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**The impact of carbon pricing in a
multi-region production network model
and an application to climate scenarios**

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Non-technical summary

Research question

This paper describes a model using macroeconomic data sets to analyze the effects of carbon prices on production in various economic sectors. For this purpose, a production network model of the global economy is set up in which the economic sectors not only produce goods for final consumption but also intermediate inputs for other economic sectors.

Contribution

In the model, the global economy is broken down into seven regions (Germany, rest of the euro area, rest of Europe, USA, China and two rest of the world blocks) and 56 economic sectors per region. The carbon pricing is modelled as a tax on the use of fossil fuels and the emission of other greenhouse gases. Taxes make fossil fuels more expensive and trigger a substitution towards lower-emission intermediate inputs and final consumption goods. The model thus captures the entire propagation of carbon prices through the production network.

Results

In an application of the model, the simulated sectoral effects of carbon taxes are shown to be very heterogeneous across sectors, with the sectors agriculture, mining, fossil fuels and transport exhibiting the greatest effects in all regions. Spillovers of carbon prices across global value chains are substantial for some sectors. In order to leverage the model's sectoral results for use in climate scenarios, the sectoral impacts are translated into scaling factors. By applying these factors to macroeconomic time series of the whole economies, one obtains sectorally disaggregated climate scenarios.

Nichttechnische Zusammenfassung

Fragestellung

Dieses Papier beschreibt ein Modell anhand volkswirtschaftlicher Datensätze, um die Auswirkungen von CO₂-Preisen auf die Produktion in verschiedenen Wirtschaftssektoren zu analysieren. Dazu wird ein Produktionsnetzwerkmodell der Weltwirtschaft genutzt, in welchem die Wirtschaftssektoren nicht nur Konsumgüter produzieren, sondern auch Vorleistungen für andere Wirtschaftssektoren.

Beitrag

In dem Modell wird die Weltwirtschaft auf sieben Regionen (Deutschland, übrige Eurozone, restliches Europa, USA, China und zwei Restregionen) und 56 Wirtschaftssektoren je Region heruntergebrochen. Die CO₂-Bepreisung wird als Steuer auf den Verbrauch fossiler Brennstoffe und der Emission anderer Treibhausgase modelliert. Die Steuern verteuern fossile Brennstoffe und lösen eine Substitution hin zu emissionsärmeren Vorleistungen und Konsumgütern aus. Das Modell erfasst somit die gesamte Ausbreitung des CO₂-Preises durch das Produktionsnetzwerk.

Ergebnisse

In einer Anwendung des Modells zeigen sich die simulierten sektoralen Auswirkungen von CO₂-Steuern zwischen den Sektoren als sehr heterogen, wobei die Sektoren Landwirtschaft, Bergbau, fossile Brennstoffe und Verkehr die größten Auswirkungen in allen Regionen aufweisen. Die Wirkung des CO₂-Preises über internationale Wertschöpfungsketten spielt dabei für einige Sektoren eine große Rolle. Um die sektoralen Ergebnisse des Modells für den Einsatz in Klimaszenarien nutzbar zu machen, werden die sektoralen Auswirkungen in Skalierungsfaktoren übersetzt. Durch Anwendung dieser Faktoren auf zeitliche Pfade von gesamtwirtschaftlichen Größen ergeben sich sektoral disaggregierte Klimaszenarien.

The impact of carbon pricing in a multi-region production network model and an application to climate scenarios*

Ivan Frankovic[†]

February 22, 2022

Abstract

This paper builds on existing production network models to study the impact of global and sub-global carbon pricing. It uses the World Input-Output Database (WIOD) to calibrate intersectoral trade between seven regions and 56 economic sectors per region as well as EXIOBASE's sectoral accounts of greenhouse gas emissions to calibrate emission costs per sector for a given carbon price. The latter taxes emissions associated with the intermediate and final demand of fossil fuels as well as other emissions inherent to production. The global setup of the model allows the international propagation of carbon prices to be analyzed along worldwide value chains. The simulated sectoral impacts of carbon taxes are highly heterogeneous across sectors and regions, with the agricultural, mining, fossil fuel processing and transport sector exhibiting the largest impacts across all regions. For several sectors in Germany and Europe, particularly manufacturing sectors, international spillovers from carbon pricing outside of Europe can be substantial and increase value added losses by up to 100% relative to the impact of European-only carbon prices. The paper furthermore outlines a simple approach for applying the sectorally disaggregated results to global climate scenarios.

Keywords: climate scenarios, carbon pricing, input-output data, production network models

JEL-Classification: D57 ; E23 ; H23; Q54

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1 Introduction

In order to reach the Paris agreement climate goal and stay within the remaining carbon budget consistent with that goal, a worldwide transition to a green, low-carbon economy is necessary (IPCC, 2018). Even though climate policies aimed at inducing such a transition are strongly cost-effective in the long-run, they are likely to lead to short and medium-term economic costs (IMF, 2020). For example, pricing of greenhouse gas emissions can result in increasing energy prices and potentially render existing business models unsustainable. In academia and at central banks, many have expressed concerns about these costs not only affecting economic outlooks but also posing a potential risk to financial systems (Carney 2015, Bolton et al. 2020). These risks are generally referred to as transition risks, as opposed to physical risks arising from the physical manifestations of climate change. Transition risks are transmitted to the financial sector through the real economy, operating via existing risk channels, most importantly credit and market risk.

To measure and assess such transition risks, central banks and supervisors have adopted the use of climate scenarios, see, for example, NGFS (2021). The climate scenarios are generated using integrated assessment models (IAMs), which capture the codependency of climate policies, economic production and climate change in one coherent framework. Specifically, IAMs can provide the carbon price paths necessary to reach a given climate goal, and their impact on the economy.¹ However, the economic model contained in IAMs is usually much less detailed than the macroeconomic models typically employed at central banks. For example, most IAMs lack macrofinancial variables such as interest rates and risk premia and they do not disaggregate country-level economic effects on a granular sector level. Hence, the need arises to complement IAMs with models that are able to translate the climate scenarios into more detailed economic pathways, which can then serve as an input to the analysis of financial stability risks.

To address the lack of sectoral heterogeneity in IAM-generated climate scenarios, this paper aims to make two contributions. First, building on existing literature on production network models, a multi-sector / multi-region model is developed that allows the sectoral impacts of carbon pricing across different regions of the world to be studied. Second, the paper presents a simple approach for applying the sectoral results to climate scenarios.

The model belongs to the class of production network models and builds directly upon the contribution by Devulder and Lisack (2020). In the model, economic sectors not only produce goods for final consumption, but also inputs to be used in the production of other economic sectors. Each sector decides on the amount of inputs bought from other sectors, depending on their price and substitutability with other inputs as well as on the amount of labor employed, the second factor of production. Substitution elasticities from energy and non-energy sectors are separately calibrated due to their importance for carbon taxation impacts. The model is set up to reflect seven regions (Germany, rest of euro area, rest of Europe, US, China and two rest of the world blocks) and 56 sectors for each region, classified in NACE 2-digit codes. The steady-state solution of the model without carbon

¹A given climate goal can give rise to several carbon price paths by varying the background assumptions about technological and population development in and across models.

taxes reflects the intersectoral trade within and across country borders as reported in the World Input-Output Database (WIOD), see Timmer et al. (2015).²

Building on this, the impact of carbon prices on the production network is analyzed. Carbon pricing is implemented in three ways to account for the different sources of carbon emissions in the economy: a) a tax on production inputs purchased from the fossil fuel sector, which introduces an incentive to substitute away from them, b) a production tax levied on emissions not accruing through the combustion of fossil fuels, which are thus inherent to production, and finally, c) a tax on the final demand consumption of fossil fuels, again prompting a substitution away to less carbon-intensive products. Given a carbon price, the level of these taxes is then calibrated such that generated tax revenue equals the emission cost based on emissions as reported in the EXIOBASE database, see Stadler (2018). EXIOBASE provides emissions for all of the sectors and regions covered in the model, differentiated by their origin and specifically whether they occur as a result of fossil fuel combustion or by other means. The model is then solved with these carbon taxes in place. First and foremost, the taxes make fossil fuel inputs more expensive, triggering a substitution towards other inputs and consumption goods. Some of the emission cost, including the cost associated with other emissions inherent to production, are passed on through price increases, which trigger a cascade of substitution and repricing effects, at the levels both of input choice and final demand. The model thus captures the entire propagation of the carbon tax through the production network. Due to the large size of the model, with 7 x 56 economic units, each trading with each other, we abstract from modeling the transition and only solve for the initial zero-tax steady state as well as the steady-state solution for carbon pricing in place.

In order to leverage the model's sectoral results for use in climate scenarios, the sectoral impacts are, in a second step, translated into scaling factors, which express the carbon price-induced effect on a sectoral variable (e.g. value added) relative to the aggregate country-level effect. For example, a scaling factor of 10 for value added in the German fossil fuel processing sector simply states that, given an aggregate GDP reduction in Germany of 1 % in response to a carbon tax, the reduction in value added in the fossil fuel sector amounts to 10 %. By multiplying the carbon pricing-induced changes in aggregate value added in climate scenarios with the scaling factors derived here, one obtains sectorally disaggregated climate scenarios.

The model is used to simulate the impact of a carbon price of 100 euro per tonne of CO₂ or CO₂-equivalents. Relative to the zero-tax solution, a global 100 euro carbon price reduces global gross value added (GVA) by approximately 5 %. However, these effects are heterogeneously distributed across regions, with Germany, the rest of Europe and the US exhibiting smaller declines of 2-3%, while China suffers losses of 7.8 % in GVA, mainly reflecting the different degrees of emission-intensity in those regions. The sectoral impacts are highly heterogeneous as well. Naturally, the fossil fuel processing sector experiences the highest losses in value added, amounting to 30-35% in the various regions. Losses are also large in agriculture (10 - 15%) and mining and quarrying (15-20 %), with the electricity sector being affected more modestly (less than 5 %) since sectors substitute fossil fuel inputs with electricity. Generally, service sectors exhibit small losses in value-added (1-5 %).

²The database is available at www.wiod.org.

The model is also used to simulate unilateral and multilateral carbon pricing in a subset of regions as opposed to global carbon pricing. In doing so we explore the role of global input-output linkages in transmitting economic disturbances in the spirit of Frohm and Gunnella (2021). International spillovers from carbon prices appear to be quite small on the aggregate level. For example, moving from European to global carbon pricing, value added losses in Europe remain mostly unchanged. This suggests, that two opposing forces are at play, roughly canceling each other out. While non-European carbon prices remove the competitive disadvantage of European-only carbon prices for the economy of Europe, they also weaken the economic activity of Europe's trading partners, reducing demand for exports from Europe. However, this masks a large variation in international spillovers on the sectoral level. Some sectors, particularly European manufacturing industries, see value added losses increase (by up to 100%) when moving from European-only to global carbon prices. This is a consequence of diminished export demand and higher prices for internationally supplied inputs. Other sectors, such as service industries, instead benefit from the improvement in competitive disadvantage given globally uniform carbon prices (relative to European-only carbon prices).

With respect to the scaling factors, the paper shows that those are relatively robust to the assumed level of the carbon price. This is because scaling factors measure the sectoral effects relative to the aggregate effect. While the aggregate impact rises with the assumed carbon prices, the distribution of these effects across sectors appears to be relatively unchanged. This allows the use of scaling factors in climate scenarios exhibiting a growing carbon price path over time.

The methodology in this paper was applied in the chapter on climate-related financial stability risk in the Bundesbank's Financial Stability Review 2021, see Bundesbank (2021).³

The analysis in this paper does not take a stance on which transition scenarios are likely to become reality, particularly with respect to the question of which regions will implement carbon pricing and to what degree. Instead, the starting point of the analysis is the insight that global (or nearly global) carbon pricing is necessary to effectively limit global warming to levels compliant with the Paris agreement (IPCC, 2018). For that reason, the climate scenarios established at the NGFS consider only global transition scenarios, see NGFS (2021).⁴ Working with these scenarios thus requires an understanding of the implications of global carbon prices for the economy and financial system of the analyzed region. These might not solely come from carbon pricing implemented in the analyzed region itself. As this paper shows, the sectoral impacts from carbon pricing are shaped to a substantial degree of by forces ultimately originating in a sectors' position in global

³For the sake of the analysis therein, two changes to the simulation design were implemented. First, the regional disaggregation was slightly altered to better reflect the relevance of the various regions for the German Financial sector. The regional disaggregation is given by i) Germany, ii) rest of the euro area, iii) UK, iv) US, v) other developed countries (including the rest of the EU), vi) China and vii) rest of the world. Moreover, the simulations was run with a 200 euro global carbon price per tonne, better reflecting the steeper rise in global carbon prices underlying the NGFS "Net Zero 2050" scenario considered (among others) in Bundesbank (2021). The results of this simulation can be found in the technical paper describing the methodology of the analysis presented in the Financial Stability Review, see Schober et al. (2021).

⁴Note, however, that the NGFS climate scenarios consider regional heterogeneity in the speed at which the transition to a low-carbon economy occurs. Nevertheless, all scenarios meeting the goals of the Paris agreement implement global carbon prices.

supply chains. Moreover, the financial systems of one region often also directly hold assets in sectors in different regions. To fully account for the impact on national financial intermediaries, economic losses in other regions can thus be important as well.

The model developed in this paper is related to the long-standing literature on multi-sector general equilibrium models, the first of which was introduced by the seminal contribution by Long and Plosser (1983). More recently, these models have been used to revisit the role of idiosyncratic sector-specific shocks in explaining variations in aggregate output. Multi-sector models for the US economy generally show, that such shocks explain a large share of business cycle dynamics in the US (Foerster et al. 2011, Atalay 2017, Baqaee et al. 2019). Bouakez et al. 2020 investigate the role of the sectoral composition of government purchases in determining the spending multiplier in a multi-sector model of the US economy. Johnson (2014) extends the framework to include several world regions rather than capturing a closed economy and studies business cycle co-movements across trading economies. Moreover, a large number of large-scale, rich computable general-equilibrium models are used for the analysis of carbon tax impacts, see Böhringer et al. (2021) for a recent review. Most related to this paper in method and scope is, however, Devulder and Lisack (2020). They develop a static multi-sector, multi-region general equilibrium model with carbon taxation used in the context of Banque de France’ climate stress test, see Allen (2020). The model is used to study the international propagation of carbon taxes within France and Europe. This paper bases much of the theory and simulation design directly on Devulder and Lisack (2020) but differs from them in a few aspects. First, rather than calibrating the model to three regions and singling out France, this model is disaggregated at the level of seven regions, singling out Germany, the US and China as single-country blocks. Second, rather than employing Eurostat emission data, we use EXIOBASE emissions, which not only cover the EU but also all other regions from the model. This allows us to study a global carbon tax as opposed to a carbon tax only employed in the EU. Moreover, the extent to which carbon prices in other jurisdictions outside of Europe affect German or European sectors can be analyzed as outlined above. This study is also related to the literature on environmentally-extended input-output analysis, where datasets like the WIOD are directly analyzed rather than used to calibrate a production network model.⁵ Ward et al. (2019) calculate the emissions associated with the entire global supply chain of each sector. Assuming a carbon price would ultimately be fully passed on to final consumers, they derive the price increase in each sector based on an assumed carbon price. Based on demand elasticities from empirical studies, they then determine losses for each sector and world region. Similarly, in the energy transition stress test by the DNB (2018) the consumption-based carbon footprint of all sectors in the WIOD is calculated and used to disaggregate climate scenarios by sector. Relative to the model-based approach in this paper, both methods cannot, however, account for carbon-price induced distortions to production as well as the effects from tax revenue redistribution.

Finally, the proposed scaling factors relate to the literature on linking climate-related models with different aggregation levels, see Delzeit et al. (2020) for an overview. That literature generally aims to establish consistency across models in one or multiple vari-

⁵Input-output tables, such as WIOD, are also used to analyze trade questions unrelated to the environment or climate, see Timmer et al. (2015) or Feenstra and Sasahra (2018).

ables.⁶

The paper is structured as follows. The model is introduced in section 2. Section 3 describes the calibration of the model in detail, while section 4 presents the simulation results for a carbon price of 100 euro. Finally, section 5 introduces the proposed method for applying the sectoral results to climate scenarios via scaling factors, before section 6 concludes.

2 The model

In the following, the model is developed in general terms, while the actual simulated regional and sectoral disaggregation level will be discussed further below.

In the model, the world economy consists of N^R many regions, which are each divided into N^S many sectors, such that we obtain a total of $N = N^R \times N^S$ economic sectors in the model. The set of sectors belonging to region r is given by $S(r) \subset [1, \dots, N]$. Furthermore, the model distinguishes between two sets of sectors, the set of energy sectors $S(E)$ and the set of non-energy sectors $S(I)$. Both sets combined yield the total set of all global sectors, i.e. $S(E) \cup S(I) = [1, \dots, N]$.

2.1 Firms

Production The production function of the representative firm of sector $j \in [1, \dots, N]$ is assumed to be given by

$$Y_j = \left[\left(\gamma_j^E \right)^{1/\theta} (E_j)^{\frac{\theta-1}{\theta}} + \left(\gamma_j^I \right)^{1/\theta} (I_j)^{\frac{\theta-1}{\theta}} + \left(\gamma_j^L \right)^{1/\theta} (L_j)^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \quad (1)$$

where Y_j is the total amount of output in sector j , E_j is the (composite) energy input, I_j is the (composite) input of other intermediate inputs and L_j is the labor input in the production of sector j . The γ -parameters determine the share of energy, non-energy and labor inputs in the total output of sector j and are assumed to sum to unity, such that constant returns to scale hold ($\gamma_j^E + \gamma_j^I + \gamma_j^L = 1$). The parameter θ captures the elasticity of substitution between the three inputs to production.

Composite energy and non-energy inputs are given by

$$\begin{aligned} E_j &= \left(\sum_{i \in S(E)} \left(\frac{\gamma_{ij}}{\gamma_j^E} \right)^{\frac{1}{\theta^E}} M_{ij}^{\frac{\theta^E-1}{\theta^E}} \right)^{\frac{\theta^E}{\theta^E-1}}, \\ I_j &= \left(\sum_{i \in S(I)} \left(\frac{\gamma_{ij}}{\gamma_j^I} \right)^{\frac{1}{\theta^I}} M_{ij}^{\frac{\theta^I-1}{\theta^I}} \right)^{\frac{\theta^I}{\theta^I-1}}, \end{aligned}$$

⁶The transition vulnerability factors developed in DNB (2018) are similar to the scaling factors derived here in the way they are applied to climate scenarios. They differ strongly, however, in the way they are constructed as they do not reflect the endogenous substitution and tax redistribution effects mentioned above.

where M_{ij} represents the amount of inputs from sector i to j and the input-providing sectors belong to the set of energy and non-energy sectors, respectively. The parameters θ^E and θ^I capture the elasticity of substitution across inputs required to produce the composite energy and non-energy input, respectively.⁷ The parameters γ_{ij} determine the share of inputs from sector i in the output of sector j and are calibrated according to the data. Consequently, adding up all these shares across sector sets yields the aggregate energy and non-energy share in output, i.e. $\gamma_j^E = \sum_{i \in S(E)} \gamma_{ij}$ and $\gamma_j^I = \sum_{i \in S(I)} \gamma_{ij}$.

Gross value added and profit The goods produced by sector j are either sold to consumers or other sectors, domestically or internationally, at a uniform price P_j , while all inputs are purchased at the corresponding sectoral prices. The sectors are subject to two types of taxes, a production tax τ_j^Y and a tax on inputs from any sector i given by τ_{ij}^M . The taxes will be used, as argued below, to proxy for the introduction of a carbon price. Hence, the value of gross value added in each sector is given by

$$\widehat{GVA}_j = P_j(1 - \tau_j^Y)Y_j - \sum_{i=1}^N P_i(1 + \tau_{ij}^M)M_{ij}. \quad (2)$$

The hat ($\widehat{\cdot}$) over a variable name indicates that the variable captures a monetary value rather than a volume. In this case, the value of gross value added is calculated, since output and inputs are multiplied with the corresponding prices. Further below, we introduce a output deflator, which will allow real gross value added GVA_j to be determined. Sectoral profits are given by the difference in gross value added and wages paid to workers:

$$\widehat{\Pi}_j = \widehat{GVA}_j - w^r L_j \quad (3)$$

As constant returns to scale and perfect competition holds, profits evaluate to zero in each sector. Hence, gross value added in each sector is exactly equal to the wage bill in each sector. Note, however, that this profit measure captures pure profits, i.e. profits that are associated with some degree of monopolistic power, which are by assumption zero in this framework. The gross value added in each sector is, however, a more adequate counterpart to the real world profits of firms.

Optimal solution to the representative firm's problem The problem of a firm representing sector j is solved by maximizing the profit function (3) subject to the production function (1). The first-order conditions are then given by

⁷Note, that assuming a unitary elasticity of substitution ($\theta = \theta^E = \theta^I = 1$), the production function would simplify to $Y_j = A_j \left(\prod_{i=1}^N M_{ij}^{\gamma_{ij}} \right) (L_j)^{\gamma_j^L}$.

$$\frac{\partial Y_j}{\partial L_j} = \frac{w^{r(j)}}{(1 - \tau_j^Y)P_j} \Leftrightarrow \frac{L_j}{Y_j} = \gamma_j^L \left(\frac{(1 - \tau_j^Y)P_j}{w^{r(j)}} \right)^\theta \quad (4)$$

$$\frac{\partial Y_j}{\partial I_j} = \frac{P_j^I}{(1 - \tau_j^Y)P_j} \Leftrightarrow \frac{I_j}{Y_j} = \gamma_j^I \left(\frac{(1 - \tau_j^Y)P_j}{P_j^I} \right)^\theta \quad (5)$$

$$\frac{\partial Y_j}{\partial E_j} = \frac{P_j^E}{(1 - \tau_j^Y)P_j} \Leftrightarrow \frac{E_j}{Y_j} = \gamma_j^E \left(\frac{(1 - \tau_j^Y)P_j}{P_j^E} \right)^\theta \quad (6)$$

$$\frac{M_{ij}}{I_j} = \frac{\gamma_{ij}}{\gamma_j^I} \left(\frac{P_j^I}{P_i(1 + \tau_{ij}^M)} \right)^{\theta^I} \text{ for } i \in S(I) \quad (7)$$

$$\frac{M_{ij}}{E_j} = \frac{\gamma_{ij}}{\gamma_j^E} \left(\frac{P_j^E}{P_i(1 + \tau_{ij}^M)} \right)^{\theta^E} \text{ for } i \in S(E) \quad (8)$$

where $P_j^I = \left(\sum_{i \in S(I)} \frac{\gamma_{ij}}{\gamma_j^I} (P_i(1 + \tau_{ij}^M))^{1-\theta^I} \right)^{\frac{1}{1-\theta^I}}$ and $P_j^E = \left(\sum_{i \in S(E)} \frac{\gamma_{ij}}{\gamma_j^E} (P_i(1 + \tau_{ij}^M))^{1-\theta^E} \right)^{\frac{1}{1-\theta^E}}$ are the price indexes for the non-energy and energy intermediate input, respectively. E

The transmission of production and input taxes As will be argued later on, the carbon price will act as both a production and an input tax on fossil fuels. The first-order conditions from above provide first insights into the way carbon prices affect firms' decisions.

Equations (4) - (6) describe the optimal level of the three factor inputs. The equations state that the marginal product with respect to each factor (i.e. the amount of output generated by a marginal increase in a factor input, e.g. $\frac{\partial Y_j}{\partial L_j}$) equals its marginal cost, which is given by the factor's price (e.g. the wage rate) relative to the sectoral after-tax price, which is its revenue per output. Since a higher production tax τ_j^Y ceteris paribus lowers the sector's after-tax price, the marginal cost increases. In other words, wages now appear more expensive relative to the after-tax earnings. As a consequence, the marginal product needs to increase, which can only occur at lower levels of factor input and production due to the concavity of the production function. The very same argument applies to energy and non-energy composite inputs. Hence, holding wages and sectoral prices constant, the production tax clearly reduces production. In general equilibrium wages and prices will adjust, although usually not in a way that could overturn the initial impulse from the tax increase, as will be shown in the simulation results.

Equations (7) - (8) pin down the optimal level of input purchases from other sectors. A positive level of input taxes ceteris paribus increases the cost of inputs purchased from the corresponding sector relative to the price index of all sectors belonging to the same composite good (energy or non-energy sectors). This then prompts a reduction of the sector's input in the overall composite good. While other sectors used for the same composite good tend to increase their share in the production of the composite good, the overall amount of the composite input falls below its zero-tax value as the price for the composite increases. As a consequence, overall output is reduced as well. Hence also the input tax ceteris paribus decreases not only the use of the taxed input but also the overall level of production. General equilibrium prices usually adjust insufficiently to overturn

this partial equilibrium result, similarly to the production tax.

2.2 Households

Household consumption There is one representative agent in each of the regions who consumes all of the N goods produced. Thus, the agent not only consumes goods from domestic sectors but also those of sectors from other regions. While only the steady state of the model is solved in the numerical simulations to be presented later, for the sake of deriving the saving decision, we need to consider the dynamic version of some of the household model equations. The utility at the point in time $t = 0$ of the household from region r is given by

$$U_0^r = \sum_{t=0}^{\infty} \left[\beta^t a^r \frac{(C_t^r)^{(1-\sigma)}}{1-\sigma} \right] \quad (9)$$

where β is the time preference rate, a^r is a weighting parameter useful in the calibration of the model, σ is the coefficient of constant relative risk aversion (CRRA) and C_t^r the consumption bundle consumed by region r . The consumption bundle, ignoring the time subscript, is a CES-aggregate of goods from all sectors and regions given by

$$C^r = \left(\sum_{j=1}^N (\alpha_j^r)^{1/\rho} (C_j^r)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \quad (10)$$

where ρ is the elasticity of substitution across consumption goods and C_j^r the consumption of goods produced by sector j by the household from region r . Note that the sum also includes all sectors abroad. The parameter α_j^r captures the weight of the corresponding consumption good in the bundling function.

Households pay a region- and good-specific consumption tax τc_j^r , such that the total expenditure on a consumption good is given by $P_j(1 + \tau c_j^r)C_j^r$. Thus, the household pays the tax rate imposed in its region independently of whether the consumption good is imported or bought domestically. Total consumption expenditures in region r are then given by

$$\sum_{j=1}^N P_j(1 + \tau c_j^r)C_j^r = P_C^r C^r,$$

where P_C^r is the price index of the consumption bundle, which includes taxes and will be derived further below. Hence we can express total consumption expenditure either as the sum of expenditures on each single consumed good, or through the price of the aggregate bundle, which combines information on the good-specific prices with their weight in the consumption bundle.

Household income Labor supply by households is fixed at the regional level and given by L^r . This total labor supply in one region is shared by all domestic sectors, such that $\sum_{j \in S(r)} L_j = L^r$, where $S(r)$ is the set of sectors located in region r . Hence in the model labor is assumed to be only employable in the home region and thus not mobile across

regions. Each household earns labor income $w^r L^r$, where w^r is the region-specific wage rate, and receives a transfer $\hat{T}^r$ from the region's government, the budget constraint of which will be introduced further below.⁸

Household budget constraint There are two ways of defining the household budget constraint, which correspond to two alternative model assumptions regarding the degree of international risk sharing (where risk in this case arises from the introduction of carbon pricing). Either (i) complete markets are assumed, implying perfect risk-sharing across the r -many representative households. Or (ii) incomplete markets are assumed, whereby each region can buy or supply only risk-free bonds, which are traded in international markets, to carry over savings or debt into the next period.⁹ The baseline model assumes option (i): complete markets. However, appendix E discusses how the results change under the assumption of incomplete markets.

The assumption of perfect international risk-sharing across regions implies that each representative household can buy and sell one-period securities for any future state of the economy. Formally, for each potential future state of the economy s_{t+1} , a representative household buys $B_t^r(s_{t+1})$ many bonds at price $P_t^B(s_{t+1})$. When a particular future state of the economy occurs in the next period, the corresponding bonds are each worth a nominal price of one, while all others become worthless. The budget constraint is thus given by

$$P_{C,t}^r C_t^r + \sum_{s_{t+1}} P_t^B(s_{t+1}) B_t^r(s_{t+1}) = w_t^r L_t^r + \hat{T}_t^r + B_{t-1}^r(s_t). \quad (11)$$

Optimal solution to the household problem The household problem is solved by finding a solution which maximizes the household's utility function (9) subject to the budget constraint (11).¹⁰ This gives rise to the following risk-sharing condition across regions

$$\frac{C^r}{C^s} = \left(\frac{a^r P_C^s}{a^s P_C^r} \right)^{1/\sigma} \quad (12)$$

⁸Note that carbon taxes are the only form of taxation in the model. If the model featured other distortionary taxes, such as taxes on labor income, the revenue from carbon taxes could be used to lower labor taxes, thereby not only inducing favorable effects on the climate but also reducing other tax-induced distortions in the economy, see Carraro and Galeotti (2002), for example. This secondary effect of carbon or more general environmental taxes is called the double dividend hypothesis, see Freire-Gonzales (2018) for a review. This paper abstracts from potential efficiency gains induced by lowering other tax rates.

⁹A third potential option is to assume complete financial autarky, and thus no degree of international risk-sharing. This would imply that each region exhibits net exports of exactly zero, holding no assets in other regions, which stands at odds with the data. For this reason we disregard this option.

¹⁰A formal derivation can be found in Kollmann (1996).

where r and s are different regions in $[0, \dots, N^R]$. On the level of the regional consumption bundle cost-minimization yields

$$C_j^r = (\alpha_j^r) \left(\frac{P_j(1 + \tau c_j^r)}{P_C^r} \right)^{-\rho} C^r \quad (13)$$

$$P_C^r = \left(\sum_{j=1}^N (\alpha_j^r) [P_j(1 + \tau c_j^r)]^{1-\rho} \right)^{\frac{1}{1-\rho}}. \quad (14)$$

Note that the absolute level of consumption is not only influenced by changes in the relative prices of the consumed goods but also by lump-sum transfers $\hat{T}^r$.

The transmission of consumption taxes Carbon taxes applied to goods from sector j directly lower the demand for these goods, as can be seen in equation (13). Furthermore, carbon taxes increase the price level in the taxed region, see (14), while also leading to a higher demand for other goods, since these become cheaper relative to the taxed good. If other regions are untaxed, equation (12) suggests that consumption falls in the taxed region r relative to other regions, as P_C^r increases (at least more so than P_C^s). The higher the degree of risk-sharing (captured by the risk-aversion parameter σ), the smaller the relative loss of consumption. Hence, more risk-aversion leads to consumption losses being shared across regions despite carbon prices only being introduced unilaterally. In fact, this argument also holds for the two other carbon taxes in the model which will lead to price increases in P_j .

2.3 Government

The budget constraint by the government in region r is given by

$$\begin{aligned} \hat{T}^r &= \hat{T}_C^r + \hat{T}_Y^r + \hat{T}_M^r \\ &= \sum_j \tau c_j^r P_j C_j^r + \sum_{j \in S(r)} \tau_j^Y P_j Y_j + \sum_i \sum_{j \in S(r)} \tau_{ij}^M P_i M_{ij}, \end{aligned} \quad (15)$$

where $S(r)$ is the set of sectors belonging to region r and $\hat{T}_X^r$ is the tax revenue associated with the base X , being either consumption expenditures, production output or inputs. The local government only taxes domestic sectors and households. However, purchases of foreign goods are also subject to taxation. Section 3.3 will introduce the details on the calibration of the tax rates.

2.4 General equilibrium

The general equilibrium in the model is given by households and firms making optimal decisions given the tax levels imposed by the government, while all sectoral good markets and the international bond market clear.

Market clearing For each sectors' goods, the market clearing is given by

$$Y_j = C_j + \sum_{i=1}^N M_{ji} \quad (16)$$

where $C_j = \sum_r C_j^r$ is the total global consumption faced by each sector. The second term in expression (16) captures all inputs produced by sector j for use in another sector i . Hence the entirety of demand faced by a sector, either in the form of consumption or input demand, must equal its level of production.

Exports, imports and the balance of payments The total value of exports from region r is given by $\widehat{X}^r$ (where the hat denotes values as opposed to volumes) and defined as

$$\widehat{X}^r = \sum_{s \neq r} \sum_{j \in S(r)} P_j C_j^s + \sum_{j \notin S(r)} \sum_{i \in S(r)} P_i M_{ij}$$

The first term captures the value of consumption goods produced in region r but consumed in other regions, while the second term captures all exports of inputs produced in region r sold to sectors of other regions. To capture the volume of exports we construct an Törnqvist-Index of exports, following the IMF's Producer Price Index Manual, see Appendix F.¹¹ The Törnqvist-Index allows for a decomposition of the value of exports into a price and volume change relative to a base price level. We then obtain

$$\widehat{X}^r = P_X^r X^r.$$

Similarly, we define the value of imports $\widehat{IM}^r$, the price index of imports P_{IM}^r and the volume of imports IM^r as

$$\widehat{IM}^r = P_{IM}^r IM^r = \sum_{j \notin S(r)} P_j C_j^r + \sum_{j \in S(r)} \sum_{i \notin S(r)} P_i M_{ij}.$$

Hence, $\widehat{IM}^r$ captures the value of consumption goods consumed in region r but produced outside of it and the value of inputs produced outside of region r but used as inputs by region r sectors.

At each point in time, the accumulation of bond savings in one region must equal the region's net exports and thus its income from abroad:

$$\sum_{s_{t+1}} P_t^B(s_{t+1}) B_t^r(s_{t+1}) - B_{t-1}^r(s_t) = \widehat{NX}_t^r = \widehat{X}_t^r - \widehat{IM}_t^r$$

If net exports ($\widehat{NX}$) are negative in a region, then the left hand side of the equation is also negative, implying that the stock of bonds is reduced over time to pay for imports. In the steady state, payments on bonds pay for net imports.

¹¹The Törnqvist-Index is regularly employed in the production of official price statistics, see IMF (2004).

Aggregate gross value added and GDP Total gross value added in a region is given by the sum over gross value added in all domestic sectors

$$\begin{aligned}\widehat{GVA}^r &= \sum_{j \in S(r)} \widehat{GVA}_j \\ &= \sum_{j \in S(r)} \left(P_j Y_j - \sum_{i=1}^N P_i M_{ij} \right) - \widehat{T}_M^r - \widehat{T}_Y^r\end{aligned}$$

where $\widehat{T}_M^r$ and $\widehat{T}_Y^r$ is the tax revenue from the input and production tax in region r . Using the sectoral market clearing, as well as the equations for exports and imports, we obtain

$$\begin{aligned}\widehat{GVA}^r + \widehat{T}_M^r + \widehat{T}_Y^r &= \sum_{j \in S(r)} \sum_s P_j C_j^s - \sum_{j \in S(r)} \sum_{i=1}^N P_i M_{ij} + \sum_{j \in S(r)} \sum_{i=1}^N P_j M_{ij} \\ &= \sum_{j=1}^N P_j C_j^r - \sum_{j \notin S(r)} P_j C_j^r + \sum_{j \in S(r)} \sum_{s \neq r} P_j C_j^s \\ &\quad - \sum_{j \in S(r)} \sum_{i=1}^N P_i M_{ij} + \sum_{j \in S(r)} \sum_{i=1}^N P_j M_{ij} \\ &= \sum_i P_i C_i^r + \widehat{X}^r - \widehat{IM}^r \\ \widehat{GVA}^r + \widehat{T}_M^r + \widehat{T}_Y^r + \widehat{T}_C^r &= P_C^r C^r + \widehat{X}^r - \widehat{IM}^r.\end{aligned}$$

We can now define the (monetary value) of GDP in region r as

$$\widehat{GDP}^r = P_C^r C^r + P_X^r X^r - P_{IM}^r IM^r = \widehat{GVA}^r + \widehat{T}^r. \quad (17)$$

Hence, GDP is given by the sum of domestic consumption and net exports, which equal total gross value added plus taxes collected by the local government. In equation (17) we already replaced the values of exports and imports with the product of its price and volumes. This allows us to derive a measure of deflated GDP, by calculating the GDP deflator P_{GDP}^r as the Törnqvist index over its components, being consumption, exports and imports, see Appendix B. Real GDP is then given by

$$GDP^r = \widehat{GDP}^r / P_{GDP}^r.$$

In order to remove inflationary effects from our measure of the value of gross value added, we also apply the GDP deflator. Hence, real gross value added in each sector and in aggregate is given by

$$\begin{aligned}GVA_j^r &= \widehat{GVA}_j^r / P_{GDP}^r, \\ GVA^r &= \widehat{GVA}^r / P_{GDP}^r.\end{aligned}$$

3 Calibration

3.1 Regional and sectoral structure

The world economy is divided into seven regions ($N^R = 7$) as shown in table 1. Germany, the euro area as well as Europe (also including non-EU countries) make up the first three regions of the model. The remaining regions are two single-country regions, the USA and China, along with the region of other developed countries and the rest of the world.

Region name	Countries
Germany	Germany
Rest of euro area	Austria, Belgium, Cyprus, Estonia, Finland, France, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Slovakia, Slovenia, Spain
Rest of Europe	Great Britain, Switzerland, Norway, Rest of EU: Bulgaria, Croatia, Czech Republic, Hungary, Poland, Romania, Denmark, Sweden
USA	USA
Other developed countries	Australia, Canada, Japan, South Korea
China	China
Rest of the world	Remaining countries

Table 1: The seven regions in the model

The number of modeled sectors per region is set to $N^S = 56$ and follows the NACE 2-digit classification available in the WIOD database. The full list of these sectors can be found in table 4 in the Appendix.

3.2 Parameters

The CRRA parameter σ is set to 1.01 to approximate logarithmic utility in line with McKibbin et al. (2021). The elasticity of substitution parameters are set in line with Devulder and Lisack (2020).

Parameter	Elasticity of substitution	Value
ρ	across consumption goods	0.9
θ	across factors of production	0.8
θ^I	across non-energy inputs	0.4
θ^E	across energy inputs	0.9

Table 2: Elasticity of substitution parameters

Devulder and Lisack (2020) base their calibration choices on Atalay (2017). Atalay (2017) estimates the substitution elasticity between labor and inputs as well as the substitution elasticity across intermediate inputs based on the cost-minimization conditions

of industries in his production network model.¹² Since input prices are endogenous, Atalay (2017) applies as instruments short-run industry demand-shifters, namely changes in military spending, to estimate the elasticities.¹³ He finds very low elasticities across intermediate inputs, with the confidence interval ranging up to a value of 0.2. This indicates that it is generally very difficult for industries to substitute from inputs on one supplying industry to another one. On the other hand, the point estimate for the elasticity of substitution across labor and input goods is 0.9, with unit elasticity not being rejected. The elasticity of substitution across consumption goods is not directly identified in Atalay (2017). Instead, the study relies on previous empirical evidence, which commonly tends to find a value of close to but below unity.¹⁴ The sensitivity of the results with respect to these elasticity of substitution parameters is investigated in the appendix F.

Two data sources are used to calibrate the remaining parameters of the model. First, the World Input-Output Database (WIOD) is used. The WIOD covers 44 Regions and 56 sectors per region and records all intersectoral trade (including crossing country borders) as well as total production, value added and final demand in each sector. The latest available year is 2014. To calibrate the model the 44 regions are aggregated up to seven regions as described in table 1, while keeping the full number of sectors. Second, the EXIOBASE provides detailed emission accounts for each of the 56 sectors and seven regions, differentiating between emissions accruing through the use of fossil fuel (in the sectors and by households) and other types of emissions inherent to production, such as methane emissions.

The remaining parameters of the model are then calibrated according to the following calibration strategy. Assuming that the WIOD input-output tables from 2014 reflect a very small and negligible degree of carbon taxation, the zero tax version of the model is used to target the WIOD data. Specifically, using the firms' first-order conditions with taxes set to zero we set γ_{ij} to match the intrasectoral trade as observed in the WIOD tables. Similarly, we set a^r and α_j^r to match the regional and sector-specific consumption shares. Obtaining the vector of final demand from each sector from the input-output tables, we set the total factor productivity in each sector to match the empirically observed size of each sector. The EXIOBASE emission accounts are then used to calibrate the emission costs imposed when simulating a particular carbon price. This is discussed in the following section.

3.3 Taxes

The parametrization of the model as described in the previous section involves setting the carbon price to zero and hence all taxes to zero. The solution of the model thus parameterized yields the production network as observed in the WIOD input-output data. The aim of this paper is then to solve the model with carbon prices. To do so, the model

¹²The conditions capture how the input cost share (i.e. the share of input costs relative to total production value) responds to the (composite) price of inputs, as well as how the share of input costs from a specific industry depends on the industry-specific price.

¹³Changes in military demand affect industries' for specific inputs only through their effect on relative prices.

¹⁴The sectoral disaggregation in those studies varies from three sectors (agriculture, manufactured goods and services) up to a full range of two-digit ISIC sectors, all yielding similar results.

is solved under the parametrization as described above but with carbon tax rates set to a positive level. This produces an endogenous change in the production network structure.

The carbon taxes are calibrated according to sectoral emission levels currently observed and an assumed carbon price for emissions. To properly account for the different origins of emissions we follow Devulder and Lisack (2020) and impose three different taxes in the model: input, production and consumption taxes. Each of these taxes is used to capture three distinct channels through which carbon taxes affect the economy.

First, the carbon tax will affect sectors' costs of using inputs from the fossil fuel sector. This is proxied by an input tax on fossil fuel inputs. Second, the carbon tax will affect all other emissions, that do not accrue from the combustion of fossil fuels but are inherent to the production processes of a sector (e.g. methane emissions in agriculture or CO₂ emissions associated with the production of cement). This is proxied by a production tax as these emissions are not caused by the use of inputs from other sectors.¹⁵ Finally, and distinct from the other two channels, consumers also cause emissions. As those are predominantly caused by the combustion of fossil fuels, this is proxied by a consumption tax on purchases from the fossil fuel sector.

This setup requires data sources for the total emissions at the sectoral level, differentiated by whether these emissions derive from the combustion of inputted fossil fuels or from other sectoral production processes. The latest release of the environmental accounts of WIOD only provide CO₂ emissions and thus cannot be used to calibrate production taxes which require the reporting of all relevant greenhouse gases. The Eurostat emission accounts, as used by Devulder and Lisack (2020), additionally provide greenhouse gas emission on a sectoral level. However, the dataset covers only the European Union. This is why in this study we use sectoral emission data from the EXIOBASE, covering all regions used in this model. The EXIOBASE also provides both CO₂ emissions caused through combustion (EXIOBASE variable 'CO₂ - combustion - air') as well as full greenhouse gas emission data (including other CO₂, methane, nitrous oxide and sulfur hexafluoride emissions).¹⁶

Input taxes We apply the following calibration strategy for input taxes. All CO₂ emissions caused by combustion are attributed to the use of inputs purchased from the fossil fuel sector. Given the total emissions of a sector j , E_j , and an assumed carbon price, P^{CO_2} , the fossil fuel input tax rate for that sector is set such that taxing the total fossil fuel inputs exactly generates the emission cost:

$$\tau_{fj}^M = \frac{P^{CO_2} E_j}{\sum_f P_f M_{fj}} \quad (18)$$

where f captures all indexes representing a fossil fuel sector and $P_f M_{fj}$ is the value of the fossil fuel inputs sector j received. Note, that each region has a fossil fuel sector, such

¹⁵While the carbon pricing of fossil fuel inputs induces firms to substitute away from them, the pricing of other emissions cannot be dealt with easily by substitution. Instead, a carbon price would in this case more likely operate like a production tax.

¹⁶The EXIOBASE is disaggregated into 163 sectors, but can be aggregated up to the disaggregation level of the WIOD to be compatible with its input-output network.

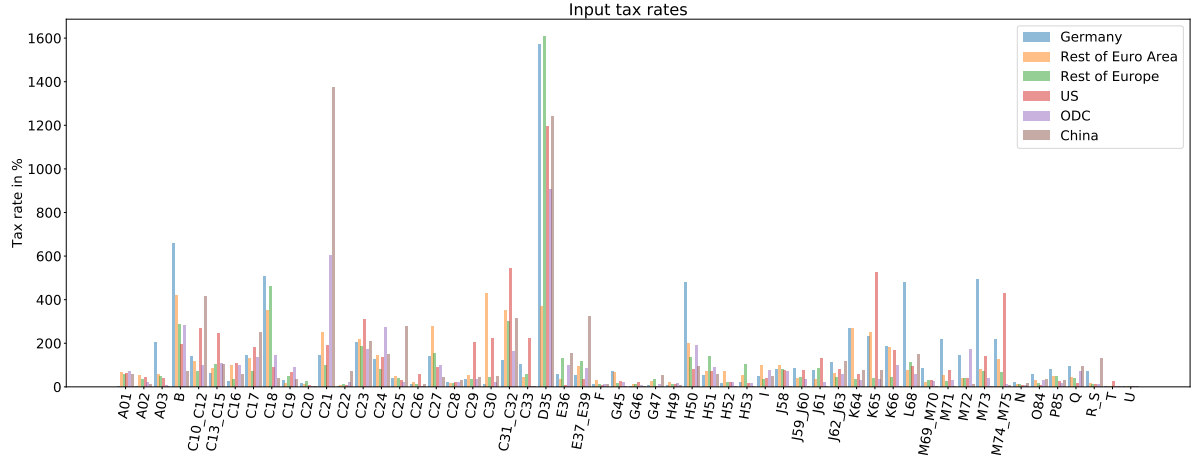


Figure 1: Fossil fuel input tax rates implied by EXIOBASE emission accounts and WIOD input-output data

that there are a total of N^R many fossil fuel sectors in the model. Fossil fuel taxes are applied to all fossil fuel inputs irrespective of their region of origin. They are paid for by the receiving sector only, however. Inputs from all other sectors remain untaxed, i.e. $\tau_{ij}^M = 0$ if $i \neq f$.

Hence, the level of the fossil fuel input tax rate is determined by the emissions per cost of fossil fuel inputs. Sectors relying on fossil fuel inputs with a high CO2 content relative to their value, such as for coal, pay a higher tax rate than sectors relying more heavily on natural gas. Figure 1 shows the fossil fuel input tax rates for each sector and region implied by this calibration strategy.

The tax rates vary greatly by sector and region. The electricity sector (D35) has the highest tax rates in all regions. In Germany, the data suggests a required tax rate on fossil fuel inputs of approx. 1500 %. This value can be interpreted in the following way: Given a carbon price of 100 euro per tonne of CO2 emitted, the German electricity sector would see its costs related to the use of fossil fuels increase by a factor of 15. This large degree of taxation can ultimately be traced back to the heavy use of emission-intensive coal inputs in the German electricity sector.¹⁷

Production taxes The approach for production taxes mirrors the input tax calculation. However, the cost of emissions is now based on the emissions of CO2-equivalents of all greenhouse gases excluding CO2 emissions from combustion, which we denote as E_j^{GHG} . This also includes CO2-emissions that are caused in the production processes of a given sector (as opposed to the combustion of fossil fuels), e.g. CO2-emissions associated with

¹⁷The data thus indicates that the German electricity sector is relatively emission-intensive relative to other euro area countries. Checking the electricity mix in Germany and euro area, one finds that Germany does indeed have a higher coal share than the EU average (the most carbon-intensive energy input among the major fossil fuel inputs), which rationalizes the high input tax in the German electricity sector. However, in reality some of the CO2 emissions might be related to purchases of mining & quarrying output, since, for example, in Germany coal will be purchased directly from firms belonging to this sector. This cannot be distinguished in the data. However, the cost burden to the electricity sector is nevertheless correctly captured.

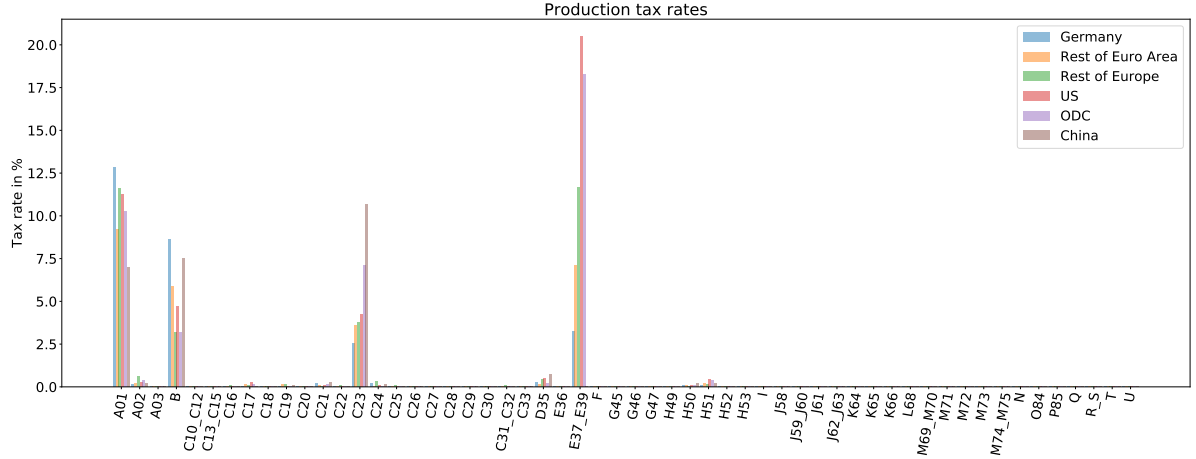


Figure 2: Production tax rates implied by EXIOBASE emission accounts and WIOD input-output data

the production of cement. The tax base is the value of the sector's production, such that tax rates are calibrated to.

$$\tau_j^Y = \frac{PCO_2 E_j^{GHG}}{P_j Y_j}. \quad (19)$$

Thus, the larger the amount of emitted greenhouse gases relative to the production value in a given sector, the larger the production tax rate.

Consumption taxes Households in each region cause CO₂-emissions E_r^{HH} , as reported in the EXIOBASE data. However, due to the lack of more detailed data we cannot allocate those emissions to the consumption of goods and services of particular sectors. Instead, we make the simplifying assumption that all the emissions are due to the purchases of fossil fuel inputs. This introduces a missallocation of some of the emissions caused by households, e.g. purchases of car fuel appear as purchases of final goods from the retail sector (which includes gas stations) in the input-output data. However, our estimates for the ultimate effect on the fossil fuel sector should not be affected greatly by this missallocation. This is because the retail sector would, if emissions were correctly allocated, pass on the emission taxes to the household and reduce its own fossil fuel purchases - amounting to the same cost and demand loss allocation as in the implemented modeling approach.

Hence, consumption tax rates are set such that, applied to the tax base, the value of fossil fuel goods purchased generates the amount of emission cost imposed by the carbon price:

$$\tau c_f^r = \frac{PCO_2 E_r^{HH}}{\sum_f P_f C_f^r}. \quad (20)$$

Analogous to the fossil fuel input tax, consumption taxes are paid on fossil fuel inputs from all regions. There is no taxation of the final consumption of other sectors, such that $\tau c_j^r = 0$ if $j \neq f$. The consumption tax on fossil fuels are, following the above approach, calibrated to 50 % for Germany, 45 % for the rest of euro area, 60 % for the rest of Europe, 69 % for the US, 50 % for other developed countries and 147 % for China. Due

to the argument made above, these values are not to be interpreted as price increases on petroleum. In fact, petroleum prices are likely to rise by 25-30 euro cent per liter as a consequence of a 100 euro per tonne carbon price, see Edenhofer and Flachsland (2018).

4 The macroeconomic and sectoral impact of carbon prices

In this section the model is solved for a carbon price of 100 euro per emitted CO₂ equivalent, a benchmark value often found in the literature.¹⁸ Later, the results for other levels of carbon prices will be shown. The effect of the carbon price introduction in different jurisdictions is determined, starting with a simulation in which a carbon price is only implemented in Germany. In other simulations, carbon prices are also introduced in other regions, subsequently adding carbon pricing to Europe, the US, other developed countries (ODC), China and ultimately to the rest of the world. The order of these simulations does not attempt to predict the order or likelihood of these regions introducing significant carbon prices in reality. However, the differences between the simulations are of interest as they carry information about the additional spillover effects on Germany or Europe of carbon pricing outside these jurisdictions. The results are obtained by comparing the production networks between the model without carbon pricing (which reflects the WIOD 2014 input-output network) with the endogenously determined production network with carbon pricing in place.

4.1 Macroeconomic impact

We first focus on the effects of a carbon price on region-level GDP and gross value added (GVA), see table 3. A unilateral introduction of carbon prices in Germany (first two rows) reduces gross value added in the economy by 1.98%, while GDP falls by only 0.45%. The difference is given by the fact that GDP also captures the tax revenue from carbon pricing, while the GVA is a measure of value added in the economy after taxes have been deducted. Other regions are little affected by carbon pricing in Germany, reflecting the limited weight of German goods and services in their economy and the ability to substitute away to output from regions without any carbon pricing. Similarly, carbon prices in Europe (rows below) appear to have little to no effect on economies such as the US and China.

As carbon pricing is introduced in more jurisdictions (moving down the rows of table 3), the effect on Germany, both in terms of GDP and GVA is now shaped not only by domestic forces but also by spillovers from international policy. There are two opposing effects on economic activity in Germany when moving to international carbon prices. First, the introduction of carbon pricing elsewhere removes the competitive disadvantage of unilateral climate policy, which materializes as prices in the taxed region increase

¹⁸For example, Devulder and Lisack (2020) employ the equal carbon price. McKibbin et al. (2021) as well as Ward et al. (2019) consider half the price, while IMF (2020) considers a range of 40 to 150 USD. In a recent review of various global CGE models, Böhringer et al. (2021) find that global carbon prices around 100 euro are consistent with limiting global warming to 2°C. As our simulations will later show, the economic impact of carbon prices in our model scales roughly linearly with the assumed carbon price. In other words, doubling the carbon tax doubles the impact on GDP.

Tax introduced	Var.	Effect in Region				
		Germany	Europe	US	China	World
in Germany	GDP	-0.45%	-0.09%	0.00%	0.00%	-0.02%
	GVA	-1.98%	-0.39%	0.00%	0.00%	-0.10%
in Eur.	GDP	-0.47%	-0.43%	0.00%	0.00%	-0.11%
	GVA	-1.99%	-2.17%	0.00%	0.00%	-0.53%
in Eur., US	GDP	-0.47%	-0.43%	-0.62%	0.00%	-0.25%
	GVA	-1.99%	-2.17%	-2.73%	0.00%	-1.16%
in Eur., US, ODC	GDP	-0.47%	-0.43%	-0.63%	0.00%	-0.33%
	GVA	-1.99%	-2.17%	-2.74%	0.00%	-1.50%
in Eur., US, ODC, China	GDP	-0.47%	-0.43%	-0.63%	-2.06%	-0.62%
	GVA	-1.99%	-2.17%	-2.74%	-7.79%	-2.57%
Worldwide	GDP	-0.48%	-0.45%	-0.64%	-2.09%	-1.11%
	GVA	-2.00%	-2.18%	-2.75%	-7.83%	-4.74%

Table 3: Effects of a 100 euro carbon price on GVA and GDP. Measured in % deviation from solution with zero carbon price.

more than elsewhere. Second, carbon prices outside of Germany also reduce economic activity among Germany’s trading partners and thus lower the demand for German goods and services abroad. The two opposing effects seem to roughly cancel each other out, neither increasing nor reducing the impact on German GDP and GVA, as carbon pricing is introduced in more and more regions. This is despite a sizable improvement in the competitiveness of German output as we move to multilateral carbon pricing: If Germany alone introduces carbon pricing, its price level (measured by the GDP deflator P_{GDP}^r) increases by 1.5 percentage points more than in the rest of the world. As global carbon prices are introduced, Germany in fact experiences lower price increases as compared to China (-2 pp.) and about the same as observed in Europe, the US and other developed countries. This indicates that the second channel, the dampening of international demand for German goods and services from global carbon pricing is significant itself. Similarly, the effect of European-only and global carbon prices on Europe (fourth column) is roughly equal to a GDP loss of just under 0.5 % and a GVA loss of roughly 2.2 %.

Note, however, while on aggregate spillovers from international carbon pricing seem to be small, this hides a lot of heterogeneity across sectors, as one of the two channels can be dominating on the sectoral level. This will be discussed in detail in section 4.3. Moreover, the model is only able to capture changes in steady states, the transition to which can temporarily yield different results.¹⁹

Moving to the last rows of table 3, we observe that carbon pricing introduced on a global scale hits emission-intensive regions, such as China and the rest of the world (not shown) considerably, reducing their GDP by roughly 2% and GVA by 7-8%. In terms of how the impact of carbon taxes is distributed worldwide, the results are well in line

¹⁹McKibbin et al. (2021) simulate the transition paths for a European-only and global carbon pricing policy and find, similar to here, that over a horizon of ten years, the GDP effect on Europe is roughly similar across the two policy scenarios. However, in the short run the global carbon policy induces a capital reallocation towards Europe (which offers higher returns given a lower emission intensity), boosting GDP, which over time is countered by a real exchange appreciation of European currencies.

with Ward et al. (2019). Their results indicate that China is likely to lose most from a globally uniform carbon tax, with the US, Germany and most other EU countries losing significantly less than the world average. Table 5 in the appendix D extends table 3 by including more regions and also the regional consumption response.

4.2 Sectoral impacts

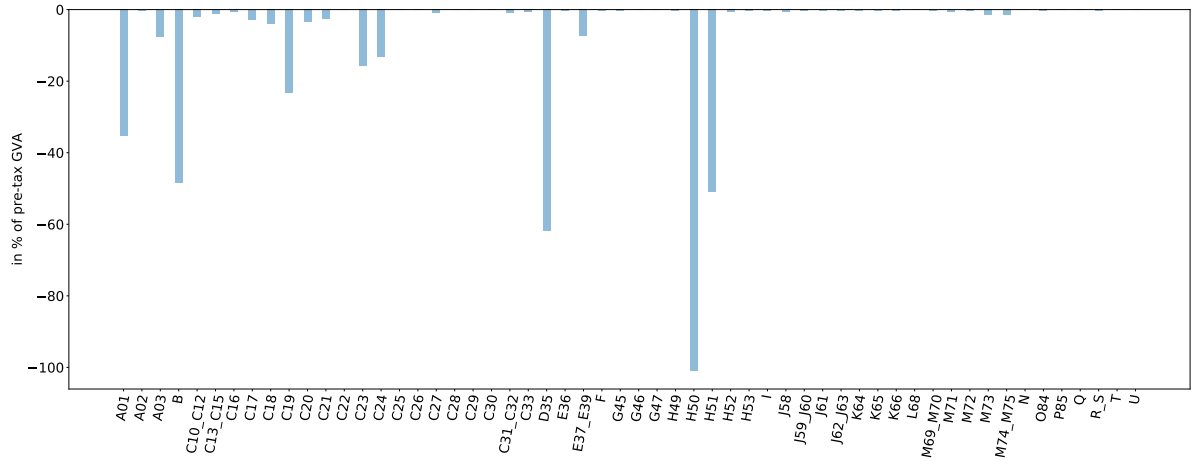
We now investigate the sectoral impacts of a global 100 euro carbon price, focusing first on Germany alone. Figure 3 illustrates the effect of a worldwide 100 euro carbon price on production volumes Y_j , real prices P_j/P_{GDP}^r and gross value added GVA_j in each sector.²⁰ We will not attempt a lengthy discussion of the patterns emerging for each individual sector, but rather focus on general patterns of groups of sectors and particularly interesting features of a few selected industries.

The tax on the use of fossil fuel inputs and the tax on other greenhouse gases lead to highly heterogeneous emission costs across sectors, reflecting the heterogeneous levels of emissions in those sectors, see figure 3a. The figure displays the amount of ex-ante emission cost per sector relative to their GVA, i.e. costs that sectors would have to pay if prices do not change and sectors do not substitute to other inputs. Particularly the sectors mining and quarrying (B), fossil fuel processing (C19), mineral / cement production (C23), electricity (D35) and water/air transport (H50/51) exhibit high emission costs, while the remaining service sectors (I-U) face almost no direct costs relative to their gross value added. The picture is more varied across the remaining manufacturing sectors (C), with some sectors having very small costs and others such as the manufacturing of chemicals (C20) exhibiting non-negligible emission costs amounting to approx. 5% of their GVA.

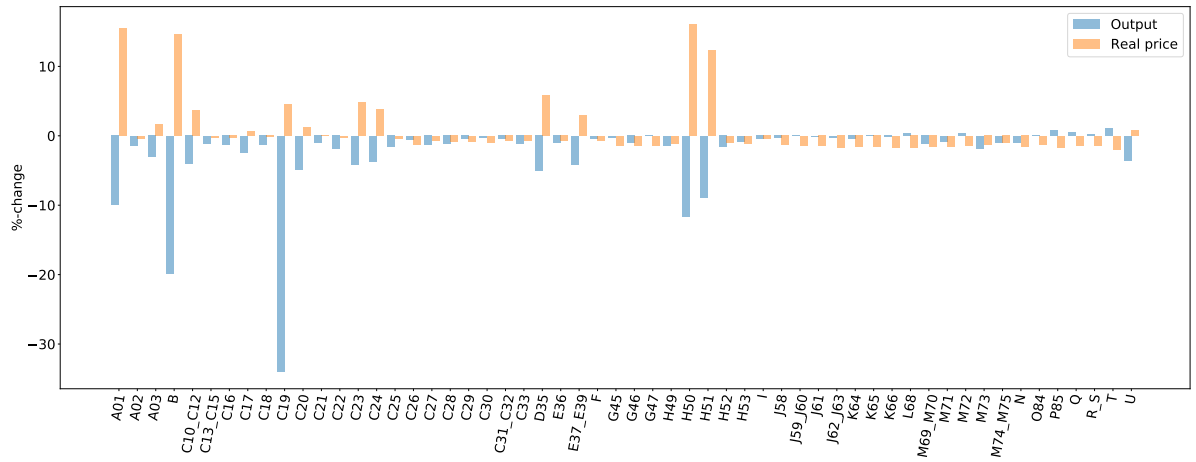
The taxes yield a number of changes to the production side of the model. The imposition of a tax on the use of fossil fuel inputs (τ^M) distorts the input choice, leading ceteris paribus to a lower level of production. Moreover, the carbon tax on emissions from other sources than burning fossil fuels acts as a direct tax on production, further working to decrease the level of output, see also section 2.1. Given that the direct impact of carbon taxes thus works to reduce output, we observe the strongest reductions in output among those sectors that exhibit the largest ex-ante emission costs, see 3b.

However, the taxes on emissions not only affect sectors through the supply side. Instead, the general equilibrium condition in the model requires adjustments in sectoral demand to be balanced by corresponding price changes in order to clear the market for each sector's goods. In sectors where production and input taxes depress output, prices need to increase in order to reduce demand to that new level of output, at least if demand does not fall for other reasons. This is, for example, the case in the agricultural sector (A01) or mining and quarrying (B), where taxation reduces optimal output, necessitating an increase in prices to lower demand. In contrast, the fossil fuel processing sector (C19) experiences a strong reduction in demand because the use of inputs from that sector and

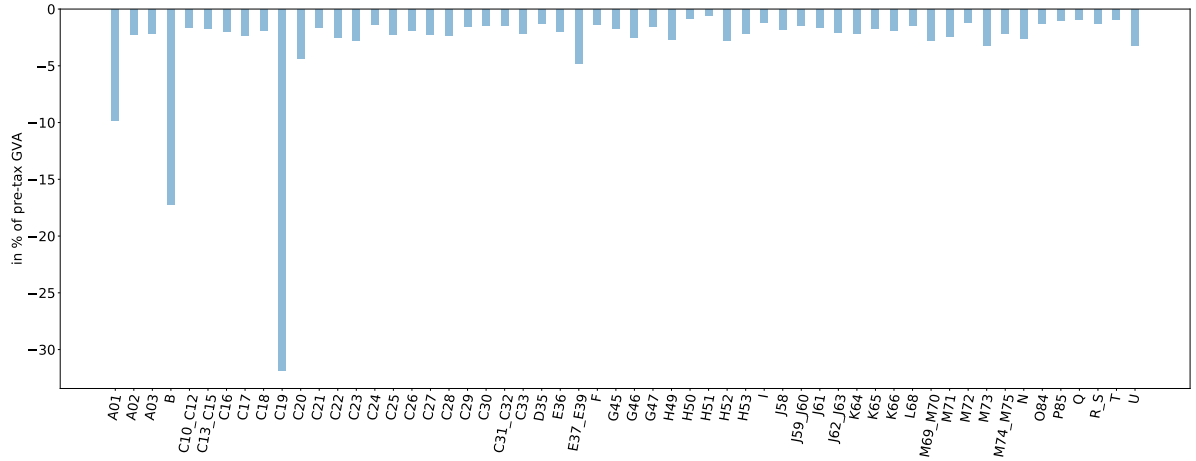
²⁰Hence, the real price of a sector's output is defined as its price P_j deflated by the regional output deflator P_{GDP}^r . The real price change thus captures price changes relative to the general price change of overall production.



(a) Ex-ante emission costs (before price changes and substitution)



(b) Effect on volumes of output (Y_j) and real sectoral prices (P_j/P_{GDP}^r)



(c) Effect on gross value added (GVA_j)

Figure 3: Effects of a 100 euro global carbon price on German sectors.

its final demand from consumers are reduced due to the direct taxation of fossil fuels. Nevertheless, (pre-tax) prices of fossil fuel goods increase by a modest amount (5%), implying that tax-induced reductions in supply of fossil fuel processing output are somewhat stronger than the reductions in demand caused by the fossil fuel tax itself.

An interesting case is also presented by the electricity sector (D35). While it faces high ex-ante emission costs and thus a large supply-side drag on output, the actual output loss is relatively modest. This is because sectors rely on energy inputs, which are made up of fossil fuel (C19) and electricity inputs. As the use of fossil fuels causes more emissions than electricity production (for the same amount of required energy inputs), the carbon price favors, overall, a substitution towards electricity, causing a shift in demand towards the electricity sector. As this demand impulse outweighs the supply-side effect on electricity output, the real price of electricity increases.

A number of other sectors see their real prices fall in response to the carbon price, including some of the manufacturing sectors (C25 - C33) and most of the service sectors (sectors I - U). This is because these sectors experience only small reductions in output due to quite low direct emission costs. This in turn requires a reduction in prices (relative to other sectors) to generate enough demand to clear the market. Note that in a small number of sectors output actually increases in response to carbon pricing. This occurs as these sectors exhibit little supply-side effects due to a low emission-intensity (e.g. sector P85, education), while facing higher demand due to substitution on the consumer level.²¹

Finally, the difference between output and the sum of all inputs determines sectoral gross value added. The effects of the global carbon price on the gross value added of German sectors is shown in figure 3c.²² Sectors reducing output more strongly than the cost of inputs will see their value added fall, which is the case for all sectors considered. Note that the ex-ante emission cost from figure 3a is considerably larger than the gross value added loss for some sectors. This indicates that these sectors are able to pass down a large share of their direct emission costs downstream along the production network by increasing their prices or they benefit from increased upstream or final demand. This occurs for example for the agricultural sector A01 (large price increase) or the electricity sector D35 (demand shift away from fossil fuels towards electricity inputs). Conversely, sectors passing costs downstream implies that sectors located downstream will have to shoulder these costs (along with the final consumer). This is why even those sectors which do not exhibit any significant ex-ante emission costs (such as several manufacturing and service sectors) still show non-negligible losses in gross value added.

Again, the fossil fuel processing sector (C19) stands out. This sector exhibits high ex-ante emission costs, which are, however, not passed downstream, but instead reinforced by a shift away from the use of fossil fuel inputs. This is why actual gross value added losses exceed the ex-ante emission cost in this sector.

Figure 4 shows the sectoral responses in gross value added to a global carbon price in

²¹Note that the nominal price level in these sectors still increases. However, real prices which express nominal prices relative to the price of total output fall because, relative to other sectors, these goods become cheaper.

²²Appendix F provides a robustness analysis of the value added impact with respect to the main parameters of the model.

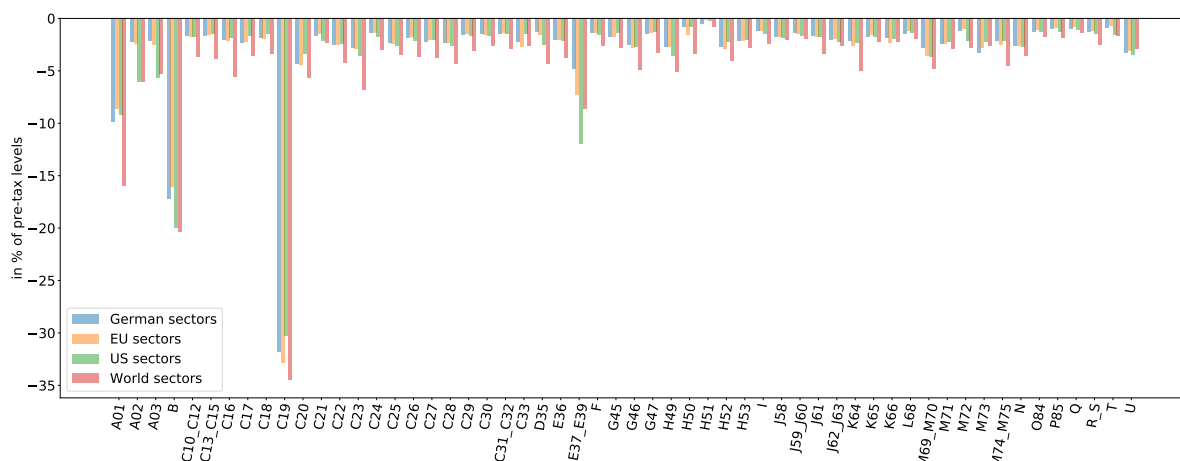


Figure 4: Effects of a 100 euro global carbon price on gross value added of sectors in Germany, Europe, the US and the world.

four different regions, Germany, Europe, the US and the world as a whole. In general, the order ranking sectors according to their gross value added losses is fairly robust across regions, with, for example, agriculture (A01), mining and quarrying (B) and fossil fuel processing (C19) consistently exhibiting the largest declines and the service sector the smallest. However, the percentage loss for each sector does differ across regions, reflecting the overall different emission intensities in the respective region. Particularly, the world as a whole exhibits higher emission-intensity than Europe or the US, a finding already explaining the results on the macroeconomic level, see 4.1.

4.3 Sectoral international spillover

In section 4.1 we concluded that, on the aggregate regional level, international spillovers appear to be rather small. In particular, we investigated, among others, two scenarios where carbon prices were either introduced in Europe only or worldwide. The two scenarios did not yield largely different macroeconomic impacts in Germany or Europe. This is because two opposing effects cancel each other out when shifting from European to worldwide carbon pricing. On the one hand, the shift removes the competitive disadvantage associated with emission costs from unilateral carbon pricing in Europe. This tends to boost economic activity in Europe. On the other hand, worldwide carbon prices harm the demand for European goods and services abroad, *ceteris paribus* decreasing activity. However, such an analysis on the macroeconomic level might hide heterogeneous responses on the sectoral level. In fact, investigating those reveals striking differences in the way international spillovers act on different parts of the economy. To gain a better overview, we group the 56 sectors of the model into 10 sector groups as illustrated in figure 5. The figure shows the losses in gross value added in each of these sectors groups associated with the carbon price introduction in different regions. Figure 5a shows the impact on German sectors, revealing that carbon prices introduced in Germany drive most of sectoral gross value added losses. Carbon pricing outside of Germany nevertheless has a sizable impact on gross value added. However, while in some sectors, international spillovers tend to increase losses, they actually reduce losses in others. For example, manufacturing sector

(C) gross value added losses increase by 8 percentage points when shifting from German-only to European carbon prices and by a further 26 percentage points when moving to global carbon prices. As will be shown in more detail below, German manufacturing sectors are well embedded in global supply chains. For that reason, they suffer a negative impact from global carbon prices because they not only export to the world, including to transition-sensitive sectors worldwide, that reduce input demand in response to carbon pricing, but also because they themselves receive inputs globally, a significant share of which come from transition-sensitive sectors. Hence, because of their centrality in global supply chains, manufacturing sectors appear to suffer more as a result of these international spillovers than they benefit from the removal of the competitive disadvantage when moving to global supply chains. Similar patterns arise for agriculture, for fossil fuel processing, mining and electricity as well as the transport sector.

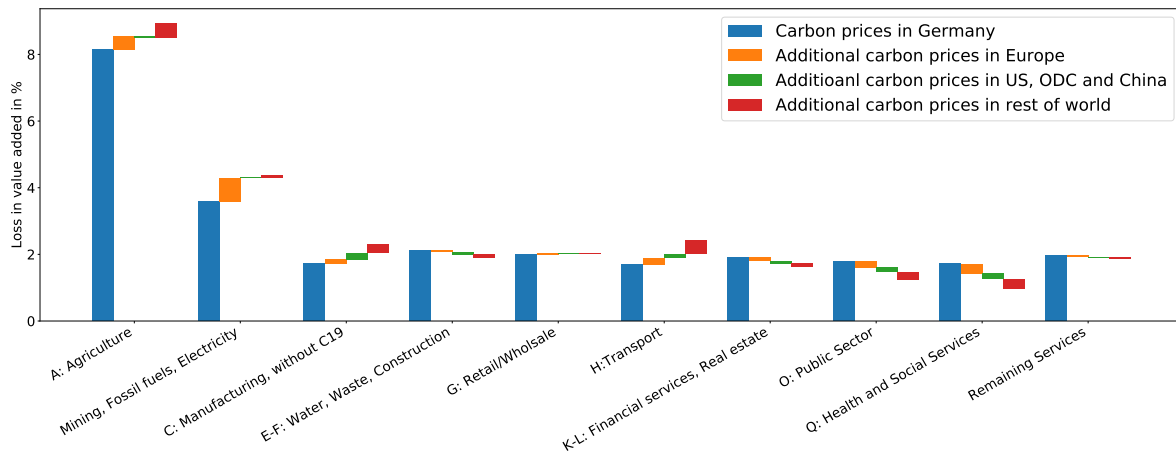
The opposite picture arises for the service industries, which see their losses induced by German-only or European-only carbon prices fall considerably in response to more global carbon pricing. This reflects the fact that for these sectors competitive disadvantages arising from unilateral carbon policy dominate. The competitive disadvantages follow from the fact that prices in the taxed region appreciate, while those in untaxed regions remain largely unaffected.

These patterns are largely identical with those observed for the sectors in Europe as a whole, see 5b.

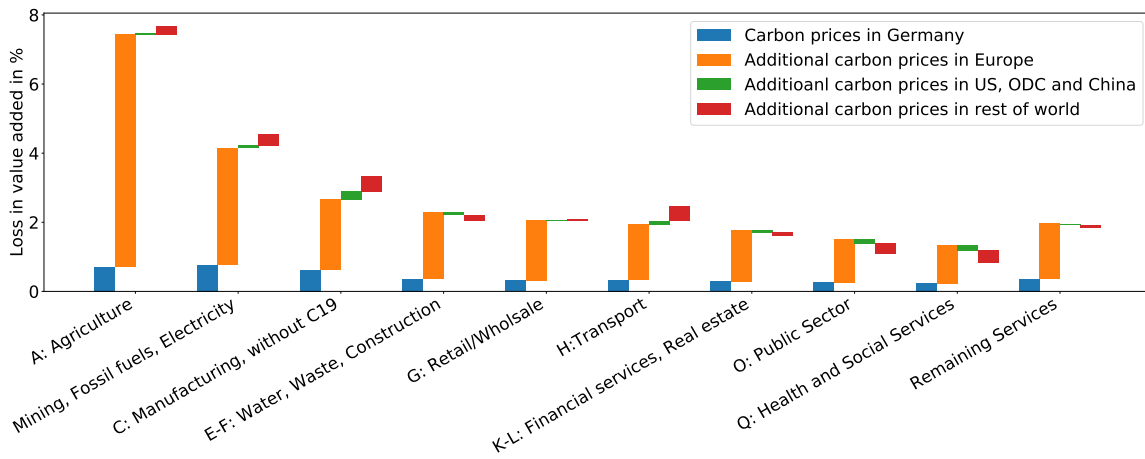
Figure 6 goes back to displaying the full 56 sectors of the model and shows the additional losses in sectoral gross value added in Germany and Europe arising from a shift from a European-only to a global carbon price.²³ We observe the same pattern already apparent in figure 5, with the manufacturing sector generally experiencing higher gross value added losses under a global carbon price introduction, with most service sectors showing a higher loss under a Europe-only emission pricing (and thus a negative additional loss in the figure). However, figure 6 reveals a large degree of heterogeneity across the sectors. Some sectors, such as mining and quarrying (B), manufacturing of chemicals (C20) as well as of basic metals (C24) appear to be subject to very large international spillover effects, boosting the gross value added loss caused by European-only carbon prices by 60 to 100 % when moving to global carbon prices. The water and air transport sectors (H50 and H51) exhibit very large spillovers. This is due to the inherent global scope of these sectors, reacting insensitively to European-only carbon prices while being very sensitive to global ones. The figure also reveals that several service sectors in fact also experience an increase in losses through non-European spillovers, as is the case for the financial services industry (K64), for example.

To make sense of this highly heterogeneous picture with respect to the exposure of different sectors to spillovers from non-European carbon pricing, we display in figure 7 different properties of the sectors against the measure of additional gross value added losses

²³The bars for the sectors H50 and H51 (water and air transport) were capped at 100% for graphical reasons. These sectors exhibit a peculiar pattern, in which European-only carbon prices lead to value added gains, rather than losses, which are reversed into losses by global carbon prices. This then gives rise to very large boosting values of 142 % for the H51 sector in Germany, and 330 % and 1043 % for the H51 and H52 sector in Europe, respectively.



(a) German sectors



(b) European sectors

Figure 5: Losses in gross value added in different sector groups, differentiated by impact from carbon pricing in different regions.

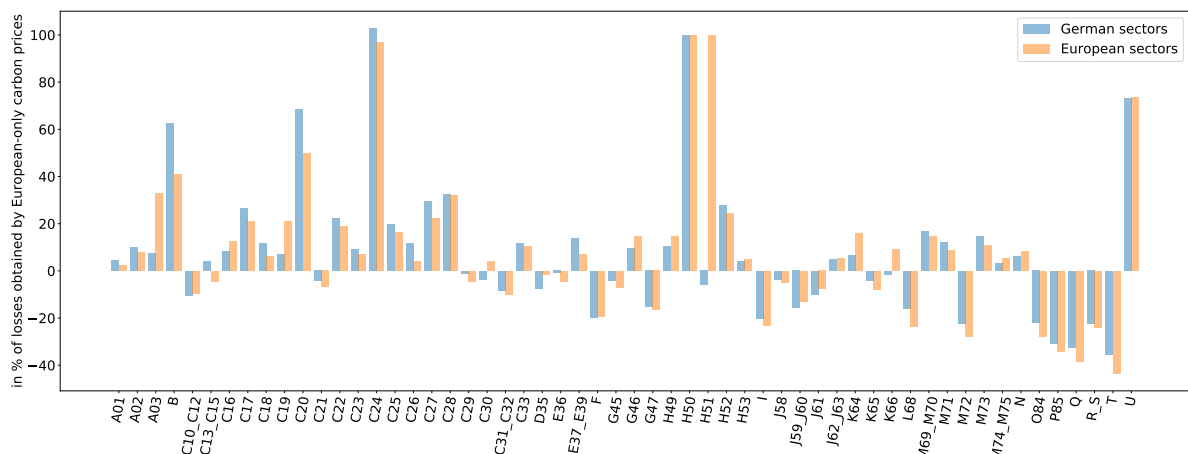


Figure 6: Additional losses in Germany and Europe's sectoral gross value added caused by global as opposed to European-only carbon prices. Measured in percent of the gross value added loss caused by European-only carbon prices.

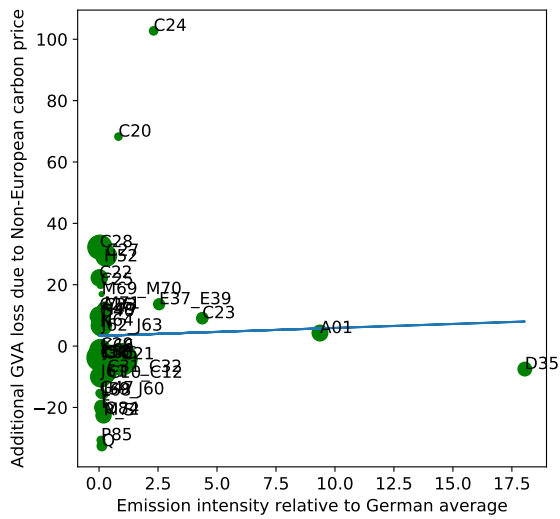
from figure 6.²⁴ We focus on German sectors, but the results for European sectors do not differ greatly. As the plots reveal, both the emission intensity of the sectors and their export share to outside of Europe are bad predictors for how much international spillovers aggravate losses. For example, the electricity sector (D35) is very emission-intensive but exhibits a very low degree of international spillovers, while many of the most export-oriented manufacturing sectors (C26-C30) exhibit modest degrees of spillovers.

Before turning to the remaining scatter plots, we first need to introduce the term transition-sensitive sectors. We define those sectors as transition-sensitive that, on a global level, lose more gross value added (relative to their starting point) in response to a global carbon price than the average sector does. Sectors with losses of more than roughly five percent in gross value added, see the world-bar in figure 4, belong to the set of transition-sensitive sectors. Returning to figure 7, we see that the output share going to non-European transition-sensitive sectors, a much more directed measure than the overall export share, as well as the input share from these sectors are much better predictors for how much sectors are exposed to adverse international spillovers. For example, the manufacture of chemicals sector (C20) depends on non-European transition-sensitive sectors, both as providers of a substantial amount of inputs to production in C20 and as buyers of C20 output. Since those transition-sensitive sectors are hit strongly by carbon prices, they charge higher prices on their output and decrease the amount of inputs, hurting the German C20 sector twofold.

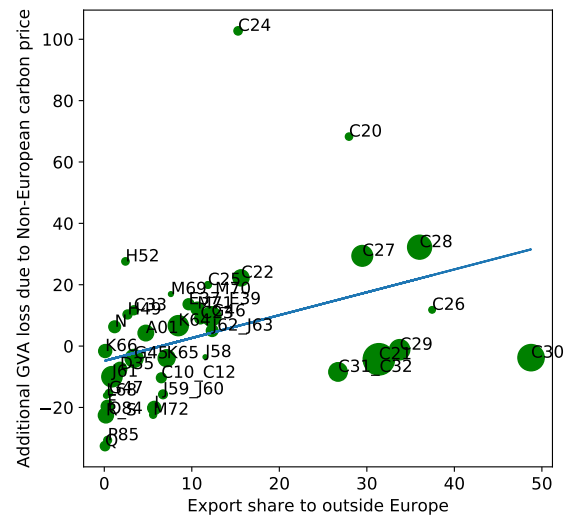
Hence, international spillovers from global carbon prices to German or European sectors are highly heterogeneous but can be well explained by the position of these sectors in global supply chains.²⁵ Sectors that depend on global transition-sensitive sectors, be it

²⁴The plots exclude the smallest sectors for a better overview.

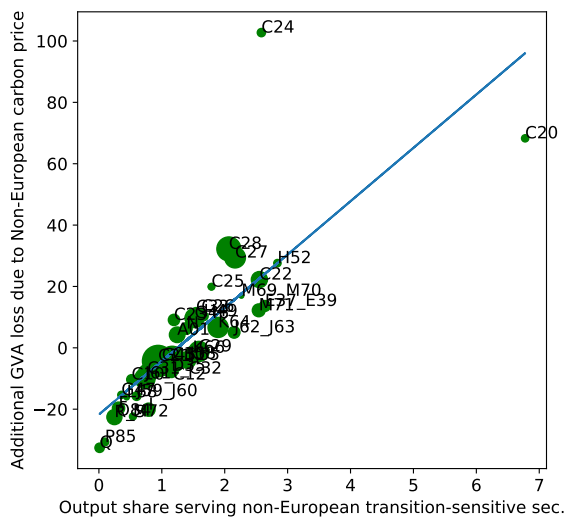
²⁵These results mirror findings in Frohm and Gunnella (2021), stressing the importance of the structure of the production network for spillovers of economics disturbances of any kind.



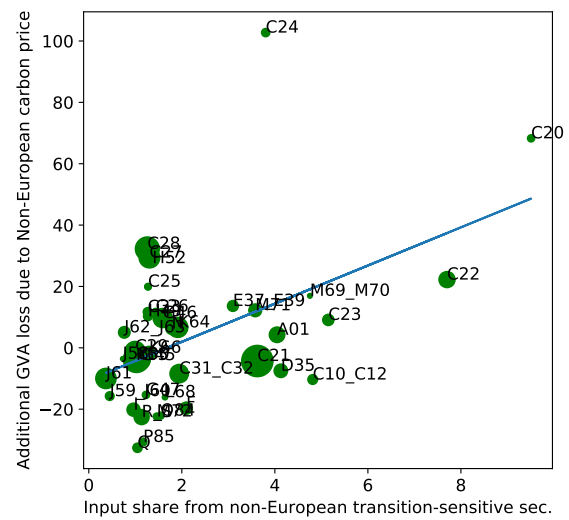
(a)



(b)



(c)



(d)

Figure 7: Additional losses in Germany’s sectoral gross value added caused by global as opposed to European-only carbon prices plotted against various sectoral properties. Circle diameters capture the relative size of German sectors in terms of gross value added.

in terms of receiving inputs from or selling output to them, are likely to be subject to substantial spillovers. Sectors that do not depend greatly on transition-sensitive sectors abroad, will not see their losses increase in response to global carbon prices, even though they themselves might be emission-intensive or highly exposed to world demand. Instead, many sectors, particularly from the service industries, might benefit from global carbon prices compared to a situation of European-only carbon prices, as in this case competitive disadvantages are alleviated.

5 Sectoral scaling factors and their application to climate scenarios

Climate scenarios from integrated assessment models, such as those representing possible transition paths to low-carbon economies (see, for example, NGFS, 2021) typically only provide a very limited number of macroeconomic variables. These are often provided only at the global or country level and not disaggregated at a granular sectoral level of the real economy. However, as illustrated by the results of the production network model above, the impact of climate policies such as carbon prices is likely to be highly heterogeneous across sectors. Consequently, when analyzing climate related financial risks and mapping transition scenarios into the balance sheets of financial intermediaries, the varying impact of carbon taxes on firms belonging to different sectors should be taken into account. In the following we present a simple method for achieving this. The method involves first calculating scaling factors for each sector based on the results of the production network model, which measure the response of single sectors relative to the aggregate country-level response to carbon prices. Second, the scaling factors are applied to aggregate economic variables in climate scenarios, yielding sector-specific paths for these variables.

5.1 Calculation of sectoral scaling factors

The first step involves calculating scaling factors. In the following, this will be carried out on the basis of gross value added but the method can equally be applied to sectoral equity valuations, production, consumption demand or employment. Let us define the following scaling factor:

$$SF_j^r = \frac{(GVA_j^{r,S} - GVA_j^{r,B})/GVA_j^{r,B}}{(GVA^{r,S} - GVA^{r,B})/GVA^{r,B}} \quad (21)$$

where $GVA_j^{r,S}$ is real gross value added in the sector j and region r in the steady state with the carbon pricing **S**tress and $GVA_j^{r,B}$ analogously the **B**ase steady state without any carbon pricing. $GVA^{r,x}$ is the aggregate gross value added in region r in state $x = S, B$. Hence the numerator of SF_j^r captures the percentage change in a sector's value added when the carbon price is implemented, while the denominator measures the change in the aggregate gross value added of the region. This can be verified by considering the sum of all scaling factors weighted by their value added share (in the zero-tax equilibrium). Let

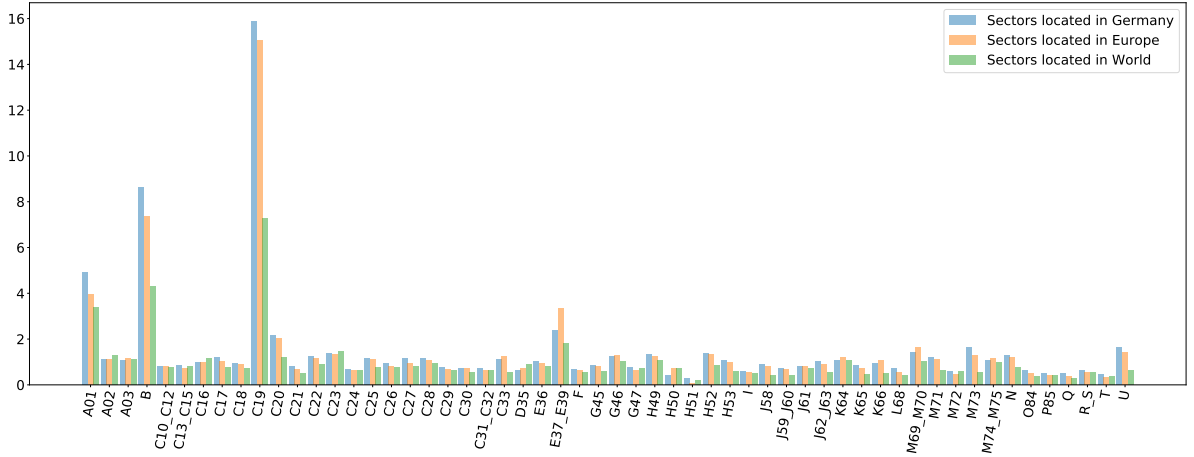


Figure 8: Sectoral scaling factors for Germany, Europe and the world given a 100 euro global carbon price

us denote the sector's value added share as $w_j^r = \frac{GVA_j^{r,B}}{GVA^{r,B}}$. Then it holds that

$$\sum_{j \in S(r)} SF_j^r w_j^r = \sum_{j \in S(r)} \frac{GVA_j^{r,S} - GVA_j^{r,B}}{GVA^{r,S} - GVA^{r,B}} = \frac{GVA^{r,S} - GVA^{r,B}}{GVA^{r,S} - GVA^{r,B}} = 1. \quad (22)$$

Hence, the average economic sector behaves exactly the same as the aggregate economy.

The scaling factors for different regions based on a simulation of a global carbon price of 100 euro are illustrated in figure 8.²⁶

5.2 Application to climate scenarios

In the second step, the scaling factors are applied to climate scenarios. Specifically, let us denote with Y_t a time series of aggregate gross value added (GVA) for a specific region r generated in an integrated assessment model.²⁷ Let us further differentiate between a base scenario GVA path Y_t^B (e.g. without carbon taxes) and a stress scenario GVA path Y_t^S (with carbon taxes). The carbon price level simulated in the production network model should of course correspond to the carbon price in the integrated stress model.

In the base scenario, we assume that each sector's value added, denoted with $Y_{t,j}^B$, evolves in just the same way as aggregate GVA, so that

$$Y_{t,j}^B = w_j^r Y_t^B \quad (23)$$

Hence, in the absence of any carbon taxation, which would lead to diverging evolutions in the value added in each sector, all sectors have the same growth rate.²⁸

²⁶Note that a higher sectoral scaling factor value in one region compared to another sector in a different region does not imply that the former sector is more emission-intensive than the latter. Instead, the higher scaling factor implies that the sector in the former region takes a larger share of the total value added loss in that region than the second sector does in its region.

²⁷Gross value added can be calculated by subtracting from GDP the amount of carbon pricing revenue.

²⁸Note that the sum of sector specific value added yields aggregate GVA, because $\sum_j Y_{t,j}^B = \sum_j w_j^r Y_t^B =$

In the stress scenario, however, we assume that sector value added paths differ from each other. The extent to which they differ is determined by the scaling factors above.

$$Y_{t,j}^S = Y_{t,j}^B \left(1 + \frac{Y_t^S - Y_t^B}{Y_t^B} S F_j^r\right) \quad (24)$$

Hence, we impose that the percentage change in sectoral value added caused by the carbon tax stress equals the aggregate GVA change caused by the carbon tax scaled by the scaling factor derived above. Note that the percentage response of the average sector, which has a scaling factor of 1, exactly equals the percentage response of the aggregate economy. This implies that all scaled-down sectors taken together behave just as given in the aggregate time series:

$$\begin{aligned} \sum_j Y_{t,j}^S &= \sum_j Y_{t,j}^B \left(1 + \frac{Y_t^S - Y_t^B}{Y_t^B} S F_j^r\right) = Y_t^B \sum_j w_j^r \left(1 + \frac{Y_t^S - Y_t^B}{Y_t^B} S F_j^r\right) \\ &= Y_t^B \left(1 + \frac{Y_t^S - Y_t^B}{Y_t^B} \sum_j S F_j^r w_j^r\right) = Y_t^B \left(1 + \frac{Y_t^S - Y_t^B}{Y_t^B}\right) = Y_t^S \end{aligned}$$

where the fact that all weights sum to 1 ($\sum_j w_j^r = 1$) and equation (22) was used.

Figure 9 illustrates the scaling method. First, the percentage impact of carbon pricing on national GVA, i.e. the percentage difference between the stress and the base scenario obtained from the integrated assessment model, is calculated for each point in time, see figure 9a.²⁹ Second, the scaling factors determined by the production network model are multiplied with the aggregate percentage difference to obtain effects on sectoral gross value added, measured again in percentage points differences between the stress and base scenario, see figure 9b. In the figure three sectors have been scaled, namely the fossil fuel sector (C19 with a scaling factor of 11.0), electricity production (D35, 0.8) and health (Q, 0.58). In a fourth step (not illustrated), the sectoral percentage differences across stress and base scenario can be translated into level paths by assuming that in the base scenario each sector grows exactly like the overall economy, as detailed above.

5.3 Extensions and robustness

The method can be extended in many dimensions, some of which are outlined in the following. First, in the above approach it was assumed that the integrated assessment model would at least be disaggregated at the country level. This might not always be the case. However, this does not pose a challenge to the method since the sectoral scaling factors can also be calculated based on the global GVA response in the production network models. The scaling factors would then measure the percentage response of a particular sector from a given country relative to the global aggregate GVA response. The scaling factors can then be applied to the global GVA path in climate scenarios, again yielding regionally and sectorally differentiated value added paths.

$Y_t^B \sum_j w_j^r = Y_t^B$.

²⁹The climate scenario depicted shows the impact on German GVA induced by a carbon pricing path starting to grow above zero in 2021. The concrete values depicted are, however, irrelevant for the illustration of how scaling factors are applied.

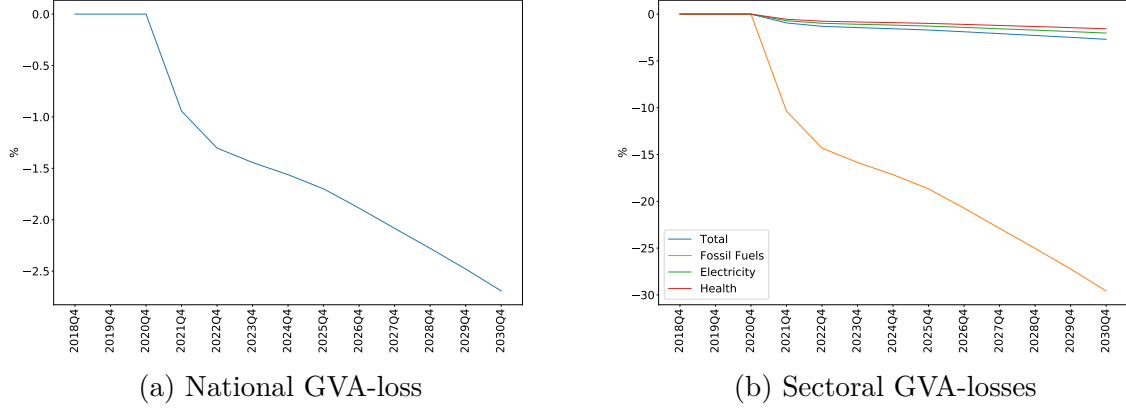


Figure 9: Applying the scaling factors to climate scenarios - an illustration

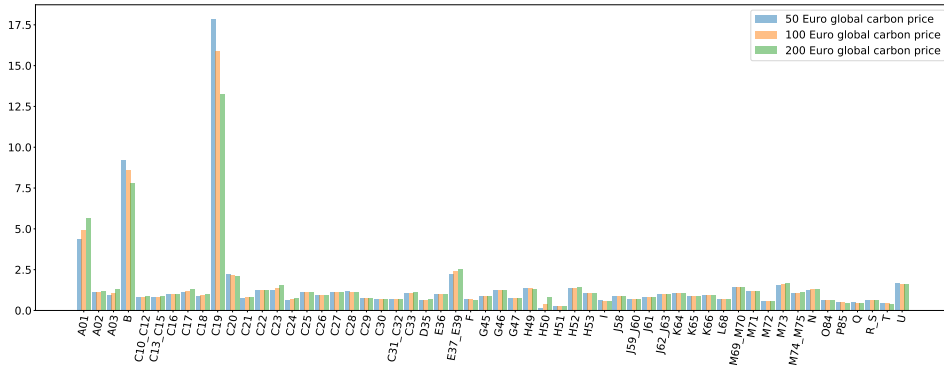


Figure 10: Scaling factors for sectors in Germany for a 50, 100 and 200 euro global carbon tax

Second, the production network model assumes a specific final carbon price *level*, whereas climate scenarios are based on a carbon price *path*. That path usually increases over time and consequently the costs to GVA relative to the zero-tax baseline increase over time. However, as shown in figure 10, the scaling factors are quite robust to the level of the assumed carbon price. This is because the scaling factors only pin down the relative impact across sectors and do not contain information on the absolute effect. While higher carbon prices naturally lead to higher sectoral impacts, the distribution of effects across sectors remains fairly stable.³⁰ The differences relate to some particularly emission-intensive sectors exhibiting higher scaling factors for low carbon prices while the service sectors have higher scaling factors at higher carbon prices.³¹ Theoretically, one could calculate different scaling factors for each point in time of the carbon price path provided by the climate scenario and apply those time-dependent scaling factors to the time series of GVA. However, practically this would not affect the scaled-down sector value added paths greatly.

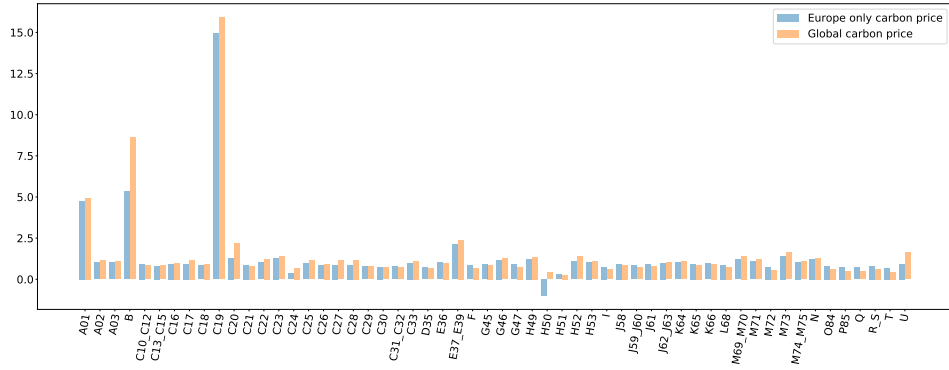
³⁰This ultimately follows from the specification of constant elasticities of substitution across inputs. Hence, the ease of substitutability remains constant in the model independently of how much substitution relative to the zero-tax steady state already occurred.

³¹Remember that the weighted sum of the scaling factors is, by construction, one in any case.

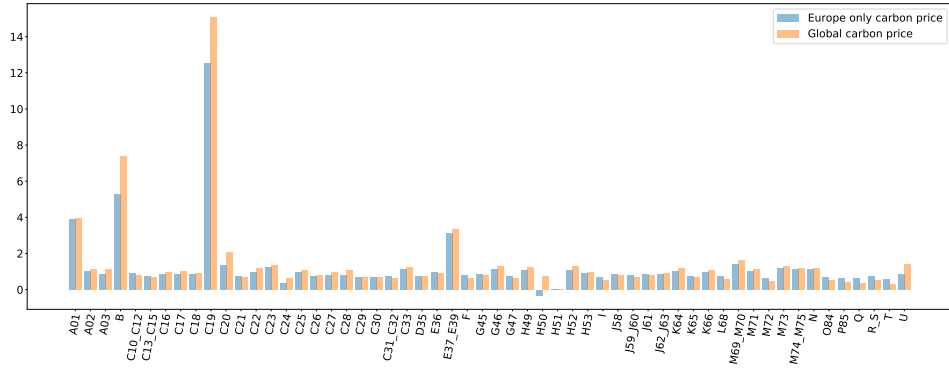
To keep the method as simple as possible, time-dependent scaling factors are thus not employed.³²

Third, the scaling factors are not invariant to assumptions about which regions implement transition policies. As has been argued in section 4.3, sectors are differently affected by international spillovers. Some sectors see their gross value added losses increase in a global carbon price scenario relative to a European-only carbon price, which implies that scaling factors are also larger in the former scenario relative to the latter. Other sectors will exhibit lower scaling factors in a global scenario. This is illustrated in figure 11 for German and European sectors. Hence, rather than capturing universal properties of sectors, such as their emission-intensity, the scaling factors measure how sectors react in different climate scenarios. In fact, the observation, that sectoral responses differ across scenarios should in fact caution against the use of scenario-invariant sectoral vulnerability indicators.

³²The scaling factors are inadequate in application to U-shaped aggregate curves. Macroeconomic models could predict a rise in carbon tax-related costs in the short- to medium-run, but a fall thereof once the switch to new low-carbon technologies and sectors has been completed. Hence, the initial losses in output and equity prices could be recouped once the tax base for the carbon tax, the emissions, have been reduced down to zero. The approach outlined above would then imply that very carbon-intensive sectors such as the fossil fuel sector would see a disproportionately fast recovery compared with the average sector. This underlines the limitations of the model and the need to only apply it to short- to medium-run dynamics.



(a) Sectors in Germany



(b) Sectors in Europe

Figure 11: Scaling factors for sectors in Germany and Europe for two scenarios: European-wide or global carbon prices

6 Conclusion

This paper presents a multi-region production network model with carbon taxation. The model is calibrated to reflect the global intersectoral trading patterns as recorded in the World Input-Output Database, while sectoral carbon emissions are calibrated to data from the EXIOBASE. The carbon tax in the model transmits through multiple channels, taking into account not only the substitution away from fossil fuels but also the drag on production caused by taxing emissions unrelated to fossil fuel use. Moreover, the model tracks the propagation of these direct sectoral impacts throughout the entire national and global supply chains of sectors. The model thus delivers a comprehensive general equilibrium evaluation of carbon taxation effects on sectoral production.

The model allows an important shortcoming of climate transition scenarios to be addressed, namely the absence of sectorally disaggregated macroeconomic variables. By constructing scaling factors that measure the relative effect on sectors caused by carbon taxes and applying those to macroeconomic country-level or global variables, climate scenarios can be much improved in terms of usability for further analysis. In particular, the method allows climate scenarios to be used to map transition stress into the balance sheets of financial intermediaries without missing the sectorally heterogeneous impacts of carbon taxes.

A number of caveats apply to this analysis. First, a shortcoming of the model is the implicit assumption of constant technologies. For that reason, the only way sectors can react to carbon taxation is by substituting to less emission-intensive inputs, while not being able to invest in more efficient technology. In particular, the marginal abatement costs have been shown to differ between sectors, see, for example, the study by McKinsey & Company (2013). Technology adoption is thus likely to differ across sectors. Moreover, the scaling factor approach can only properly account for the initial cost-increasing impact of carbon prices, not the economic recovery arising through a reduction in emissions and related emission costs. While this is less of a concern for the short to medium-run, the model results should be interpreted with caution when considering long-run effects. Second, the model features only two energy sectors, the electricity and the fossil fuel sector. The model can account for a carbon tax-induced substitution away from fossil fuels demanded by the electricity sector and, at the same time, an increase in inputs from other sectors, such as machinery and equipment. The latter can be interpreted as a switch to renewable energy sources. However, it would be preferable to explicitly differentiate between electricity sectors to track their diverging paths. The exposure of the financial systems to these different electricity sectors obviously affects their risk level greatly. Addressing these caveats is left to future work.

References

- [1] Allen T., Dees S., Boissinot J., Caicedo Graciano C.M., Choard V., Clerc L., de Gaye A., Devulder A., Diot S., Liscak N., Pegoraro F., Rabaté M., Svartzman R and L. Vernet (2020), Climate-Related Scenarios for Financial Stability Assessment: an Application to France, Banque de France Working Paper No. 774.

- [2] Atalay E (2017), How Important are Sectoral Shocks, *American Economic Journal: Macroeconomics* 2017, 9(4): 254-280.
- [3] Baqaee DR and E Farhi (2019), The Macroeconomic Impact of Microeconomic Shocks: Beyond Hulten’s Theorem, *Econometrica*, Vol 87, No 4, 1155-1203.
- [4] Böhringer C, S Peterson, TF Rutherford, J Schneider and M Winkler (2021), Climate policies after Paris: Pledge, Trade and Recycle: Insights from the 36th Energy Modeling Forum Study (EMF36), *Energy Journal*, 103.
- [5] Bolton P, M Despres, LA Pereira da Sliva, F Samama and R Svartzman (2020), The green swan: Central banking and financial stability in the age of climate change, Bank of International Settlements paper.
- [6] Bouakez H, O Rachedi and E Santaro (2020), The Sectoral Origins of the Spending Multiplier, Mimeo.
- [7] Bundesbank (2021), Financial Stability Review 2021, Deutsche Bundesbank.
- [8] Carney M (2015), Breaking the Tragedy of the Horizon ? climate change and financial stability, Speech, available at <https://www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability>.
- [9] Carraro C and M Galeotti (2002), The Benefits of Environmental Fiscal Reforms in an Integrated Europe, *Review of International Economics*, 5:111-133.
- [10] Delzeit R, R Beach, R Bibas, W Britz, J Chateau, F Freund, J Lefevre, F Schuene-mann, T Sulser, H Valin, BV Ruijven, M Weitzel, D Willenbockel and K Wojtowicz (2020), Linking Global CGE models with Sectoral Models to Generate Baseline Scenarios: Approaches, Challenges, and Opportunities, *Journal of Global Economic Analysis*, 5(1), 162-195.
- [11] Devulder A and N Lisack (2020), Carbon Tax in a Production Network: Propagation and Sectoral Incidence, Banque de France Working Paper Series, 760.
- [12] DNB (2018), An energy transition risk stress test for the financial system of the Netherlands, DNB Occasional Study, No 7.
- [13] Edenhofer O and C Flachsland (2018), Eckpunkte einer CO2-Preisreform für Deutschland. MCC Working Paper 1/2018.
- [14] Feenstra R C and A Sasahara (2018), The “China shock,” exports and U.S. employment: A global input-output analysis, *Review of International Economics*, 26:1053-1083.
- [15] Foerster A.T., P G Sarte and M W Watson (2011), Sectoral versus Aggregate Shocks: A Structural Factor Analysis of Industrial Production, *Journal of Political Economy*, 119(1).

- [16] Freire-Gonzales J. (2018), Environmental taxation and the double dividend hypothesis in CGE modelling literature: A critical review, *Journal of Policy Modeling*, 40, 194-223.
- [17] Frohm E and V Gunnella (2021), Spillovers in global production networks, *Review of International Economics*, 29:663-680.
- [18] IMF (2004), *Producer Price Index Manual: Theory and Practice*, International Monetary Fund.
- [19] IMF (2020), *World Economic Outlook, October 2020: A Long and Difficult Ascent*, Chapter 3: Mitigating Climate Change, available at <https://www.imf.org/en/Publications/WEO/>.
- [20] IPCC (2018), Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.
- [21] Johnson R. C. (2014), Trade in Intermediate Inputs and Business Cycle Comovement, *American Economic Journal: Macroeconomics*, 6(4), 39-83.
- [22] Kollmann R. (1996), Incomplete asset markets and the cross-country consumption correlation puzzle, *Journal of Economic Dynamics and Control*, 20, 945-961.
- [23] Long J. B. and C. I. Plosser (1983), Real Business Cycle, *Journal of Political Economy*, 91(1), 39-69.
- [24] W. McKibbin, M. Konradt and B. Weder di Mauro (2021), Climate Policies and Monetary Policies in the Euro Area, ECB Sintra Forum 2021 papers.
- [25] McKinsey & Company, 2013. Pathways to a low-carbon economy. [online] McKinsey & Company. Available at: <https://www.mckinsey.com/business-functions/sustainability/our-insights/pathways-to-a-low-carbon-economy> [Accessed 21 May 2021].
- [26] NGFS (2021), NGFS Climate Scenarios for central banks and supervisor, available at <https://www.ngfs.net/ngfs-scenarios-portal/data-resources/>.
- [27] Schober D, T. Etzel, A. Falter, I. Frankovic, C. Gross, A. Kablau, P. Lauscher, J. Ohls, L. Strobel and H. Wilke (2021). Sensitivitätsanalyse klimabezogener Transitionsrisiken des deutschen Finanzsektors, Bundesbank Technical Paper 13/2021.
- [28] Stadler K, R. Wood, T. Bulavskaya, C.J. Sodersten, M. Simas, S. Schmidt, A. Usubiaga, J. Acosta-Fernandez, J. Kuenen, M. Bruckner, S. Giljum, S. Lutter, S. Merciai,

- J.H. Schmidt, M.C. Theurl, C. Plutzar, T. Kastner, M. Eisenmenger, K. Erb, A. de Koning, and A. Tukker (2018), EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables, *Journal of Industrial Ecology* 22(3)502-515. doi: 10.1111/jiec.12715.
- [29] Timmer M. P., E. Dietzenbacher, B. Los, R. Stehrer and G. J. de Vries (2015), An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production, *Review of International Economics*, 23: 575-605.
- [30] Ward H., Steckel J.C. and M. Jakob (2019), How Global Climate Policy Could Affect Competitiveness, *Energy Economics*, 84.

A Appendix: Sectors

Nace Code	Description
A01	Crop and animal production, hunting and related service activities
A02	Forestry and logging
A03	Fishing and aquaculture
B	Mining and quarrying
C10_C12	Manufacture of food products, beverages and tobacco products
C13_C15	Manufacture of textiles, wearing apparel and leather products
C16	Manufacture of wood and of products of wood and cork, except furniture;
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, trailers and semi-trailers
C30	Manufacture of other transport equipment
C31_C32	Manufacture of furniture; other manufacturing
C33	Repair and installation of machinery and equipment
D35	Electricity, gas, steam and air conditioning supply
E36	Water collection, treatment and supply
E37_E39	Sewerage; waste collection, treatment and disposal activities; materials recovery
F	Construction
G45	Wholesale and retail trade and repair of motor vehicles and motorcycles
G46	Wholesale trade, except of motor vehicles and motorcycles
G47	Retail trade, except of motor vehicles and motorcycles
H49	Land transport and transport via pipelines
H50	Water transport
H51	Air transport
H52	Warehousing and support activities for transportation
H53	Postal and courier activities
I	Accommodation and food service activities
J58	Publishing activities
J59_J60	Motion picture, sound recording and music publishing activities; programming and broadcasting activities
J61	Telecommunications
J62_J63	Computer programming, consultancy and related activities; information service activities
K64	Financial service activities, except insurance and pension funding
K65	Insurance, reinsurance and pension funding, except compulsory social security
K66	Activities auxiliary to financial services and insurance activities
L68	Real estate activities
M69_M70	Legal and accounting activities; activities of head offices; management consultancy activities
M71	Architectural and engineering activities; technical testing and analysis
M72	Scientific research and development
M73	Advertising and market research
M74_M75	Other professional, scientific and technical activities; veterinary activities
N	Administrative and support service activities
O84	Public administration and defence; compulsory social security
P85	Education
Q	Human health and social work activities
R_S	Other service activities
T	Activities of households as employers
U	Activities of extraterritorial organizations and bodies

Table 4: Sectors covered in the model, based on WIOD sectoral disaggregation. Energy sectors are shown in bold print.

B Appendix: Törnqvist index

Consider n -many goods of quantity q_i^b and price p_i^b in the initial base calibration of the model, constituting a total value of $\hat{Q}^b = \sum_{i=1}^n p_i^b q_i^b$. Now consider a change in quantities and prices (in our model caused by an increase in carbon taxes) to a new values given by q_i^c , p_i^c and $\hat{Q}^c = \sum_{i=1}^n p_i^c q_i^c$.

Hence, the change in the total value from $\hat{Q}^b$ to $\hat{Q}^c$ is due to both changes in quantities and prices. In order to differentiate between them, we need to identify the aggregate price index and the volume for each of the values:

$$\begin{aligned}\hat{Q}^b &= P^b Q^b \\ \hat{Q}^c &= P^c Q^c,\end{aligned}$$

where P and Q denote the price index and the volume. To determine the change in prices (from which the change in volumes can be inferred) we apply the Törnqvist index, see IMF (2004). The index calculates the geometric mean of the price changes, weighted by the average of value shares in the base calibration and the new equilibrium:

$$\frac{P^c}{P^b} = \prod_{i=1}^n \left(\frac{p_i^c}{p_i^b} \right)^{\frac{1}{2} \left(\frac{p_i^b q_i^b}{\hat{Q}^b} + \frac{p_i^c q_i^c}{\hat{Q}^c} \right)}$$

The volume change is then given by

$$\frac{Q^c}{Q^b} = \frac{\hat{Q}^c / P^c}{\hat{Q}^b / P^b} = \frac{\hat{Q}^c}{\hat{Q}^b} \frac{P^b}{P^c}.$$

We can index the base price level to unity ($P^b = 1$), allowing us to calculate the level of volumes in the baseline and after the carbon price shock.

To provide an example, the price index construction for the exports is derived in the following. As follows from the main text, the value of exports is given by

$$\begin{aligned}\hat{X}^r &= \sum_{s \neq r} \sum_{j \in S(r)} P_j C_j^s + \sum_{j \notin S(r)} \sum_{i \in S(r)} P_i M_{ij} \\ &= \sum_{j \in S(r)} P_j \left(\sum_{s \neq r} C_j^s + \sum_{i \notin S(r)} M_{ji} \right) \\ &= \sum_{j \in S(r)} P_j x_j,\end{aligned}$$

where $x_j = \sum_{s \neq r} C_j^s + \sum_{i \notin S(r)} M_{ji}$ is the total amount of exports from sector j .

Given base prices and quantities for exports (P_j^b and x_j^b , with $\hat{X}^{r,b} = \sum_j P_j^b x_j^b$) and the prices and quantities for the new equilibrium after a carbon price introduction (P_j^c and x_j^c , with $\hat{X}^{r,c} = \sum_j P_j^c x_j^c$), we can use the above formula to derive the aggregate price index change for exports $P_{\hat{X}^r}^c / P_{\hat{X}^r}^b$. This in turn allows, after normalizing the base price

level $P_{X^r}^b$, the volume of exports after the carbon price introduction to be calculated by

$$X^{r,c} = \widehat{X}^{r,c} / P_{X^r}^c.$$

Analogously, the import price deflator can be derived using sectoral import prices and quantities as well as the GDP deflator. For the latter, n is set to three, capturing the components regional consumption C^r , exports and imports as well as their respective prices.

C Appendix: Incomplete markets

In this model variant, the representative household in each region can save in the form of a one-period risk-free bond (and has no access to all state-contingent bonds as in the complete markets framework). The price of the bond (and thus the implied return on it) is determined on international markets such that the supply of bonds equals its demand on a global level.

Household budget constraint The budget constraint of the household in region r is given by

$$P_t^r C_t^r + P_t^B B_t^r = w_t^r L_t^r + \widehat{T}_t^r + B_{t-1}^r \quad (25)$$

where P_t^B is the price of a bond B_t^r which yields the value of one consumption bundle in the next period. Finally, w^r is the region-specific wage rate and T^r a lump-sum transfer by the local government to be defined further below. The balance of payments is given by

$$P_t^B B_t^r - B_{t-1}^r = \widehat{X}_t^r - \widehat{I}M_t^r.$$

Optimal solution to the household problem The household problem is solved by finding a solution which maximizes the household's utility function (9) subject to the budget constraint (11). This gives rise to the following first-order conditions for the household

$$\begin{aligned} P_t^B &= \beta \frac{\lambda_{t+1}^r}{\lambda_t^r} \\ \lambda_t^r &= a^r (C_t^r)^{-\sigma} / P_t^r \end{aligned}$$

Steady-state equations The steady-state versions of the equations are given by

$$\begin{aligned} P^B &= \beta \\ \lambda^r &= a^r (C^r)^{-\sigma} / P_C^r \\ P_C^r C^r &= w^r L^r + \widehat{T}^r + B^r (1 - P^B) \\ B^r (1 - P^B) &= \widehat{I}M^r - \widehat{X}^r \end{aligned}$$

The last line implies that in the steady state, a positive stock of bonds pays for excess imports (since $P^B = \beta < 1$). The impact of carbon taxes in the model with this alternative assumption is discussed in appendix F.

Tax introduced	Var.	Effect in Region					
		Germany	euro ar.	Europe	US	China	World
in Germany	GDP	-0.45%	-0.13%	-0.09%	0.00%	0.00%	-0.02%
	GVA	-1.98%	-0.57%	-0.39%	0.00%	0.00%	-0.10%
	Cons.	-1.06%	-0.23%	-0.14%	0.01%	0.01%	-0.02%
in euro area	GDP	-0.46%	-0.43%	-0.29%	0.00%	0.00%	-0.07%
	GVA	-1.99%	-2.15%	-1.46%	0.00%	0.00%	-0.36%
	Cons.	-1.09%	-0.87%	-0.56%	0.04%	0.02%	-0.07%
in Eur.	GDP	-0.47%	-0.43%	-0.43%	0.00%	0.00%	-0.11%
	GVA	-1.99%	-2.15%	-2.17%	0.00%	0.00%	-0.53%
	Cons.	-1.07%	-0.83%	-0.80%	0.05%	0.03%	-0.11%
in Eur., US	GDP	-0.47%	-0.44%	-0.43%	-0.62%	0.00%	-0.25%
	GVA	-1.99%	-2.15%	-2.17%	-2.73%	0.00%	-1.16%
	Cons.	-1.05%	-0.80%	-0.76%	-0.91%	0.05%	-0.25%
in Eur., US, ODC	GDP	-0.47%	-0.44%	-0.43%	-0.63%	0.00%	-0.33%
	GVA	-1.99%	-2.15%	-2.17%	-2.74%	0.00%	-1.50%
	Cons.	-1.02%	-0.78%	-0.74%	-0.90%	0.04%	-0.33%
in Eur., US, ODC, China	GDP	-0.47%	-0.44%	-0.43%	-0.63%	-2.06%	-0.62%
	GVA	-1.99%	-2.15%	-2.17%	-2.74%	-7.79%	-2.57%
	Cons.	-0.98%	-0.75%	-0.71%	-0.90%	-2.72%	-0.62%
Worldwide	GDP	-0.48%	-0.46%	-0.45%	-0.64%	-2.09%	-1.11%
	GVA	-2.00%	-2.17%	-2.18%	-2.75%	-7.83%	-4.74%
	Cons.	-0.87%	-0.62%	-0.56%	-0.77%	-2.68%	-1.11%

Table 5: Effects of a 100 euro carbon price on GDP, GVA and consumption. Measured in % deviation from solution with zero carbon price.

D Appendix: Details on macroeconomic impact

Table 5 extends table 3 from the main text, including more regional details as well as aggregate (real) consumption as an additional macro variable.

E Appendix: Results under incomplete markets

In this section, we investigate how a departure from the assumption of complete markets affects the results derived in the main text.

First, we focus on the differences in macroeconomic outcomes across the two model versions, which are summarized in table 6. The table focuses on two scenarios, a European-only and a global carbon price. As we can see, the effects on GDP and GVA are very similar across the two models. However, the effect on consumption depends noticeably on the assumptions about risk-sharing. This is because under perfect risk-sharing the tax revenue obtained in one region is shared with other regions. Hence in the case of a European-only carbon price, the consumption drop in Europe is less pronounced if there is less risk-sharing (i.e. in the case of incomplete markets) and thus less sharing of tax revenues with other regions. In the case of a global carbon price, the tax revenue asso-

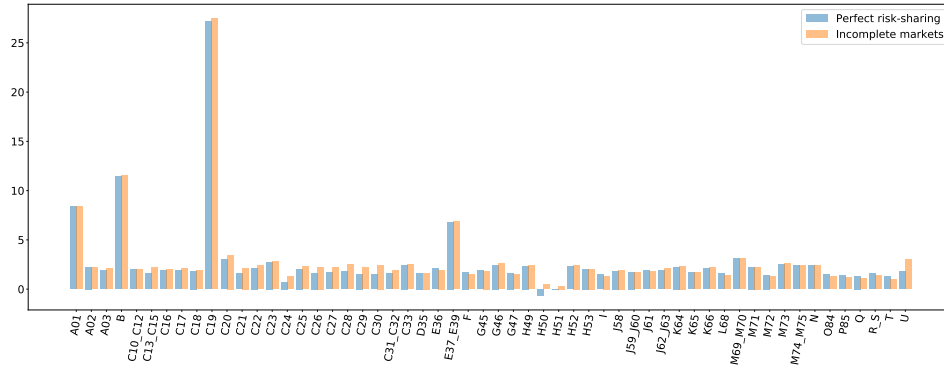
ciated with carbon prices (relative to GDP) is smaller in Europe than in the rest of the world, as the latter region is more emission-intensive. Hence, perfect-risk sharing implies net transfers of tax revenue to Europe, dampening the consumption response in Europe. Hence, assumptions about risk-sharing are important for the aggregate consumption response. They are less important for how GVA respond, the main focus of this paper.³³ However, this is ultimately due to the fact, that tax revenue is redistributed to consumers through lump-sum transfers. If it were instead used to lower corporate tax rates or increase corporate subsidies, assumptions about risk-sharing would also impact responses on the production side.

Second, turning to the sectoral level, figure 12 shows that the gross value added impact on European sectors varies according to the assumption about risk-sharing, for the scenario of both European-only and global carbon prices. Under incomplete markets and European-only carbon pricing, the consumption drop in Europe is less pronounced, as explained above. Hence, the service sectors with a high home-bias have lower losses, while a number of manufacturing sectors exhibit higher losses due to their high export exposure (and higher consumption losses in the rest of the world). Under global carbon pricing, the picture is reversed. Here the consumption drop in Europe is larger for incomplete markets, leading to higher losses among service sectors with a high home bias.

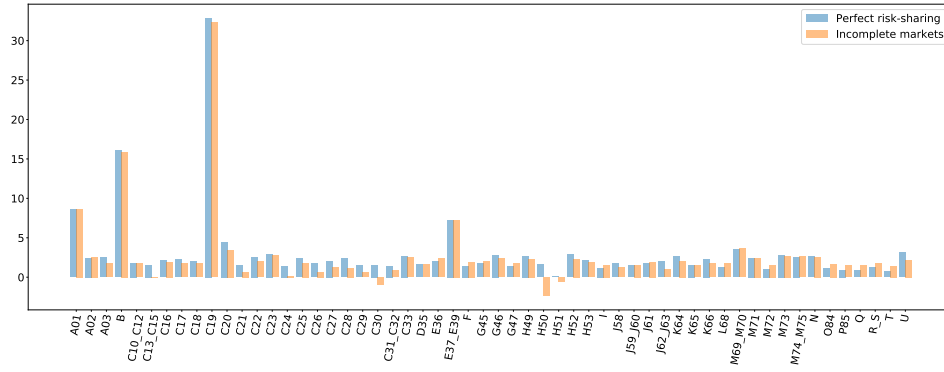
³³In fact, assuming the third option mentioned in the text, financial autarky, also does not significantly change the implications for GDP and GVA in the two scenarios, while making the differences in the consumption response even starker.

Tax introduced in	Var.	Perfect risk-sharing: Effect in		Incomplete markets: Effect in	
		Europe	World	Europe	World
Europe	GDP	-0.4%	-0.1%	-0.4%	-0.1%
	GVA	-2.2%	-0.5%	-2.2%	-0.5%
	Cons.	-0.8%	-0.1%	-0.3%	-0.1%
World	GDP	-0.5%	-1.1%	-0.5%	-1.1%
	GVA	-2.2%	-4.7%	-2.2%	-4.8%
	Cons.	-0.6%	-1.1%	-1.6%	-1.1%

Table 6: Effects of a 100 euro carbon price on GDP, GVA and consumption in Europe and the world under different assumptions about the degree of international risk-sharing. Measured in % deviation from solution with zero carbon price.



(a) European-only carbon pricing



(b) Global carbon pricing

Figure 12: Gross value added loss for European sectors under different assumptions about the degree of international risk-sharing.

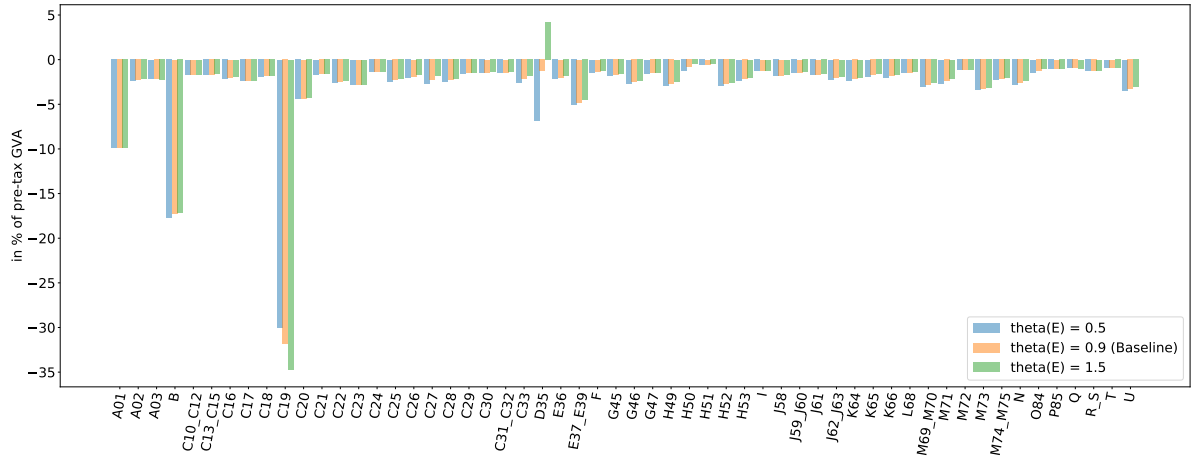


Figure 13: Effect of a 100 euro global carbon price on the gross value added of German sectors - Robustness with respect to θ^E .

F Appendix: Robustness checks

Figure 13 shows that the degree of substitutability between energy inputs (θ^E), i.e. fossil fuels (C19) and electricity (D35), is important for the results of those two sectors. A larger value for the elasticity leads to a larger negative effect on fossil fuels and a more positive effect on electricity (as other sectors can more easily substitute towards this sector). The picture is reversed with a very low elasticity. In this case less substitution occurs, reducing the losses in the fossil fuel sector relative to the baseline calibration but intensifying losses in the electricity sector. Generally, less substitutability implies more negative effects for all sectors on average. However, the broad picture of the relative effects on sectors is also preserved under alternative, and more extreme, parameter values.

The robustness with respect to the remaining four parameters is illustrated by Figures 14 - 17. Importantly, the results for non-energy sectors are naturally sensitive to the degree of substitution among them, which is governed by the parameter θ^I . This particularly affects emission-intensive sectors such as agriculture (A01) and mining and quarrying (B). The literature cited in the calibration section, however, points strongly towards elasticities much smaller than unity. Here, the simulation with an elasticity of 0.1 is relatively close to the results obtained in our baseline.

Similarly, the elasticity of substitution between energy and non-energy inputs affects (θ) the results for same sectors noticeably. The larger the elasticity, the easier it is for sectors to substitute towards non-energy inputs and the higher the losses in the energy sector. Note that the range for this parameter usually employed in the literature is quite narrow at around 0.8, such that the two robustness values can be considered extreme values. Even for these extreme values the range of results is quite contained.

Finally, the results are generally robust to assumptions about the elasticity of substitution across consumption goods (ρ) and the coefficient of constant relative risk aversion (σ).

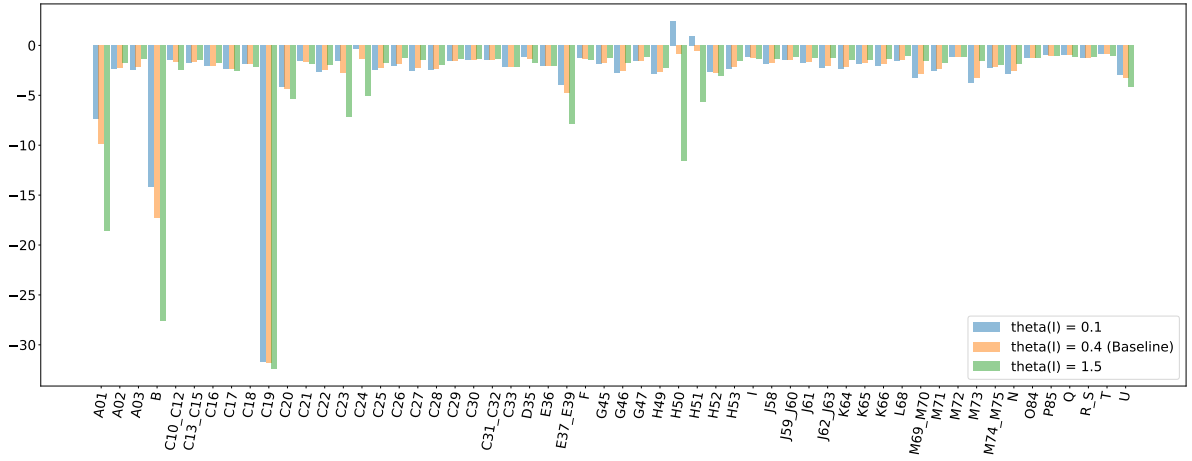


Figure 14: Effect of a 100 euro global carbon price on the gross value added of German sectors - Robustness with respect to θ^I .

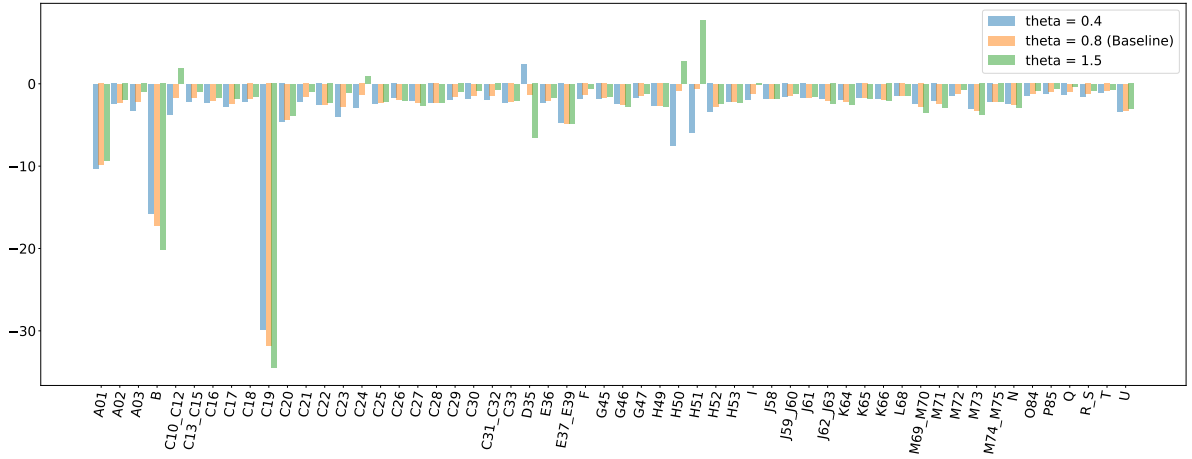


Figure 15: Effect of a 100 euro global carbon price on the gross value added of German sectors - Robustness with respect to θ .

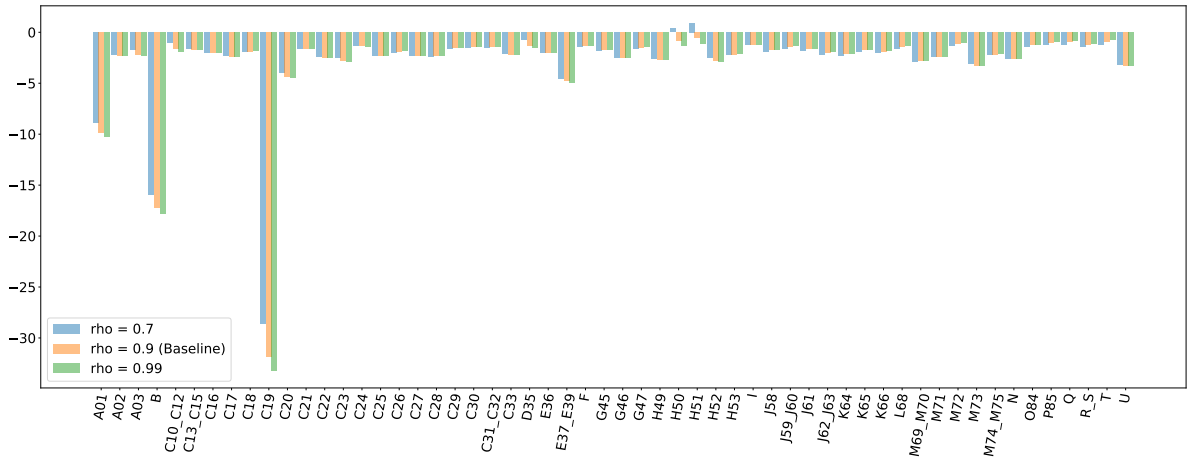


Figure 16: Effect of a 100 euro global carbon price on the gross value added of German sectors - Robustness with respect to ρ .

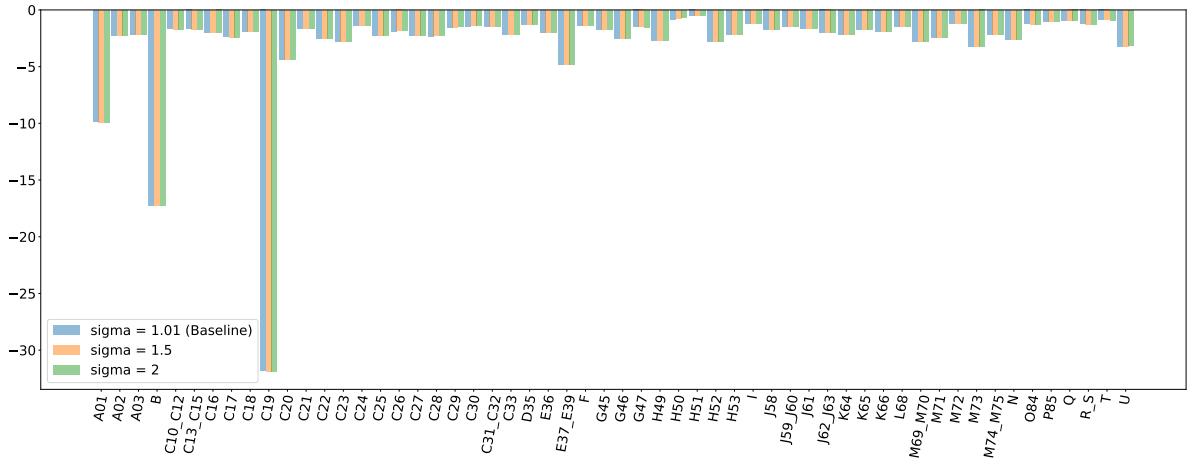


Figure 17: Effect of a 100 euro global carbon price on the gross value added of German sectors - Robustness with respect to σ .

G Appendix: Replicating the results from Devulder and Lisack (2020)

The model presented above is based on Devulder and Lisack (2020), henceforth abbreviated by DL. DL calibrate the model to the regions France, rest of EU and rest of world. In this section we seek to replicate the results from DL by mimicking their choice of regional disaggregation. We also adopt their use of the Eurostat emission database. In a second step, we run the same specification as used in DL but using EXIOBASE emission data, showing that the results remain the same. We conclude, that the results obtained by this model do not appear to be driven by the choice of database.

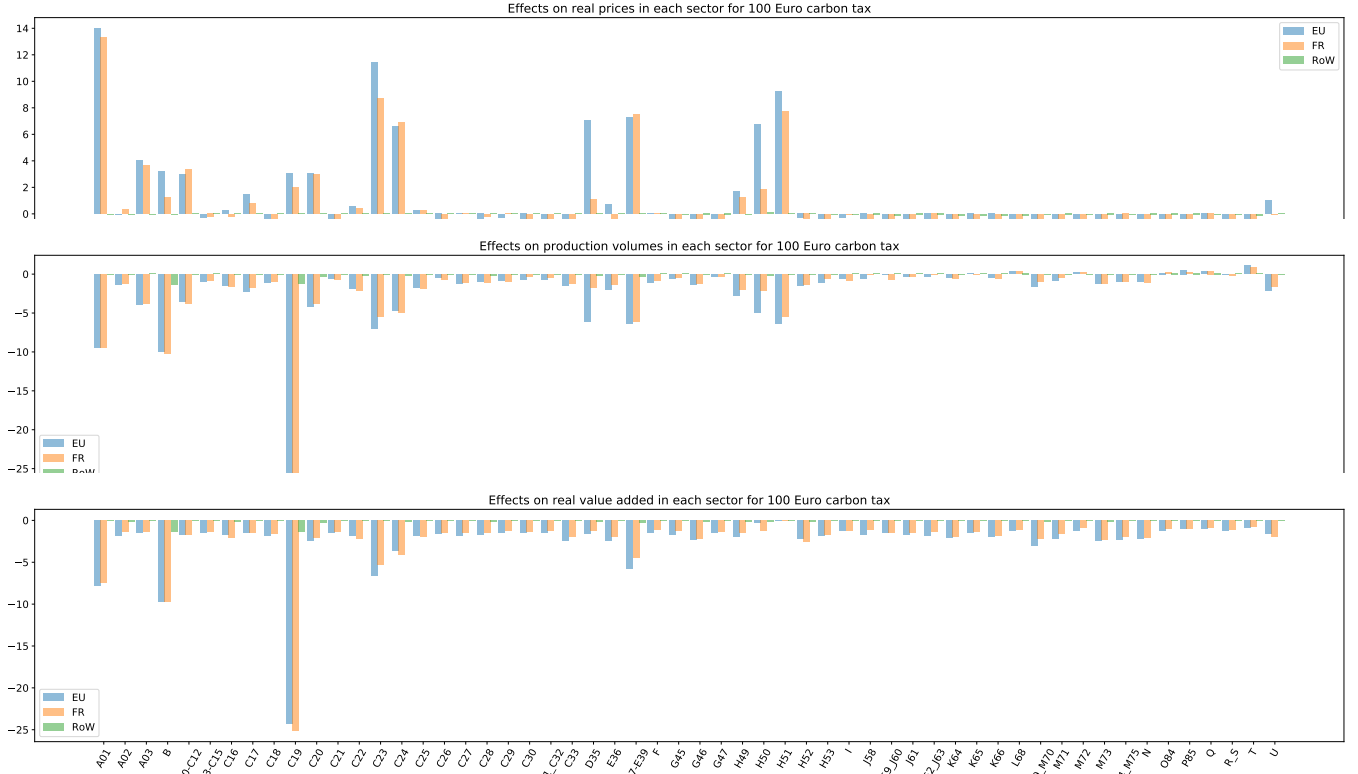
Aggregate effects Table 5 in DL presents the effect of a 100 euro carbon tax, introduced in the EU only, on aggregate real value added and consumption in each of the three regions considered. The results are disaggregated by the considered tax channel, which are identical to the ones discussed in this paper. Table 7 shows the results from DL (in brackets) alongside the simulation results from the model developed here. The results for the input and consumption tax are almost identical, while there is a small but negligible discrepancy for the production tax.

	Variable	France	Rest of EU	Rest of world
Production tax	Value added	-0.64 (-0.56)	-0.76 (-0.85)	-0.03 (-0.03)
	Consumption	-0.06 (-0.05)	-0.06 (-0.07)	+0.01 (+0.01)
Input tax	Value added	-0.57 (-0.56)	-0.89 (-0.88)	-0.10 (-0.10)
	Consumption	-0.36 (-0.35)	-0.48 (-0.47)	+0.04 (+0.04)
Consumption tax	Value added	-0.40 (-0.41)	-0.31 (-0.32)	-0.00 (-0.00)
	Consumption	-0.24 (-0.24)	-0.14 (-0.14)	+0.03 (+0.03)
All taxes	Value added	-1.61 (-1.51)	-1.95 (-2.04)	-0.13 (-0.13)
	Consumption	-0.66 (-0.64)	-0.68 (-0.69)	+0.08 (+0.08)

Table 7: Effects of a 100 euro carbon tax on real value added and consumption in each region. Measured in % deviation from initial steady-state with zero carbon tax. Values in brackets show results from Devulder and Lisack (2020).

Sectoral effects Figure 18 shows the effects of the introduction of a EU-wide carbon tax of 100 euro on the sectoral level. The results are generally very close to those reported in DL. The agricultural sector A01 (No 3 in DL) exhibits the largest increases in real prices, in France it amounts to 13 % (DL: 13%) and in the rest of EU to 14% (15%), followed by the effects on manufacturing of non-metallic minerals (C23, No 15 in DL) with 8% (8%) in France and 11% (11%) in the rest of the EU. In line with DL, we observe general price increases in the manufacturing sectors and decreases in the service sector.

In terms of sectoral production, the largest fall occurs in the fossil fuel sector (C19, No 1 in DL) with about 25 % in both regions, mirroring the result in DL. Next in line is the mining sector (B, No 6 in DL) with about 10 % losses (10 % in DL). Also with respect to other sectors the results are indistinguishable from those reported in DL. The same applies to the last figure showing the effects on real value added.



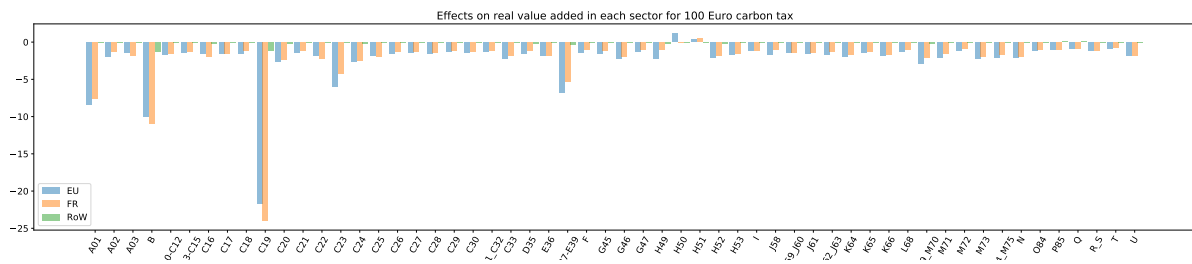


Figure 19: Effect on value added in each sector