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Cascading Effects of Carbon Price through the Value Chain: Impact on Firm's Valuation

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Abstract

To avoid the worst climate change scenario, Greenhouse Gas (GHG) emissions should be reduced drastically during the next decades. Placing an adequate price on GHG emissions, either through the adoption of a carbon tax or an internal carbon pricing mechanism by firms, is key to internalize the external cost of climate change.

In this paper, we assess the impact of carbon pricing in a global framework considering both the cost of corporate idiosyncratic emissions and their cross-sector diffusion. The impact on corporate valuation is shared among intensive companies and less intensive ones through the introduction of a carbon cost pass-through in a sector diffusion model, based on a World Input-Output table. Focusing on the constituents of the MSCI World Index, we show that apart from the usual carbon-intensive sectors, such as Energy, Utilities and Materials, less carbon-intensive ones, such as Industrials, Consumer Staples, Consumer Discretionary or Information Technology can contribute significantly to the global risk, due to the expected pass-through of the carbon cost in the value chain. World indices could experience large changes in their investment universe and sector composition.

Keywords: Transition risk, Carbon price, Risk diffusion, World input-output table, Cascading effect, Leontief price model.

JEL classification: C67, E22, Q5

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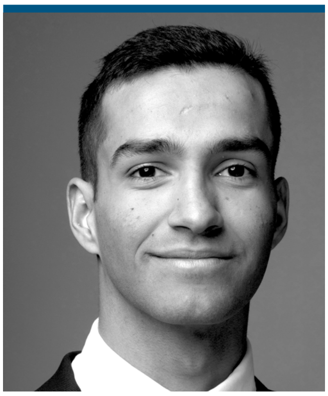

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1 Introduction

In 2021, the Intergovernmental Panel on Climate Change (IPCC) released the First Chapter of its Sixth Assessment Report (AR6), highlighting the need to reach net-zero emissions as soon as possible to avoid the disastrous effects of climate change. At COP26 in November 2021, governments shared the need to take concrete and radical measures to cut global GHG emissions and reach this objective. Many countries, including members of the European Union, the United States and China, strengthened their carbon reduction targets prior to or during COP26.

The need to transition towards a low-carbon economy is now shared among governments and there is no doubt that this will affect all economic agents. Among the tools available to governments, investors and corporations to achieve those pledges, carbon pricing schemes are likely to play a key role, whether they take the form of direct carbon taxes, emissions trading systems[1], or the use of internal carbon pricing models by corporations and by financial analysts who evaluate them (Postic & Fetet, 2021; Ramstein *et al.*, 2019). By placing an adequate price on GHG emissions, carbon pricing will help decision makers internalize the external cost of climate change and set economic incentives to develop clean technology. In particular, investors can use carbon pricing to analyze the potential impact of climate change on their investment portfolios and efficiently reallocate capital towards low-carbon or climate-resilient activities.

In this paper, we focus on assessing the effect of carbon pricing on corporate income statements. Although the cost of carbon could be incorporated by firms through different mechanisms, we consider the case of introducing a carbon pricing mechanism that would impact the operating cost of emitting corporations. We study the cross-sector diffusion of this cost through the value chain and its impact on consumers' demand and firms' earnings.

A significant amount of research has been conducted on climate stress testing frameworks and methodologies (Alogoskoufis *et al.*, 2021; Battiston *et al.*, 2017; Jung *et al.*, 2021). Among the few papers assessing the climate risk impact at the firm level, Bouchet and Le Guenedal (2020) develop a methodology to assess the credit risk sensitivity of debt issuers to a carbon tax. Based on Scope 1 emissions, they estimate the impact of a carbon tax on firms' EBITDA[2], and its medium and long-term impact on corporate issuers credit risk. Reinders *et al.* (2020) use a Merton contingent claims model to assess the impact of a carbon tax shock on the market value of corporate debt and residential mortgages. Berner *et al.* (2021) introduce a measure of systemic climate risk, which is a financial institution's expected capital shortfall in a climate stress scenario and develop a stress testing procedure to measure the resilience of financial institutions. A limitation of the above-mentioned approaches, however, is that they only tackle direct impacts of carbon taxation on issuers and do not consider how this tax is diffused in the economy through indirect costs via a firm's suppliers. We propose to go further and to introduce a cross-sector diffusion methodology.

It is widely acknowledged that transition and physical risks can cascade through countries and sectors and spread among unaffected parts of the economy (Naqvi & Monasterolo, 2021; Raymond *et al.*, 2020). Focusing on the sector diffusion of transition risks, Cahen-Fourot *et al.* (2019) use an Input-Output (IO) model to assess the exposure of economic systems to capital stranding

[1] In 2021, the price of the European Union Emissions Trading System (EU-ETS) passed the symbolic threshold of EUR 50 per tCO_{2eq}, demonstrating that market participants anticipate more stringent regulations on corporate carbon emissions.

[2] Earnings Before Interest, Taxes, Depreciation and Amortization

cascades triggered by the reduction of fossil fuel production and use. They estimate how supply-side capital stranding might propagate across sectors and countries via production networks. In particular, they provide sector-level estimates of the exposure of capital stocks to the risk of becoming unusable due to a marginal loss of primary inputs employed in a country's fossil fuel sector. Gemechu *et al.* (2014), Mardones and Mena (2020), and Muñoz-Zamponi and Mardones-Poblete (2016) develop a sector-level stress testing method based on the Leontief (1970) approach, allowing the effects of the diffusion of carbon tax costs to be measured across various sectors in the economy. For example, Mardones and Mena (2020) estimate the impact of environmental taxes on carbon emissions and local air pollutants introduced in Chile, and use the environmental extension of the Leontief (1970) price model and micro-simulations to analyze the main economic, environmental, and distributive effects of this policy.

In these applications, however, the sector-level results cannot be used to evaluate the heterogeneous impact of the introduction of a carbon price on each specific firm. In this paper, we propose an extension of the above-mentioned framework to estimate the shock suffered by a given firm, considering both the costs of (1) firm-level direct carbon emissions and (2) indirect emissions, whose costs propagate through the various sectors and countries because of their trading links. These costs have a price impact on the goods and services produced, and affect the final consumers' demand (Calvet & Marical, 2012), which in turn affects the firms' revenues and their earnings. Our empirical investigation derives the impact of the introduction of a carbon price on firms' earnings on the universe of firms belonging to the MSCI World Index. We consider three distinct scenarios for the carbon price, set to be equal to USD 50, 100 or 300 per ton of CO_{2eq}. This corresponds broadly to the suggested values for the SSP2-26 (1.8°C) in 2030, SSP2-19 (1.5°C) in 2030 and SSP2-19 (1.5°C) in 2040.

Our contribution to literature is twofold. First, our research is, to our knowledge, the first to apply an Input-Output framework to estimate the effect of a carbon price diffusion at the firm level. Second, while most of the Input-Output analyses are conducted for a single country, (Gemechu *et al.*, 2014; Mardones & Mena, 2020; Muñoz-Zamponi & Mardones-Poblete, 2016), we assess the impact of carbon price on firms across a large set of countries, both developed and emerging, which requires us to incorporate cross-country dependencies between sectors. We find that apart from the high carbon-intensive sectors, such as Energy, Utilities and Materials, several low carbon-intensive sectors could be significantly impacted by the introduction of a carbon price, because of its cascading effect through the firms' supply chain. The three most carbon intensive sectors, Energy, Utilities and Materials could suffer an earnings shock of between than 7% and 12%, with the introduction of a carbon price at USD 50. However, less intensive sectors such as Information Technology, Consumer Discretionary or Consumer Staples could also incur a non-negligible shock, close to 4%.

If we consider two alternative scenarios of a carbon price at USD 100 or USD 300, in line with temperature scenarios of 1.5°C in 2030 and in 2040, respectively, these effects could be exacerbated. The average earnings shocks for carbon-intensive firms could reach 22% and 47%, respectively, for the most impacted sector (Utilities). In these two scenarios, less intensive sectors would also be heavily impacted. For example, Information Technology could be subject to earnings shocks of 8% and 23% respectively. With simple hypotheses on the relationship between earnings and the firm's value, we derive a plausible scenario for the evolution of each sector's market share in the MSCI World index. The introduction of a carbon price could have a substantial impact on the investment universe, distorting its sector composition towards less carbon intensive sectors such as Financials and Health Care.

The paper is structured as follow. Section 2 presents the model, Section 3 the data used and Section 4 our results. Section 5 provides some concluding remarks.

2 Model

We aim to measure the impact of carbon pricing on firms' value. Carbon pricing will change consumer behavior by incentivising the consumption of low-carbon alternatives versus more carbon-intensive products. The model derives the impact of carbon pricing on firms' value by computing the change in demand for a product resulting from a higher selling price. Indeed, firms are likely to increase their selling prices in order to absorb the rising marginal costs due to the introduction of a carbon price. These carbon costs are likely to diffuse across the economy. Our model estimates the carbon cost pass-through across various sectors and countries of the World economy.

2.1 Cross-sector diffusion model

Leontief (1970) introduced Input-Output models to quantify and represent the interdependencies between various sectors in an economy or different regional economies. In what follows, we present the way production functions are modeled in the original framework and the way this framework can be applied to estimate environmental externalities.

Leontief production function and intermediary sector consumption Following Leontief (1970), we consider a fixed-proportions production function. This means that the factors of production used to produce a given good or service are supposed to be fixed and constant, as there is no substitutability between factors. In this framework, each sector j makes use of the inputs from sector i in the fixed proportion:

$$a_{ij} = \frac{x_{ij}}{x_j} \quad 1 \leq i \leq n \quad 1 \leq j \leq n \tag{1}$$

where x_j is the production of the j-th sector and $x_{i,j}$ denotes the quantity sold by the i-th sector to the j-th sector[3].

Based on the assumption that the final demand net of imports for sector i y_i is exogenous and that the production of sector i, x_i and its demand for inputs x_{ij} are endogenous, the Input-Output model can be represented in a matrix form as:

$$X = AX + Y \quad X \in \mathbf{R}^{n\times 1} \quad A \in \mathbf{R}^{n\times n} \quad Y \in \mathbf{R}^{n\times 1} \tag{2}$$

where:

$$X \equiv \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \quad A \equiv \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \quad Y \equiv \begin{pmatrix} y_1 \\ \vdots \\ y_n \end{pmatrix} \tag{3}$$

[3]Depending on the data source, these tables can be found in quantity ratios or monetary value ratios. In practice, it is easier to find data in monetary value as they are easier to measure than quantities. When in monetary value, the matrix A components (a_{ij}) becomes: $\frac{x_{ij}p_i}{x_j p_j}$.In this paper, we develop the theory using tables in quantity ratios. Fortunately, under certain assumptions described below, it is possible to use the more common monetary tables.

Equation (2) can be written as:

$$X = (I - A)^{-1}Y \tag{4}$$

The matrix $(I - A)^{-1}$ is called the Leontief inverse. The element in position ij of this matrix represents the impact of a change in final demand in the j-th sector on the i-th sector. These constant proportions parameters are retrieved from an Input-Output table (in our case, the World Input-Output database, WIOD) in the form provided Table 1.

Table 1: Illustration of WIOD dataset (normalized in %)

	USA				
	Sectors	(1) Crop and animal production	(2) Forestry and logging	(3) Fishing and aquaculture	···
USA	(1) Crop and animal production	0.159	0.018	0.018	···
	(2) Forestry and logging	0.025	0.041	0.041	···
	...	...	...	... ...	

Source: World Input-Output database (WIOD)

Table 1 should be understood as follows: to produce 1 dollar of output, the crop and animal production sector in the United-States buys 0.159 cents of products from itself and 0.018 cents of products from the forestry and logging (in the United States). In general, at the World level, the incidence matrix is very sparse. Figure 13 on page 38 illustrates some sector dependencies in the United-States, and Figure 14 represent the aggregated dependencies between countries. The data source used to represent these dependencies is further described section 3.1.

Application to the estimation of environmental externalities The Leontief (1970) approach can be applied to estimate environmental externalities, and in particular GHG emissions. Each sector's total attributable emissions includes direct (Scope 1) and indirect emissions related to the required inputs for its activity from other sectors (i.e. upstream emissions: Scope 2 and, to some extent, Scope 3). At a sector level, the direct emission intensities are supposed to be inversely proportional to the production: $g_i = \frac{c_i}{x_i p_i}$, where c_i is the direct absolute carbon emissions and g_i the direct emissions intensity (expressed in tCO_{2e}/mUSD) of the i-th sector. The vector of total (direct and indirect) upstream emission intensities M can be calculated using the Leontief inverse (Mardones & Mena, 2020). Noting $G = (g_1, .., g_n)^T$ the vector of sector direct GHG emission intensities, we have:

$$M = (I - A^T)^{-1} \times G \tag{5}$$

Let φ be the carbon price in USD/tCO_{2e}, which is supposed to be fixed. By multiplying M by the scalar φ we obtain the vector of carbon price rate representing the amount paid per dollar of output in each sector. Let $\mathcal{E} = (\varepsilon_1, ...\varepsilon_n)^T$ denotes this carbon price rate vector, we have:

$$\mathcal{E} = \varphi \times M \tag{6}$$

where the coefficient ε_i represents the mean carbon cost of a dollar unit of production from the sector i.

Leontief price model The Input-Output approach allows to analyze the price structure of goods and services offered in each sector of the economy. Leontief (1970) assumes that firms in a given sector set their price by taking into account their marginal costs and not the variation of demand ('cost-push' price model)[4]. When there is no carbon price, and following Mardones and Mena (2020) and Mardones and Muñoz (2018) the unitary price of a the i-th sector can be defined as a function of the other sector's unitary prices, of its ad valorem taxation rate: τ_i and of its value-added produced v_i, depending on the costs of labor and capital:

$$p_i = (1+\tau_i)\left[\sum_{j=1}^{n} p_j a_{ij} + wl_i + rk_i\right] \tag{7}$$

We can simplify these expressions above with by noting, $\forall i \in [1;n]$, $v_i = wl_i + rk_i$.

$$p_i = (1+\tau_i)\left[\sum_{j=1}^{n} p_j a_{ij} + v_i\right] \tag{8}$$

where w is the price of labor, l_i is the coefficient of labor intensity, r is the cost of capital, k_i is the coefficient of capital intensity[5]. In matrix form, Equation (8) can be rewritten:

$$P = (I - (A_\tau)^T)^{-1} V \tag{9}$$

with $V = (v_1, .., v_n)^T$ the vector of value added in each sector, and the matrix A_τ^T, is the transpose of the matrix of *direct requirements*, reporting the proportion in which an input from a given sector is demanded to generate a product unit of another sector:

$$(A_\tau)^T \quad \equiv \quad \begin{pmatrix} a_{11} + (1 - \frac{1}{(1+\tau_1)}) & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} + (1 - \frac{1}{(1+\tau_n)}) \end{pmatrix} \tag{10}$$

The implementation of a carbon pricing mechanism modifies unitary prices. Under these new assumptions, sector prices will be equal to the average cost of production, which encompass the carbon cost. Let p_i^ε denote the new unitary price of sector i affected by carbon pricing. Under the assumption that the cost of labor and capital (and thus the value added) are the same before and after the introduction of the carbon price, p_i^ε can be written:

$$p_i^\varepsilon = (1+\epsilon_i)(1+\tau_i)\left[\sum_{j=1}^{n} p_j^\varepsilon a_{ij} + v_i\right] \tag{11}$$

In matrix form, this Equation can be rewritten:

$$P(\varepsilon) = \left[(I - A_\tau^\varepsilon)^{-1}\right]^T V \tag{12}$$

[4]See appendix B.

[5]Note that because our analysis is run at the World level, a slight difference with Mardones and Mena (2020) is that we do not have to consider the price of imports, the coefficient of imported inputs intensity and the tariff on imports (supposed to be comprised in the tax rate at the country/sector level).

The matrix A^{ε}_{τ} of *direct requirements* is thus slightly modified to account for the carbon price impact. It includes both carbon price and ad-valorem tax rates (respectively noted ε and τ). Its expression thus becomes (Mardones & Mena, 2020):

$$(A^{\varepsilon}_{\tau})^T \equiv \begin{pmatrix} a_{11} + (1 - \frac{1}{(1+\tau_1)(1+\varepsilon_1)}) & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} + (1 - \frac{1}{(1+\tau_n)(1+\varepsilon_n)}) \end{pmatrix} \tag{13}$$

Using Equation (9) to express the exogenous value added V as a function of the price vector $P = (p_1, .., p_n)$ when there is no carbon pricing mechanism in place, the vector of sector prices accounting for carbon pricing follows from Equation (12):

$$P(\varepsilon) = \left[(I - A^{\varepsilon}_{\tau})^{-1}\right]^T (I - (A_{\tau})^T) P \tag{14}$$

The introduction of a carbon price affects prices for consumers. If we further assume that the monetary value of what is purchased by consumers at the sector level remains constant before and after the introduction of the carbon price,[6] – i.e. the price elasticity of demand of all sectors is also constant equal to one – we derive from $P(\varepsilon)$ and P a *sector impact ratio* defined as the ratio between the production after environmental taxation on the original production. The impact ratio of the i-th sector (x^{ε}_i) can be calculated as:

$$\mathcal{R}_i = \frac{x^{\varepsilon}_i}{x_i} = \frac{p_i}{p^{\varepsilon}_i} \tag{15}$$

By further assuming that equilibrium sector prices before the introduction of carbon pricing are normalized and equal to 1[7] (i.e. $\forall i \in [1; n], p_i = 1$), we get that:

$$\mathcal{R}_i = \frac{1}{p^{\varepsilon}_i} \tag{16}$$

2.2 Firm-level estimation

Our objective is to calculate an impact ratio for each firm We have granular information on firms' specific direct carbon intensities. The carbon indirect exposure of each firm however (i.e. the upstream impact of the carbon price on the firm's suppliers) can only be defined at the sector level.

Considering an issuer k part of the i-th sector, with a direct emission intensity g^k, we hypothesize that the vector of direct plus indirect emission intensities m^k is defined as the sum of an indirect carbon intensity estimated at the sector level and a direct carbon intensity. It can be written as follows:

$$m^k_i = \underbrace{m_i}_{\text{Sector direct + indirect intensity}} + \underbrace{\left(g^k - g_i\right)}_{\text{Issuer direct intensity relative to its sector}} \tag{17}$$

[6]This is a strong assumption. It would be possible to calculate empirically the elasticity of substitution i.e. a price elasticity of demand for each sector, or even for each issuer by taking into account its market power. We leave this development for further applied research.

[7]This assumption also allows us to use IOTs in monetary value because then: $\frac{x_{ij}}{x_j} = \frac{x_{ij}p_i}{x_i p_j}$

where m_i is the sector direct and indirect (upstream) intensity, g^k is the direct emission intensity of issuer k belonging to sector i. We then calculate an adapted carbon pricing rate vector ε^k at the issuer level:

$$\mathcal{E}^k = \varphi \times m^k \tag{18}$$

Then, Equations (14) and (16) become respectively:

$$P(\varepsilon^k) = \left[(I - A_\tau^{\varepsilon^k})^{-1}\right]^T \times (I - A_\tau^T) \times P \tag{19}$$

$$\mathcal{R}_i^k(\varepsilon^k) = \frac{x_i^{\varepsilon^k}}{x_i} = \frac{p_i}{p_i^{\mathcal{E}^k}} \tag{20}$$

where $\mathcal{R}_i^k(\boldsymbol{\epsilon^k})$ is the impact ratio measuring the reduction in demand due to the introduction of the carbon price on the issuer k.

Finally, let $\text{EBITDA}^k(0)$ be the firms' earnings before the introduction of the carbon price (we suppose the carbon price to be equal to 0 à that time)[8] and $\text{EBITDA}^k(\varphi)$ the earnings impacted by the introduction of a carbon price φ through the value chain (20), we make the hypothesis that the firms' EBITDA depends linearly on the demand for the goods and services it sells and that this relationship does not change through time or with the introduction of the carbon price. Thus, for a given value of the carbon price φ we can estimate for each issuer the percentage change in earnings due to the introduction of carbon pricing, i.e. the earnings' shock ES^k:

$$ES^k = \frac{\text{EBITDA}^k(0) - \text{EBITDA}^k(\varphi)}{\text{EBITDA}^k(0)} = 1 - \mathcal{R}_i^k(\varepsilon^k) \tag{21}$$

In what follows, we will focus on the earnings shock due to the carbon price introduction relative to its 2019 level.

3 Data

3.1 Input-Output table

As previously discussed, an Input-Output table describes the sale and purchase relationships between producers and consumers within an economy. Our worldwide Input-Output table is provided by the World Input-Output Database (WIOD), and was lastly updated in 2015.[9] It covers 43 countries plus the 'rest of the world' region.[10] Our universe of firms is split between 55

[8] in a refined version of this work, we could examine the impact of the carbon price relative to its current level, that my differ by country or sector

[9] The World Input–Output Database (WIOD) is the outcome of a project that was funded by the European Commission from 2009 to 2012 (Timmer *et al.*, 2015). It is available at: http://www.wiod.org/database/wiots16. WIOD data has been widely used by scholars to measure global value chains (see for example Timmer *et al.*, 2014; Wang *et al.*, 2013). Among its main advantages, it offers a reasonable (but not too granular) decomposition in 55 sectors and a relatively recent update of the data. Alternative Input-Output tables are currently available, the most popular one being Exiobase: https://www.exiobase.eu/index.php/about-exiobase, but its last update is from 2012.

[10] Some countries in investment universe have no direct match in WIOD sectors (e.g. Bermudas, Cayman Island, Singapore), we therefore associated in the Rest of the world cluster in this first exercise.

private sectors within each country (table 8 page 45 provides WIOD sector decomposition). We are thus dealing with a $(44 \times 55)^2$ matrix.

Figure 1 represents the direction of the main Input-Output relationships between sectors in the United States in a Kamada Kawai forced-directed graph. Interestingly, we notice that some sectors have unidirectional relationships. For example, "mining and quarrying" (4) is a clear sector input for "manufacture of basic metals" (15). On the other hand, others have bi-directional relationships, for example "motion picture video programming" (38) and "telecommunications" (39). This representation allows us to visualize potential clusters, also called communities. For examples, sub-sectors 7, 10, 12, 14, 17, 18 (all belonging to the GICS manufacturing sector), 45 ("legal and accounting activities") and 51 ("public administration and defense") have closed relationships in the United States. We can expect a similar response to a variation of carbon price between firms in this community.

Each WIOD sub-sector was mapped to a GICS sector.[11] In practice, we mapped the GICS (sub-industry) level 3 to WIOD sectors.[12] One major advantage of the WIOD table is to provide a uniform indicator of sector interdepencies worldwide.[13]

3.2 Firm characteristics

In our empirical estimation, we focus on the 1 552 firms that compose the MSCI World Index.

Financial data Firm-level Earnings before Interest, Taxes and Depreciation (EBITDA) are provided by FactSet.

Emission data We use two types of emission data:

- **Sector-level GHG emissions**: Sector-level average intensities of GHG emissions (Scope 1) are provided by Exiobase 3[14] (see Stadler *et al.* (2018) for more detail). It covers 43 countries and 5 rest of the World regions split up between 163 sectors.

- **Issuer-level GHG emission:** Data are provided by Trucost. We retrieve Scope 1 emissions intensity for all firms in our investment universe.

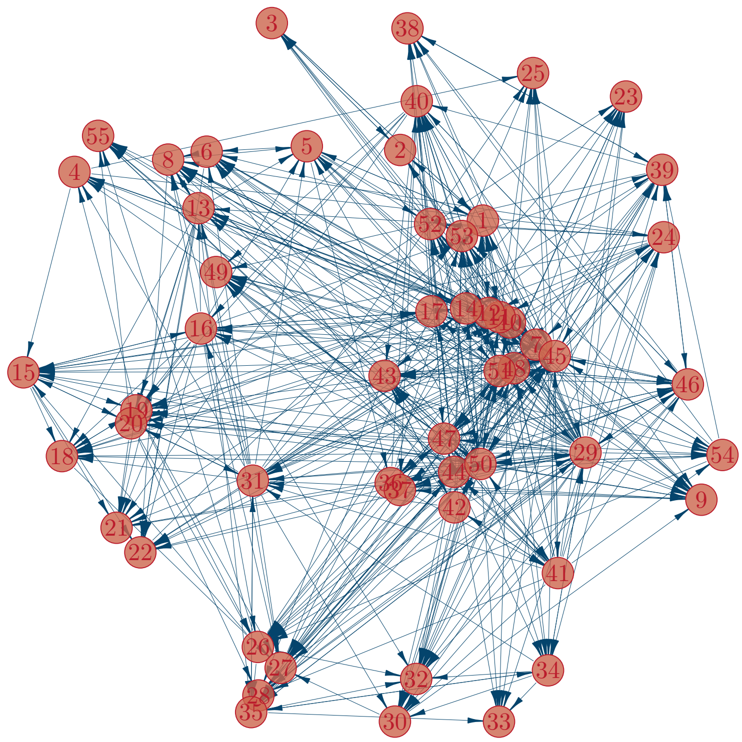
[11] Figure 13 on page 38 represents (a symmetrical version) of the sector interconnections within the United States, as available in WIOD Input-Output table. Note that a slightly different representation has been adopted, allowing us to represent in the same graph the carbon intensities of each sector. See heatmap on page 36 for an alternative representation of these cross-sector dependencies.

[12] The mapping used in provided in the Table 9. Because the classification GICS 3 is finer than WIOD, some WIOD sector can be related to multiple GICS 1. For instance, computer programming, consultancy and related activities; information service activities (WIOD 40), contains the sub-GICS 'Data Processing & Outsourced Services' (IT), 'Application Software' (IT), 'Systems Software' (IT) and 'Interactive Media & Services' (CS). Therefore, this WIOD sector falls into IT and Communication services.

[13] Figure 14 illustrates the countries interconnections (all sectors being aggregated at the country level). As expected, we notice a strong average dependence between the United States and other countries (in particular Canada and Mexico, two countries with large trade relationships with the US). In Europe, Germany, Luxembourg and Ireland are also strongly connected internationally. The "rest of the world" (ROW) comprises large emerging countries such as China, Russia, Brazil, South Africa, Australia, and Turkey and is very central. This aggregation of emerging countries in a single block is a clear limitation of the WIOD data.

[14] Available at: https://zenodo.org/record/4588235#.YQQJwqgzabg.

Figure 1: Force-directed (Kamada Kawai) graph representation of the sector Input-Output relationships (WIOD table) in the United States



Note: Kamada Kawai drawing algorithm takes binary graphs as input. This chart was built taking in consideration only relations exceeding 1%. A similar chart with a threshold value at 2% can be found in appendix on page 37 and the aggregation at a world level of sector requirement with a 50% threshold is provided 37.

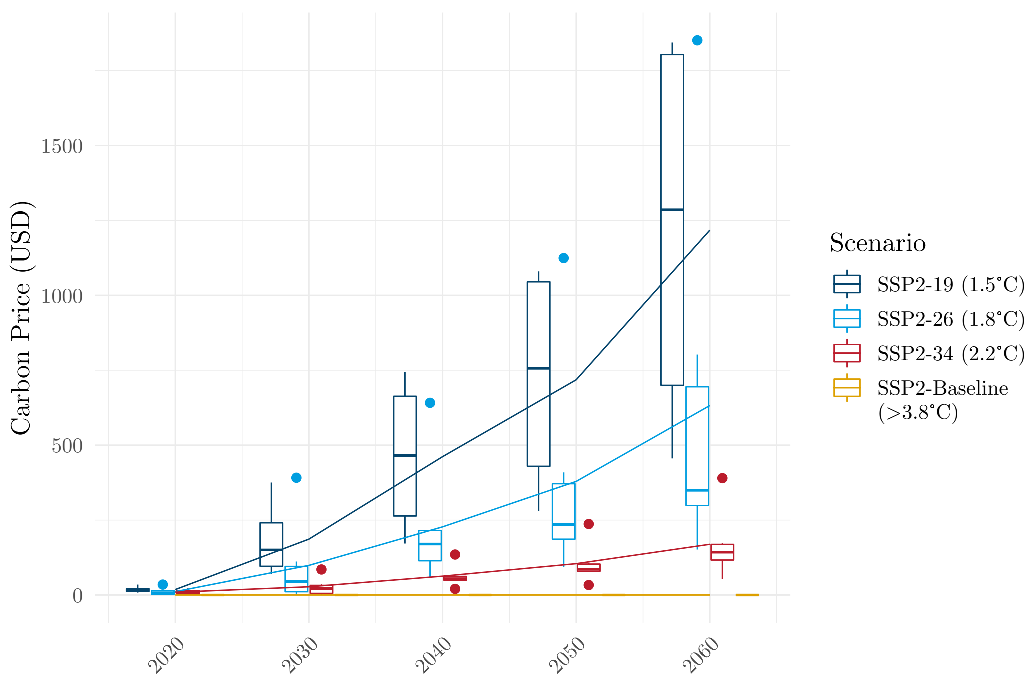
Financial data and carbon intensities are retrieved as of December 2019. Figures 8 and 9 in Appendix page 33 present the country distribution of carbon intensities and carbon absolute emissions, by sector. Based on the data available, we can provide an estimate of the earning shock for 94% of the firms belonging to the MSCI world Index (covering 96% of the total market capitalization of the index). Table 6 in the same Appendix provides more detail about this coverage, in terms of number of stocks and market capitalization, for each GICS Sector.

3.3 Carbon price scenarios

To make realistic assumptions about carbon price evolution, we collect carbon prices corresponding to different climate scenarios as per the Shared Socioeconomic Pathways (SSP) of the IPCC. In these scenarios, the carbon price increases over time - along with the model uncertainty - and is directly linked to the ambition of the scenario expressed in temperatures - the lower the temperature, the higher the carbon price - (see Figure 2 presenting the long-term mean, median and 25-75 percentiles of the carbon price across the various SSP scenarios in IIASA database, from 2020 to 2060).

Whether these pathways are optimal is still an open debate and some would argue that a consistent trajectory would be setting a higher price today (Daniel *et al.*, 2019). In this paper, we consider three different scenarios for the carbon price: USD 50, USD 100 and USD 300 per tCO_{2eq}, which correspond broadly to the suggested carbon prices for the SSP2-26 (1.8°C) in 2030, SSP2-19 (1.5°C) in 2030 and SSP2-19 (1.5°C) in 2040.

Figure 2: Long-term carbon price evolution in the different SSP scenarios in IIASA database



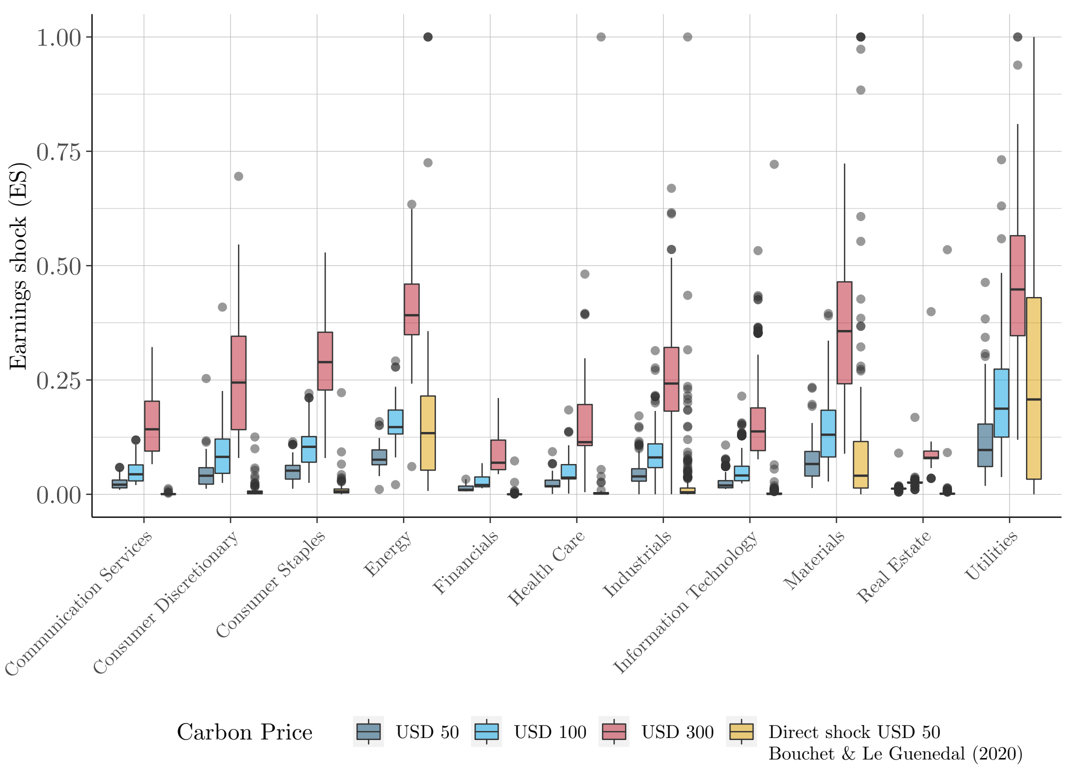
Source: IASAA SSP database version 2.0.
Note: The box-plot (25-75 percentile and median) illustrates the cross-sectional dispersion of the suggested carbon price across models (dots are outliers) and the line is the mean carbon price.

4 Results

4.1 Impact of a carbon price introduction

Figure 3 shows the dispersion of the firms' shocks to EBITDA within each GICS sector,[15] when a carbon price of USD 50, USD 100 and USD 300 is introduced. Table 2 provides the corresponding statistics. In yellow, we also present the direct impact of the introduction of a USD 50 carbon price on EBITDA, when there is no sector diffusion of the carbon tax i.e. when only direct costs are considered, as in Bouchet and Le Guenedal (2020).[16] In dark blue, light blue and red, we present the results of our estimation considering the sector propagation of the carbon price impact on demand, when the carbon price is set at USD 50, USD 100 and USD 300 per tCO_{2eq} respectively.

Figure 3: Earnings shock due to the introduction of a carbon price of USD 50, 100 and 300 per tCO_{2eq} on firms belonging to the MSCI World Index, by sector



[15]To facilitate the representation of our results, the 56 sectors have been mapped into the 11 GICS sectors.

[16]Direct cost are computed as:

$$\xi_d^k = \frac{\mathrm{CP} \times \mathrm{Scope}_1^k}{\mathrm{EBITDA}^k}$$

where CP is the carbon price and $Scope_1^k$ are the emission of the firm k.

When only direct emissions are considered, only three (carbon intensive) sectors are significantly impacted: Utilities, Energy and Materials, with an average percentage change in earnings of 28.1%, 20.4% and 13.4% respectively. All other sectors see their earnings change by less than 3% with the introduction of a carbon price of USD 50. When considering the cross-sector diffusion of the carbon price, the picture changes dramatically. The most impacted sectors, Energy, Materials and Utilities remain largely hit by a carbon price introduction, but their impact ratio is on average twice smaller than with direct costs. The percentage change in EBITDA is 11.6% vs 28.1% for Utilities, 8.2% (vs 20.4%) for the Energy sector, and 7.2% vs 13.4% for Materials (see Table 2). This is because firms in these sectors are selling their products across sectors and worldwide, thus disseminating their carbon costs.

For a carbon price level at USD 50, the least impacted sectors are Real Estate (1.3% reduction in EBITDA), Financials (1.4%) and Health Care (2.5%). The most impacted sectors (Utilities, Energy and Materials) are closely followed by Consumer Staples, Industrials and Consumer Discretionary (5.1%, 4.4% and 4.2% decrease in earnings respectively). The shock to EBITDA rises rapidly with the carbon price. For example, for the Energy sector, it goes from 8.2% to 15.7% and 40.1% when the carbon price goes from USD 50 to USD 100 and USD 300. Strikingly, for a small number of firms belonging to the Energy, Health Care, Industrials, Materials and Utilities sectors, the firm's earnings goes to zero when a carbon price is set at USD 300. These firms will likely have to adapt before a large carbon price is set, unless they lose completely their profitability.

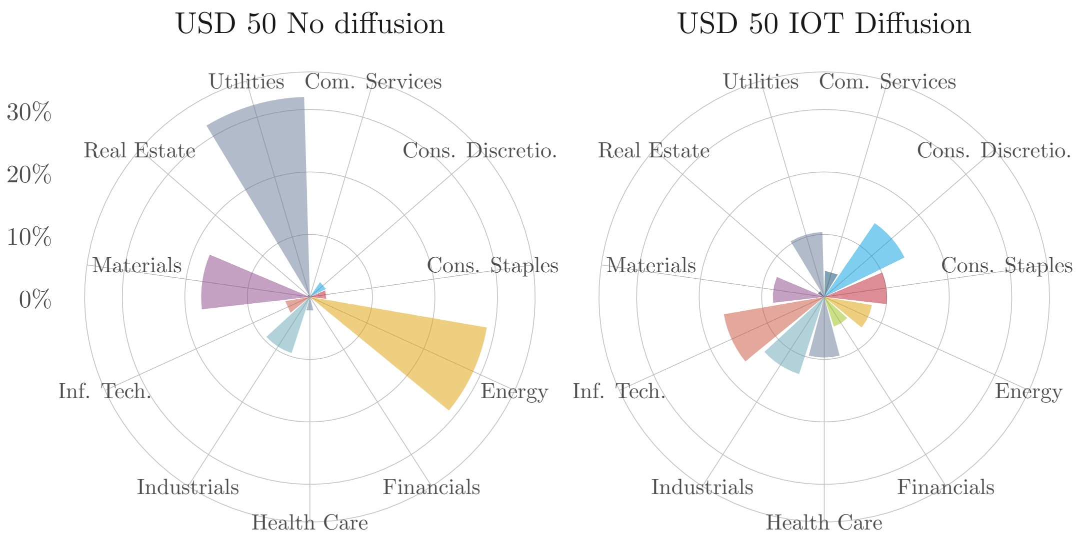
By aggregating the firms' earnings shocks at the sector level, we derive transition risk exposures for each sector. We define the market capitalization weighted *sector risk contribution* as:

$$C_i = \sum_k w_k \times \mathcal{R}_i^k(\varepsilon^k)$$

where w_k is the weight in the MSCI World index computed from the free-float Equity value the in December 2021. We find a total shock $C_{ind} = \sum_i C_i$ of 2.37% of MSCI World Equity Index with direct shock to a rise of USD 50 in the carbon price that become 3.16% with diffusion (See Figure 4a). The sector breakdown shows that the contribution of sectors such as Information Technology or Consumer Discretionary cease to be negligible, because of the large share of the index they currently represent. This suggests that sector exclusions of the most intensive sectors (Utilities, Energy and Materials) will not allow us to mitigate transition risk at the index level because of the cascading effects in the real economy. Figure 4b includes the thinner breakdown of relative risk contribution in WIOD sectors. Interestingly, we observe that for sub-industries such as computer programming or manufacture of computer component, contribution to global risk clearly ceases to be negligible.

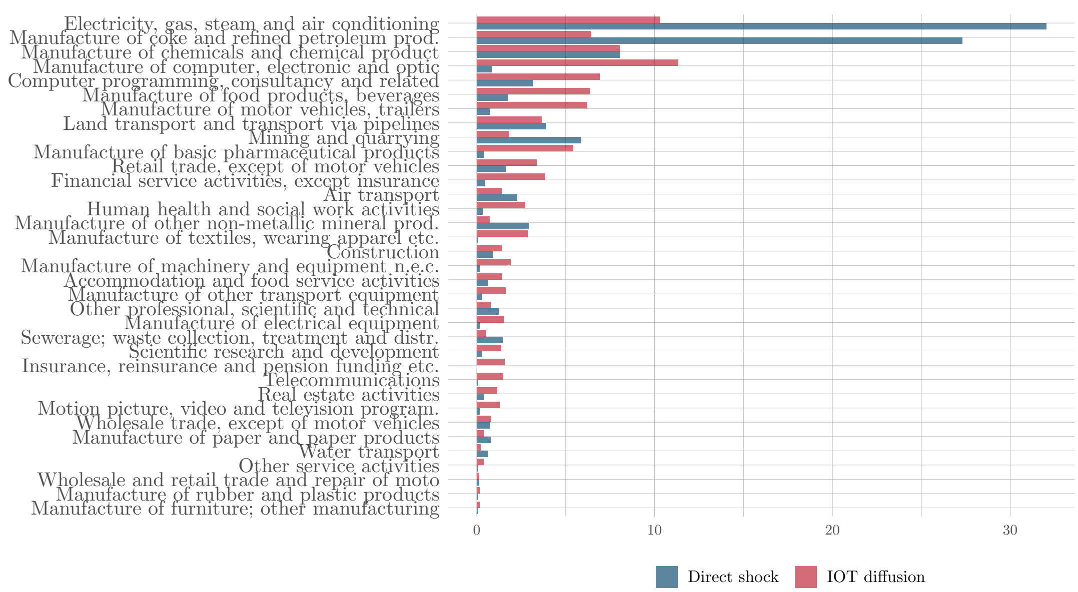
Figure 4: Sector decomposition of the MSCI World total earnings shock due to the introduction of a carbon price of USD 50 per tCO_{2eq}

(a) Relative contributions of GICS sectors earning shocks



Note: the total risk contribution is respectively 2,37% in the simulation with no diffusion and 3.16 % in the simulation with USD 50 IOT diffusion. The contribution in the chart above are rebased i.e. we display $C_i / \sum(C_i)$.

(b) 35 largest relative contributions of WIOD sectors earning shocks



Note: Table 7 on page 40 gives the results on all WIOD sectors

Table 2: Earnings shock distribution by sector

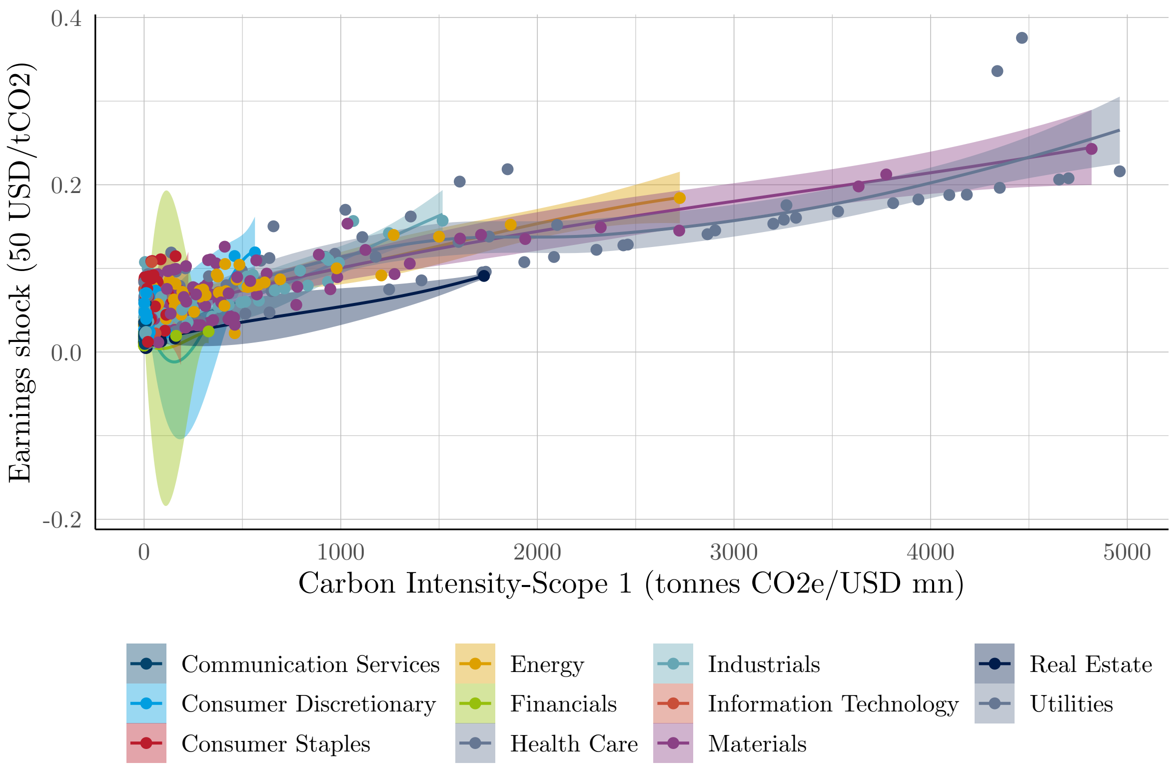
	Carbon price	Sector.name	Mean	St. dev.	Q1	Median	Q3
Direct chock	$ 50.00	Communication Services	0.09%	0.17%	0.02%	0.04%	0.09%
		Consumer Discretionary	0.74%	1.54%	0.12%	0.38%	0.71%
		Consumer Staples	1.18%	2.37%	0.32%	0.65%	1.16%
		Energy	20.42%	24.92%	5.28%	13.37%	21.49%
		Financials	0.22%	1.00%	0.00%	0.01%	0.02%
		Health Care	1.07%	8.60%	0.06%	0.17%	0.37%
		Industrials	2.72%	8.45%	0.20%	0.45%	1.37%
		Information Technology	0.75%	5.71%	0.02%	0.08%	0.25%
		Materials	13.45%	23.18%	1.38%	4.07%	11.54%
		Real Estate	0.91%	5.63%	0.07%	0.12%	0.21%
		Utilities	28.13%	29.64%	3.31%	20.74%	43.00%
IOT shock diffusion	$ 50.00	Communication Services	2.49%	1.34%	1.41%	2.11%	3.12%
		Consumer Discretionary	4.19%	2.75%	2.22%	4.06%	5.82%
		Consumer Staples	5.07%	2.49%	3.32%	5.17%	6.32%
		Energy	8.16%	2.77%	6.46%	7.56%	9.71%
		Financials	1.38%	0.69%	0.80%	0.99%	1.80%
		Health Care	2.50%	1.44%	1.63%	1.77%	3.10%
		Industrials	4.40%	2.44%	2.88%	3.91%	5.58%
		Information Technology	2.67%	1.84%	1.43%	1.94%	2.98%
		Materials	7.24%	4.14%	3.99%	6.63%	9.37%
		Real Estate	1.32%	0.83%	1.19%	1.24%	1.29%
		Utilities	11.59%	8.53%	6.07%	9.69%	15.36%
IOT shock diffusion	$ 100.00	Communication Services	5.12%	2.69%	2.93%	4.37%	6.43%
		Consumer Discretionary	8.60%	5.17%	4.58%	8.18%	12.09%
		Consumer Staples	10.19%	4.86%	7.02%	10.38%	12.62%
		Energy	15.71%	4.99%	13.19%	14.70%	18.43%
		Financials	2.86%	1.45%	1.64%	2.04%	3.80%
		Health Care	5.17%	2.94%	3.36%	3.65%	6.48%
		Industrials	8.95%	4.66%	5.84%	8.06%	11.03%
		Information Technology	5.57%	3.81%	2.97%	4.12%	6.13%
		Materials	14.07%	7.24%	8.16%	13.03%	18.38%
		Real Estate	2.71%	1.54%	2.47%	2.55%	2.68%
		Utilities	20.76%	13.45%	12.51%	18.73%	27.38%
IOT shock diffusion	$ 300.00	Communication Services	15.82%	7.23%	9.45%	14.22%	20.36%
		Consumer Discretionary	24.50%	11.97%	14.14%	24.44%	34.56%
		Consumer Staples	28.16%	11.41%	22.80%	28.90%	35.44%
		Energy	40.09%	10.12%	34.90%	39.16%	45.97%
		Financials	9.24%	4.48%	5.39%	6.90%	11.85%
		Health Care	15.71%	7.88%	10.66%	11.40%	19.63%
		Industrials	25.47%	10.78%	18.19%	24.23%	32.12%
		Information Technology	16.92%	9.91%	9.56%	13.75%	18.89%
		Materials	36.07%	13.73%	24.17%	35.67%	46.46%
		Real Estate	8.69%	3.63%	7.80%	7.99%	9.45%
		Utilities	45.10%	19.86%	34.68%	44.80%	56.55%

4.2 Sensitivity analysis

Sensitivity to firms' direct emissions The large cross-sectional dispersion observed at the firm level within sectors, should reflect (at least partly) firms' dispersion in their levels of direct emissions. Figure 5 plots the firms' carbon price impact on earnings (for a carbon price set to USD 50 / tCO_{2e}) as a function of their Scope 1 carbon intensity[17]. There is a global positive relationship between firm level carbon intensity and the carbon price impact on earnings. However, at a global level, the relationship is not linear. To measure the sensitivity of the earnings' shock ES (our transition risk metric) to the firms' direct emissions (Scope 1 carbon intensity $\mathcal{CI}_1$), we perform the following regression:

$$ES = a + \beta\mathcal{CI}_1 \tag{22}$$

Figure 5: Firms' earnings shock due to the introduction of a carbon price of USD 50, depending on their carbon intensity, MSCI World



For directly intensive sectors, such as Energy, Utilities, Materials, but also for Real Estate, the level of emissions is the main factor explaining the earnings shocks. Table 3 shows that the explanatory power of the single factor regression is high for intensive sectors (R-square higher than 64%). Figure 15 in the appendix reproduces this sensitivity analysis (Figure 5) at the sector level. Results are consistent with the fact that the carbon risk of intensive actors should be proportional to their level of emission while we expect non-intensive actors to be impacted by other indirect effects. Note that removing one outlier firm (Swire Pacific) classified by GICS in the Real Estate

[17] firms' sector can be visualized through the colors of the dots.

Table 3: Descriptive statistics of single factor linear regressions of earnings shocks (due to a USD 50 carbon price introduction) and Carbon Intensity, for each sector - Equation (22)

Sector	β	R^2_{adj}	N obs
Health Care	0.0799	0.3 %	146
Financials	$0.0385^{\star\star}$	1.33 %	218
Industrials	$0.0638^{\star\star\star}$	48.60 %	240
Consumer Staples	$0.190^{\star\star}$	6.48 %	113
Consumer Discretionary	$0.0363^{\star\star\star}$	42.69 %	159
Information Technology	$0.184^{\star\star}$	4.97 %	177
Utilities	$0.0392^{\star\star\star}$	75.58 %	84
Materials	$0.0405^{\star\star\star}$	64.78 %	111
Real Estate	$0.0459^{\star\star\star}$	94.70 %	94
Energy	$0.0485^{\star\star\star}$	69.50 %	49
Communication Services	0.0232	-0.92 %	89

Signif. codes: $\star\star\star$ 0.01 $\star\star$ 0.05 $\star$ 0.1
Note: firm carbon intensities (Scope 1 emissions) are in $GtCO_{2e}$/USD mn.

sector, while its activity involves many other activities such as aviation, beverages and food chain, marine services, and trading and industrial, reduces the R-square of the Real Estate Sector to 12.6%. Figure 16f on page 42 confirms that this high R-square is due to this outlier.

Sensitivity to indirect sector intensity Firms belonging to less carbon intensive sectors should have their transition risk measure much less explained by their idiosyncratic Scope 1 direct emissions intensity. Table 3 confirms that for sectors such as Health Care, Financials, Information Technology, or Communication Services, the relationship is weak. This is consistent with the idea that for firms belonging to these low carbon-intensive sectors, profitability will not be affected by the direct pricing on the relatively low emissions implied by their activity, but rather by the change of prices in their supply-chain[18]. Our methodology allows to encompass both idiosyncratic and sector-level or country-level systematic risk implied by a shift in carbon price.

Because our model is based on sector × country level indicators, we should be able to capture the influence of this supply-chain indirect intensity by considering for each firm the indirect carbon intensity of its sector and country. Thus, we will measure the sensitivity of the firms' issuer direct intensity ($\mathcal{CI}_1$) and indirect emissions, by running the following regression:

$$ES = a + \beta_{\text{direct}}\mathcal{CI}_1 + \beta_{\text{indirect}}\left(m_{i,c} - g_{i,c}\right) \tag{23}$$

where $m_{i,c}$ denotes upstream direct and indirect intensities at the WIOD sector i and country c level. To account only for indirect upstream emissions, we subtract the average sector intensity $g_{i,c}$ to the $m_{i,c}$ (containing both direct and indirect emission by construction).

Table 4 presents the descriptive statistics of the regression corresponding respectively to the impact of the variation of USD 50 in the world carbon price for intensive and non intensive sectors.

[18]In fact, these sectors risk arise from their scope 3. In this paper, we focus on upstream component of the scope 3. We leave the downstream emission for further research, as data on the matter in not mature.

Table 4: Descriptive statistics of multi-factor linear regressions of earnings shocks (due to a USD 50 carbon price introduction) on firm's direct Carbon Intensity and sector indirect emissions, for each sector - Equation (23)

Sector	β_{direct}	β_{indirect}	R^2_{adj}	N obs
Health Care	0.0656***	0.157***	98.3%	142
Financials	0.0550***	0.154***	94.2 %	200
Industrials	0.0386***	0.167***	97.2 %	223
Consumer Staples	0.0153	0.146***	95.6 %	108
Consumer Discretionary	0.0391***	0.172***	97.5 %	149
Information Technology	0.0543***	0.169***	99.7 %	81
Utilities	0.037***	0.102***	94.8 %	76
Materials	0.044***	0.162***	98.1 %	106
Real Estate	0.0486***	0.0974***	72.1 %	76
Energy	0.0470***	0.124***	92.7 %	46
Communication Services	0.0466***	0.139***	95.4 %	38

Signif. codes: ⋆ ⋆ ⋆ 0.01 ⋆⋆ 0.05 ⋆ 0.1

Note: firm carbon intensities (Scope 1 emissions) are in $GtCO_{2e}$/USD mn. The difference between the number of observation is related to issuer in countries not in the WIOD tables. To increase the coverage in the stress-test however, we mapped these issuer to the rest of the world aggregate.

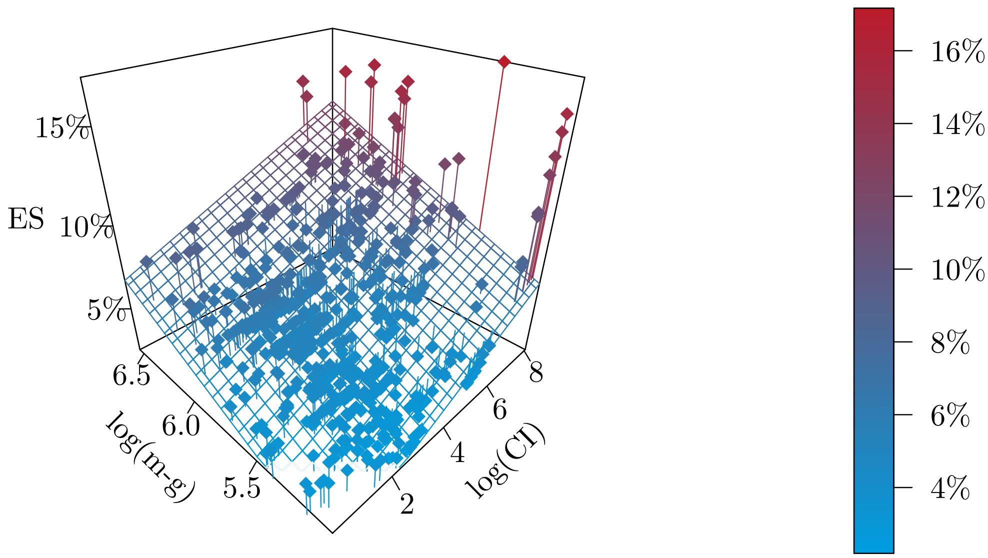
We note that for non-intensive sectors, the scope 1 emission intensity is less significant (Consumer stable, discretionary, and communication services). In general, the two factor model explains well the earnings shock obtained with the diffusion methodology for a given value of carbon price variation but the betas and intercept both depend on the carbon price[19]. Figure 6 illustrates the relationship between the earning shock *ES*, the logarithms of the carbon intensities and the indirect carbon intensity $m_{i,c}$ when introducing a carbon price of USD 50[20].

Using a proxy of firms' indirect carbon emissions at the sector × country level improves significantly the explanatory power of the regressions. In particular, the dispersion of firms' transition risk, for firms belonging to the Information Technology sector, and to a lesser extent non directly intensive sectors such as Communication Services and Financials, is relatively well explained by the linear supply-chain multi-factor model. For these sectors, non-negligible residuals errors remain, as can be seen from Figure 17 on page 43. For the highly interconnected sectors, estimating the firms' earning shock requires the full network analysis and cannot be captured by linear effects.

[19] However, the relative sector exposures ($\frac{\beta}{\sum_{i=1}^{11} \beta_i}$) is stable although there are slight non-linear effect at a GICS level because the diffusion is performed using the WIOD mapping. Also, the value of the betas are hard to interpret because of the very different possible values (and scales) of variables $\mathcal{CI}_1$, $m_{i,c}$ and $g_{i,c}$.

[20] Similar figures can be obtained when considering a higher carbon price at USD 100 or USD 300. The *height* of the plot, characterizing the intercept of the regression, depends mostly on the carbon price. The higher the price, the higher the global impact.

Figure 6: Firms' earnings shock due to the introduction of a carbon price of USD 50, depending on their idiosyncratic carbon intensity and indirect upstream sector×country emission intensities, MSCI World



4.3 Impact on index composition

The transition risk estimated in the previous section might have important consequences on the composition of the investment universe. Assuming that earning shocks will translate into firm value and thus market capitalization shocks, we can estimate the potential impact of a carbon price introduction on index constituents and measure the resulting distortion in the index composition.

Let us assume that the firms' value (EV_k) is proportional to its earnings (Bouchet & Le Guenedal, 2020), we can write:

$$EV_k(t) = r_k \times EBITDA^k(t) \tag{24}$$

where r_k is a corporate-specific ratio that is supposed to be constant through time[21]. This implies

[21] In practice, this ratio can be subject to non negligible variations when considering long time periods.

that:

$$\frac{(\mathrm{EV}_k(\varphi) - \mathrm{EV}_k(0))}{\mathrm{EV}_k(0)} = \frac{(\mathrm{EBITDA}^k(\varphi) - \mathrm{EBITDA}^k(0)) \times r_k}{\mathrm{EBITDA}^k(0) \times r_k} = -ES^k \tag{25}$$

The enterprise value represents the total asset summing over the free-float market capitalization (Equity) and total debt:

$$EV_k = E_k + D_k \tag{26}$$

Assuming that the debt remains constant we have:

$$\Delta EV_k(\varphi) = \Delta E_k(\varphi) \tag{27}$$

and, using Equation (25) the shock is fully passed on the equity price such as:

$$\Delta E_k(\varphi) = (\mathcal{R}_i^k(\varepsilon^k) - 1) \times \mathrm{EV}_k(0) \tag{28}$$

We can now estimate the changes in firms' weights in the index due to the carbon price introduction. For each firm, its new weight in the index depends on the experienced earning shock, leading to a shock to its market capitalization.

$$E_k(\varphi) = E_{k,0} - ES_k \times \mathrm{EV}_k(0) \quad \text{and} \quad w_k(\varphi) = \frac{E_k(\varphi)}{\sum_k^N E_k(\varphi)} \tag{29}$$

where $E_k(\varphi)$ is the estimation of float-adjusted market capitalization of the firm k after the introduction of a carbon price φ, and $w_k(\varphi)$ is the corresponding weight in the index[22].

We aggregate firms' weights shocked by the carbon price at the sector level and obtain a new sector composition of the MSCI World index (for each carbon price scenario: USD 50, 100 or 300). We can then compare this projected sector composition of the MSCI World to the current composition of the index as displayed in Table 5 and Figure 7.

We find that the introduction of a carbon price has a non-negligible impact on the investment universe, distorting the sector composition of the MSCI World index. Introducing a USD 50/ton shock would reduce the weight of the Utilities, Energy and Materials sectors by respectively 18.8%, 8.6% and 4.7% in relative terms. On the contrary, the Financial and Real Estate sectors benefit substantially from the carbon shock because of their relatively low direct carbon intensity and limited first tier (upstream) indirect emissions (3.3% and 2.5% relative increase in their weight, respectively). These results should however be interpreted with caution because the impact on the Financial sector could most likely derive from other channels (downstream impact and financial contagion to other sectors) than the ones investigated in this analysis. The Information Technology, which is currently the largest sector in the index, sees its weight increase by 2.2% in relative terms. When considering the introduction of a carbon price at USD 100 or 300, the sector deviations in the index become very large, with a relative sector weight reduction up to 84.6% for Utilities, 49.8% for the Energy sector and 26.6% for Materials. The Financial sector benefits the most. Its sector weight in the index increases by 21.6% in relative terms for a carbon price at USD 300.

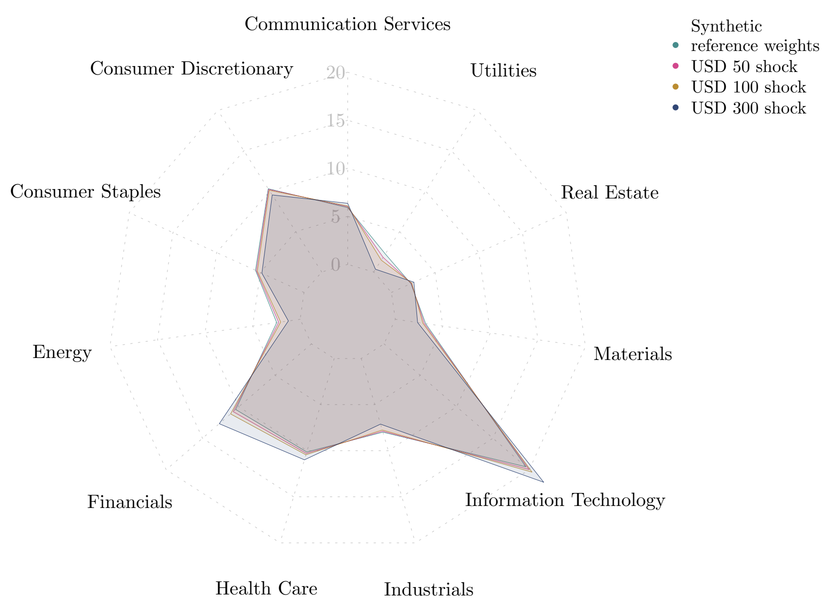
[22] Note that for financial firms, we apply the ratio directly to market cap at at t=0: $E_k(\varphi) = E_{k,0} - \mathcal{R}_i^k(\varepsilon^k) \times \mathrm{E}_k(0)$, so we do not introduce irrelevant debt for this sector. Applying a similar methodology for all sectors would provide similar results with lower amplitude impacts.

Table 5: Sector composition of the MSCI World before and after a carbon price introduction at USD 50, 100 and 300

		USD 50		USD 100		USD 300	
	MSCI World*(%)	weight (%)	relative change	weight (%)	relative change	weight (%)	relative change
Communication Services	7.4	7.5	1.6%	7.6	3.0%	7.9	7.6%
Consumer Discretionary	12.9	12.8	-0.8%	12.6	-1.9%	11.9	-7.5%
Consumer Staples	6.9	6.8	-1.8%	6.7	-3.9%	6.0	-13.2%
Energy	3.1	2.8	-8.6%	2.6	-16.9%	1.6	-49.8%
Financials	13.0	13.5	3.3%	13.9	6.7%	15.9	21.6%
Health Care	12.7	12.9	1.5%	13.1	3.0%	13.7	8.4%
Industrials	10.0	9.9	-1.3%	9.7	-3.0%	8.9	-10.9%
Information Technology	24.4	25.0	2.2%	25.5	4.3%	27.5	12.5%
Materials	4.0	3.8	-4.7%	3.6	-9.3%	2.9	-26.6%
Real Estate	2.8	2.9	2.5%	2.9	5.0%	3.2	15.4%
Utilities	2.8	2.3	-18.8%	1.8	-34.5%	0.4	-84.6%

* The original MSCI World index composition has been rebased to account for missing data on firms' carbon emissions. We cover 96% of the original index.

Figure 7: Carbon price adjusted indices



5 Conclusion

Central bankers are now used to conduct stress testing exercises of banks' exposures to climate risk (see for example Allen *et al.* (2020), Alogoskoufis *et al.* (2021)). A number of supervisors already considered the extension of climate stress tests to investors, such as insurance companies and pension funds (Vermeulen *et al.* (2018), EIOPA (2022)). However, climate stress tests are still not widespread in the investment management industry, despite the recent recommendation by ESMA (2022). Our paper offers a methodological step in that direction, that could hopefully be useful for investors willing to implement simple stress testing exercises at their portfolio level.

An important insight from our analysis is that even low carbon-intensive sectors could be substantially impacted by the introduction of a carbon price, because of its cascading effect on firms' supply chains. Although carbon intensive sectors, such as Utilities, Energy and Materials, could suffer earnings shocks between 7% and 12%, with the introduction of a carbon price at USD 50, less intensive sectors such as Information Technology, Consumer Discretionary and Consumer Staples could also incur non negligible shocks, close to 3-4%. In the case of a higher carbon price, these effects could be exacerbated. The earnings shock for carbon-intensive firms could reach 21% (and even 45%) on average for the most impacted sector (Utilities), with a carbon price of USD 100 and USD 300 respectively. In these two scenarios, less intensive sectors would be also heavily impacted. For example, the Information Technology sector could be subject to earnings shocks of 6% and 17% in these two carbon price scenarios, respectively. Interestingly, the introduction of a carbon price will have a substantial impact on the investment universe, distorting the sector composition of the main indices. Our exercise based on the MSCI World index shows that introducing a USD 50/ton shock would significantly lower the weight of the Utilities, Energy and Materials sectors, while the Financials and Real Estate sectors would benefit the most.

Our results should be put into perspective as they rely on simplifying model assumptions and data limitations. On the data side, the Input-Output tables of direct requirements provide static information about flows between sectors. In the past, the supply-chain relationships between sectors have remained relatively stable over time. However, in the context of a rapidly evolving environment, such as the one triggered by the shift in climate change, this assumption might no longer be valid. Firms in our analysis, even if they are dealing with multiple activities, have been assigned to one unique sector, which might bias the estimates for highly diversified firms. Moreover, the Input-Output tables describe broad supply chain relationships between sectors, but there might be considerable dispersion at the firm level within a given sector. The same limit applies to the firm's country classification. Issuers are only associated with their country of incorporation, attached to their ISIN. Firm-level supply chain data, allowing us to establish precise relationships between a given supplier and its clients, could be used to improve the framework. But, like Input-Output data, supply-chain data provide little information on the nature, strength or substitutability of the supply-chain relationships.

On the methodological side, we made several strong assumptions that could probably be relaxed. Prices on the benchmark equilibrium before carbon pricing are normalized equal to 1. In practice, elasticities of substitution are likely to be specific to products, sectors and countries and depend on exogenous factors. Additionally, we considered a global carbon price that would be imposed on all sectors and countries uniformly. This does not factor in existing carbon pricing mechanisms and their plurality. Carbon pricing initiatives are local, and taxes or allowance prices are sometimes fixed at a sector level. Finally, we assumed cost pass-through to be equal to 1, meaning that the entire cost would be passed on by firms to their customers. In practice, firms may choose to absorb part of this cost by reducing their margins. More complex methods could be designed to assess the impact of a carbon price. For example, Xie (2000) developed an environmentally extended social accounting matrix, which describes in a more comprehensive way the relationships between production activities, production factors, income, consumption and capital accumulation in an accounting framework. Other alternative approaches would involve using a General Equilibrium model (Guo *et al.*, 2014; Siriwardana *et al.*, 2011) to simulate the effect of the carbon price on firms' profits, while making assumptions on economic agents' behavior.

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A Notations

Indices	
i, j	Sectors
k	Issuer
Variables	
y_i	Final demand net of imports for the i-th sector
x_i	Initial production level of the i-th sector
x_i^{ε}	Production level of the j-th sector after carbon price introduction
$x_i^{\varepsilon^k}$	Production level of firm k after carbon price introduction
x_{ij}	Production sold by the i-th sector to the j-th sector
a_{ij}	Technical coefficient: Input-Output matrix element
g_i	Direct emissions intensity of the i-th sector
m_i	Direct and indirect emissions intensity of the i-th sector
e^k	Direct emissions intensity of firm c
m_i^k	(Cie k not in the i-th sector) Direct and indirect emissions intensity of the i-th sector
m_i^k	(Cie k in the i-th sector) Direct emissions intensity of firm c and indirect emissions intensity of the j-th sector
φ	Carbon price ($\$/tCO_2e$)
ε_i	Carbon price rate ($ taxed/$ output)
τ_i	Ad valorem tax in the i-th sector
p_i	Initial unitary price in the i-th sector
p_i^{ε}	Unitary price in the i-th sector after carbon price introduction
$p_i^{\epsilon^k}$	Unitary price of firm k carbon price
w	Price of labor
l_i	Coefficient of labor intensity in the i-th sector
r	Cost of capital
k_i	Coefficient of capital intensity in the i-th sector
t_i^m	Tariff on imports in the i-th sector
p_i^m	Unitary price of imports in the i-th sector
q_i	Coefficient of imported inputs intensity in the i-th sector
EBITDA^k	Initial EBITDA of firm k
$\text{EBITDA}^{\epsilon^k}$	EBITDA of firm k after carbon price introduction
$\mathcal{R}^k$	Enterprise Value to EBITDA ratio
EV^k	Enterprise Value of firm k

B Leontief price model

The Input-Output approach allows to decompose the price structure of goods and services offered by each sector of the real economy. Indeed, with p_i, the unit prices of sector i, the input cost of a unit of j is $\sum p_i a_{ij}$. The added value plus the imported inputs V_j per unit of product is defined by v_j, which the difference between the product price and the unit cost in domestic inputs (Mardones & Mena, 2020; Mardones & Muñoz, 2018):

$$v_j = \frac{V_j}{x_j} = p_j - \sum p_i a_{ij} \tag{30}$$

Following Mardones and Mena (2020, p. 5) this can be represented in matrix form as $P - P^T A \in \mathbb{R}^{n \times 1}$ leading to the equation below:

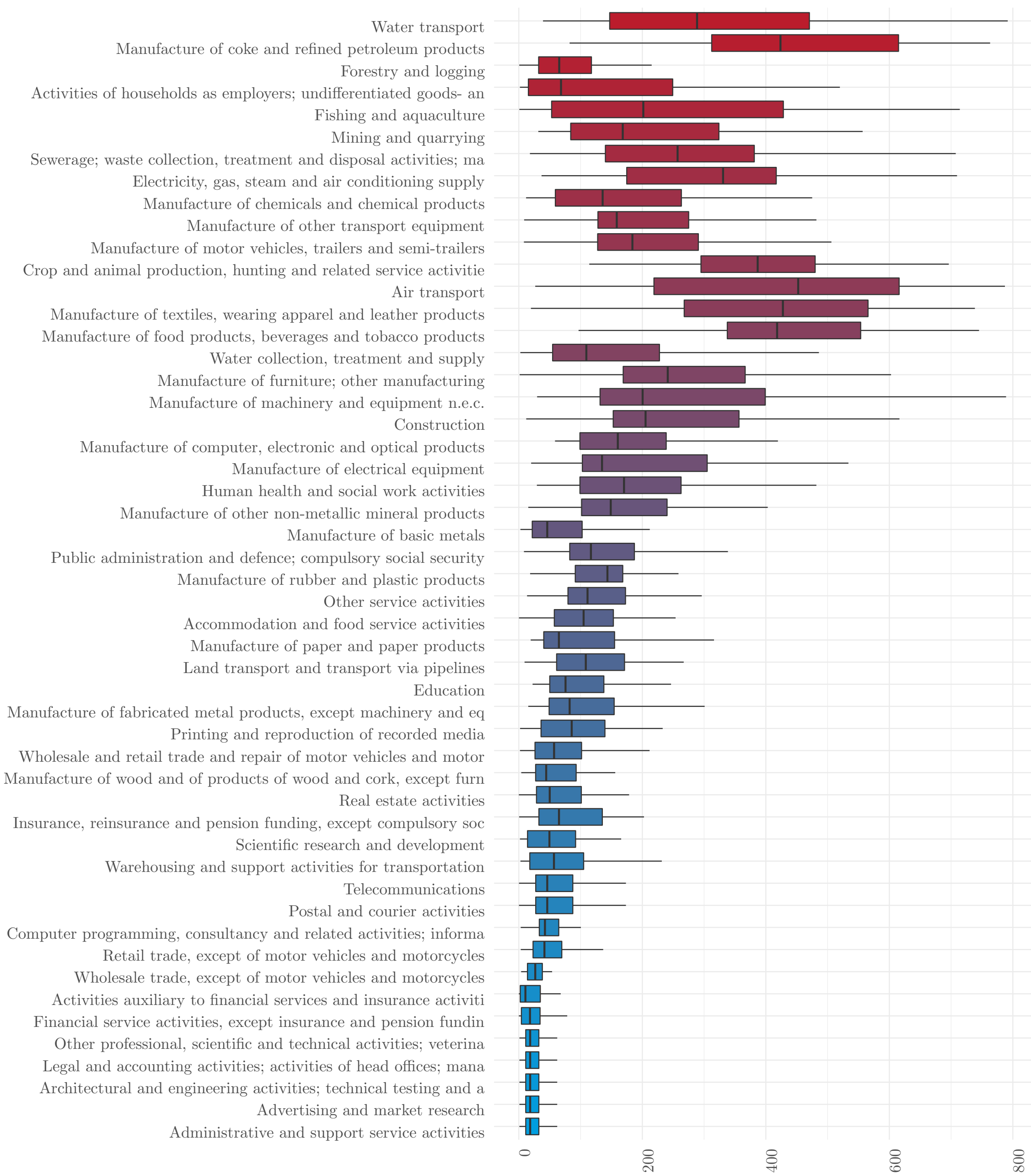
$$P = A^T P + V \tag{31}$$

and then:

$$P = \left[(I - A)^{-1} \right]^T V \tag{32}$$

C Additional materials

Figure 8: Distribution of carbon intensities (emission/output) across countries, by sector



Source: Exiobase and World Input-Output database (WIOD).
Note: Carbon intensities by sector (from Exiobase) have been projected on WIOD sectors. For each sector on the vertical axis, the distribution (25-75 percentiles and median) over countries is represented. Sectors are ranked by their average carbon intensity, from the highest (red) to the lowest (blue). Outliers are not represented for scaling reasons. Sectors which box appears *lower* with respect to surrounding contains outliers.

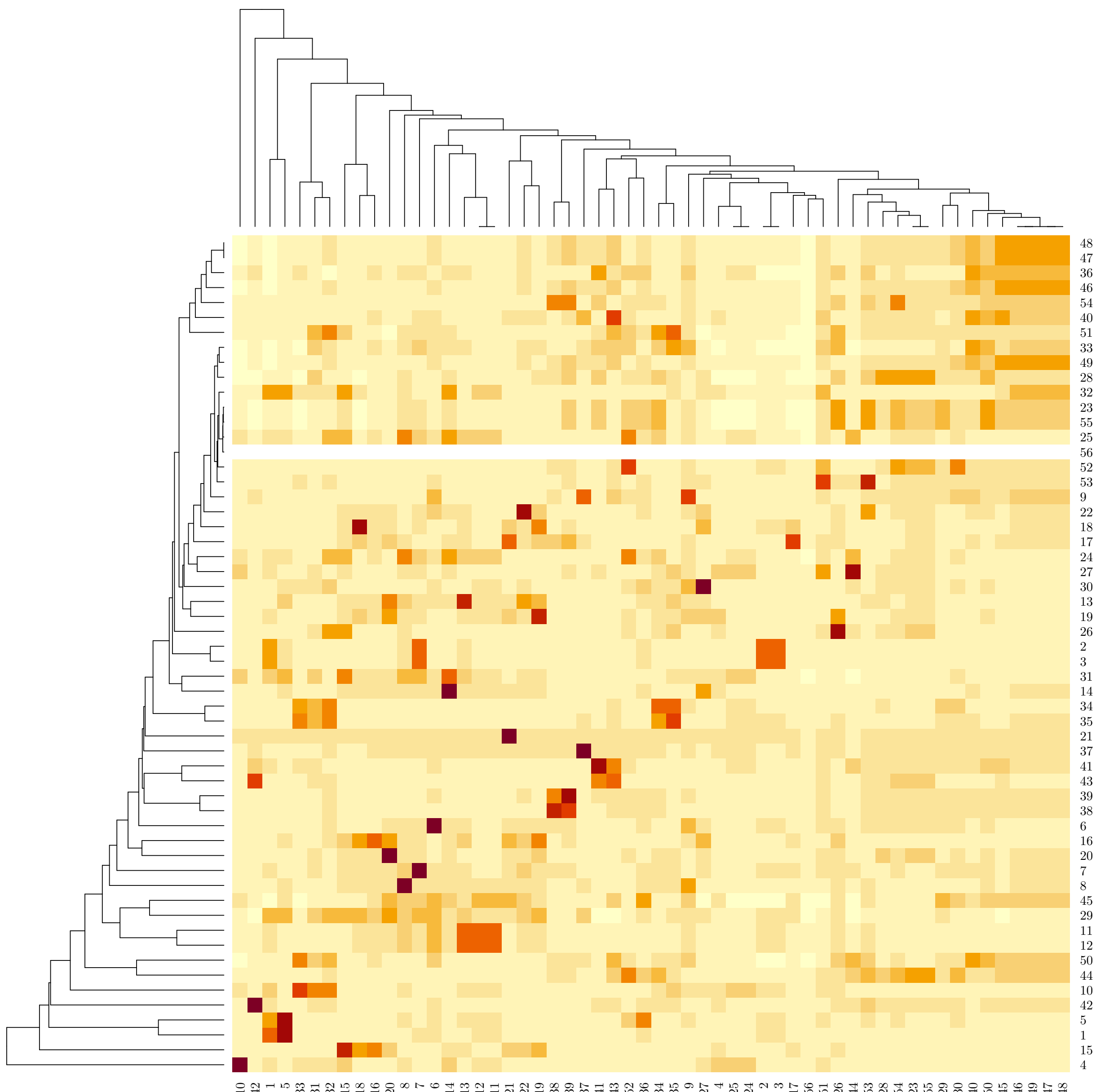
Figure 9: Distribution of absolute carbon emissions across countries, by sector

Source: Exiobase and World Input-Output database (WIOD).
Note: The distribution (25-75 percentiles and median) of carbon emissions over countries is represented in the plots and the vertical scale is determined by the sector average. Sectors which box appears *lower* with respect to surrounding contains outliers.

Table 6: Investment universe covered in our analysis

GICS	Cov. (N stocks)	Mkt cap (MSCI World)	Mkt cap (study)	Cov. (Mkt cap)
Communication Services	88,00%	8,58%	7,09%	82,61%
Consumer Discretionary	93,49%	12,64%	12,36%	97,77%
Consumer Staples	94,07%	6,78%	6,66%	98,24%
Energy	96,00%	3,09%	2,96%	95,79%
Financials	96,89%	13,27%	12,51%	94,28%
Health Care	92,90%	12,32%	12,17%	98,72%
Industrials	94,07%	10,03%	9,59%	95,57%
Information Technology	94,12%	23,88%	23,44%	98,14%
Materials	93,91%	4,01%	3,84%	95,61%
Real Estate	95,83%	2,70%	2,67%	99,04%
Utilities	98,81%	2,68%	2,68%	100,00%
Total	94,3%	100,00%	95,97%	95,98%

Figure 10: USA sectors diffusion heat-map



Sector 56 is not connected to the network and have to be removed.

Figure 11: Force-directed (Kamada Kawai) graph representation of the WIOD table in the US binarized with threshold value at 2%

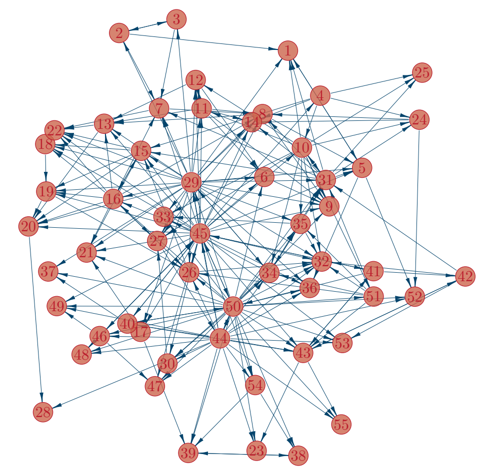
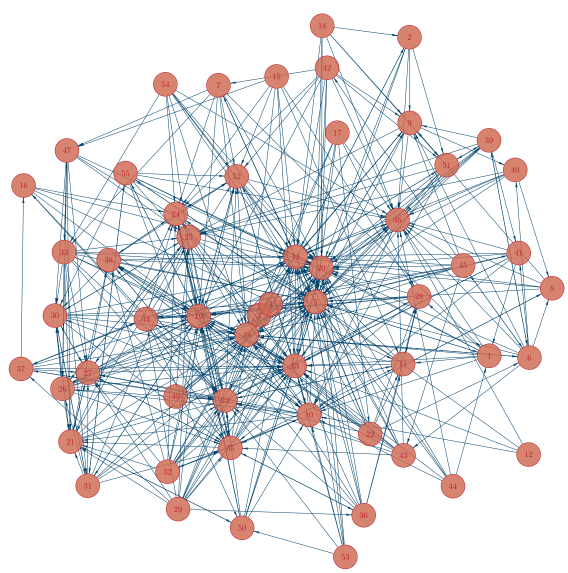


Figure 12: Force-directed (Kamada Kawai) graph representation of the entire WIOD table aggregated per sector binarized with threshold value at 50%.



Note:
The threshold value can sum over one in the context of this worldwide aggregation.

Figure 13: Connection between WIOD sectors (within the US) mapped in GICS categories

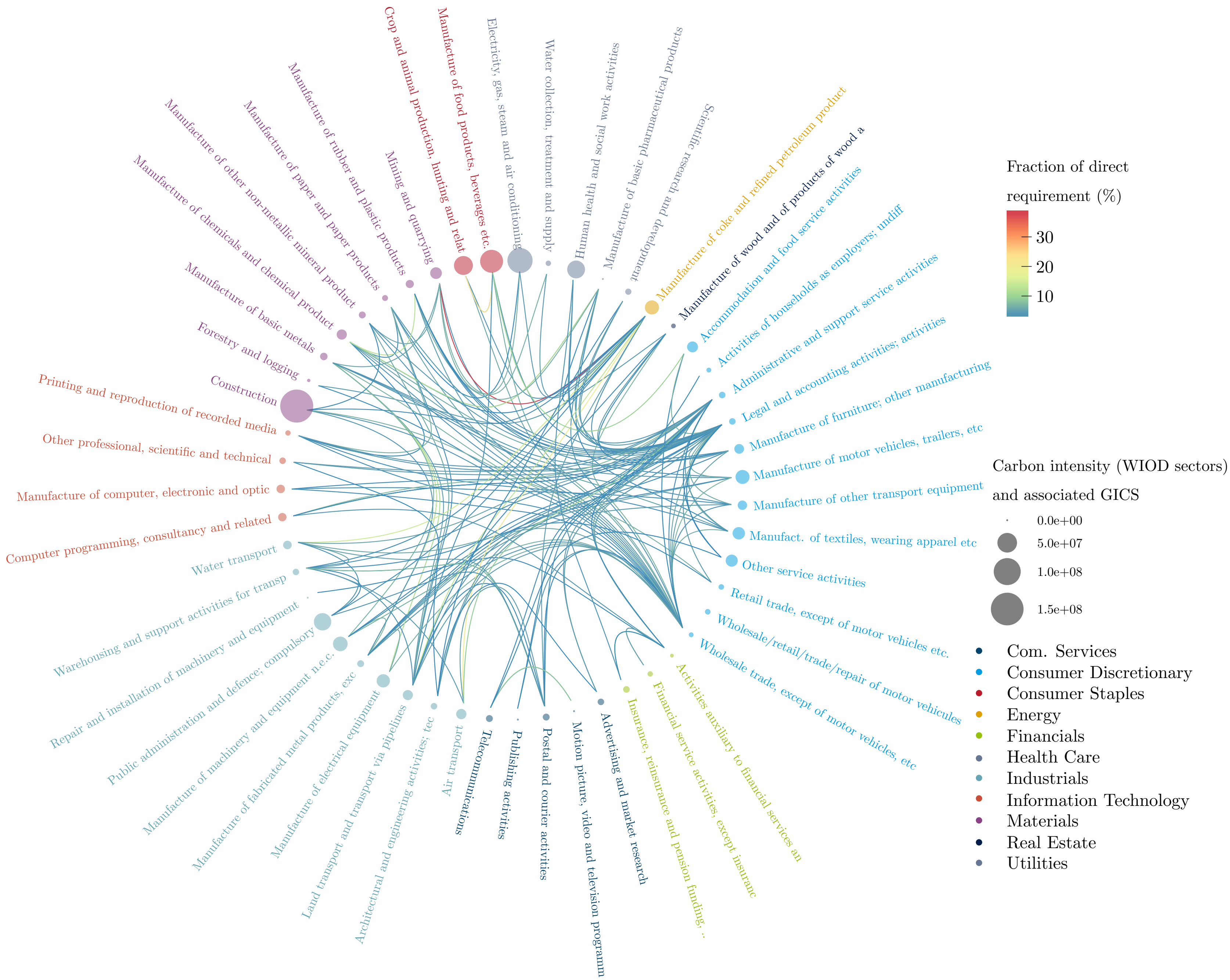
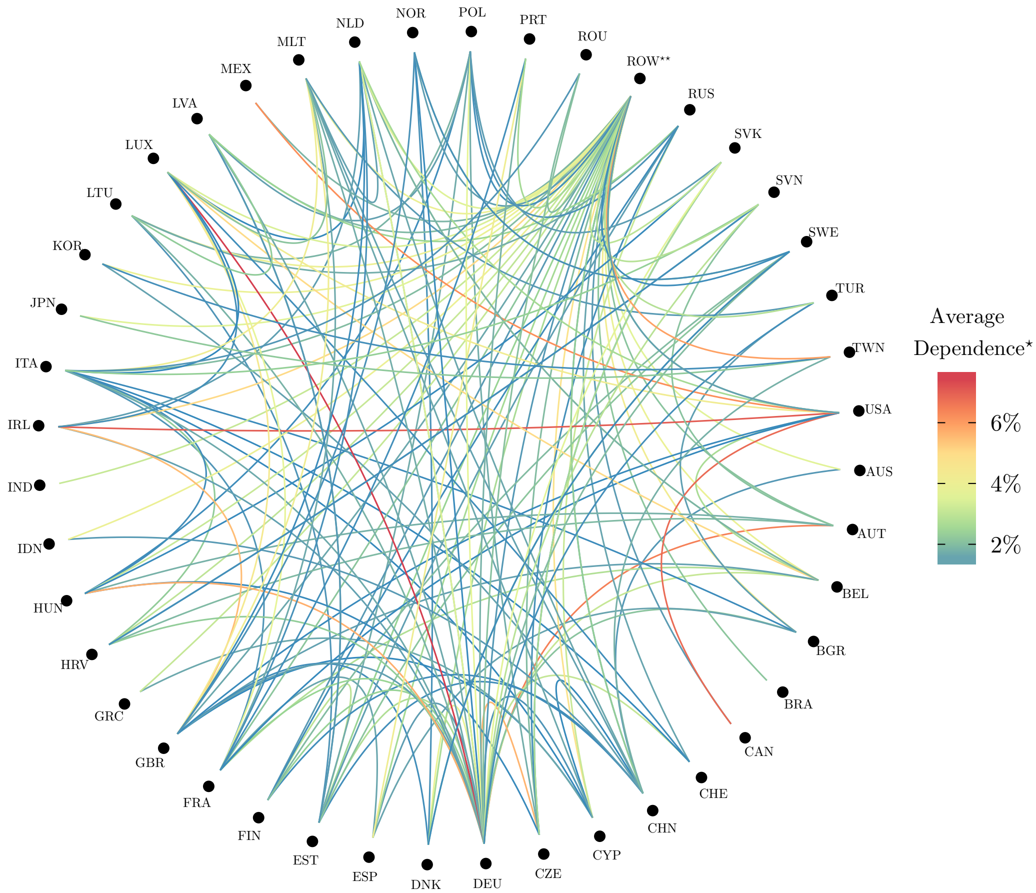


Figure 14: Countries average connections from WIOD



Note:
* average dependencies are computed summing over sectors and dividing by the number of sector (55) - equally weighted
** Core ROW Countries means China, Russia, Brazil, South Africa, Australia, and Turkey.

Table 7: Relative contribution of USD 50 carbon price shock in WIOD sectors in (%)

WIOD Sectors	**No diffusion (USD 50)**	**IOT diffusion (USD 50)**
Electricity, gas, steam and air conditioning	32,01	10,31
Manufacture of coke and refined petroleum pro	27,29	6,44
Manufacture of chemicals and chemical product	8,07	8,02
Manufacture of computer, electronic and optic	0,85	11,32
Computer programming, consultancy and related	3,15	6,91
Manufacture of food products, beverages and t	1,77	6,38
Mining and quarrying	5,87	1,82
Land transport and transport via pipelines	3,90	3,64
Manufacture of motor vehicles, trailers and s	0,73	6,20
Manufacture of basic pharmaceutical products	0,41	5,40
Retail trade, except of motor vehicles and mo	1,62	3,36
Financial service activities, except insuranc	0,47	3,85
Manufacture of other non-metallic mineral pro	2,94	0,71
Air transport	2,26	1,38
Human health and social work activities	0,33	2,71
Manufacture of textiles, wearing apparel and	0,04	2,86
Construction	0,92	1,43
Manufacture of machinery and equipment n.e.c.	0,16	1,89
Accommodation and food service activities	0,64	1,40
Other professional, scientific and technical	1,23	0,77
Sewerage; waste collection, treatment and dis	1,45	0,49
Manufacture of other transport equipment	0,29	1,62
Manufacture of electrical equipment	0,15	1,53
Scientific research and development	0,27	1,38
Insurance, reinsurance and pension funding, e	0,01	1,55
Real estate activities	0,40	1,14
Telecommunications	0,04	1,47
Wholesale trade, except of motor vehicles and	0,75	0,76
Motion picture, video and television programm	0,15	1,27
Manufacture of paper and paper products	0,77	0,41
Water transport	0,64	0,21
Other service activities	0,04	0,38
Wholesale and retail trade and repair of moto	0,14	0,13
Manufacture of rubber and plastic products	0,07	0,17
Manufacture of furniture; other manufacturing	0,05	0,18
Manufacture of fabricated metal products, exc	0,05	0,12
Administrative and support service activities	0,02	0,13
Advertising and market research	0,01	0,12
Water collection, treatment and supply	0,01	0,07
Forestry and logging	0,04	0,03
Legal and accounting activities; activities o	0,01	0,02
Printing and reproduction of recorded media	0,01	0,02
Publishing activities	0,00	0,01

Figure 15: firms' carbon price impact on earnings depending on their carbon intensity, with a carbon price of USD 50, by intensive sector

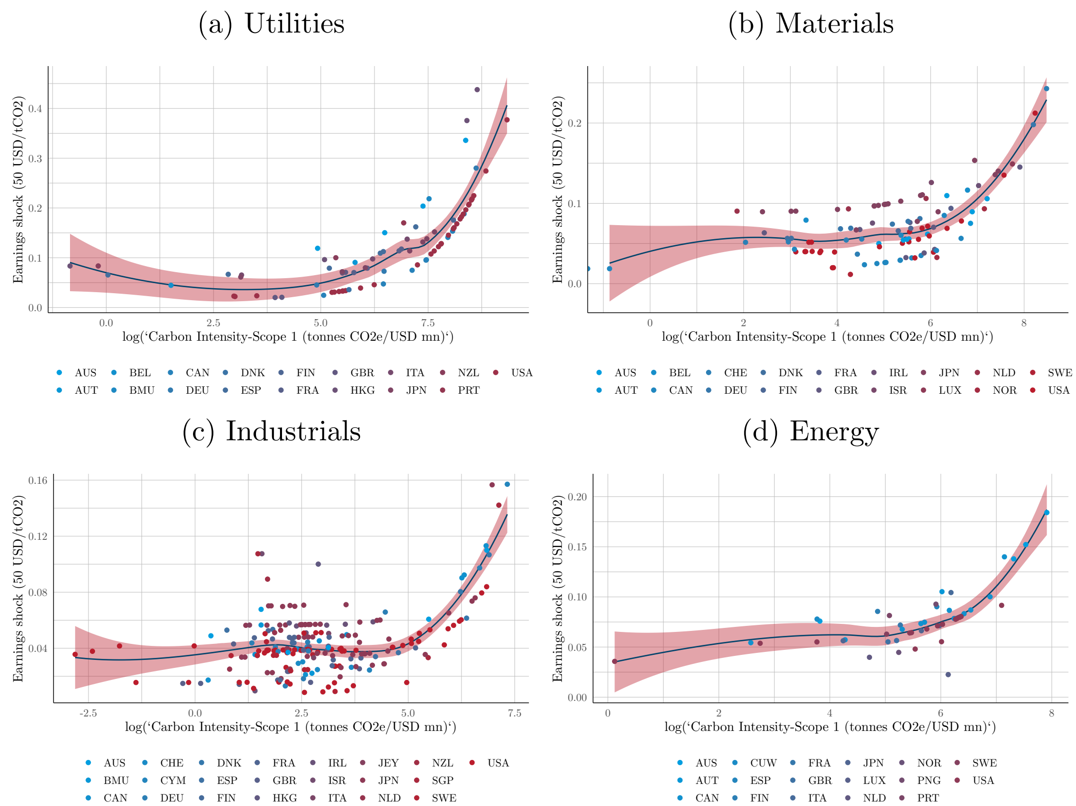
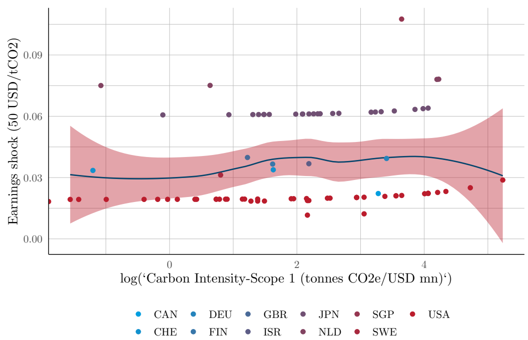
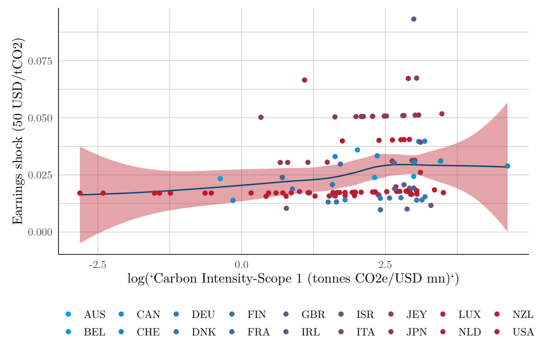


Figure 16: firms' carbon price impact on earnings depending on their carbon intensity, with a carbon price of USD 50, by sector

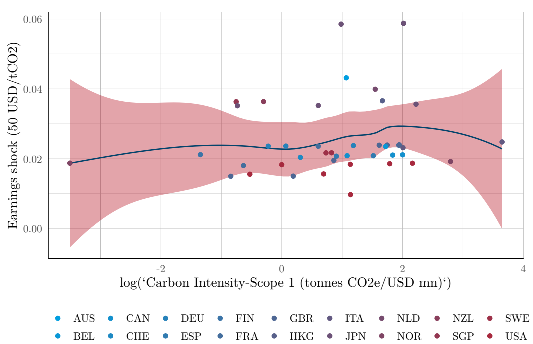
(a) Information technology



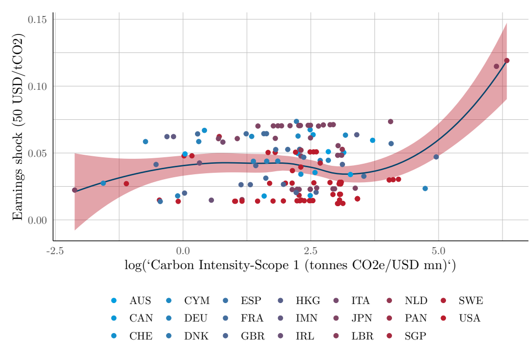
(b) Health Care



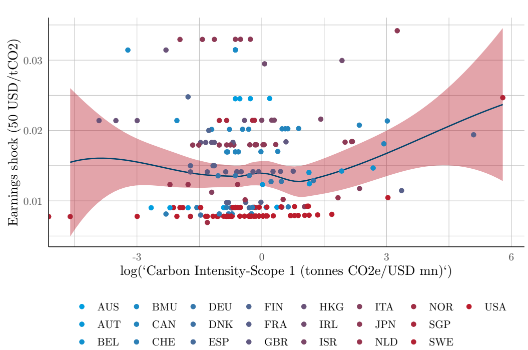
(c) Communication Services



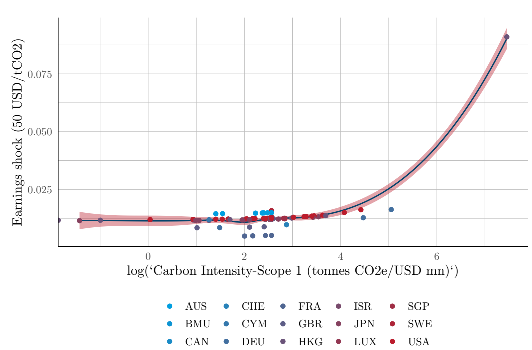
(d) Consumer Discretionary



(e) Financials



(f) Real Estate



(g) Consumer Staples

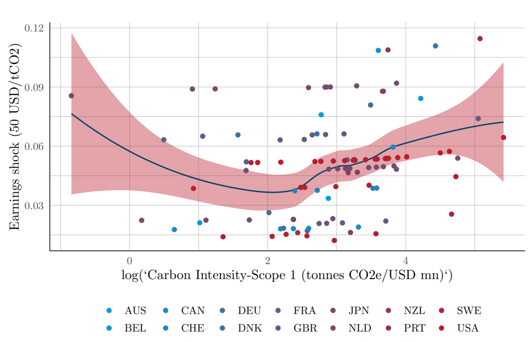


Figure 17: Residual of the multi-factor model of the earning shock, GICS sectors

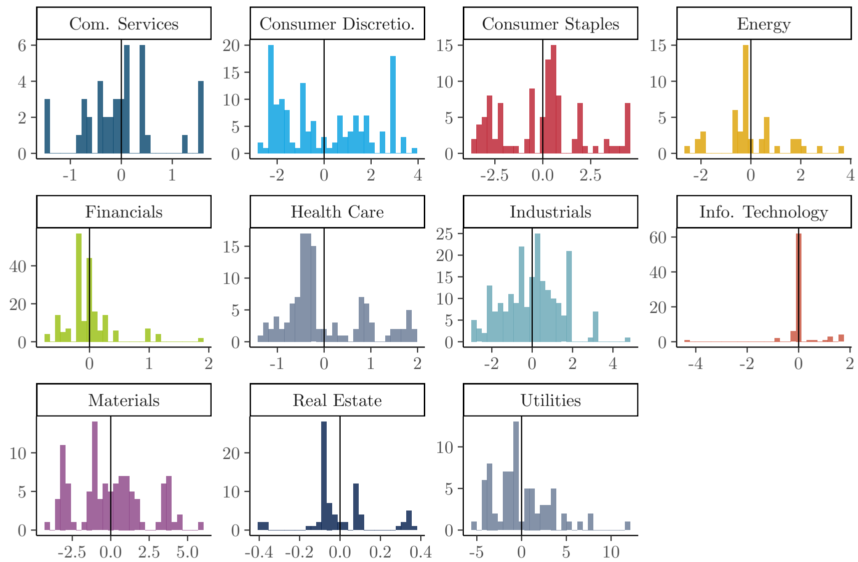


Figure 18: Residual of the multi-factor model of the earning shock, selection of WIOD sectors

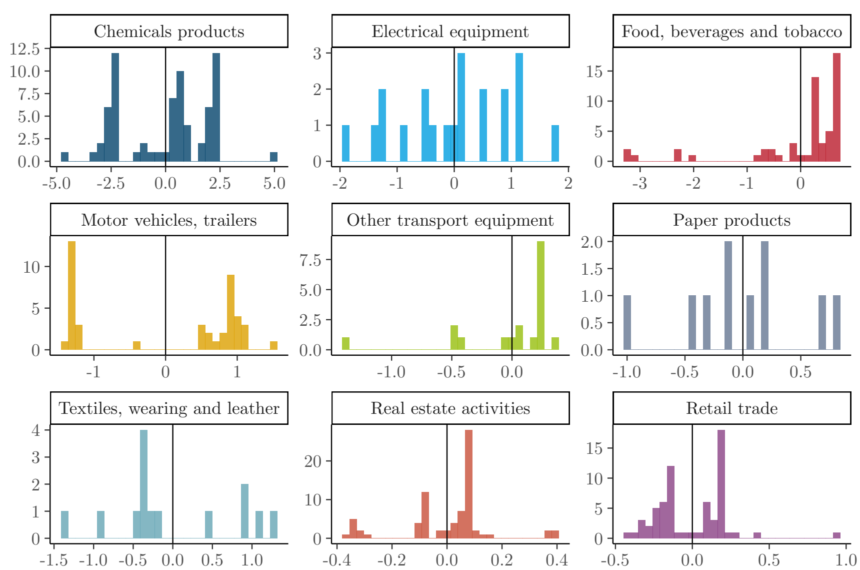
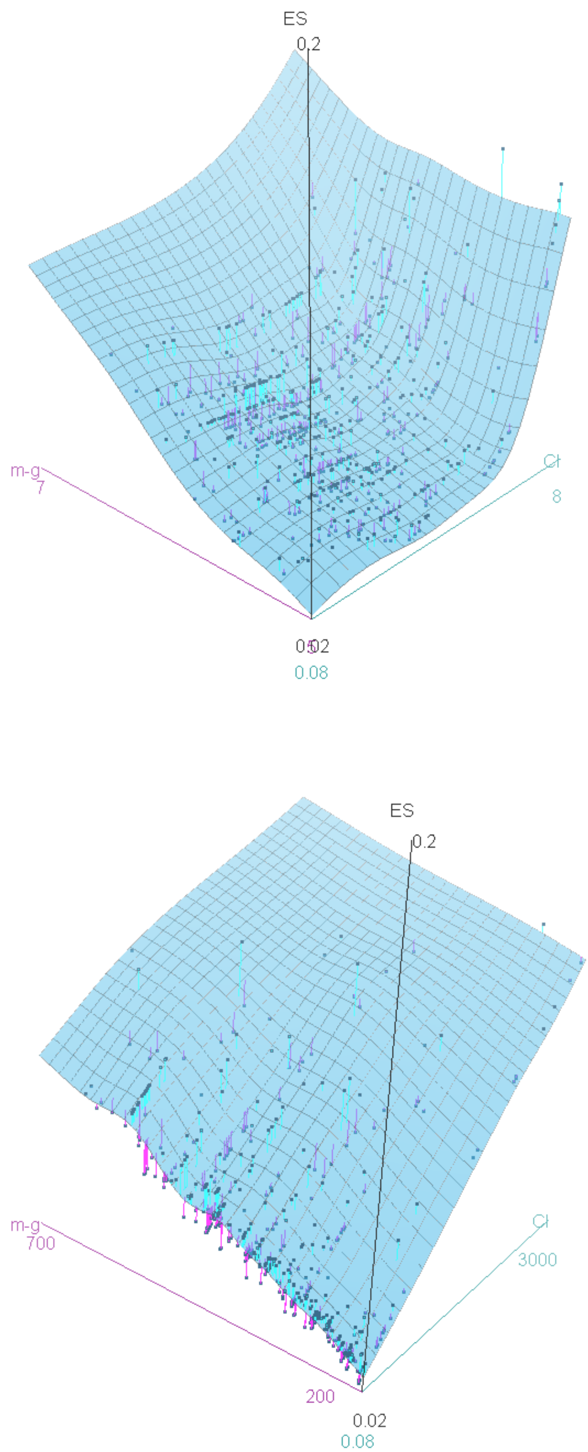


Figure 19: Empirical 3D visualization of the two factor risk model



Top figure represent the ES in function of log(m-g) and log(CI) while bottom chart does not use the log transformation

D Mapping

Table 8: Sector mapping

N	Code	Sector name
1	A01	Crop and animal production, hunting and related service activities
2	A02	Forestry and logging
3	A03	Fishing and aquaculture
4	B	Mining and quarrying
5	C10-C12	Manufacture of food products, beverages and tobacco products
6	C13-C15	Manufacture of textiles, wearing apparel and leather products
7	C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
8	C17	Manufacture of paper and paper products
9	C18	Printing and reproduction of recorded media
10	C19	Manufacture of coke and refined petroleum products
11	C20	Manufacture of chemicals and chemical products
12	C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
13	C22	Manufacture of rubber and plastic products
14	C23	Manufacture of other non-metallic mineral products
15	C24	Manufacture of basic metals
16	C25	Manufacture of fabricated metal products, except machinery and equipment
17	C26	Manufacture of computer, electronic and optical products
18	C27	Manufacture of electrical equipment
19	C28	Manufacture of machinery and equipment n.e.c.
20	C29	Manufacture of motor vehicles, trailers and semi-trailers
21	C30	Manufacture of other transport equipment
22	C31_C32	Manufacture of furniture; other manufacturing
23	C33	Repair and installation of machinery and equipment
24	D35	Electricity, gas, steam and air conditioning supply
25	E36	Water collection, treatment and supply
26	E37-E39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
27	F	Construction
28	G45	Wholesale and retail trade and repair of motor vehicles and motorcycles
29	G46	Wholesale trade, except of motor vehicles and motorcycles
30	G47	Retail trade, except of motor vehicles and motorcycles
31	H49	Land transport and transport via pipelines
32	H50	Water transport
33	H51	Air transport
34	H52	Warehousing and support activities for transportation
35	H53	Postal and courier activities

N	Code	Sector name
36	I	Accommodation and food service activities
37	J58	Publishing activities
38	J59_J60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
39	J61	Telecommunications
40	J62_J63	Computer programming, consultancy and related activities; information service activities
41	K64	Financial service activities, except insurance and pension funding
42	K65	Insurance, reinsurance and pension funding, except compulsory social security
43	K66	Activities auxiliary to financial services and insurance activities
44	L68	Real estate activities
45	M69_M70	Legal and accounting activities; activities of head offices; management consultancy activities
46	M71	Architectural and engineering activities; technical testing and analysis
47	M72	Scientific research and development
48	M73	Advertising and market research
49	M74_M75	Other professional, scientific and technical activities; veterinary activities
50	N	Administrative and support service activities
51	O84	Public administration and defence; compulsory social security
52	P85	Education
53	Q	Human health and social work activities
54	R_S	Other service activities
55	T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
56	U	Activities of extraterritorial organizations and bodies

Table 9: Sector mapping

GICS Sector	WIOD Sector
Energy	Manufacture of coke and refined petroleum products
Energy	Land transport and transport via pipelines
Materials	Manufacture of chemicals and chemical products
Materials	Manufacture of other non-metallic mineral products
Materials	Manufacture of fabricated metal products, except machinery and equipment
Materials	Manufacture of paper and paper products
Materials	Mining and quarrying
Materials	Forestry and logging
Industrials	Manufacture of other transport equipment
Industrials	Construction
Industrials	Manufacture of electrical equipment
Industrials	Financial service activities, except insurance and pension funding
Industrials	Manufacture of motor vehicles, trailers and semi-trailers
Industrials	Manufacture of machinery and equipment n.e.c.
Industrials	Wholesale trade, except of motor vehicles and motorcycles
Industrials	Printing and reproduction of recorded media
Industrials	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
Industrials	Manufacture of furniture; other manufacturing
Industrials	Administrative and support service activities
Industrials	Legal and accounting activities; activities of head offices; management consultancy activities
Industrials	Scientific research and development
Industrials	Air transport
Industrials	Water transport
Industrials	Land transport and transport via pipelines
Consumer Discretionary	Manufacture of motor vehicles, trailers and semi-trailers
Consumer Discretionary	Manufacture of rubber and plastic products
Consumer Discretionary	Manufacture of computer, electronic and optical products
Consumer Discretionary	Manufacture of furniture; other manufacturing
Consumer Discretionary	Construction
Consumer Discretionary	Manufacture of electrical equipment
Consumer Discretionary	Manufacture of other non-metallic mineral products
Consumer Discretionary	Manufacture of textiles, wearing apparel and leather products
Consumer Discretionary	Other service activities
Consumer Discretionary	Accommodation and food service activities
Consumer Discretionary	Education
Consumer Discretionary	Wholesale trade, except of motor vehicles and motorcycles
Consumer Discretionary	Retail trade, except of motor vehicles and motorcycles

Sector.name	**WIOD_Sector.name**
Consumer Discretionary	Wholesale and retail trade and repair of motor vehicles and motorcycles
Consumer Staples	Retail trade, except of motor vehicles and motorcycles
Consumer Staples	Wholesale trade, except of motor vehicles and motorcycles
Consumer Staples	Manufacture of food products, beverages and tobacco products
Consumer Staples	Manufacture of chemicals and chemical products
Health Care	Human health and social work activities
Health Care	Other professional, scientific and technical activities; veterinary activities
Health Care	Manufacture of basic pharmaceutical products and pharmaceutical preparations
Health Care	Scientific research and development
Financials	Financial service activities, except insurance and pension funding
Financials	Insurance, reinsurance and pension funding, except compulsory social security
Information Technology	Computer programming, consultancy and related activities; information service activities
Information Technology	Telecommunications
Information Technology	Manufacture of computer, electronic and optical products
Information Technology	Wholesale trade, except of motor vehicles and motorcycles
Communication Services	Telecommunications
Communication Services	Advertising and market research
Communication Services	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
Communication Services	Publishing activities
Communication Services	Computer programming, consultancy and related activities; information service activities
Utilities	Electricity, gas, steam and air conditioning supply
Utilities	Water collection, treatment and supply
Real Estate	Real estate activities

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ASSET MANAGEMENT

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