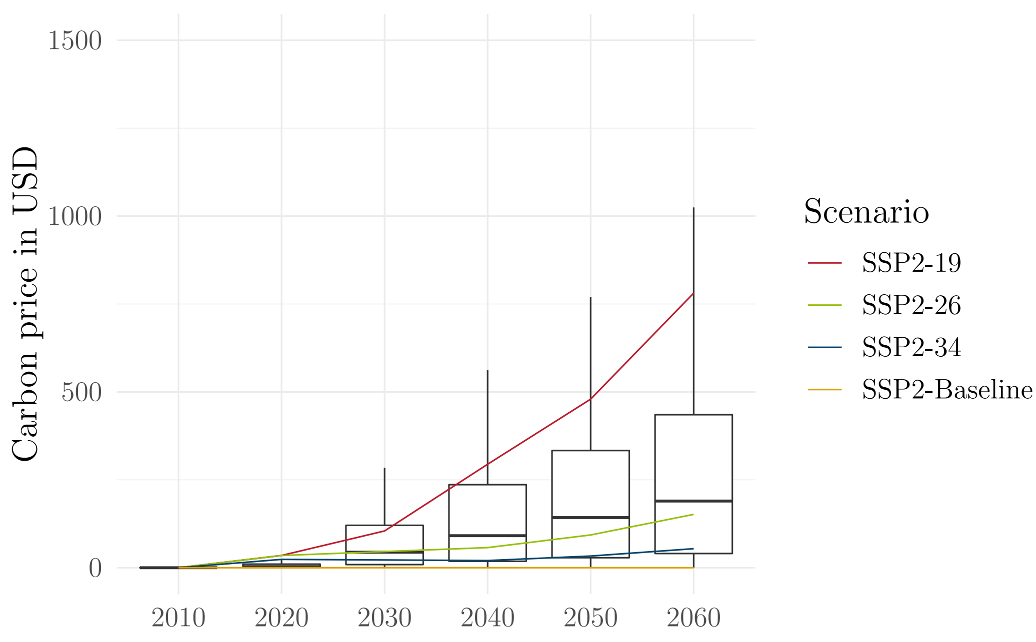
Financial Data EBITDA, equity value, equity volatility and face value of debt are retrieved from Bloomberg and Orbis Datastream[42].

Missing data EBITDA is relevant for non-financial companies only. Financials companies are therefore excluded from our sample (leading to 1 395 companies). Companies with missing financial data for 2018 were also removed (leading to 1 199 companies). Among them, we select those for which repartition of scope 1 emissions by country is available on the CDP database, leading to a final sample of 795 companies (see Appendix D for the detail of missing companies by sector).

[39]Source: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/, visited on September 16th, 2019.
[40]Scope 1 emissions are direct emissions from owned or controlled sources (GHG Protocol).
[41]Question 9.1.a. of the questionnaire.
[42]As of December 31, 2018.

Figure 7: Scenario selection and global distribution of carbon price (all models and scenarios)



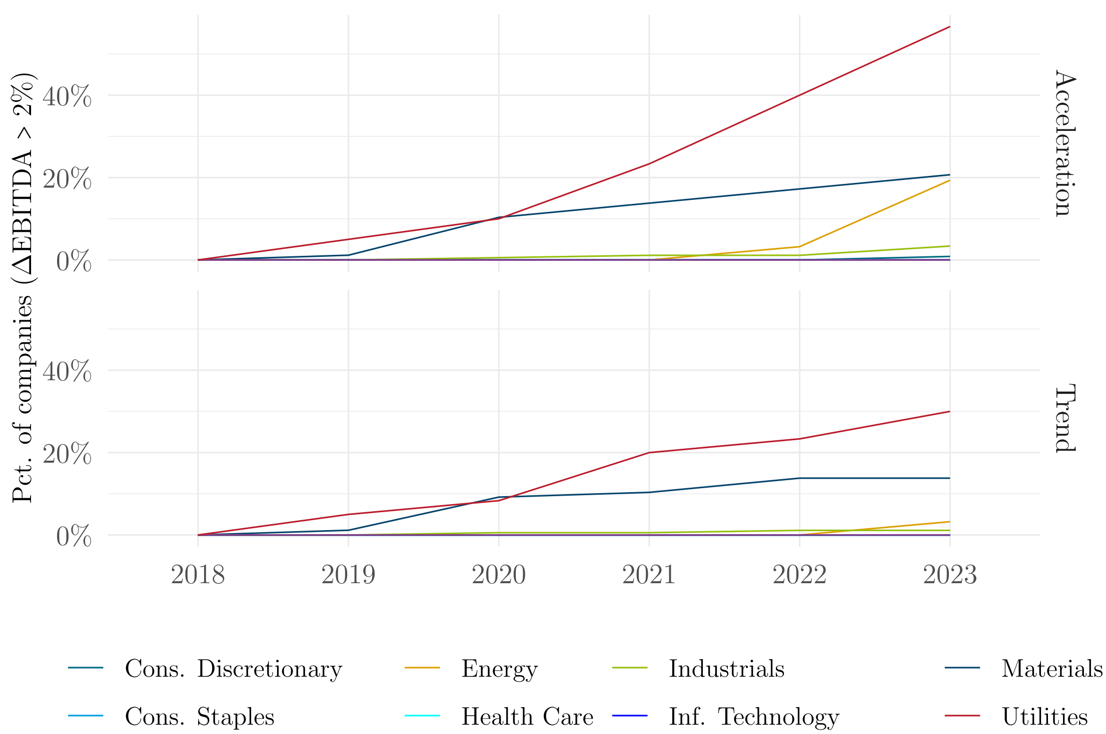


Above: medium-term carbon price scenarios.
Below: long-term carbon price scenarios.

5 Results

Medium-term economic impact We measure the economic impact of the carbon price rise on the EBITDA of each company with regard to its reference value in 2018[43]. Carbon price variations in medium-term scenario (maximum of USD 20 by 2023 in the EU-ETS region in an acceleration scenario) are limited. To study the sectoral distribution of the shock, we focus on companies whose EBITDA is diminished by more than 2%. Figure 8 shows the variation over time of the percentage of companies per sector whose EBITDA was affected by more than 2%. Only utilities, materials and energy sectors are directly impacted by rise of carbon price by 2023. In the acceleration scenario, utilities remains the main sector impacted, with more than 50% of its companies above the threshold. Materials and energy sectors are impacted to a small extent, with 20% of their companies above the threshold. The distribution of EBITDA shocks is larger for utilities, with a median above 2% and some companies impacted by 8% in an acceleration scenario (4% in a trend scenario). Energy and materials sectors have very similar distributions of impact with maximum impact remaining below 4%.

Figure 8: Medium-term impact on EBITDA



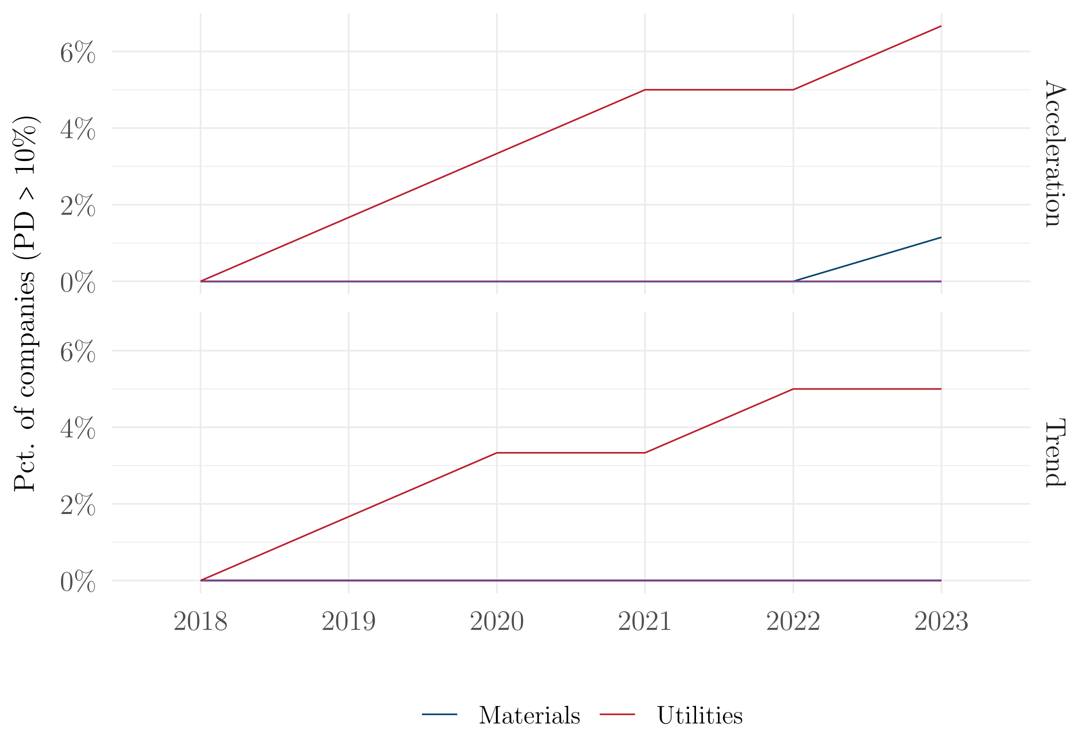
The energy sector is the most sensitive to the scenario with the percentage of its companies whose EBITDA is reduced by more than 2% by 2023 of less than 5% in a trend scenario but reaching 20% in an acceleration scenario. The utilities sector is also sensitive with a percentage

[43]We consider that EBITDA would remain static otherwise.

of its companies impacted of 30% in a trend scenario but 55% in an acceleration scenario. On the other hand, the percentage of materials companies only varies from 15% in a trend scenario to 20% in an acceleration scenario.

Medium-term impact on credit risk Due to the reduced impact on EBITDA compared to its average variation (see Figure 17 in Appendix D), we can hardly observe the effect on probability of default in the medium-term. Figure 9 presents the percentage of companies by sectors whose probabilities of default are above 10%.

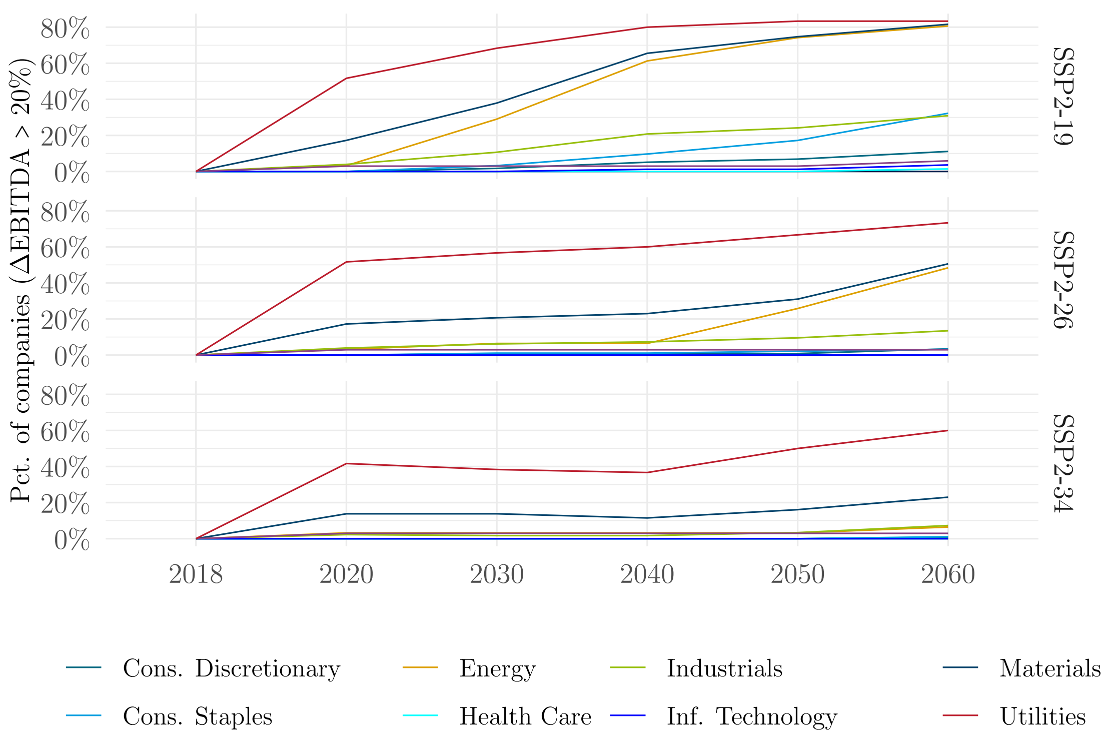
Figure 9: Medium-term impact on probabilities of default



Few utilities companies and only one material from the steel industry are relatively significantly impacted. Other sectors' probabilities of default remain unchanged, suggesting that medium-term carbon prices variation have a negligible direct impact on credit risk. However, if these companies pass the carbon price on the price of their products, the effect of the tax will pass through and affect either every other sector (through their scope 2 or 3 upstream), or households, potentially affecting political stability. In other words, these slight variations can be amplified in the supply chain and affected other actors.

Long-term economic impact In the long-term scenarios, prices are allowed to vary up to USD 780 by 2060 in the SSP2-19 scenario. Figure 10 shows the percentage of companies per sector whose margin was affected by more than 20%[44]. Three sectors are highly impacted: utilities, materials and energy, with about 80% of the companies that reach the threshold by 2060 in the SSP2-scenario[45]. Industrials and consumer staples are impacted to a lesser extent with 30% of companies reaching the threshold by 2060. The utilities, materials and energy sectors are similarly impacted by the USD 780 per tCO2 price in 2060. However, their sensitivity evolves differently in time. The utilities sector appears to be more sensitive to smaller price variations and already 50% of companies have a margin reduced of more than 20% in 2020. On the other hand, both materials and energy remain below 20%. In Figure 14 (in Appendix B), we see that the distribution of EBITDA variation is wider for utilities. This sector is the most sensitive to carbon price variation. While medians for energy and materials are similar, materials distribution is also wider than energy.

Figure 10: Long-term impact on EBITDA



The sensitivity to scenarios also varies among sectors. The utilities sector is similarly impacted by the three scenarios, with the percentage of companies with EBITDA affected by more than 20% ranging between 60% (SSP2-34) and 80% (SSP2-19). On the other hand, energy companies

[44]This threshold is arbitrary. It allows us to define to some extent a *worst-in-class* category in terms of transition risk management. We show in Appendix D that such an EBITDA variation is not common and therefore poses a risk.

[45]As the only variable affecting the earnings is the price, dates and carbon price can be substituted. 2060 correspond to a USD 780 per tCO2.

are impacted very little in a SSP2-34 scenario (less than 10%), while reaching a similar level to utilities (80%) in a SSP2-19 scenario. In a SSP2-19 scenario, we also observe a direct effect on industrials and consumer staples, with more than 25% of the companies of those sectors impacted.

Long-term impact on credit risk The influence on credit risk is measured through the Merton probability of default[46]. Therefore, the next step of our analysis is to explore how the EBITDA shock may have an impact on the probability of default of each company within the universe. Figure 11 provides a snapshot of probability of default accounting for the carbon price at each date in the SSP2-19. It confirms the prior observation concerning sectoral sensitivity.

Figure 11: Long-term probabilities of default in SSP2-19 snapshot

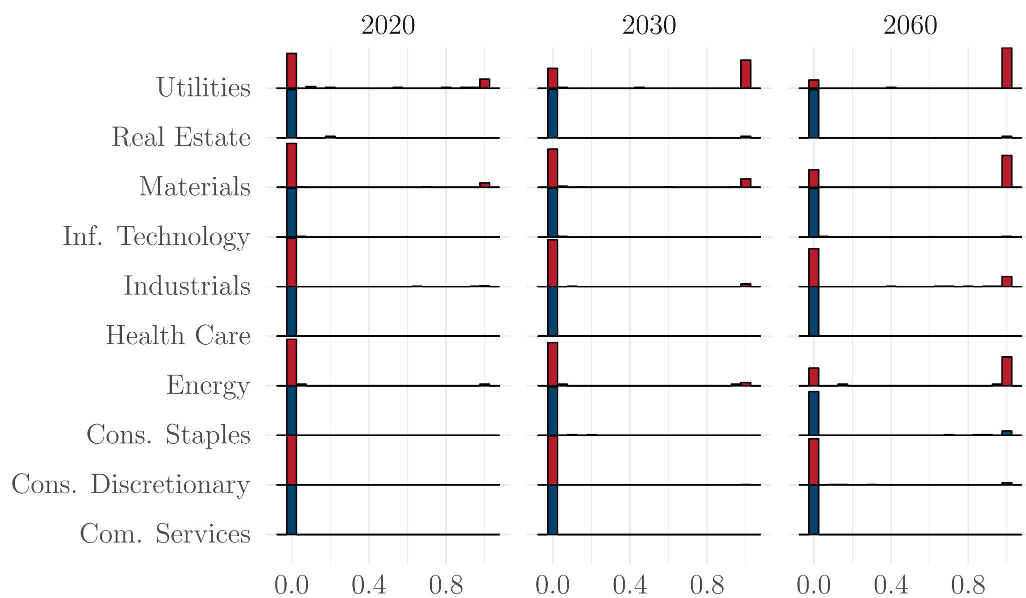
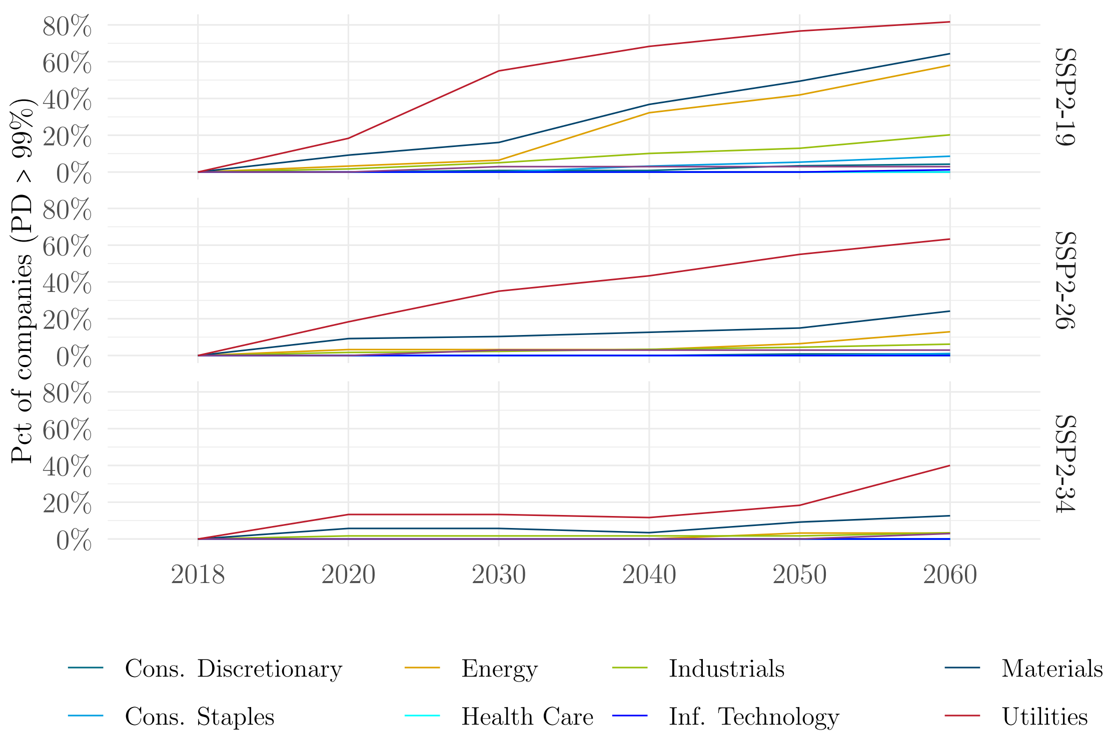


Figure 12 presents the percentage of companies by sector and by scenario whose probabilities of default are above 99%. The tendency remains similar to the EBITDA impact, suggesting that transition risk is not mitigated by companies' capital structures. In the utilities sector, almost 80% of the companies are likely to default by 2060 in a SSP2-19 scenario price (USD 780) if governments do not intervene. Concerning materials and energy, approximately 60% of the businesses might no longer be profitable and lead issued financial instruments to default in this same configuration.

Nonetheless, some sector exposures appear to be mitigated by their capital structure. In a SSP2-19 scenario, fewer than 10% of consumer staples companies are at risk, while more than 25% of them have an EBITDA reduced by more than 20% by 2060. It is also interesting to compare the dynamics of utilities companies in a SSP2-34 scenario. Focusing on EBITDA variation, the main change appears between 2018 and 2020, where 40% of companies have already reached the threshold. In 2020, only 12% of companies are already in credit risk and this percentage only rise by 2060 (to 40%).

[46]See Appendix D covering the Merton methodology.

Figure 12: Long-term impact on probabilities of default



6 Discussion

Sectoral effects Our results confirm that some sectors are more sensitive to carbon price variation. These sectors were already identified in the literature as *climate-relevant*: utilities, materials and energy[47] (Vermeulen *et al.*, 2018). Our study contributes to a better understanding of the sensitivity of these sectors by taking the distribution of financial risk within each sector into account, instead of considering the average risk for the sector. For example, utilities companies experience higher losses on average, but the losses are also more heterogeneous within the sector. However, the case of utilities needs to be discussed. As we focus on a regulatory risk[48], it is unlikely that governments will implement a carbon price mechanism that would slow public services without introducing sector-specific exemptions. Therefore, if many defaults seem to arise in this sector, the price is more likely to be capped to maintain profitability. Moreover, the sector is highly concentrated and companies are often supported by the governments. If the price is not capped, the debt generated by the rising price will be redeemed by the state. On the other hand, the utilities sector provides essential services to households. Consequently, they are limited in terms of pass-through as an abrupt rise in the price of water or power might also affect social and political stability. Therefore, an idea of how a rapid rise in carbon price might affect these companies' profitability

[47]Sectors such as transport do not appear in the study due to the focus on scope 1 emissions.
[48]Or a transition risk by the bias of a regulation.

has informative value for investors. However, in general, the absence of second round effects and pass-through naturally implies that the sectors that are the most up-stream in the supply chain will suffer more in this stress test. This remains the major limitation of this methodology.

The two main limitations to a better understanding of the sectoral effects can be summarized as follow. First, the carbon price is sector-specific. Second, this study must be extended to encompass indirect effects. One way to address the first limitation would be to consider specific carbon prices by region and by sector. In that way, OECD (2018) provides a rich database of Organisation for Economic Cooperation and Development (OECD) countries[49]. Concerning the indirect impact of a carbon price, it is necessary to introduce the scopes 2 and 3. However, this type of study requires developing more advanced microeconomic models, for example focusing on a particular sector, to take into account elasticity of demand in that sector, supply chain, etc. We reiterate that a branch of the literature already sets the mathematical specification for the diffusion effects into the financial system and real economy (Battiston *et al.*, 2017; Cahen-Fourot *et al.*, 2019). Therefore, adding a diffusion module to study the propagation of the tax is an interesting next step.

Scenarios and horizons Our results suggest that, in the conditions posed by the shared socio-economic pathway 2 (SSP2, considered as *the middle road*), only those scenarios associated with a concentration pathway of 1.9 $w.m^{-2}$ (which corresponds to 1.5℃) and 2.6 $w.m^{-2}$ (which corresponds to 1.8℃) generate important credit risk by 2060 in the three sectors (in a SSP2-34 scenario, the risk is concentrated in the utilities sector). The carbon price levels associated with these scenarios (USD 780 by 2060 in a SSP2-19 scenario) are far from the current carbon prices (USD 1.24 in average in 2018). In the medium term, credit risk associated with a *trend* or an *acceleration* scenario is concentrated in the utilities sector and involves less than 5% of the companies by 2023. From a financial institution perspective, these results suggest the global credit risk associated with the direct impact of carbon price remain low in the medium term. However, a bottom-up approach helps identify some utilities companies at risk in the medium term.

Given the static nature of our exercise, i.e. the assumption that companies do not adapt their GHG emissions or business model[50], as well as the use of deterministic scenarios these results must be interpreted with caution.

This approach proposes to lay the foundation stone in order to fill the gap between the academic narrative describing the plausible futures (see Appendix C) and financial models. We reiterate that, in an operational configuration of credit risk assessment, this approach could help highlight a company at *transition risk* but must be supplemented by an analysis of the decarbonization strategy of the issuer, among other information.

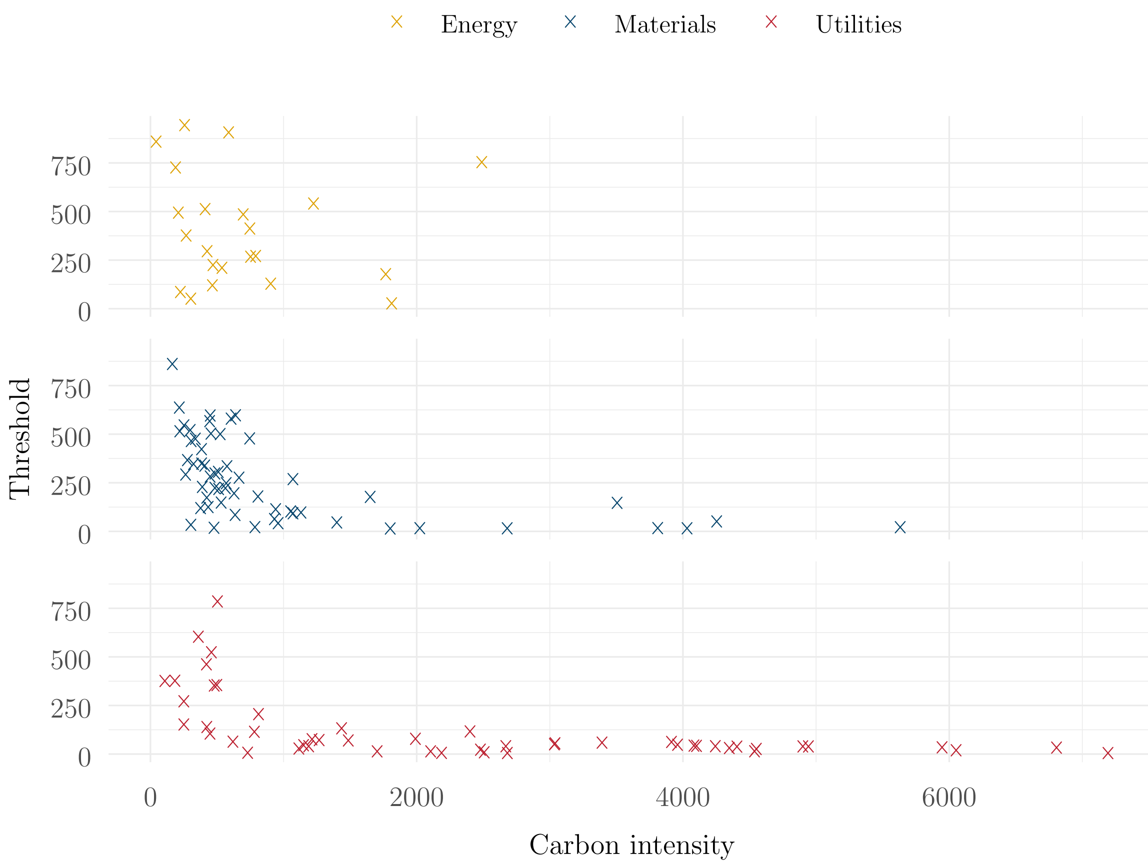
New indicator for carbon risk Emerging literature aims at defining a metric that optimally translates carbon risk. Absolute emissions is a measure that is hardly comparable to a financial metric, as it does not encompass information about the profitability of the underlying business.

[49]We provide an example for France in Table 4 on page 44. However, the data is outdated (published in 2015 with effective price of 2014) and the sectoral mapping is not identical.

[50]Note that companies' EBITDA projections could be improved with more sophisticated models. As this paper focuses on the incorporation of the carbon price into financial risk models, we remain schematic on the economic projection side.

Therefore, carbon intensity, defined as scope 1 and 2 emissions / revenues, is the most commonly used risk indicator. However, carbon intensity ignores the firm's economic model and financial structure. We therefore propose to introduce the following metric. For each of the companies of our sample, we compute the carbon price that would raise the probability of default to 50%[51]. Figure 13 shows the relation between this carbon price threshold and carbon intensity. While there is an overall inverse correlation between the two indicators, the relation is not strictly linear. For example, the most intensive company in the energy sector also has one of the highest carbon price threshold (i.e. a lower associated credit risk). Such an indicator may also be easier to understand for financial analysts, as it can be compared with current and future carbon prices.

Figure 13: Carbon intensity and carbon price threshold



There are numerous limitations on the use of this threshold. From a practical perspective, the theoretical Merton model used for our computation is highly schematic, and these thresholds must therefore be interpreted with caution. Another avenue for development would be to replicate the approach with an empirically calibrated credit risk model. We show, however, in Appendix D,

[51]This threshold was arbitrary chosen in this exercise. In empirically calibrated credit risk models, it can be defined from observations.

particularly in Figure 18, that the probability of default and distance to default are historically representative enough of the variation of the credit default swap. Therefore, this model provides a representative answer despite its simplicity.

7 Conclusion

Transition risk has already been flagged by regulators and financial institutions (Campiglio *et al.*, 2018), but little research has been done on the related credit risk at the company level (Howard & Patrascu, 2017; Monnin, 2018; UNEP, 2019). In this study, we focus on one policy and regulation risk, a rise of the carbon price, by taking a prospective and bottom-up approach on a sample of international companies. We focus on the direct effects of the tax, but discuss how to encompass further dimension in a similar modeling framework. We explore how the impact of a carbon price increase on credit risk varies within sectors and scenarios. In order to take into account the *tragedy of horizon* pointed out by Carney (2019), our study includes a medium-term (five-year) and a long-term (40-year) analysis. Following the recommendations of TCFD (2017) and the previous study of Vermeulen *et al.* (2018), Vermeulen *et al.* (2019), our approach is based on IPCC scenarios and on current effective carbon prices. Our main results are threefold:

- We find a sectoral effect. Utilities, materials and energy sectors are particularly impacted. Utilities companies experience higher losses on average, but these losses are also more heterogeneous within the sector. Materials and energy sectors have similar behavior, while materials companies are impacted earlier and more heterogeneously. While this result derives from the fact that we limit our study to scope 1, it remains informative in terms of intra-sectoral distributions.

- The risk is sensitive to scenarios and horizons. The global credit risk associated with the direct impact of carbon price remains low in the medium-term, with the exception of the utilities sector, where 5% of the companies have their probabilities of default move above 10% in an acceleration scenario. In the long term, while the SSP2-34 scenario (which corresponds to 2.2℃) only impacts utilities, the SSP2-26 (1.8℃) and SSP2-19 (1.5℃) scenarios generate credit risk for materials and energy companies, and, to a less extent, for industrials.

- We propose a new indicator for carbon risk. For each company, we computed the carbon price threshold that would raise the probability of default to 50%. While there is a global inverse correlation between this carbon price threshold and the carbon intensity (scope 1 and 2 emissions / revenue), the relation is non-linear. This result suggests that the economic and financial structure of the firm matters when measuring carbon risk. In practice, measuring this risk through a carbon price threshold may also be easier to understand for financial analyst as it can be compared with current and future carbon prices.

Our study contributes to the emerging literature on climate-related credit risk and aims to provide a framework that can be applied by future academic research and by financial institutions. We suggest that, while average credit risk is low in the medium term, some utilities companies may already be impacted and that only a bottom-up approach can identify them. On the other hand, it seems that rising the carbon price (acceleration scenario) will not lead to many defaults, suggesting that there is room for policy to strengthen its efforts to mitigate climate change. Our work is obviously subject to many limitations, some of which could be addressed in future developments. Sector-specific and dynamic studies would better take into account the indirect effects of a carbon price through scope 2 and 3 emissions, as well as the decarbonization strategies of companies.

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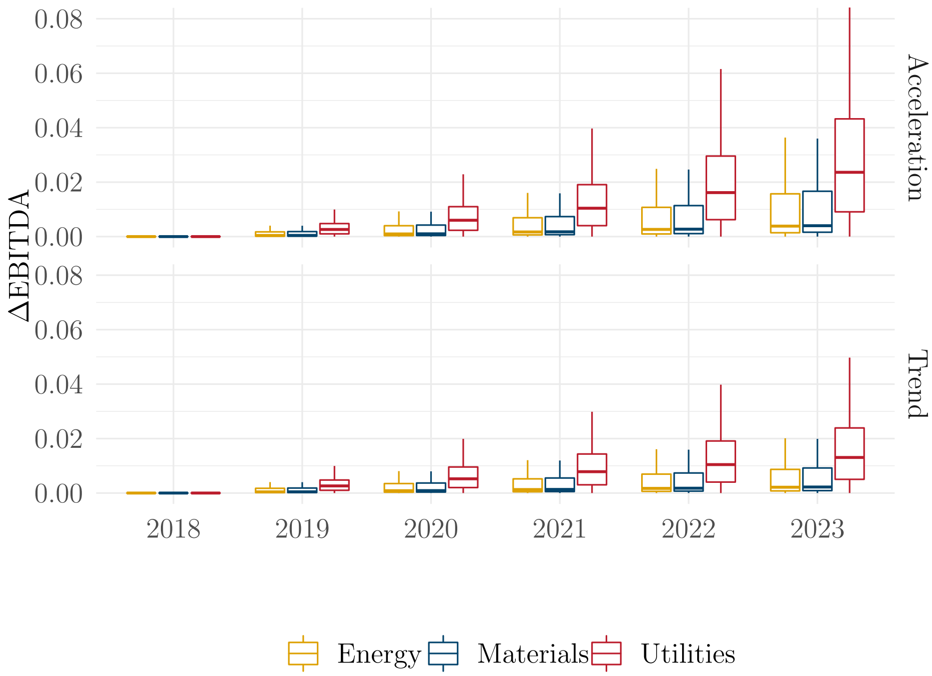
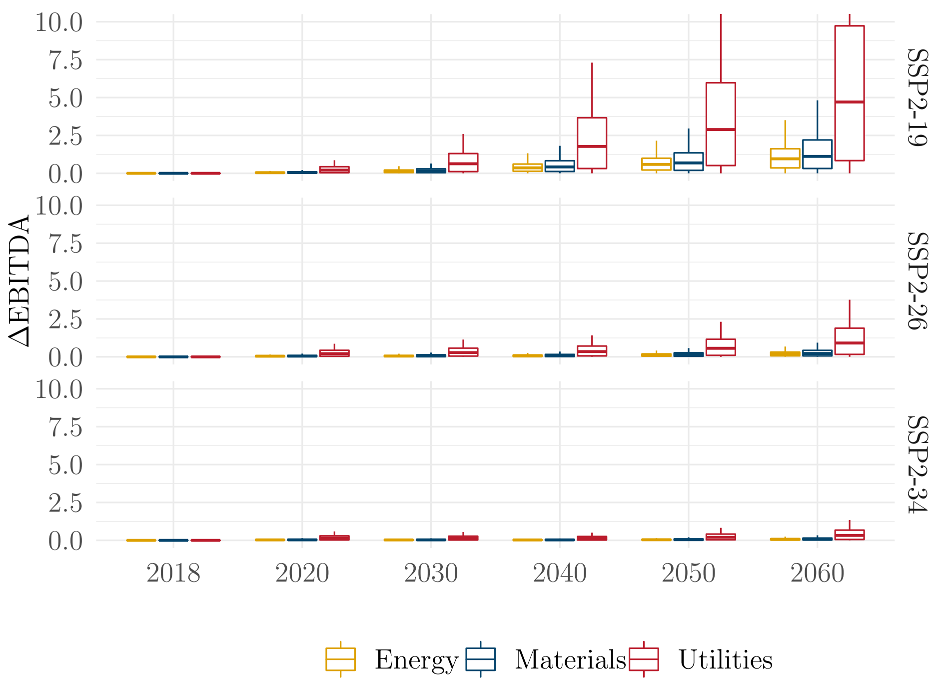
A Notations

Indices	
$i \in \mathcal{U}$	Company
$j \in \mathcal{M}$	Country
k	Scenario
t	Date
Variables	
CC_i	Total carbon expense (cost) of an entity
CP	Local representative carbon price
D_i	Total dept
DD_i	Distance to default
PD_i	Probability of default
E_i	Equity value
EBITDA_i	Earnings before interest, taxes, depreciation, and amortization
r	risk free rate
Scope_{1_i}	Direct reported emissions
T	Maturity (Merton)
$\sigma_{v,i}$	Asset volatility
$\sigma_{e,i}$	Equity volatility
V_i	Total asset value
ξ_i	Regulatory shock on EBITDA

B Complementary materials

Figure 14: Impact on EBITDA distribution





Above: Medium-term impact.
Below: Long-term impact.

C Long-term scenarios

The current database used by IPCC (2018) is composed of more than 400 scenarios. Some of these scenarios can be classified around a framework composed of two dimensions (Van Vuuren *et al.*, 2014).

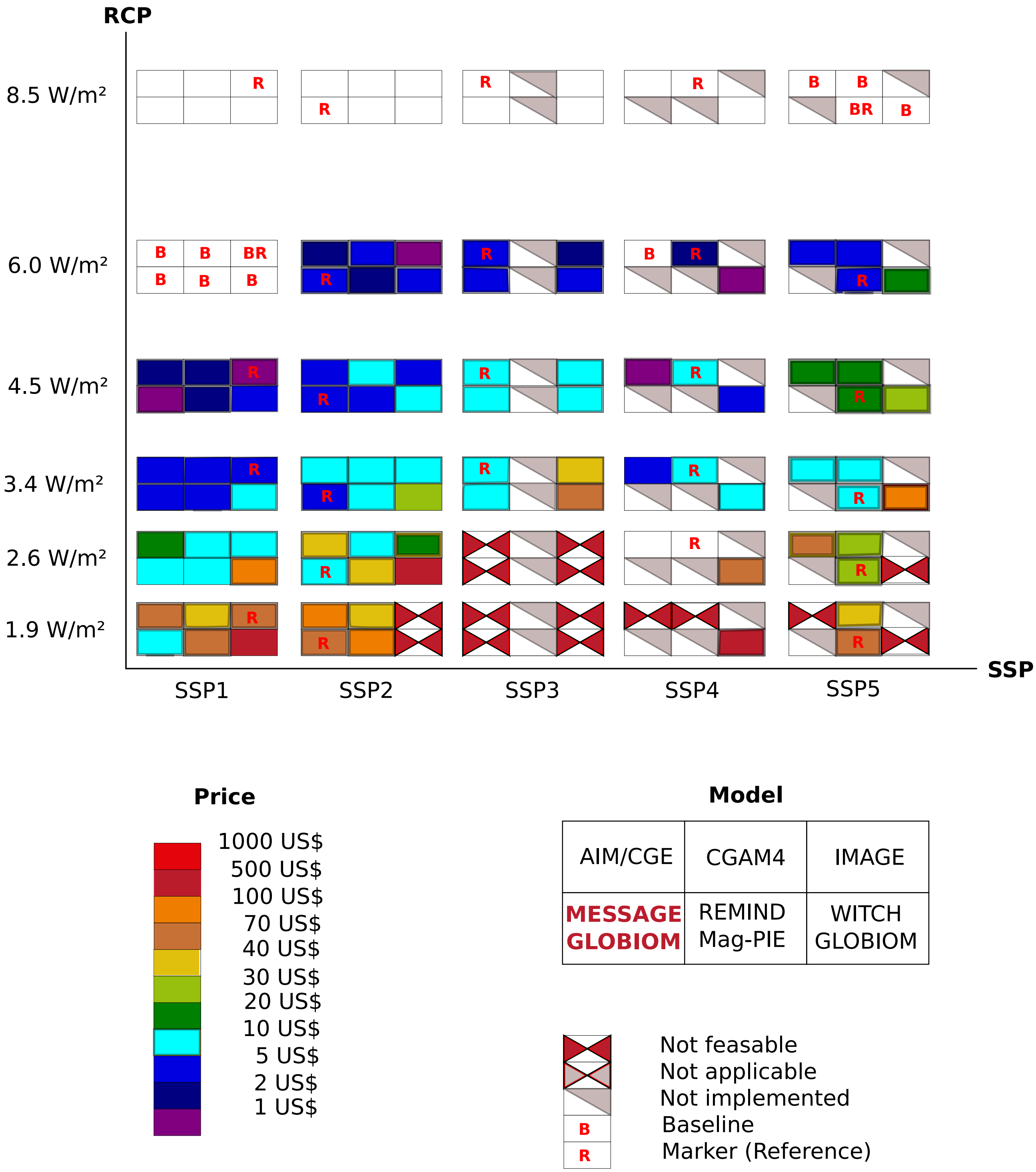
Shared socio-economic pathways The shared socio-economic pathways (for an overview, see Riahi *et al.* (2017)) represent five different pathways about future socio-economic developments independent of explicit additional policies and measures to limit climate change. The study relies on the SSP2 scenario. This scenario leads to steady emission concentration increases over the 21st century, with projected end-of-century warming nearing 4C relative to pre-industrial levels. On the other hand, SSP2 also shows that global mean temperature increase can be limited to below 2C, pending stringent climate policies throughout the world (Fricko *et al.*, 2017). This scenario is a narrative. SSP2 Middle of the Road, medium challenges to mitigation and adaptation, is described as follow:

> "*The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain*" (Riahi *et al.*, 2017, p. 157).

As SSP quantitative variables are run by different models, marker SSPs were selected as representative of the broader developments of each SSP. The SSP2 marker is provided by the model MESSAGE-GLOBIOM (Fricko *et al.*, 2017). The main quantitative variables translating the narrative into quantitative are population growth, urbanization, GDP, GDP per capital and GINI. As represented in Figure 15, not all configurations are possible. We chose SSP2 because the narrative is relatively stable regarding the history and out of the six models, three were able to reach the objective of maintaining the temperature rise below 1.5°C.

Representative Concentration Pathways On the other hand, Representative Concentration Pathways (RCP) represent different forcing levels in 2100. In order to provide comprehensive results, we selected four scenarios that cover the range of carbon price given by all models and scenarios of the IPCC database.

Figure 15: Scenario socio-economic and concentration configurations



Original source: Rogelj *et al.* (2018)

Table 3: Scenario Selection

k	IPCC ref.	RCP	Mean temperature 2081-2100*	MAGICC model
LTHIG	SSP2-19	1.9W/m^2	1.5℃ with approximately 66% probability	
LTMED	SSP2-26	2.6W/m^2	1.6℃ +- 0.4	1.8℃
LTLOW	SSP2-34	3.4W/m^2		2.2
-	SSP2-45	4.5W/m^2	2.4℃ +-0.5	2.6℃
-	SSP2-60	6.0W/m^2	2.8℃ +- 0.5	3.2℃
LTBAS	SSP2-Baseline	6.5W/m^2		3.8

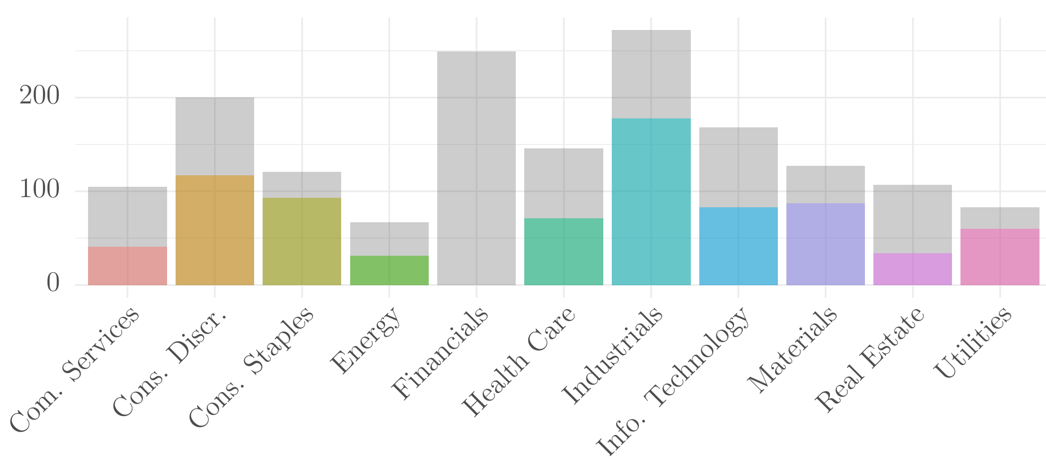
* Above 1850-1900 level.

Source: Collins *et al.* (2013) (p.1056), Rogelj *et al.* (2018) and Fricko *et al.* (2017) (MAGICC climate model).
Scenarios below 1.5℃: IPCC (2018), Rogelj *et al.* (2018).

D Methodology and coverage

Coverage and data quality Coverage of global universe by environmental, social and governance data providers is a well-known issue in finance (Campiglio *et al.*, 2018). In this paper, we use the CDP dataset on the MSCI World index, a universe constituted of large cap companies that minimizes the problem (covering mid and small caps remains a challenge). Figure 16 represents the coverage of our study.

Figure 16: Companies with financial data and regional ghg emissions split available



Different carbon prices and mechanism for different sectors In this paper, the price was defined using IPCC (2018) for the long-term analysis and through a trend approach for the medium-term analysis. We reiterate that, in practice, the effective carbon price is more representative of the risk than the social cost of carbon. The question becomes who pays this *effective price*. Unlike models, the reality is subject to specific time bounded deals making the real average priced paid by companies much lower than the officially disclosed value of the tax or allowance of the ETS, particularly in the case of monopolistic situations (which is often the case for utilities and can be for materials companies).

If we ignore these specific agreements, each country/sector can be subject to a tax and an ETS. Each of them is characterized by a price and by a percentage of emissions covered. As there can be an overlap between taxes and quotas, we must postulate that companies that are subject to an ETS will be dispensed form taxes (as this is the case in France). Consequently the *average price* becomes:

$$\mathrm{CP}(j,s) = \mathrm{Cr}(j,s) \times r_{Cr}(j,s) + \tau(j,s) \times \ \min(r_\tau(j,s); 1 - r_{Cr}(j,s))$$

where s is the sectoral index, j the country, and Cr the allowance. The carbon price defined this way is an average exposure but is in fact not paid by any actors, strictly speaking. Actors are either paying tax, which is much higher, quotas, or nothing. However, at a portfolio level this indicator as a representative value of the risk.

The Organisation for Economic Cooperation and Development (OECD) provides this type of statistic at a macro sector level. For instance, the breakdown of emissions in France is given in Table 4. These data being partly outdated, some updates must be applied to use this type of data. This table contains, for each sector in each country, total emissions, the price of the tax $\tau_{s,c}$, the ratio of emissions concerned r_τ, the price of the carbon credit given by the regional referring ETS $\mathrm{Cr}_{s,c}$ and, again, the ratio of emissions concerned r_{Cr}.

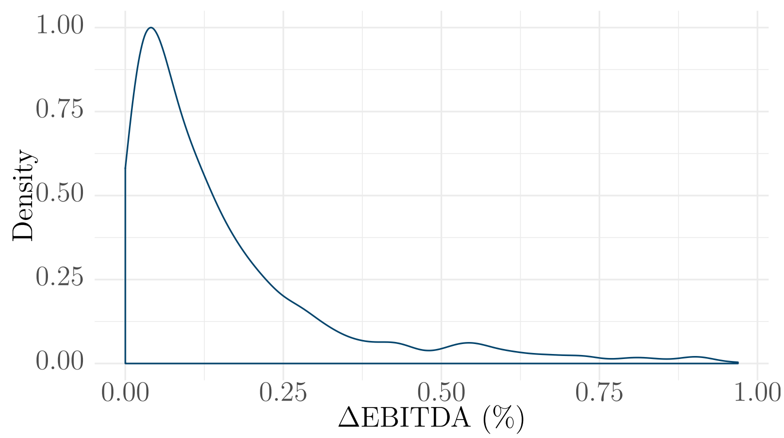
Table 4: France taxation system EOCD (2015)

Country	Sector	CO2 Emissions	$\tau_{s,c}$	r_τ	$\mathrm{Cr}_{s,c}$	r_{Cr}
France	Agriculture & Fishing	11394	24.41	88.91%	7.24	0.07%
	Electricity	27113	12.36	100.00%	7.24	96.31%
	Industry	102676	8.28	54.98%	7.24	59.21%
	Offroad transport	4798	21.27	10.99%	7.24	60.47%
	Residential & Commercial	114853	18.67	37.57%	7.24	0.69%
	Road transport	127112	180.16	99.84%	0.00	0.00%
France	Total	387945	63.75	68.12%	1.69	23.36%

Economic impact and dynamic version The economic impact is measured as a variation of the EBITDA. As a reference we provide the standardized variation distribution in Figure 17. An EBITDA variation over 20% is rare and therefore, can be considered as an extreme risk.

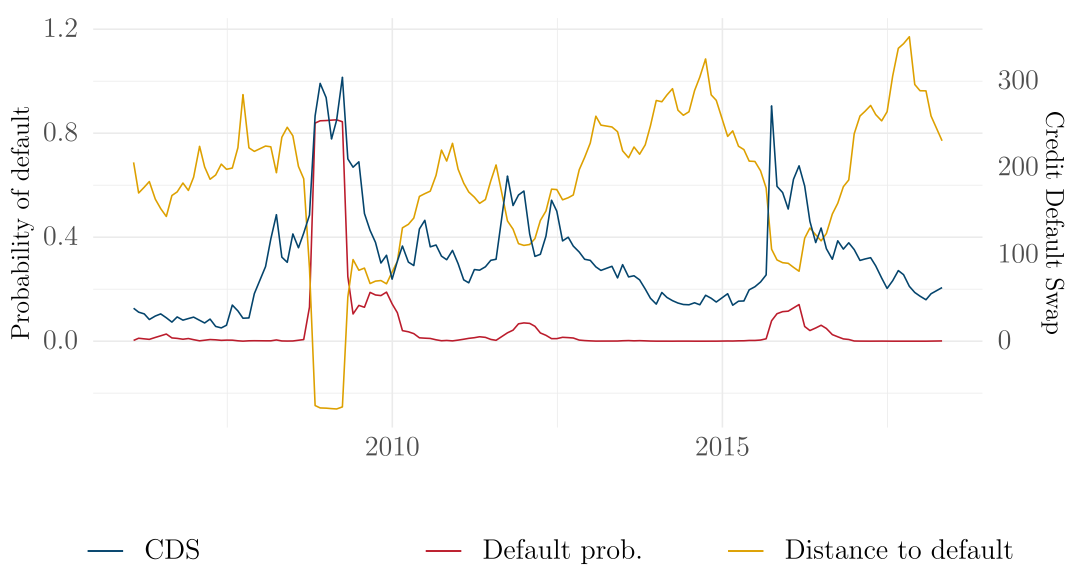
Merton Model (1974) A reference model to determine if a company will be able to retain solvency was developed by Merton (1974). In his framework, bankruptcy occurs if the total asset value of the company at maturity is less than the face value of the debt. This model relies on multiple assumptions: European options are exercised only at maturity, no dividends, markets

Figure 17: EBITDA variation distribution between 2017 and 2018



are efficient, no commissions or fees included, underlying stocks' volatility and risk-free rates are constant and stocks returns are regularly distributed. The materiality of this study for financial practitioners, lies on this model representativeness of the *real risk*. We can see on the example of Figure 18 that the metrics computed in our study on the historical data of one company corroborate the observed historical value of the credit default swap (CDS) for the same company. In general, it is accepted that the Merton model has indicative value, at least when comparing two corporate bonds *ceteris paribus*.

Figure 18: Merton example of application



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