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# Carbon Tax in a Production Network: Propagation and Sectoral Incidence

**Antoine Devulder and Noëmie Lisack**[1]

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## Abstract

We analyse the propagation of carbon taxation through input-output production networks. To do so, we use a static multi-sector general equilibrium model including France, the rest of the European Union and the rest of the world to simulate the impact of carbon tax scenarios on economic activity. We find that a tax increase on sectors' and households' greenhouse gas emissions corresponding to a carbon price of 100 euros per ton of carbon dioxide equivalent entails a decrease in French aggregate real value added by 1.2% at a 5-to-10-year horizon when implemented in France only, vs. 1.5% when implemented in the whole EU. Impacts on sectoral real value added range from -20% to negligible. The most affected sectors are generally the most polluting ones, but the tax also propagates across sectors via intermediate inputs. Specifically, the network structure tends to affect comparatively more upstream sectors than downstream ones, given their taxation levels. International financial markets also play an important role by neutralizing the positive response of final demand that would result from the redistribution of the tax proceeds to domestic households.


Keywords: Carbon tax, multi-sector model, international production networks

JEL classification: D57 ; F11 ; H23

[1] Banque de France, 31 rue Croix des Petits-Champs, 75001 Paris, France, emails : antoine.devulder@banque-france.fr , noemie.lisack@banque-france.fr. We warmly thank Maurice Bun from De Nederlandsche Bank for sharing with us an early version of his work, and Fanny Henriet for her very useful discussion of the paper. We are also grateful to Valère Fourel, Michel Juillard, Nicolas Maggiar, and Jean-Stéphane Mésonnier for helpful comments and suggestions.

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# NON-TECHNICAL SUMMARY

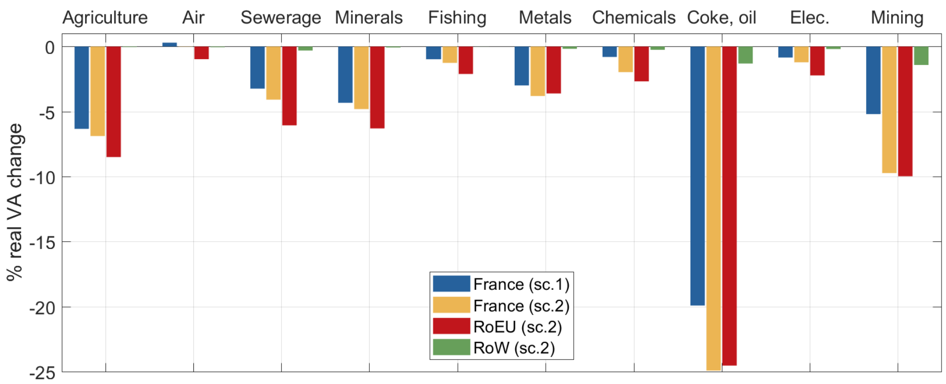
While issues related to climate change and environment become more and more present in the public debate, there is a political will to encourage a transition towards a greener economy, and a wide range of countries have committed to greenhouse gas emissions reduction objectives within the Paris Agreement. One of the instruments often mentioned to achieve these objectives is a carbon tax. Central banks and international organisations have also started to engage in the matter. In particular, financial supervisors need tools to build adverse low-carbon transition scenarios disaggregated at the sectoral level to evaluate the resilience of financial systems against the implementation of large-scale climate policies.

This paper focuses on the implications for carbon taxation of disaggregrating production into interconnected sectors in a macroeconomic model. We build a static general equilibrium model embedding an input-output production network for the world economy and allowing substitution across intermediate inputs entering production and across final consumption goods. We analyse the propagation of various carbon taxes throughout this network.

We calibrate the model for three regions, namely France, the rest of the European Union and the rest of the world, each including 55 sectors. The model includes three types of climate-related tax. The first two types of taxes cover firms' greenhouse gas emissions with sector-specific rates. One is a tax on firms' fossil energy purchases and induces a substitution towards cleaner energy sources within firms. The other one covers firms' emissions that are inherent to their production activity (like methane produced by cows for farming or carbon dioxide generated by the chemical reactions involved in cement manufacture). The third tax applies to households' refined oil purchases. Carbon tax scenarios considered in the paper involve all three taxes, calibrated so as to correspond to a benchmark price of 100 euros per ton of carbon dioxide equivalent.

We consider two scenarios. First, we look at the impact of a carbon tax implemented in France only (scenario 1). We find a decrease in French aggregate value added by 1.2%, with effects on sectoral real value added ranging from -20% (in the *Coke and refined petroleum* sector) to negligible. Second, we consider a carbon tax implemented in the whole European Union (scenario 2). In that case, aggregate value added drops by 1.5% in France and by 2% in the rest of the EU. Sectoral impacts show a pattern similar to the first scenario, apart from a few differences.

Impact of a carbon tax on sectoral real value added (% change)




The carbon tax is calibrated to match a carbon price of 100 euros/t$CO_2$e. Scenario 1 shows the impact of a tax implemented in France only, scenario 2 the impact of a tax implemented in France and the rest of the EU. Source: Authors' calculations.

Our sectoral results reflect the characteristics of the production network represented in the model. While the most impacted sectors are generally the most polluting ones, the tax also propagates across sectors via intermediate inputs. In the end, the network structure tends to affect comparatively more upstream sectors than downstream ones, given their taxation levels: some sectors, such as *Mining and quarrying* or *Chemical products*, are disproportionately harmed, whereas relatively high-polluting ones like *Health*, *Education* or *Trade and repair of motor vehicles* are hardly affected.

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# Taxe carbone et réseaux de production: propagation et incidence sectorielle


## Résumé

Ce papier étudie l'effet des réseaux de production sectoriels de type entrées-sorties sur la propagation d'une taxe carbone. Nous construisons pour cela un modèle d'équilibre général multi-secteurs comprenant la France, le reste de l'Union européenne et le reste du monde et simulons les effets économiques de différents scénarios de taxe. Nous trouvons qu'une hausse d'impôt appliquée en France sur les émissions de gaz à effet de serre des différents secteurs productifs et des ménages, correspondant à un prix du carbone de 100 euros par tonne d'équivalent $CO_2$, conduit à une baisse de la valeur ajoutée agrégée de 1.2% à un horizon de 5 à 10 ans (contre 1.5% si la taxe est appliquée par l'ensemble de l'Union européenne). Les effets sur les valeurs ajoutées sectorielles varient suivant les secteurs, allant de négligeables à -20%. Les secteurs les plus impactés sont généralement les plus polluants, mais les effets de la taxe se propagent également d'un secteur à l'autre via leurs consommations intermédiaires. Ainsi, la structure de production représentée dans le modèle tend, à niveau de taxe donné, à accentuer l'impact de la taxe pour les secteurs en amont des chaînes de production. Les marchés financiers internationaux jouent également un rôle important dans la propagation des effets, en neutralisant la hausse de la demande finale induite par la redistribution de la taxe.



Mots-clés : Taxe carbone, modèle multisectoriel, réseaux internationaux de production



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# 1 Introduction

While issues related to climate change and environment become more and more present in the public debate, there is a political will to encourage a transition towards a greener economy, and a wide range of countries have committed to greenhouse gas emissions reduction objectives within the Paris Agreement. One of the tools often mentioned to achieve these objectives is a carbon tax. Central banks and international organisations have also started to engage in the matter, via for instance the Network for Greening the Financial System (NGFS), as well as the Task Force on Climate-related Financial Disclosures. In particular, financial supervisors need adverse low-carbon transition scenarios to evaluate the resilience of financial systems against the implementation of large-scale climate policies. Since these policies by nature affect differently the more- or less-polluting economic activities in the economy, the models needed to simulate and analyse the economic impact of carbon taxation for such purposes should preferably be disaggregated at the sectoral level.

This paper focuses on the propagation of carbon taxation within a macroeconomic model embedding a disaggregrated production network. Using a static general equilibrium model, we analyse carbon taxation scenarios, the inter-sectoral spillovers they trigger and their impact for domestic and foreign aggregate economies.

More specifically, each sector's output is produced using intermediate inputs, energy and labour in a representative firm. Substitution across these various inputs is possible, as well as across final goods in the households' consumption baskets. We assume perfect risk sharing across countries via international financial markets. This assumption turns out to be crucial to ensure that relative consumption decreases in the taxed country. Indeed, it overturns the income effect induced by the redistribution of tax revenues to domestic households and the real exchange rate appreciation implied by the tax. In order to keep the model tractable, we voluntarily choose a parsimonious set-up abstracting from capital accumulation, nominal frictions, endogenous technological progress and international labour mobility. For these reasons, our view is that the results are to be interpreted as a medium-run impact, corresponding to a time horizon of 5 to 10 years. We calibrate the model for three regions, namely France, the rest of the European Union and the rest of the world, each including 55 sectors, using the World Input Output Database for 2014.

The model includes three types of climate-related tax. The first two types of tax cover firms' green house gas emissions with sector-specific rates. One is a tax on firms' fossil energy purchases and induces a substitution towards clener energy sources within firms. The other one covers firms' emissions that are inherent to their production activity (think of methane produced by cows for farming or carbon dioxide generated by the chemical reactions involved in cement manufacture). Based on sales, this tax discourages demand for the product concerned in downstream sectors. Since we assume perfect competition, these supply side taxes are fully passed through to selling prices. The third tax covers households' emissions. It enters the model as a levy on their refined oil purchases (mainly used for heating and transport purposes). In what follows, a "carbon tax" means the joint implementation of all three taxes described above, for agents either located in a single country or in several countries. The corresponding product-specific rates are chosen in such a way that the ex ante amount of tax paid by each agent corresponds to the cost of her own emissions, priced at a benchmark value of 100 euros per ton of carbon dioxide equivalent.

We consider two taxation scenarios. First, a carbon tax is implemented in France only. This induces a decrease in French aggregate value added by 1.2 %, with effects ranging from -21% to +0.5% in terms of sectoral quantities produced, and from -20 % to negligible in terms of sectoral real value added. Second, the carbon tax is implemented in the whole European Union. In this case, aggregate value added drops by 1.5 % in France and by 2 % in the rest of the EU. Sectoral impacts show a pattern similar to the first scenario, but the *Electricity* and, to a lesser extent, the *Water transport* sectors in the rest of the EU are more heavily affected than their French counterparts. While the most impacted sectors are generally the most polluting ones, the tax also propagates across sectors via intermediate inputs. Upstream sectors experience depressed demand from more heavily taxed ones whereas downstream sectors face an increase in the prices of their intermediate inputs from polluting sectors. To uncover how the characteristics of the production network affect these results, we investigate in the second scenario how the relative positions of the different sectors in the production line influence the propagation of the shocks. To do so, we compute downstreamness indices following Antràs and Chor [2013]. We compare them to the inter-sectoral spillovers of taxes for each sector, defined as the effect on a sector's production of all production taxes except those that affect that sector directly. Interestingly, we find that inter-sectoral spillovers often account for a large part of the effect, with upstream sectors suffering on average higher adverse spillover effects than downstream sectors.

**Related literature.** Our study relates to two main strands of literature, regarding production networks and shocks transmission on one hand and the effects of a carbon tax on the other hand. First, this paper borrows from theoretical multi-sector production network models, such as the nested-CES models described by Baqaee and Farhi [2019]. We build a similar framework, generalised to allow for multiple countries and sector-specific taxes, in the same vein as Johnson [2014] or Bouakez et al. [2018]. While Johnson [2014] focuses on business cycle co-movements, and Bouakez et al. [2018] on government multipliers, we focus on the impact of sectoral taxes and their diffusion. This paper also examines the role of international financial markets in the transmission of shocks to macroeconomic aggregates, which has received considerable attention in the New Open Economy Macroeconomic literature. Since the shock we consider here is a tax shock involving some redistribution, the income and substitution effects obtained are somewhat amended compared for instance to Corsetti et al. [2008]. We show in the paper that assuming either perfect risk-sharing or financial autarky in the model critically affects our results, especially for country-level aggregates such as value added and consumption.

Second, a number of studies focus on green transition policies and their effectiveness. Henriet et al. [2014] use a micro-founded model with endogenous technical progress to assess the level of carbon tax needed in France to reach the carbon dioxide reduction objectives set in 2003 at a forty-year horizon. They find unrealistically high tax levels, suggesting that additional instruments such as research subsidies should be used. Large-scale models used to address similar questions include GEMINI-E3 (Vielle and Bernard [1998]) – a sectoral general equilibrium model, IMACLIM-R (Hourcade et al. [2010]), Three-Me (Callonnec et al. [2013]) – both hybrid models, and the G-Cubed (McKibbin and Wilcoxen [1998]) – a very rich and complex multi-sector, multi-country model suited to study a large range of economic questions beyond environmental regulation, such as trade, monetary or fiscal policy. Our model is more focused, centered on the sectoral impact of a carbon tax within a production network. In particular, we do not seek to evaluate the ability of such a tax to achieve a successful transition, so we did not embed the reaction of greenhouse gas emissions in the model.

Furthermore, since Pigou [1920] suggested that negative externalities should be offset by taxes, many papers have investigated the potential double dividend from carbon taxation, mostly relying on computable general equilibrium models. By introducing distortions in agents' consumption choices, the tax reduces economic efficiency, but may still improve welfare if it is used to offset existing distortions stemming from the initial tax system. The second dividend then refers to this gain – the first one being the environmental benefits (see Freire-González [2018] for a review). Since our study compares the implementation of a carbon tax to an initial tax-free (hence distortion-free) situation, it does not account for the second dividend mentioned above. To include such effect, we would need to enrich the model with additional initial tax distortions, which goes beyond the scope of this paper. Closer to our analysis, King et al. [2019] show that carbon tax reforms that target sectors based on their position in the production network are more efficient in reducing green house gas emissions than reforms that only take sectoral direct emissions into account. Yet, their model differs from ours notably in that it features a closed economy and uses Cobb-Douglas aggregators; moreover, sectoral emissions are explicitely modelled and taxed.

Finally, our paper also builds on recent attempts to develop tools for climate transition policy analysis, e.g. Batten [2018] at the Bank of England or Bun [2018] and Hebbink et al. [2018] at De Nederlandsche Bank.[1] The latter provide quantitative evaluations of the macroeconomic impact of carbon taxation, both for aggregate economic variables and sectoral sales. We contribute to this stream of work by developing a transparent general equilibrium model that is able to quantify the impact of sectoral carbon taxes and can be easily adjusted to consider any set of countries provided that they are covered by the world input-output database.

The structure of the paper is as follows: sections 2 and 3 detail the model and its calibration,

[1]Specifically, our paper builds upon Bun [2018].

section 4 analyses the propagation of each type of tax present in the model with simple examples, and section 5 shows the impact of introducing full carbon tax scenarios (in France only then in the whole European Union), and discusses how sectors' positions in the production network shape the results. Finally, section 6 discusses robustness checks and the role of international financial markets, and section 7 concludes.

# 2 Model

We develop a static general equilibrium model whose purpose is to propagate a tax shock across production sectors. Our focus being on the production side, we keep the final demand side as parsimonious as possible.

The supply side is modelled as a sectoral production network. For simplicity, the model ignores physical capital, so that production requires labour and intermediate inputs, while the demand side amounts to final consumption from households. For ease of presentation and since all production sectors across the world enter similarly into each sector's production wherever it is located (the only difference stemming from the calibration of the share parameters in the CES aggregators), we will present the production side of the model without country indices, only specifying sectoral indices $i$ taken from the global set of sectors $\{1, \ldots, N\}$, where $N$ is equal to the number of countries times the number of sectors per country.[2] In the household subsection, we will differentiate sectors in the notations according to their location. We assume a representative household per country with distinct preferences in terms of product shares in the consumption basket, and whose revenues include domestic labour income, firms' profits and taxes proceeds (in the form of lump-sum transfers). Finally, labour is perfectly mobile across sectors within each country but immobile across countries.

We include three types of taxes: (i) a tax on sectoral production, related to the GHG emitted during the production process besides energy input consumption, and denoted $\tau$; (ii) a tax on oil and coal intermediate consumption, to reflect the $CO_2$ emitted when burning these energy inputs for production, and denoted $\zeta$; (iii) a tax on oil and coal final consumption, to reflect the $CO_2$ emitted by households when burning them both for domestic use and private transportation, and denoted $\kappa$. These taxes will be calibrated specifically for households in each country and producers in each sector, in order to better reflect their respective emissions and energy mix. More detail on the calibration of these taxes will follow in section 5.1.

[2]The only exception is labour cost, which is country specific. Still, we omit country indices in the description of the production side for convenience.

## 2.1 Production

Sectors all over the world are represented by similar production functions. Each sector in each country uses the production of all sectors in all countries as intermediate input, assuming no trade frictions, and that the total number of sectors $N$ corresponds to the number of countries times the number of sectors per country.

The $N$ production sectors consist of $N_E < N$ energy sectors and $N - N_E$ non-energy sectors. For the remainder of the presentation and without loss of generality, we will re-order the sectors such that the energy sectors correspond to sectors $1, 2, \ldots, N_E$. In each sector $i \in \{1, \ldots, N\}$, firms use intermediate inputs $\{Z_{ji}\}$ from all sectors $j \in \{1, \ldots, N\}$ and labour $L_i$ to produce the sectoral good in quantity $Q_i$. We further assume that firms are operating in a perfectly competitive environment within each sector, with one representative firm per production sector. The production technology is modelled as nested CES functions. On the energy side, the energy inputs (for instance, oil and electricity) are substitutable across each others via a CES aggregator with elasticity of substitution $\sigma$. Non-energy intermediate inputs are also substitutable across each others with elasticity of substitution $\epsilon$. Last, the producer aggregates energy, intermediate inputs and labour via a CES aggregator with elasticity $\theta$ to produce the sectoral good. This specification defines the production function below, for a firm in sector $i \in \{1, \ldots, N\}$:

$$Q_i = \left( \mu_i^{\frac{1}{\theta}} L_i^{\frac{\theta-1}{\theta}} + \alpha_{Ei}^{\frac{1}{\theta}} E_i^{\frac{\theta-1}{\theta}} + \alpha_{Ii}^{\frac{1}{\theta}} I_i^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}} \tag{1}$$

where:

$$E_i = \left( \sum_{j=1}^{N_E} \left( \frac{\alpha_{ji}}{\alpha_{Ei}} \right)^{\frac{1}{\sigma}} Z_{ji}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{2}$$

$$I_i = \left( \sum_{j=N_E+1}^{N} \left( \frac{\alpha_{ji}}{\alpha_{Ii}} \right)^{\frac{1}{\epsilon}} Z_{ji}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}} \tag{3}$$

Parameters $\alpha_{ji}$ correspond to the share of input $j$ in output $i$ and we can define the total energy share $\alpha_{Ei}$, the total non-energy intermediate input share $\alpha_{Ii}$ and the labour share $\mu_i$ used by each sector $i$ such that:

$$\alpha_{Ei} + \alpha_{Ii} + \mu_i = 1 \tag{4}$$

$$\sum_{j=1}^{N_E} \alpha_{ji} = \alpha_{Ei} \tag{5}$$

$$\sum_{j=N_E+1}^{N} \alpha_{ji} = \alpha_{Ii} \tag{6}$$

$P_i(1-\tau_i)$ is the price obtained by sector $i$'s producers for their output, once the production tax $\tau_i$ is deducted, and $w$ is the wage faced by the firm.[3] The tax on energy intermediate inputs consumed by sector $i$ is denoted $\zeta_{ji}$; it is non-zero only for inputs $j$ belonging to the oil and coal sectors. The profit of the representative firm in sector $i \in \{1, \ldots, N\}$ is defined by:

$$\pi_i = P_i(1-\tau_i)Q_i - wL_i - \sum_{j=1}^{N} P_j(1+\zeta_{ji})Z_{ji} \tag{7}$$

The firms' maximisation program is then :

$$\max_{L_i, Z_{ji}} \pi_i = P_i(1-\tau_i)Q_i - wL_i - \sum_{j=1}^{N} P_j(1+\zeta_{ji})Z_{ji} \tag{8}$$

s.t. equations (1), (2), (3) are verified.

This implies the optimality conditions below in each sector $i \in \{1, \ldots, N\}$:

$$\frac{L_i}{Q_i} = \mu_i \left(\frac{P_i(1-\tau_i)}{w}\right)^{\theta} \tag{9}$$

$$\frac{E_i}{Q_i} = \alpha_{Ei} \left(\frac{P_i(1-\tau_i)}{P_{Ei}}\right)^{\theta} \tag{10}$$

$$\frac{I_i}{Q_i} = \alpha_{Ii} \left(\frac{P_i(1-\tau_i)}{P_{Ii}}\right)^{\theta} \tag{11}$$

$$\frac{Z_{ji}}{E_i} = \frac{\alpha_{ji}}{\alpha_{Ei}} \left(\frac{P_{Ei}}{P_j(1+\zeta_{ji})}\right)^{\sigma} \forall 1 \leq j \leq N_E \tag{12}$$

$$\frac{Z_{ji}}{I_i} = \frac{\alpha_{ji}}{\alpha_{Ii}} \left(\frac{P_{Ii}}{P_j(1+\zeta_{ji})}\right)^{\epsilon} \forall N_E + 1 \leq j \leq N \tag{13}$$

where price indices are defined for energy and non-energy intermediate inputs in each sector $i$ as:

$$P_{Ei} = \left(\sum_{j=1}^{N_E} \frac{\alpha_{ji}}{\alpha_{Ei}} (P_j(1+\zeta_{ji}))^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \tag{14}$$

$$P_{Ii} = \left(\sum_{j=N_E+1}^{N} \frac{\alpha_{ji}}{\alpha_{Ii}} (P_j(1+\zeta_{ji}))^{1-\epsilon}\right)^{\frac{1}{1-\epsilon}} \tag{15}$$

[3] As detailed in the upcoming household and market clearing sections, there is one labour market per country, so that firms (sectors) face different wages depending on their production location. For notations simplicity, we abstract from this when detailing the producer's program.

Rearranging the first order conditions (10) to (13):

$$\frac{Z_{ji}}{Q_i} = \alpha_{ji}\frac{(P_i(1-\tau_i))^\theta}{(P_j(1+\zeta_{ji}))^\sigma}P_{Ei}^{\sigma-\theta} \qquad \forall 1 \le j \le N_E \tag{16}$$

$$\frac{Z_{ji}}{Q_i} = \alpha_{ji}\frac{(P_i(1-\tau_i))^\theta}{(P_j(1+\zeta_{ji}))^\epsilon}P_{Ii}^{\epsilon-\theta} \qquad \forall N_E + 1 \le j \le N \tag{17}$$

We further impose that the producers make zero profit, implying for each sector $i$:

$$P_i(1-\tau_i) = \left(\mu_i w^{1-\theta} + \alpha_{Ei}P_{Ei}^{1-\theta} + \alpha_{Ii}P_{Ii}^{1-\theta}\right)^{\frac{1}{1-\theta}} \tag{18}$$

## 2.2 Final demand

To present the households' program, we now turn back to multi-country notations with a set of countries $\mathcal{C}$. Final demand is modelled with a representative household in each country $A \in \mathcal{C}$ who consumes a bundle of goods from all sectors and all countries, aggregated via a CES aggregator with elasticity $\rho$:

$$C_A = \left(\sum_{j=1}^{N} \gamma_{jA}^{\frac{1}{\rho}} C_{jA}^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}}$$

where $\gamma_{jA}$ are the consumption shares of the representative household in each country $A \in \mathcal{C}$ and:

$$\sum_{j=1}^{N} \gamma_{jA} = 1 \qquad \forall A \in \mathcal{C}$$

The representative household inelastically supplies a fixed amount of labour $L_A$ to firms operating in her own country, owns her country's firms, and receives the proceeds of the taxes levied by her country, redistributed as a lump-sum transfer. Labour is assumed to be perfectly mobile across sectors within country, but immobile across countries, so that the wage $w_A$ differs across countries but is the same across sectors within a given country.[4] Finally, her preferences are represented by a constant-relative-risk-aversion utility function:

$$u_A = \frac{C_A^{1-\varphi}}{1-\varphi}$$

where $\varphi > 0$ determines her degree of risk aversion.

As is the case for producers, households in each country pay a tax $\kappa_{iA}$ set their final consumption of oil and coal, and . Burning fuel either for heating or travelling by car indeed represents the main cause of households' green house gas emissions. The rate $\kappa_{iA}$ is non-zero for goods produced

[4]Note that change in the consumer's labour income $L_A w_A$ will hence only respond to changes in her wage rate $w_A$.

by the oil refining sectors in all countries and bought in country $A$ and zero for all goods $i \neq oil$ produced in all countries. Concretely, if a country $A$ implements a carbon tax, households living in country $A$ will pay a tax on all their purchases of oil, whether refined domestically or abroad, while in any country $B \neq A$ not implementing the carbon tax, all tax rates $\kappa_{iB}$ will be zero.

Households can perfectly share risk across countries by trading internationally a complete set of Arrow-Debreu securities.[5] Because the trading of assets involves at least two time periods (purchase and settlement), it is necessary to introduce time notations to write and solve for the household's program. This yields a static risk-sharing condition that is sufficient to solve the steady state equilibrium.

We define "$\omega_{t+1}$-type" securities as follows: one security bought at price $q(\omega_{t+1})$ in period $t$ pays one unit of the numeraire in period $t+1$ if state $\omega_{t+1}$ is realized at that period, and 0 otherwise.[6] Let $b_A(\omega_{t+1})$ the quantity of "$\omega_{t+1}$-type" securities purchased by country $A$'s household in period $t$.

In addition to financial flows, country $A$ household's resources include labour income $w_A L_A$, firms' profits $\Pi_A$ and the lump-sum transfer $T_A$. Her budget constraint, assuming that state $\omega_t$ is realised in period $t$, is:

$$P_{At}C_{At} + \int q(\omega_{t+1}) b_A(\omega_{t+1}) d\omega_{t+1} = w_{At}L_{At} + \Pi_{At} + T_{At} + b_A(\omega_t)$$

where $P_{At}$ is defined similarly to equation (24). The household's program is then:

$$\max_{C_{At},\{C_{jAt}\},\{b(\omega_{t+1})\}} E_t \sum_{\tau=1}^{\infty} \beta^{\tau} \frac{C_{At+\tau}^{1-\varphi}}{1-\varphi} \tag{19}$$

$$\text{s.t. } \forall t, \qquad C_{At} = \left( \sum_{j=1}^{N} \gamma_{jA}^{\frac{1}{\rho}} C_{jAt}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \tag{20}$$

$$\begin{aligned} \text{and} \qquad & \sum_{j=1}^{N} P_{jt}(1+\kappa_{jAt})C_{jAt} + \int q(\omega_{t+1}) b_A(\omega_{t+1}) d\omega_{t+1} \\ & = w_{At}L_{At} + \Pi_{At} + T_{At} + b_A(\omega_t) \end{aligned} \tag{21}$$

Solving for the optimal decisions, the first order conditions of the household's program boil down

[5] To get more insight into the role of this assumption, we also consider a variant of the model assuming financial autarky in Section 6.

[6] The numeraire is specified in Section 2.4.

in steady state to the relative demand and the perfect risk-sharing conditions below:

$$\forall A \in \mathcal{C},\ \forall j \in \{1, \dots, N\}, \qquad \frac{C_{jA}}{C_A} = \gamma_{jA} \left( \frac{P_j(1+\kappa_{jA})}{P_A} \right)^{-\rho} \tag{22}$$

$$\forall B \in \mathcal{C}, \qquad \frac{C_B}{C_A} = \nu_{AB} \left( \frac{P_A}{P_B} \right)^{\frac{1}{\varphi}} \tag{23}$$

where $P_A$, the consumption price index of the household's consumption basket in country $A \in \mathcal{C}$, is defined as:

$$P_A = \left( \sum_{k=1}^{N} \gamma_{kA} \left[ P_k(1+\kappa_{kA}) \right]^{1-\rho} \right)^{\frac{1}{1-\rho}} \tag{24}$$

and $\{\nu_{AB}\}_{B \in \mathcal{C}}$ are parameters determining relative aggregate consumption sizes across countries in the initial steady state.

### 2.3 Market clearing

The market clears for each sectoral good $i \in \{1, \dots, N\}$ and for labour in each country $A \in \mathcal{C}$. The market clearing conditions are hence:

$$\forall i \in \{1, \dots, N\}, \qquad Q_i = \sum_{j=1}^{N} Z_{ij} + \sum_{A \in \mathcal{C}} C_{iA} \tag{25}$$

$$\forall A \in \mathcal{C}, \qquad L_A = \sum_{j \in \mathcal{S}_A} L_j \tag{26}$$

where $\mathcal{S}_A \subset \{1, \dots, N\}$ is the subset of sectors located in country A.

The government is not explicitly modelled here, but it is implicitly collecting the taxes and redistributing them to the household in a lump-sum fashion. To keep the set-up parsimonious, there are neither government consumption nor public goods. Profits and transfers are taken as given by the household, and are computed as follows for each country $A \in \mathcal{C}$:

$$\Pi_A = \sum_{j \in \mathcal{S}_A} \pi_j \tag{27}$$

$$T_A = \sum_{j \in \mathcal{S}_A} \tau_j P_j Q_j + \sum_{j=1}^{N} \kappa_{jA} P_j C_{jA} + \sum_{i \in \mathcal{S}_A} \sum_{j=1}^{N} \zeta_{ji} P_j Z_{ji} \tag{28}$$

Since we assume perfect competition, firms make zero profit and $\Pi_A = 0$.

The securities markets also clear, hence:

$$\forall \omega, \qquad \sum_{A \in \mathcal{C}} b_A(\omega) = 0 \tag{29}$$

This implies the following resource constraint of the world economy:

$$\sum_{A\in\mathcal{C}} P_A C_A = \sum_{A\in\mathcal{C}} w_A L_A + \sum_{A\in\mathcal{C}} T_A \tag{30}$$

It is straightforward to show from the product market clearing equations (25), the profit equations (7) and the household budget constraints (46) that international trade balances each country's representative household budget constraint:

$$\forall A \in \mathcal{C}, \quad T_A + w_A L_A = P_A C_A + X_A - M_A \tag{31}$$

with country $A$'s imports defined as:

$$M_A = \sum_{i\notin\mathcal{S}_A} \sum_{j\in\mathcal{S}_A} P_i Z_{ij} + \sum_{i\notin\mathcal{S}_A} P_i C_{iA} \tag{32}$$

and exports as:[7]

$$X_A = \sum_{i\in\mathcal{S}_A} \sum_{j\notin\mathcal{S}_A} P_i Z_{ij} + \sum_{i\in\mathcal{S}_A} \sum_{B\neq A} P_i C_{iB} \tag{33}$$

### 2.4 Equilibrium

We can now define the equilibrium. We choose units of labour in country 1 as the numeraire and thus normalise $w_1$, the wage in country 1, to 1 to have well defined prices. Note that aggregate labour supply in each country $\{L_A\}_{A\in\mathcal{C}}$ is also normalised to define the scale of the model and the relative size of each country within the model. An equilibrium in this model corresponds to a set of quantities

$$\{Q_i, L_i\}_{i=1}^N, \qquad \{Z_{ij}\}_{i,j=1}^N, \qquad \{\{C_{iA}\}_{i=1}^N\}_{A\in\mathcal{C}}, \qquad \{C_A, T_A\}_{A\in\mathcal{C}}$$

and prices

$$\{P_i, P_{Ei}, P_{Ii}\}_{i=1}^N, \qquad \{P_A\}_{A\in\mathcal{C}}, \qquad \{w_A\}_{A\in\mathcal{C}\setminus\{1\}}$$

such that equations (9), (16), (17), (18), (14) (15), (28), (22), (24), (25), (26), (23) and (30), are verified. We solve for the equilibrium numerically.

All variables and the equilibrium equations can be summarized as functions of prices $P_i$, wages $w_A$ ($A \neq 1$) and quantities $Q_i$. We then solve for the values of those variables verifying the

[7] Note that the taxes $\zeta_{ij}$ and $\kappa_{iA}$ are not included in the nominal imports and exports expressions, as these taxes correspond to domestic (and not international) payments.

following system:[8]

$$
\begin{aligned}
Q_i &= \sum_{j=1}^{N} Z_{ij} + \sum_{A \in \mathcal{C}} C_{iA} \qquad \forall i \in \{1, \ldots, N-1\} \\
P_i(1-\tau_i) &= \left(\mu_i w_A^{1-\theta} + \alpha_{Ei} P_{Ei}^{1-\theta} + \alpha_{Ii} P_{Ii}^{1-\theta}\right)^{\frac{1}{1-\theta}} \qquad \forall i \in \mathcal{S}_A, \forall A \in \mathcal{C} \\
L_A &= \sum_{i \in \mathcal{S}_A}^{N} L_i \qquad \forall A \in \mathcal{C}
\end{aligned}
$$

where:

$$
\begin{aligned}
P_{Ei} &= \left(\sum_{j=1}^{N_E} \frac{\alpha_{ji}}{\alpha_{Ei}} (P_j(1+\zeta_{ji}))^{1-\sigma}\right)^{\frac{1}{1-\sigma}} \\
P_{Ii} &= \left(\sum_{j=N_E+1}^{N} \frac{\alpha_{ji}}{\alpha_{Ii}} (P_j(1+\zeta_{ji}))^{1-\epsilon}\right)^{\frac{1}{1-\epsilon}} \\
Z_{ji} &= \alpha_{ji} Q_i \frac{(P_i(1-\tau_i))^{\theta}}{(P_j(1+\zeta_{ji}))^{\sigma}} P_{Ei}^{\sigma-\theta} \qquad \forall j \leq N_E \\
Z_{ji} &= \alpha_{ji} Q_i \frac{(P_i(1-\tau_i))^{\theta}}{(P_j(1+\zeta_{ji}))^{\epsilon}} P_{Ii}^{\epsilon-\theta} \qquad \forall j \geq N_E + 1 \\
L_i &= \mu_i Q_i \left(\frac{P_i(1-\tau_i)}{w}\right)^{\theta} \\
P_A &= \left(\sum_{k=1}^{N} \gamma_{kA} \left[P_k(1+\kappa_{kA})\right]^{1-\rho}\right)^{\frac{1}{1-\rho}} \\
C_A &= \frac{\sum_{B \in \mathcal{C}} \left(w_B L_B + \sum_{j \in \mathcal{S}_B} \tau_j P_j Q_j + \sum_{i \in \mathcal{S}_B} \sum_{j=1}^{N} \zeta_{ji} P_j Z_{ji}\right)}{\sum_{B \in \mathcal{C}} \nu_{AB} \left(P_A/P_B\right)^{1/\varphi} \left(\sum_{j=1}^{N} \gamma_{jB} P_B^{\rho} (1+\kappa_{jB})^{-\rho} P_j^{1-\rho}\right)} \\
C_{iA} &= \gamma_{iA} \left(\frac{(P_i(1+\kappa_{iA}))}{P_A}\right)^{-\rho} C_A
\end{aligned}
$$

### 2.5 Some definitions

Before exploring the experiments and their results, it is useful to define a few additional variables. The sectoral value added $VA_i$ of sector $i$ in this framework corresponds to sector $i$'s labour costs. Country $A$'s aggregate value added is the sum of the value added of sectors located in country

[8]We drop one of the product market clearing equations, namely the one for sector $N$, as it is redundant.

$A$, such that:

$$VA_i = w_A L_i \tag{34}$$

$$AVA_A = w_A \sum_{i \in \mathcal{S}_A} L_i \tag{35}$$

In particular, summing over French (resp. rest of the EU or rest of the world) sectors only gives us French (resp. rest of the EU or rest of the world) aggregate value added. Real value added and sectoral real prices in each country $A$ are deflated by the consumer price index $P_A$ of the relevant country as defined below:

$$rVA_i = \frac{w_A}{P_A} L_i \tag{36}$$

$$rAVA_A = \frac{AVA_A}{P_A} \tag{37}$$

$$p_i = \frac{P_i}{P_A} \tag{38}$$

This definition departs somewhat from national accounts which rather use a distinct value added deflator reflecting production prices. In particular, aggregate consumption prices are impacted by the price of imported goods, whereas the value added deflator is not. However, in this paper, we adopt a demand side perspective in the sense that we are interested in measuring impacts on the purchasing power of production factors' revenues.[9] For this reason, we use the consumption price index to deflate sectoral and aggregate value added.

Regarding trade flows, we define real imports and exports as:

$$rM_A = \sum_{i \notin \mathcal{S}_A} \sum_{j \in \mathcal{S}_A} Z_{ij} + \sum_{i \notin \mathcal{S}_A} C_{iA} \tag{39}$$

and

$$rX_A = \sum_{i \in \mathcal{S}_A} \sum_{j \notin \mathcal{S}_A} Z_{ij} + \sum_{i \in \mathcal{S}_A} \sum_{B \neq A} C_{iB} \tag{40}$$

The way trade flows enter domestic production and consumption via different CES aggregators makes it difficult to define exact imports and exports price indices. The above definitions are useful approximations that enable us to disentangle price and volume effects to study the real impact of taxes on trade while remaining simple.

Last, we define the bilateral real exchange rate of country $A$ with respect to country $B$ as:

$$RER_{AB} = \frac{P_B}{P_A}$$

so that a decrease is a real exchange rate appreciation for country $A$.

[9] Aggregate value added also differs from GDP because, in national accounts, GDP would include the proceeds of the carbon tax on domestic products.

# 3 Calibration

To calibrate the parameters, we need information on intermediate consumption and labour used by each sector and on sectoral final consumption in each country. These can be found in the input-output tables provided by the World Input Output Database (WIOD) for the latest year available, namely 2014. The data encompass 55 relevant sectors, including agriculture, industry and services, for 43 countries and the rest of the world (see sector list in Appendix A). In our quantitative exercise, we keep the 55 sectors but aggregate the countries into 3 blocks: France, the rest of the EU (RoEU) and the rest of the World (RoW). The parameters $\alpha$s in the production functions are set using the intermediate input shares for each sector, while $\mu$ corresponds to the share of value added in the production of each sector. The $\gamma$s are set to match the total final demand shares obtained from the data by summing household, government and non-profit organisations consumption plus investment and changes in inventories.[10]

There are two relevant sectors for energy production: *Manufacture of coke and refined petroleum products* (r10) and *Electricity, gas, steam and air conditioning supply* (r24). Unfortunately, there is no data publicly available with a more detailed decomposition of the energy sources (for instance separating between gas and electricity), so we work with $N_E$ equal to 2 times the number of countries.

Calibrating the elasticities of substitution $\sigma$, $\epsilon$, $\theta$ and $\rho$ is more difficult, as the values suggested by the literature are relatively varied. We use the same calibration for all countries, although it is technically possible to differentiate. The consumption elasticity is set to $\rho = 0.9$ following Atalay [2017] and Baqaee and Farhi [2019], while the elasticity of substitution across energy, intermediate inputs and labour is $\theta = 0.8$ following Baqaee and Farhi [2019]. Similarly, the elasticity across non-energy intermediate inputs is $\epsilon = 0.4$ and the elasticity of substitution across types of energy is set to $\sigma = 0.9$. Finally, households' risk-aversion is $\varphi = 2$, which is a widely used value in the literature. The values chosen for $\epsilon$ and $\theta$ are somewhat on the high side, which we preferred for two reasons: (i) it gives more flexibility to the model to adjust to the changes in tax rates and avoids extreme results; (ii) it is better suited to the medium-term horizon we have in mind (5 to 10 years). Note also that Johnson [2014] uses an elasticity of 1 across intermediate inputs in the baseline version of his model, and tests both higher and lower values. Table 1 summarises the values used for elasticities.

Since there remains considerable uncertainty around the values of elasticities in the literature, we do robustness checks in section 6.

[10] The inputs shares ($\alpha$s and $\mu$s) are fixed in our model, which partially rules out technological change, as the only adjustment possible is via substitution without deep modifications in the production process. We considered the possibility of modifying these shares to allow for innovation over the long run. However, looking at the WIOD data over the entire available time period (2000 to 2014), there was no clear time-trend for the input shares, even when focusing specifically on energy inputs. For this reason, we preferred to keep the $\alpha$s and $\mu$s fixed and have a clean substitution effect due to relative prices only.

| definition | symbol | value |
|---|---|---|
| elasticity subst. across energy types | $\sigma$ | 0.9 |
| elasticity subst. across other intermediate inputs | $\epsilon$ | 0.4 |
| elasticity subst. between energy, other inputs and labour | $\theta$ | 0.8 |
| elasticity subst. across consumption goods | $\rho$ | 0.9 |
| households relative risk-aversion | $\varphi$ | 2.0 |

Table 1: Parameter values

# 4 Simple transmission examples

To gain some intuition regarding the diffusion of tax changes across sectors and countries, we start by analysing separately the three types of tax included in the model, namely the production tax $\tau$, the intermediate consumption tax $\zeta$ and the final consumption tax $\kappa$. In each case, we only raise the tax rate for a single French production sector or a single final consumption product.

## 4.1 Production tax

We pick the French sector with the highest production tax rate in the complete scenario presented in section 5, which is the *Crop and animal production* (3) sector. We set $\tau_3 = 10\%$ and keep all other production taxes, the intermediate and final consumption taxes ($\zeta$) and ($\kappa$) at zero.

| Sector | Real after-tax prices (%) | Quantities (%) | Real value added (%) |
|---|---|---|---|
| Crop and animal production, hunting and related service | 12.25 | -7.92 | -6.47 |
| Manufacture of food products, beverages and tobacco | 2.83 | -2.61 | -0.46 |
| Fishing and aquaculture | -0.09 | -0.78 | -0.91 |
| Accommodation and food service activities | 0.46 | -0.42 | -0.11 |
| Forestry and logging | 0.14 | -0.29 | -0.24 |
| Total France | | | -0.29 |

Table 2: Impact of a 10%-production tax in the French *Crop and animal production* sector

Impacts for most affected sectors and aggregate value added are summarised in Table 2. The tax imposed on the *Crop and animal production* sector directly increases the real price (tax included) of its output by more than 12%, which is more than the tax rate. Indeed this sector re-uses its own produced goods for 16% of its intermediate inputs. The tax increases therefore also the price of its own intermediate inputs and raises all the more the price of the final output of the sector. The *Crop and animal production* is located rather upstream in the French production network: it ranks in the 33$^{\text{rd}}$ place among 55 in terms of downstreamness according to its DownMeasure index.[11] The tax shock is hence expected to propagate mostly downstream,

[11] See Section 5.4. This downstreamness measure is equal to 0.40 for the *Crop* sector, vs. 0.27 for the most

that is rather via an increase in the price of its products than via a decrease in its demand for intermediate inputs. This is exactly what we observe, looking at the diffusion of this higher price: it follows the importance of the *Crop and animal production* in the intermediate inputs of other sectors. The sectors that see an increase in their real prices are thus the *Manufacture of food products* (7), the *Accommodation and food services* (36) and the *Forestry and logging* (4), for which respectively 21.5%, 2.4% and 1.9% of inputs consist in products from the *Crop and animal production* sector. This implies an increase in the aggregate CPI in France, and hence a decrease in all other French products' real prices. Higher prices deter the demand for the goods produced by affected sectors. Hence a mirror effect can be observed in terms of quantity produced, with the same sectors seeing a decrease in their production by 7.9%, 2.6%, 0.4% and 0.3% respectively.

The impact of the tax on real prices, quantities and real value added in the RoEU is much smaller – about 2 orders of magnitude – than in France, because RoEU production sectors have a more indirect link to the French *Crop and animal production* sector and other French food-related sectors. Still, the diffusion of the tax via prices shows the same logic, the most impacted European sectors being the ones with the highest share of intermediate inputs produced by the French *Crop and animal production* sector. Since the links with France are even dimmer, impacts on the rest of the World are about 10 times smaller than for the RoEU.[12] Part of the international transmission of the shock is channeled through financial markets; bonds trading results in a transfer from French households, who receive the proceeds of the tax, to foreign households, who enjoy relatively lower prices. The impact on final demand abroad is not significant, especially because the size of the French *Crop and animal production* sector is very small relatively to the world economy. But more importantly, these financial transfers explain the slight fall in French consumption (by 0.02 %), which would otherwise increase as a result of the redistribution of the tax proceeds to French households.[13]

On aggregate, the French value added decreases by -0.3%. In order to interpret this result, it is tempting to compare it to Hulten [1978]'s theorem as stated by Baqaee and Farhi [2019]: at first order, the impact of a sectoral productivity shock on the aggregate value added is equal to that sector's sales share in value added, times the shock. Our context is somewhat different: we are considering a tax shock instead of a productivity shock. Despite the parallel between a positive sectoral tax shock and a negative sectoral productivity shock, the tax receipts are redistributed and alleviate the tax shock's aggregate impact, which is not the case with a productivity shock. Given that we have an international production network, we would want to compare the tax' impact found on World aggregate value added, that is -0.014%, to the share of the French *Crop* sector sales in the World value added (0.14%) times the shock (10%). Here, this first order approximation turns out to be fairly accurate. It is different if we transpose it at the

upstream sector and 1.00 for the most downstream sector.

[12]RoEU and RoW results can be obtained from the authors upon request.

[13]See section 6 for more insights on the role of financial markets in the transmission of the taxes.

country level: the *Crop* sector sales represent 4% of French value added, so that a similar rule of thumb implies a 0.4% drop in total value added – a quarter more than the actual effect. This reflects the non-linearities included in the model, the substitution possibilities towards agricultural goods produced outside France, as well as the redistribution of the tax proceeds to the French household.

### 4.2 Intermediate consumption tax

Next, we apply a 100% tax on intermediate consumption of *Coke and refined petroleum products* (1) by the French *Sewerage and waste treatment* (26) sector. This sector faces the second largest tax $\zeta$ in the complete scenario described in section 5.1.[14]. We consider a larger increase in the rate than for production tax in order to get bigger effects. Other intermediate consumption, production ($\tau$) and final consumption taxes ($\kappa$) are kept at zero.

| Sector | Real after-tax prices (%) | Quantities (%) | Real value added (%) |
|---|---|---|---|
| Sewerage and waste treatment | 1.19 | -0.56 | 0.38 |
| Manufacture of coke and refined petroleum products | 0.00 | -0.18 | -0.18 |
| Mining and quarrying | 0.00 | -0.05 | -0.05 |
| Water collection, treatment and supply | 0.05 | -0.04 | -0.00 |
| Manufacture of basic metals | 0.08 | -0.04 | 0.02 |
| Total France | | | -0.01 |

Table 3: Impact of a 100%-intermediate consumption tax on fossil fuels in the French *Sewerage and waste treatment* sector

Table 3 presents the results for the most affected sectors and aggregate value added in France. The tax on fossil fuel purchases modifies the optimal input choices of the *Sewerage and waste treatment* sector, with a substitution away from fossil fuels towards other factors including labour. Hence, despite a decrease in production by 0.6%, the sector's real value added increases by 0.4%.

Although the *Sewerage* sector is located upstream in the French production network (it ranks 46$^{\text{th}}$ out of 55 according to the DownMeasure index defined in Section 5.4), the tax shock propagates more strongly towards further upstream sectors. This is due to the specific format of this tax, set on purchases of fossil fuels for intermediate consumption. The tax propagates upstream via a decrease in the *Sewerage* sector's demand addressed to the *Coke and refined petroleum products* sectors, because of substitution in favour of other sources of energy and intermediate inputs. The French *Coke and refined petroleum* sector is directly affected, with a decline of 0.2% in both its production and real value added. So is, though indirectly, the French *Mining and quarrying* (6) sector whose production and value added decrease by 0.1%. Indeed,

[14] The sector with the highest tax $\zeta$ is the *Electricity, gas and air conditioning* (2) sector, but it is less convenient for this analysis than *Sewerage* because it is connected with more sectors.

the latter is a major supplier of the *Coke and refined petroleum* sector, but not of the *Sewerage* sector. Conversely, the production of the French *Electricity, gas and air conditioning* sector increases, albeit in a small proportion only (+0.01%) because the French *Sewerage and waste treatment* sector only represents a small share of its total sales.

Substitution across production factors mitigates the tax impact on the *Sewerage* sector's production price. In addition, fossil fuel purchases only represent a bit more than 2% of its total intermediate consumptions so that its real price only increases by 1.2%. As a result, the propagation to downstream sectors is rather subdued. Exceptions are the *Water collection, treatment and supply* (25) and *Manufacture of basic metals* (16) sectors. Indeed, *Sewerage and waste treatment* is one of their main suppliers, representing respectively 6% and 7% of their intermediate inputs. These sectors are hence negatively affected by the increase in *Sewerage and waste treatment*'s price, with, for both, a 0.04% decrease in production. However, their real value added is not deteriorated due to a substitution effect towards labour. Hence, it should be noted that, while upstream propagation is associated with a joint decrease in production and value added in sectors that face lower demand, downstream propagation affects those variables in opposite directions.

Finally, the aggregate impacts of the tax on both final consumption and real value added in France, as well as its international propagation, are quantitatively negligible.

### 4.3 Final consumption tax

Last, we consider a 10% tax on French final consumption of *Coke and refined petroleum products*, regardless of their origin, while all other taxes are kept at zero. The main sectoral and aggregate impacts are summarized in Table 4. Unsurprisingly, the main effect of the tax is a drop in the final demand addressed to the French *Coke and refined petroleum products* sector, which entails a decrease in its production and value added by 3.2 and 3.3% respectively. The effect propagates upstream, especially to the *Mining and quarrying* sectors of both France and the rest of the EU, because of lower demand for their products by the *Coke and refined petroleum products* sector.

| Sector | Real after-tax prices (%) | Quantities (%) | Real value added (%) |
|---|---|---|---|
| Coke and refined petroleum products (FR) | -0.13 | -3.19 | -3.31 |
| Mining and quarrying (FR) | -0.12 | -0.78 | -0.89 |
| Manufacture of rubber and plastic products (FR) | -0.12 | -0.07 | -0.19 |
| Mining and quarrying (RoEU) | -0.00 | -0.07 | -0.07 |
| Warehousing and support for transportation (FR) | -0.11 | -0.06 | -0.18 |
| Total France | | | -0.11 |

Table 4: Impact of a 10%-final consumption tax on fossil fuels in France

French final oil consumption decreases by a bit more than 8%, while other products benefit from a positive substitution effect: French final consumption of other goods increases by approximately 0.05%. In the end, real aggregate consumption in France is 0.07% lower after the tax implementation. At the same time, by raising consumption prices, the tax induces a 0.14% appreciation of the real exchange rate of France with respect to the rest of the EU and the rest of the world, resulting in lower exports. For this reason and aside from the *Coke and refined petroleum products* and *Mining and quarrying* sectors, production and real value added decrease by around 0.1% in all French sectors, the precise impact depending on their international exposure and their connection with sectors involved in oil production. Notably, the *Manufacture of rubber and plastic products* (14) and *Warehousing and support for transportation* (34) sectors suffer a decline of 0.2% in their value added.

Finally, apart from the *Mining and quarrying* sector in the rest of the EU, international spillovers are not significant. Despite small financial transfers towards the rest of the EU and the rest of world, final consumption abroad is hardly affected.

To sum up, the intermediate and final consumption taxes propagate mostly upstream towards the inputs taxed, having an impact on total production and value added, while the production tax propagates rather downstream via higher prices. The taxes' impact on the taxed sector itself depends on its input shares and substitution possibilities. Let us now turn towards policy experiments implementing the Carbon tax to all sectors.

# 5 Policy experiments: Carbon tax in France and in Europe

Using our theoretical framework, we consider now two policy experiments. First, we look at the impact of a complete carbon tax in France. Second, we consider a similar carbon tax in France and in the rest of the EU. The set-up we use allows for substitution across inputs but has fixed production functions and considers comparative statics only. Consequently and as stated in the introduction, results can be best interpreted as the medium-run (about 5 to 10 year) impact of the taxation scenarios.

## 5.1 Setting the tax rates

To calibrate the tax rates, we use green house gas (henceforth, GHG) emissions data provided by Eurostat separating across $CO_2$ and non-$CO_2$ gases, expressed in tons of $CO_2$ equivalent, for the year 2016 (latest year available).[15] We have three sets of tax rates to calibrate: on fossil fuels intermediate consumption by producers ($\zeta_{ji}$), on sectoral production ($\tau_i$) and one on fossil fuels final consumption by households ($\kappa_{iA}$).

[15] Green house gas emissions as measured by Eurostat include $CO_2$, $N_2O$ and $CH_4$. $N_2O$ and $CH_4$ are measured in $CO_2$ equivalent, i.e. the amount of $CO_2$ that would have the same global warming potential.

### 5.1.1 Calibration methodology

For each production sector $i$, we attribute the $CO_2$ emissions to the use of oil and coal, and adjust the tax rate $\zeta_{oil,i}$ on these specific inputs in order to cover these emissions' cost, given the price of carbon. The non-$CO_2$ GHG emissions (denoted $\widetilde{GHG_i}$) are attributed to the sectoral production process besides the use of energy inputs and determine the level of the sectoral production tax $\tau_i$ that the producer of output $i$ will have to pay. This approach separating between $CO_2$ and non-$CO_2$ GHG with two different taxes has a number of advantages. First, it reflects the incentives producers have to turn away from fossil fuels and modify their energy mix towards electricity, as the consumption of the former as intermediate input is specifically taxed at rate $\zeta_{ji}$, for $j \in \{\text{fossil fuels}\}$. Second, despite having a unique sector for both oil and coke, the tax rate $\zeta_{ji}$ takes into account the specificity of sector $i$'s energy mix between oil and coal: a sector that uses relatively more coal will emit more $CO_2$ and face a higher tax rate on his fossil fuel consumption. Third, it is well suited to sectors like *Crop and animal production* that emit a large amount of non-$CO_2$ GHG not related to their energy use, but inherent to their production process: in our set-up, only the $CO_2$ emissions are attributed to their fossil fuel consumption, and taxed via the oil intermediate input tax rate $\zeta_{ji}$, while non-$CO_2$ emissions are taxed via the production tax $\tau_i$. This distribution of non-$CO_2$ and $CO_2$ emissions to production process and energy use respectively is a convenient approximation for most sectors. There are however a few sectors which we treat separately to better reflect their production process. The calibration of each tax in the general case and exceptions are detailed below.

**Tax on fossil fuels intermediate consumption $\zeta$**

Concretely, the tax rate $\zeta_{ji}$ on sector $i$'s intermediate consumption of fossil fuels is the same for all fossil fuels inputs, whether bought domestically or imported. It is set such that:

$$\zeta_{ji} = 0 \text{ if } j \notin \text{oil refining}$$

$$\zeta_{ji} = \zeta_i \text{ if } j \in \text{oil refining}$$

$$\sum_{j=1}^{N} \zeta_{ji} P_j Z_{ji} = P_{CO_2} CO_{2i}$$

where $P_{CO_2}$ is the price of a ton of $CO_2$ and $CO_{2i}$ is the $CO_2$ emissions of sector $i$. Sector $i$'s tax rate is thus:

$$\zeta_i = \frac{P_{CO_2} CO_{2i}}{\sum_{j \in oil} P_j Z_{ji}} \qquad \forall i = 1, \dots, N$$

The calibration explained above is implemented using prices and quantities at the initial steady state.[16]

[16] Since these prices and quantities will adjust once the tax is implemented, at the new equilibrium the equations

**Tax on sectoral production $\tau$**

The tax rate on sector $i$'s production is set such that:

$$\tau_i Q_i P_i = P_{\mathrm{CO}_2} \widetilde{GHG}_i \tag{41}$$

where $\widetilde{GHG}_i$ are the non-$CO_2$ GHG emissions of sector $i$. So $\tau_i$ is defined as:

$$\tau_i = P_{\mathrm{CO}_2} \frac{\widetilde{GHG}_i}{Q_i P_i} \tag{42}$$

**Tax on fossil fuels final consumption $\kappa$**

In a similar way, tax rates $\kappa_{iA}$ are calibrated such that tax proceeds amount to the cost of GHG, given by the same price of the ton of $CO_2$ as the one used in the production sector, multiplied by total GHG emissions of households living in the country. Since households don't have a production process as such and their emissions are almost entirely $CO_2$ from burning fossil fuel, we do not separated between $CO_2$ and non-$CO_2$ emissions. The tax proceeds from the fossil fuels final consumption tax covers the cost of all household emissions. The tax rate is applied identically to the consumption of products from the oil refining sectors irrespective of their origin countries, but may change across countries implementing the tax depending on the local household's GHG emissions. Concretely, for a given $CO_2$ price, $\kappa_{iA}$ is calibrated in country $A$ such that:

$$\begin{aligned} \kappa_{iA} &= 0 \text{ if } i \notin \text{oil refining} \\ \kappa_{iA} &= \kappa_A \text{ if } i \in \text{oil refining} \\ \sum_{i=1}^{N} \kappa_{iA} P_i C_{iA} &= P_{\mathrm{CO}_2} GHG_A^H \end{aligned}$$

where $GHG_A^H$ is the tons of GHG emitted by households in country $A$. This implies:

$$\kappa_A = \frac{P_{\mathrm{CO}_2} GHG_A^H}{\sum_{i \in \text{oil}} P_i C_{iA}}$$

**Exceptions**

We make two exceptions to the calibration procedure described above, for the following production sectors: *Other non-metallic mineral products* (15) and *Basic metals* (16). The large quantities of $CO_2$ these sectors emit are inherent to their production process (for instance for cement, iron or steel) and not to their energy use. To reflect this situation, we set $\zeta_{j15}$ and $\zeta_{j16}$ to zero and calibrate $\tau_{15}$ and $\tau_{16}$ taking into account all sectoral GHG emissions, including $CO_2$.

defining the $\tau$s, the $\zeta$s and the $\kappa$s may not be exactly verified.

Note that the tax rates $\zeta$, $\tau$ and $\kappa$ obtained for each country and sector do not depend on whether other countries are or not implementing a carbon tax, but are different across countries and sectors depending on the emission intensity of production and consumption.

### 5.1.2 Numerical application

For our policy experiments, we choose a benchmark carbon price of 100 euros per ton of $CO_2$ equivalent, which is within the range of values suggested by Quinet [2019] as shadow carbon price over the 2020-2025 period.

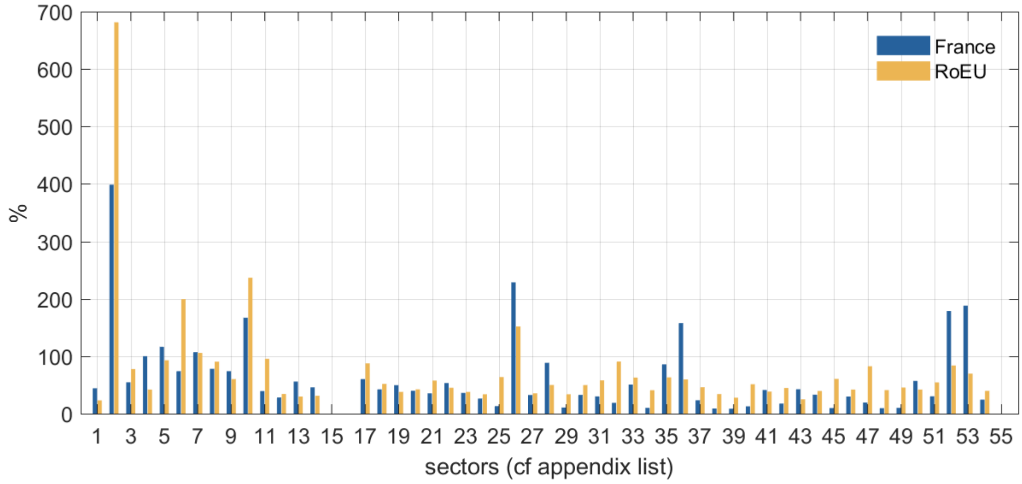



Figure 1: Calibrated tax rate $\zeta_i$, by sector $i$, in France and EU (%)

The corresponding tax rates are shown in Figures 1 and 2, respectively for goods produced in France (dark blue), and in the rest of the EU (yellow).

Although the tax rates on fossil fuels intermediate consumption $\zeta$ may seem very high at first glance, a quick rule of thumb supports this order of magnitude. Indeed, computing CO2 emitted from burning a ton of coal, multiplied by the price of carbon, and adding it to the original price of coal, we obtain price increases reflecting a tax rate ranging from 227% to 1450% depending on the type of coal considered. The same logic would bring a much lower tax rate for oil, as it is more expensive and emits less $CO_2$. Since the intermediate input we are taxing is mixing oil and coal, the tax rates $\zeta_i$ we obtain for each sector consuming oil is below the coal-only upper bound. The tax rate close to 700% applied to intermediate fossil fuels consumption of the *Electricity* sector in the rest of Europe hence remains reasonable, as this industry relies heavily on coal. Note that the French *Electricity* sector faces a much lower tax rate, as it relies mostly on nuclear energy.

The highest production tax rates $\tau$ in both France and the rest of the EU are applied to sectors whose production process emits more non-$CO_2$ GHG, like *Crop and animal production* (3), *Sewerage and waste collection* (26), *Non-metallic mineral products* (15) and *Basic metals* (16)

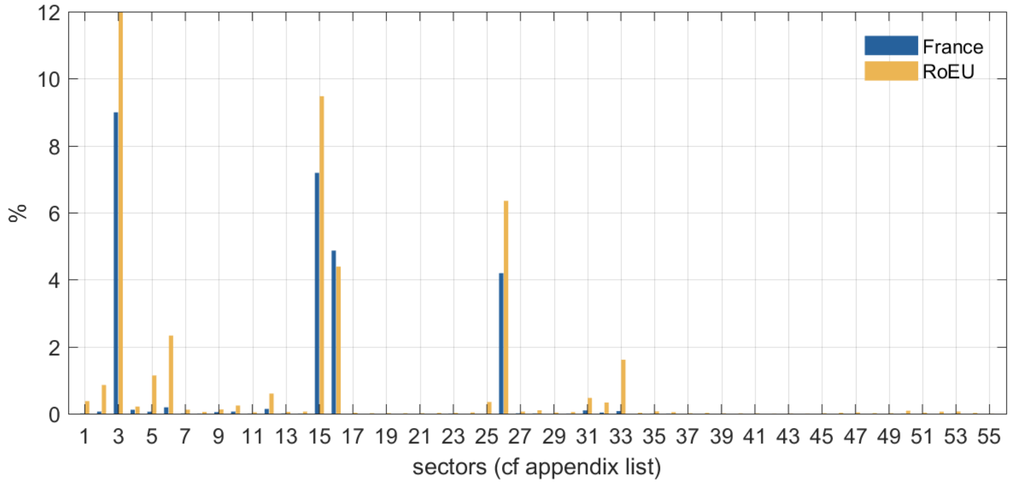



Figure 2: Calibrated tax rate $\tau_i$, by sector $i$, in France and EU (%)

for the reasons mentioned above. In general, the production in the rest of the EU is more intensive in non-$CO_2$ emissions, which explains the higher tax rates $\tau$ (yellow bars, except for *Basic metals*).

Last, the consumption tax rates imposed to households for a similar carbon price of 100 euros are $\kappa_{FR} = 41\%$ and $\kappa_{RoEU} = 28\%$ for French and European (non-French) households respectively. These relatively high rates reflect the assumption that all emissions by households are due to consumption of refined petroleum products. To get a sense of orders of magnitude, note that according to Eurostat data, households emissions in France amounted approximately to 108.5 Mt in 2016. The total final consumption of refined oil in the 2014 WIOD table is 32.6 billions of USD – that is approximately 26.1 billions of EUR.[17] We see that the value of emissions, that is 10.8 billions of euros for a carbon price of 100 EUR/ton, represents approximately a third of oil consumption in France.

We now turn to the simulation results. We first consider effects on aggregate variables then sectoral impacts.

## 5.2 Impact on aggregate variables

The impact on real aggregate value added is summarized in Table 5. As clarified in equations (34) and (35), the impact on real value added and real wage in each country is the same. The carbon tax has a much larger impact in the countries where it is implemented – and a fairly small one in other countries. When a tax is implemented both in France and in the rest of the EU, the EU's value added is more heavily impacted than France. The main reason is that the rest of the EU uses technologies emitting more GHG, for instance for the electricity production.

[17] France's total emissions are 427.1 Mt, of which 318.5 Mt are due to the production side of the economy. The rest is attributed to households.

Implementing the tax both in France and in the rest of the EU also has a much more detrimental impact on world value added: indeed such an EU-wide tax affects a larger part of the world economy, and the size of the tax as a proportion of world value added is larger.

| % change | France | Rest of the EU | Rest of the world |
|---|---|---|---|
| **Tax in France** | | | |
| *All taxes* | | | |
| Real VA | -1.18 | -0.05 | -0.01 |
| Real consumption | -0.56 | 0.01 | 0.01 |
| *Production tax $\tau$* | | | |
| Real VA | -0.41 | -0.02 | -0.00 |
| Real consumption | -0.03 | -0.00 | 0.00 |
| *Intermediate oil consumption tax $\zeta$* | | | |
| Real VA | -0.36 | -0.03 | -0.01 |
| Real consumption | -0.28 | 0.00 | -0.01 |
| *Final oil consumption tax $\kappa$* | | | |
| Real VA | -0.41 | -0.00 | -0.00 |
| Real consumption | -0.25 | 0.01 | 0.01 |
| **Tax in whole EU** | | | |
| *All taxes* | | | |
| Real VA | -1.51 | -2.04 | -0.13 |
| Real consumption | -0.64 | -0.69 | 0.08 |
| *Production tax $\tau$* | | | |
| Real VA | -0.56 | -0.85 | -0.03 |
| Real consumption | -0.05 | -0.07 | 0.01 |
| *Intermediate oil consumption tax $\zeta$* | | | |
| Real VA | -0.56 | -0.88 | -0.10 |
| Real consumption | -0.35 | -0.47 | 0.04 |
| *Final oil consumption tax $\kappa$* | | | |
| Real VA | -0.41 | -0.32 | -0.00 |
| Real consumption | -0.24 | -0.14 | 0.03 |

Table 5: Impact of carbon tax on aggregate variables (% change)

The implementation of the tax also impacts bilateral real exchange rates (RER), as shown in Table 6. In the case of a tax in France, its real exchange rate appreciates with respect to the rest of Europe (RoEU) and the rest of the World (RoW). Indeed the tax increases the relative prices of goods produced in France, which compose the vast majority of the French household's consumption basket due to home bias.[18] Although this RER appreciation creates a wealth effect in favour of domestic consumption, it is more than compensated by financial transfers from the French household to foreign households related to international risk-sharing, and French consumption decreases by 0.56%. Similar mechanisms are at play when the tax is implemented both in France and in the RoEU, with the RER of both countries appreciating

[18]Home bias is observed in the calibration data and reproduced by the model via consumption share parameters.

with respect to the RoW.

| % change (decrease=appreciation) | *with respect to:* | | |
|---|---|---|---|
| *In:* | France | RoEU | RoW |
| **Tax in France** | | | |
| France | – | -1.13 | -1.15 |
| RoEU | 1.14 | – | -0.02 |
| RoW | 1.16 | 0.02 | – |
| **Tax in whole EU** | | | |
| France | – | 0.09 | -1.45 |
| RoEU | -0.09 | – | -1.53 |
| RoW | 1.47 | 1.56 | – |

Reading: After a tax in France, the RER of France with respect to the rest of the World decreases by 1.13%, corresponding to a 1.13% appreciation.

Table 6: Impact of carbon tax on bilateral real exchange rates

The RER movements implied by the tax implementation have fairly intuitive impacts on trade patterns. As detailed in Table 7, the taxed countries see their total export decrease all the more as their RER appreciates. In the case of a tax in France only, France's total real exports decrease by 1.07%. In parallel, France's total real imports decrease by 2.28%: despite the RER appreciation for France, increasing the French household's purchasing power for foreign goods, imports suffer from the general decrease in the French household's consumption.

| % change | | *To:* | | |
|---|---|---|---|---|
| *Exports From:* | France | RoEU | RoW | Total |
| **Tax in France** | | | | |
| France | – | -1.17 | -0.96 | -1.07 |
| RoEU | -1.60 | – | -0.02 | -0.23 |
| RoW | -3.35 | -0.10 | – | -0.48 |
| Total | -2.28 | -0.26 | -0.12 | -0.42 |
| **Tax in whole EU** | | | | |
| France | – | -2.95 | -1.26 | -2.15 |
| RoEU | -3.36 | – | -1.40 | -1.66 |
| RoW | -3.87 | -3.71 | – | -3.73 |
| Total | -3.56 | -3.60 | -1.38 | -2.50 |

Reading: After a tax in France, exports from France to the rest of the EU decrease by 1.17%.

Table 7: Impact of carbon tax in France on real trade flows

Note that in every scenario, the implementation of the carbon tax has a recessive effect on total real trade. This effect is stronger when the tax is applied to a broader geographical area, namely the whole EU. In that case, total real trade decreases by 2.5%, which is the combined effect of lower real imports into and lower real exports from France and the RoEU.

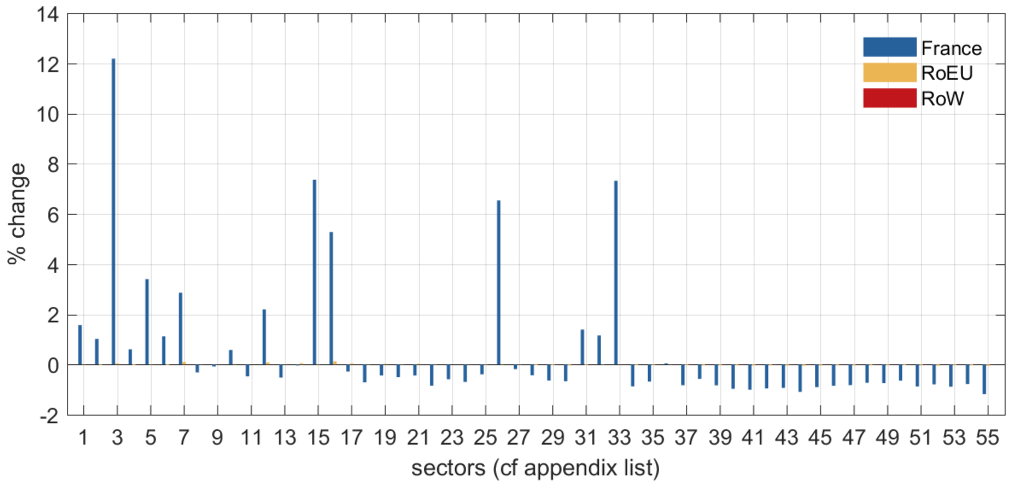
To clarify the role of each type of tax, we run separate experiments implementing only one type of tax at a time. The results of this exercise are presented in Table 5. They show that the separate taxes' effects are fairly independent from each other and additive: adding the impacts of each separate tax, we obtain almost exactly the impact of implementing all taxes simultaneously. While the three taxes have a similar effect on value added, the production tax $\tau$'s impact on consumption is much smaller. This is explained by this tax's strong negative effect on labour demand in the countries where it is applied, while this effect is mitigated by substitution in response to the oil consumption taxes $\kappa$ and $\zeta$. Overall, the effect on the RER is dominated by the mechanical positive impact of the tax on prices, leading to an appreciation with respect to non-taxed countries. Yet, the fall in the value of domestic labour, relatively to foreign goods and to foreign labour, contributes to weaken this appreciation in the case of the production tax.[19] Consistently with the perfect risk-sharing condition (23), international financial flows towards non-taxed countries are thus smaller and consumption declines by less.

### 5.3 Sectoral impact

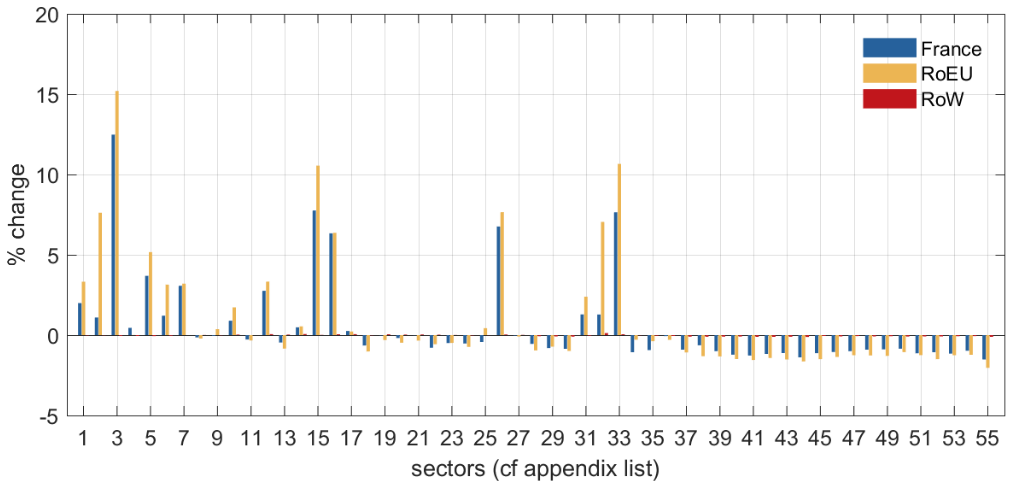
As discussed in Section 4, a carbon tax impacts sectoral production and value added through several channels. First, it propagates to prices through the input-output structure of production: the output price in each sector raises proportionally to its own GHG emissions, but also incorporates intermediate input price increases from upstream sectors emitting GHG. Next, changes in relative prices induce substitution between intermediate inputs within each production sector and between final goods in the households' consumption baskets: the share of intermediate inputs from polluting sectors used for production declines to the benefit of inputs from other, less polluting (hence less taxed) sectors and of labour. Finally, the country where the tax is implemented faces a drop in competitiveness: for most sectors, the real output price of domestically produced goods increases more than that of goods produced abroad, due to the tax hike. This induces an additional substitution effect, where intermediate and final demands worldwide shift towards foreign-produced goods. Overall, the tax introduces a distortion in production and, as such, causes a decrease in aggregate production in the areas where it is applied and, to a lesser extent, in the rest of the world.

The effect on sectoral real prices (see Figure 3) follows closely the sectoral tax rates: the largest increase in France is seen for *Crop and animal production* (3), followed by *Non-metallic mineral products* (15), *Air transportation* (33) and *Sewerage and waste collection* (26). There is little impact outside France when the carbon tax is implemented for goods and services produced in France only. When the tax is implemented in the whole EU, real prices of goods produced

[19] Looking closer, the mechanical impact of taxes on prices does not dominate in all sectors. The production tax $\tau$ improves the competitiveness of sectors paying low tax rates, or of services sectors with relatively high labour shares in production – i.e. it decreases the ratios of their prices to the prices of the same goods produced abroad.



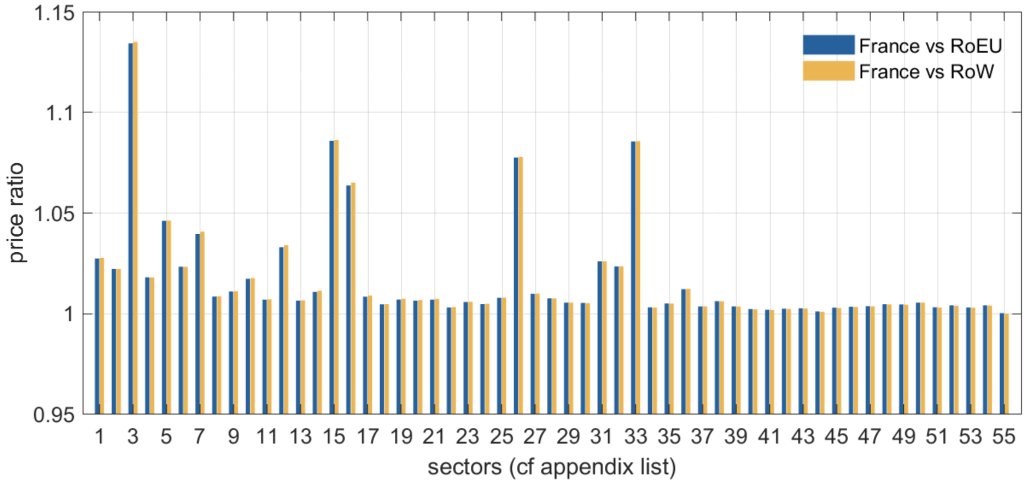

(a) Tax in France only



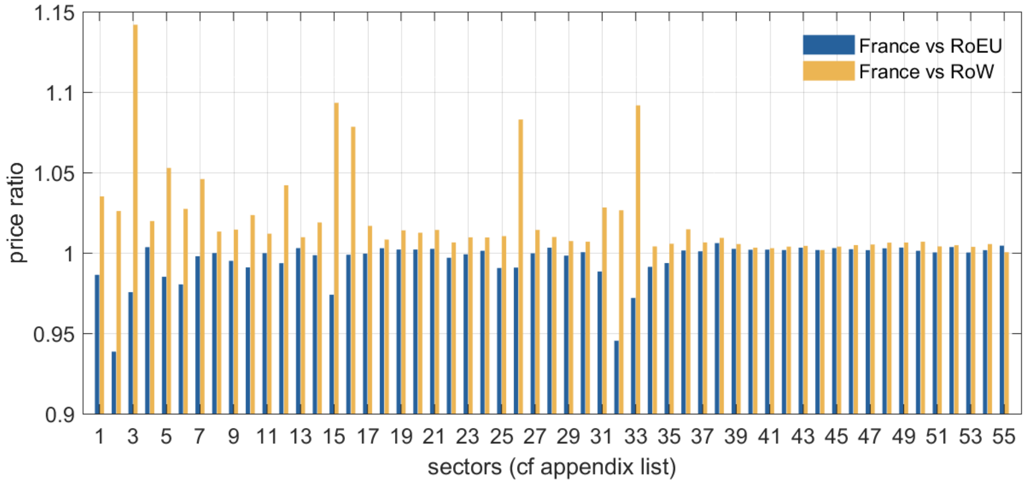

(b) Tax in France and the rest of the European Union

Figure 3: Impact on after-tax real sectoral prices, depending on their production country (% change)

in the RoEU tend to increase more than in France, especially for electricity production with a 7.6% increase against only 1.1% for French electricity. Again, this is related to the use of nuclear energy. In the rest of the World, real prices are relatively stable. In both scenarios, most services sectors see their real prices decrease slightly. Indeed, their activities emit very little non-$CO_2$ GHG and do no use much fossil fuels intermediate inputs, so that they do not face high tax rates $\zeta$ and do not need to heavily substitute away from oil.




(a) Tax in France only




(b) Tax in France and the rest of the European Union

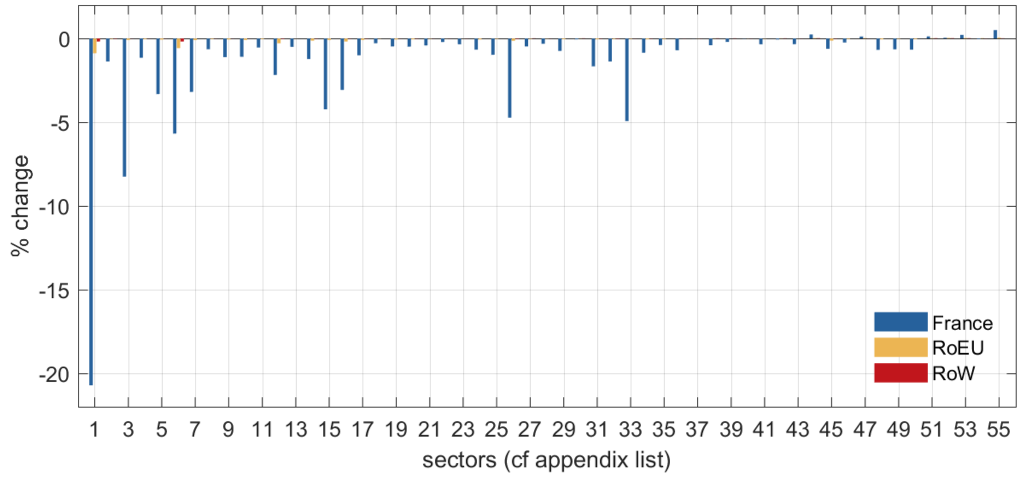
Figure 4: Relative sectoral price ratios (France/RoEU and France/RoW)

Figure 4 shows the relative prices of French products compared to European and World ones, by sector. This corresponds to the price ratio considered by (intermediate and final) buyers when choosing between products from the same sector, but with different origins. As expected, this price ratio is most often larger than one (which is the ratio's value at the initial steady state) when the tax is implemented in France only (Panel 4a), meaning that French products loose in competitiveness compared to similar goods produced in the RoEU and the RoW. Sectors with the highest tax rate, namely agriculture and manufacturing ones, loose the most. For service sectors, the price ratio is very close to one, showing that the carbon tax does not necessarily negatively affect the competitiveness of sectors subject to a low tax rate. The overall deterioration of French products' competitiveness is consistent with the appreciation of France's bilateral RER with respect to the other two country blocks. Although RoEU producers tend to use more intermediate inputs imported from France than RoW producers, and pass the price increase of these inputs on to the buyers via higher output prices, the competitiveness of French products changes in a similar way with respect to both the RoEU and the RoW.

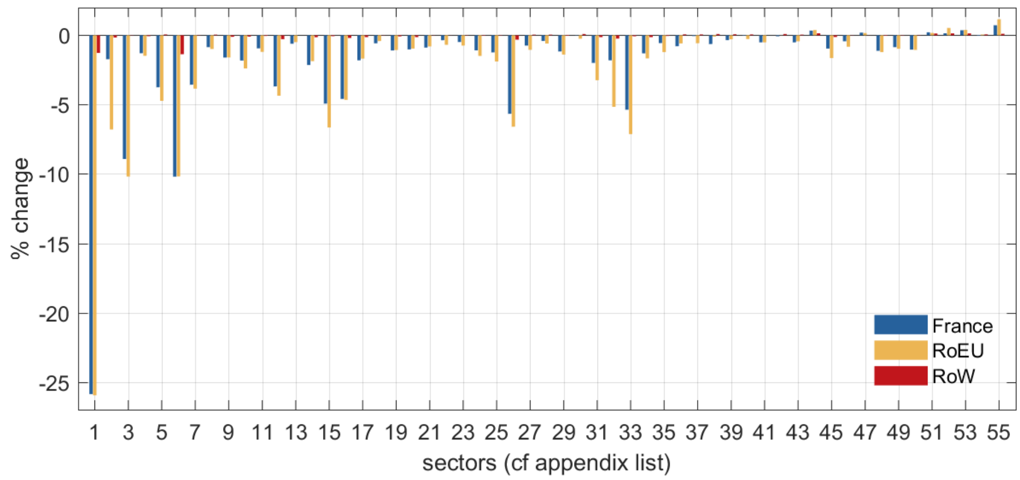
When both France and the rest of the EU implement the carbon tax, France's competitiveness with respect to products from the rest of the World still decreases in most sectors, again with agricultural and manufacturing sectors loosing more than service ones. This is however not the case any more with respect to the rest of the EU, and some French sectors' output actually show lower prices than their RoEU counterparts. This happens for sectors where the RoEU production processes are more polluting than the French ones, hence face higher tax rates in the RoEU than in France. See, for instance, the *Electricity* (2) and the *Water transport* (32) sectors.

Impacts on sectoral production are shown on Figure 5. As expected, the *Coke and oil refining* (1) sector in the taxed countries are the most affected, with a drop of production by more than 20%, as they suffer directly both from the production tax $\tau$ and the intermediate and final consumption taxes $\zeta$ and $\kappa$. This transmits to its upstream sectors, mainly *Mining and quarrying* (6), both domestically and abroad. For instance, the production of the RoW *Mining and quarrying* sector decreases by up to 1.4%, even though the RoW does not implement any carbon taxation. Besides oil production, the sectors with the highest tax rates are also among the most impacted, e.g. *Crop and animal production* (3) or *Sewerage* (26). Last, sectors using intensively oil and coke as intermediate inputs will be more impacted by these inputs' higher prices. This is the case of the French *Air transport* (33) sector, with an input share for oil and coke equal to 0.18: its production drops by 5%.

We now turn towards impacts on sectoral real value added, shown in Figure 6 when it is implemented in France (panel 6a) and in both France and the RoEU (panel 6b). While impacts on sectoral production mostly reflect the change in sectoral prices due to full pass-through of the tax, and the lower demand for those goods, the mechanisms at play differ for value added. In our model, the sectoral real value added is measured as the sectoral real wage bill, and is affected not only by the demand faced by each sector, but also by the substitution between labour and other inputs optimally chosen by each producer. Take again the example of *Air transport* in France. Its price rises strongly (+7.6%), its production drops (-4.9%), still its value added increases slightly (+0.3%). Indeed, this sector initially uses large quantities of oil as intermediate inputs. Facing a higher oil price, it substitutes other inputs, including labour, for oil. This substitution effect drives up the quantity of labour hired by that sector, explaining the slight increase in its value added in France, and more generally the differences observable between impacts on sectoral production and on real value added.



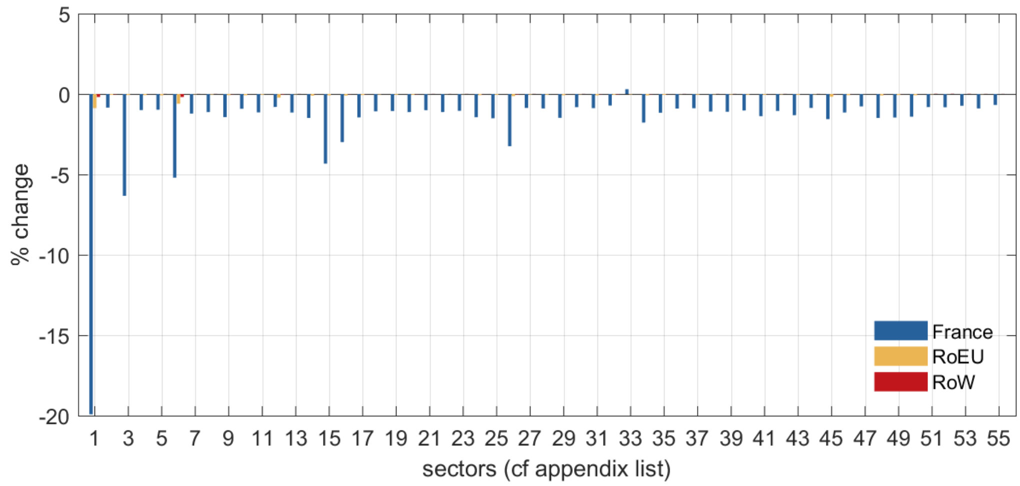

(a) Tax in France only



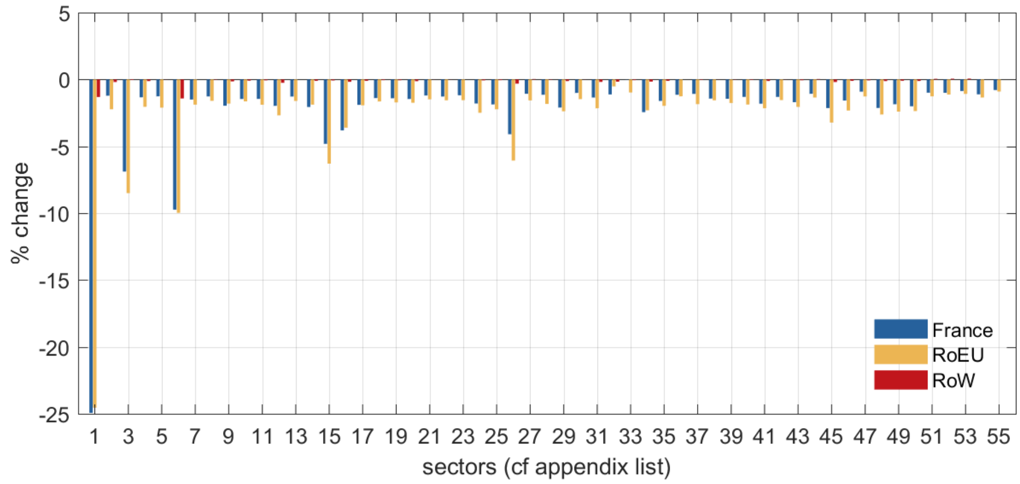

(b) Tax in France and the rest of the European Union

Figure 5: Impact on sectoral production (% change)

Due to the specific intermediate and final consumption taxes $\zeta$ and $\kappa$ it faces, the most impacted sector is the *Coke and refined petroleum* (1) with a decrease in real value added by 20%. Because of their important GHG emissions driving up their production tax rates $\tau$, the *Crop and animal production* (3), *Non-metallic mineral products* (15) and the *Sewerage* (26) sectors are also very affected by the France-only tax scenario (between -6.3% and -3.2%). The impact on the *Mining and quarrying* (6) is a good example of upstream transmission. It is indeed not facing particularly high tax rates $\tau$ and $\zeta$; the strong decrease in its real value added relates to its upstream position in the refined oil production process. It is thus directly impacted by the drop in production observed in the *Refined oil* (1) sector. The EU sectoral value added is only marginally affected when the tax is applied to France only, showing that transmission channels across countries are




(a) Tax in France only




(b) Tax in France and the rest of the European Union

Figure 6: Impact on real sectoral value added (% change)

present but remain relatively weak. This confirms the intuition obtained in section 4.

When the tax is applied to both France and the EU, patterns are similar in both blocks, with some key differences. The real value added of the RoEU *Crop and animal production* (3) sector decreases by 8.5%, somewhat more than its French counterpart (-6.9%). The impact on *Coke and refined petroleum* (1) is also similar in both country blocks (close to -25%), translating into a value added loss of close to 10% in the *Mining and quarrying* (6) sector. Even though its final oil consumption tax $\kappa$ is lower, the RoEU is suffering from larger negative consequences overall as its tax rates $\tau$ and $\zeta$ are higher in general. Notably, the *Non-metallic mineral products* (15) and *Sewerage* (26) sectors in the RoEU is more impacted than their French equivalents (-6% vs. -4%). In both scenarios, the sectors of the rest of the world only see little change.

### 5.4 Downstreamness and the propagation of taxes

The model's production network plays a key role in the propagation of the tax. Each sector of course responds to the taxes directly applied to that sector. In addition, it also responds to the taxes applied to the others production sectors with which it is interconnected. These spillovers are shaped in a complex manner by the global input-output structure embedded in the model; they depend in particular on sectors' positions in the production network (e.g. upstreamness, downstreamness).

In this section, we quantitatively assess of these spillovers and relate them to sectoral positions in the production network. We define the spillovers in a given sector as the response of its production ($Q_i$ for sector $i$) to all taxes in the economy except those that are directly applied to it. For each sector $i$, these "direct taxes" include the tax on sector $i$'s direct emissions, $\tau_i$, and the taxes on the purchases of input $j \in \{$*Coke and refined petroleum products*$\}$ by sector $i$, $\zeta_{ji}$. For any sector $k$ corresponding to *Coke and refined petroleum products*, direct taxes also include $\zeta_{ki}$ for all sectors $i$, and $\kappa_{kA}$ for all countries $A$.[20]

In order to characterize the position of each sector in the production network, we use two downstreamness indices described by Antràs and Chor [2013]. The first one (DUse_TUse) measures the share of each sector's production bought as intermediate input by other sectors which will be used by only one sector before being available for final consumption (i.e. which is one step ahead of final consumption). Formally, the goods and services market clearing conditions are:

$$\forall i \in \{1, \ldots, N\}, \qquad Q_i = \sum_{j=1}^{N} Z_{ij} + C_i$$

[20]This measure of spillovers is not clear-cut. Notably, all taxes entail broad-based wealth effects which decrease final demand for all products, which is a mechanism that would exist in an economy even if production sectors were not interconnected. Such wealth effects cannot be easily separated.

where the final use $C_i$ of good $i$ is defined as:

$$C_i = \sum_{A \in \mathcal{C}} C_{iA}$$

Define $z_{ij}$ the share of intermediate input from sector $i$ entering production in sector $j$ as:

$$z_{ij} = \frac{Z_{ij}}{Q_j}$$

With this notation, any $Q_i$ can be rewritten as:

$$Q_i = \sum_{j=1}^{N} z_{ij} Q_j + C_i$$

Introducing recursively the definition of the $Q_j$'s in this expression, we get:

$$Q_i = \sum_{j=1}^{N} z_{ij} C_j + \sum_{j=1}^{N} \sum_{k=1}^{N} z_{ik} z_{kj} C_j + \sum_{j=1}^{N} \sum_{k=1}^{N} \sum_{l=1}^{N} z_{ik} z_{kl} z_{lj} C_j + \ldots + C_i \tag{43}$$

Using the matrix notations $\mathbf{z} = [z_{ij}]$, $\mathbf{C} = [C_1 \ldots C_N]'$, $\mathbf{Q} = [Q_1 \ldots Q_N]'$, equation (43) becomes:

$$\mathbf{Q} = \mathbf{C} + \mathbf{zC} + \mathbf{z}^2\mathbf{C} + \mathbf{z}^3\mathbf{C} + \ldots = \sum_{m=0}^{\infty} \mathbf{z}^m \mathbf{C} \tag{44}$$

The first downstreamness index is defined in vector form as:

$$\text{DUse\_TUse} = \mathbf{zC} ./ (\mathbf{Q} - \mathbf{C})$$

where ./ denotes entry by entry division of vectors. The index for sector $i$ is the $i$-th entry of vector DUse_TUse. The larger the index, the larger the share of products $i$ dedicated to intermediate consumption that will be available for final consumption after only one final transformation by another sector, thus indicating that sector $i$ is located downstream in the production network. This definition however does not consider the further indirect uses of product $i$ various steps ahead of final demand. That is why Antràs and Chor [2013] develop a second index (denoted DownMeasure) that takes into account the full information regarding the number of stages that products must go through to reach final demand. The definition of this index is based on the decomposition of production (44). In this expression, the successive terms of the sum, $\mathbf{z}^m\mathbf{C}$, for $m = 1, 2, \ldots$, correspond to the quantities (in vector form) of products that are $m$ steps ahead of final demand. Antràs and Chor [2013] compute a weighted sum of these terms (with growing weights), then normalize it by production, hence providing a comprehensive measure of each sector's distance from final demand:

$$\text{UpMeasure} = \left( \sum_{m=0}^{\infty} (m+1)\mathbf{z}^m \mathbf{C} \right) ./\mathbf{Q} = \left[ (I - \mathbf{z})^{-2} \mathbf{C} \right] ./\mathbf{Q}$$

Higher values of the index reflect larger shares of production going through many sectors before reaching final demand, which corresponds to upstream sectors. Finally, Antràs and Chor [2013]'s DownMeasure index is, for each sector, the inverse of the corresponding sectoral UpMeasure:

$$\text{DownMeasure} = \mathbf{1}./\text{UpMeasure}$$

We compute spillovers in the scenario where the carbon tax is applied to the whole European Union (as described in section 5.1), and downstreamness indices at the economy's initial steady state.

In what follows, we report the values of both indices TUse_Duse and DownMeasure, but we preferably use the latter to rank sectors, because it reflects more comprehensively the network structure. In addition, DUse_TUse may be meaningless for some sectors. For example, the index is zero for *Activities of households as employers of for own use*, as shown in Table 8, while it is obviouly a downstream sector.[21] Yet, the two indices are fairly well correlated across sectors (with a correlation coefficient of 0.59).

Figure 7 highlights the relationship between inter-sectoral spillovers and downstreamness. It shows the position of all sectors in the world economy in terms of downstreamness (indices DownMeasure and DUse_TUse on the x-axis) and the size of the spillovers on their production (normalized by the country average size of the spillovers to account for regional differences in tax level, on the y-axis). The correlation coefficients between normalized spillover effects and downstreamness indices across sectors are found significant and positive (0.43 for DownMeasure and 0.44 for DUse_TUse): downstream sectors are more likely to experience low negative or even positive spillovers from other sectors' taxes. There are a number of channels affecting spillovers, possible compensating each other. Positive drivers stem from favourable substitution effects in both intermediate and final demand for the considered sector's products. Negative drivers result from two effects: first, demand for a sector's products, both from the successive sectors which use them as intermediate inputs in the production chain and from final consumers, decreases. Second, the price of its intermediate inputs increases unevenly, requiring it to adjust its purchases and raise its selling price. The relative importance of these channels depends on the sector's upstreamness in the production network and on the level of the tax in the sectors to which it is interconnected (or equivalently on the intensity of their GHG emissions). In upstream sectors, the negative demand effect dominates: in their client sectors paying a tax, production and demand for intermediate inputs decrease. And the same applies recursively to the latter

[21] The coefficient is zero because the production of the sector is entirely used as final consumption, but rounding differences make production minus final consumption (the denominator) slightly different from zero.

sectors' own clients, and so on. In the end, upstream sectors are most affected as a result of this domino effect. In downstream sectors, negative spillovers mostly result from the second negative channel: their output prices include carbon taxes paid by upstream sectors due to full pass through.[22] We conclude that this second negative channel entails quantitatively smaller spillovers than the first one (the negative demand effect).

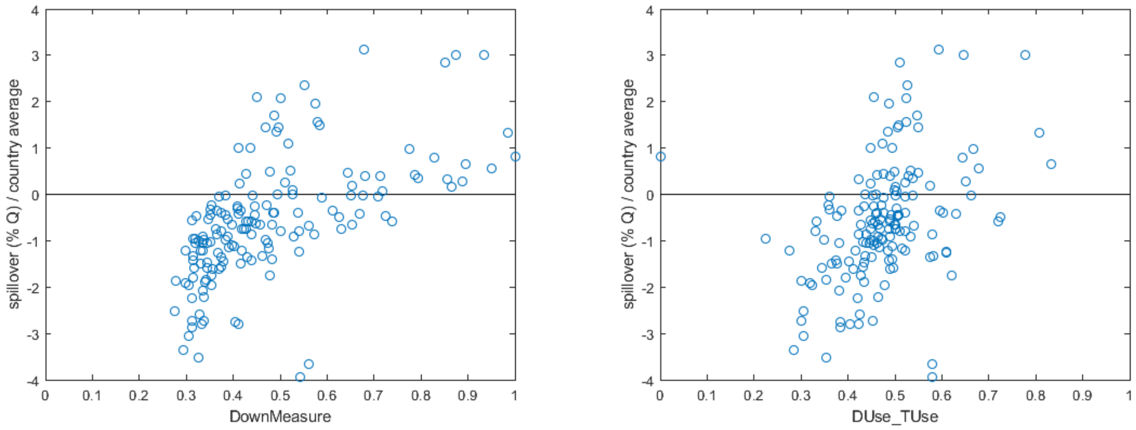



Figure 7: Downstreamness and normalized size of spillovers across sectors

Note: the points for *Mining and quarrying* in the three regions have been removed from this plot because the normalized spillover effects are much larger for them than for other sectors – respectively -5.1, -4.3 and -10.6 for France, the rest of the EU and the rest of the world.

This intuition is confirmed looking at tail sectors in terms of downstreamness shown in Table 8. This table reports the downstreamness indices for the top-10 and bottom-10 downstream sectors in the French economy (according to our preferred index DownMeasure), and the spillover effects reflecting the inter-sectoral propagation of taxes to these sectors through the production network. It also recalls the total sectoral impacts of the complete carbon tax shown in Figure 5b. For most upstream sectors (i.e. with the lowest values of DownMesure), spillovers are negative and substantial: they explain most of the total effect of the complete carbon tax. in this case, the link with oil production or other polluting activities determines the size of the spillover. For example, *Activities auxiliary to financial services and insurance* (43) mainly feeds other services sectors and faces relatively small spillover effects (-0.5 %). On the contrary, a large share of the *Mining and quarrying* (6) sector is used by *manufacture of coke and refined petroleum products* (1) sectors, the consumption of which is heavily taxed both in France and in the rest of the EU. This explains the strong impact (-9.5 %) found for this sector.

Among the downstream sectors considered (i.e. with the highest values of DownMeasure), spillovers are often positive and explain most of the total effect of the tax. Indeed, in this case, the total effect generally remains positive but is reduced because of these sectors' own taxes.

[22]These additive impacts of carbon prices are not reflecting any double taxation of GHG emissions. Their sum corresponds to the actual tax amount that would be collected on final consumption if taxing emissions embedded in each sectoral product.

| Sector | DownMeas. | DUse_TUse | Spillover ($Q_i$ in %) | Total effect ($Q_i$ in %) |
|---|---|---|---|---|
| *Lowest 10 values* | | | | |
| Mining and quarrying | 0.27 | 0.29 | -9.5 | -10.2 |
| Manufacture of basic metals | 0.27 | 0.31 | -2.2 | -4.6 |
| Activities auxiliary to financial services and insurance | 0.31 | 0.45 | -0.5 | -0.5 |
| Manufacture of chemicals and chemical products | 0.31 | 0.30 | -2.4 | -3.7 |
| Warehousing and support activities for transportation | 0.31 | 0.37 | -1.3 | -1.3 |
| Printing and reproduction of recorded media | 0.31 | 0.47 | -0.8 | -0.9 |
| Legal and accounting; head offices; management consultancy | 0.32 | 0.38 | -0.9 | -1.0 |
| Administrative and support service activities | 0.33 | 0.46 | -0.9 | -1.0 |
| Manufacture of paper and paper products | 0.33 | 0.37 | -1.3 | -1.8 |
| Sewerage; waste treatment; materials recovery; remediation | 0.33 | 0.38 | -1.8 | -5.7 |
| *Highest 10 values* | | | | |
| Real estate activities | 0.68 | 0.49 | 0.4 | 0.3 |
| Trade and repair of motor vehicles and motorcycles | 0.71 | 0.52 | -0.0 | -0.4 |
| Other service activities | 0.72 | 0.50 | 0.1 | -0.0 |
| Construction | 0.74 | 0.72 | -0.5 | -0.7 |
| Education | 0.79 | 0.54 | 0.3 | 0.2 |
| Public administration, defence; compulsory social security | 0.86 | 0.42 | 0.3 | 0.2 |
| Retail trade, except of motor vehicles and motorcycles | 0.87 | 0.50 | 0.2 | -0.0 |
| Scientific research and development | 0.89 | 0.65 | 0.2 | 0.2 |
| Human health and social work activities | 0.95 | 0.68 | 0.5 | 0.4 |
| Activities of households as employers or for own use | 1.00 | 0.00 | 0.7 | 0.7 |

Table 8: Tail values of downstreamness among French sectors and size of spillover effects on production after a carbon tax in the whole EU

Yet some downstream sectors suffer from negative spillovers, especially when they are located downstream of polluting activities in the production network. This is the case for *Construction* (27), which consumes large quantities of cement, or to a lesser extent for *Trade and repair of motor vehicles and motorcycles* (28), which is notably served by the *Manufacture of motor vehicle* (21) sector, itself consuming *Metal products* (17), the production of which emits large quantities of $CO_2$.

In summary, these results show that production networks play a significant role in the propagation of the carbon tax across sectors. Especially, upstream sectors are more strongly affected because of reduced demands from the successive sectors which use their products as intermediate inputs in the production chain. Positive substitution effects occur but only dominate negative spillovers when the domino effect on demand is small, that is for downstream sectors when these sectors are not closely interconnected to polluting ones. In the end, as Figure 8 illustrates in the case of France, some sectors are negatively impacted by the tax even though their activity is not GHG-intensive. This is notably the case for *Legal and accounting activities* (45), which ranks 49$^{\text{th}}$ among the 55 French sectors in terms of downstreamness. Other high-polluting sectors are disproportionately affected by the tax, like *Mining and quarrying* of course, but also, to a lesser extent, *Chemical products* (12), which ranks 52$^{\text{nd}}$. Conversely, *Human health and social work* (53), *Education* (52), or *Trade and repair of motor vehicles* (28), respectively ranking 2$^{\text{nd}}$, 6$^{\text{th}}$ and 9$^{\text{th}}$, are rather GHG-intensive activities but are hardly impacted by the tax (with even minor positive effects on production for the first two).

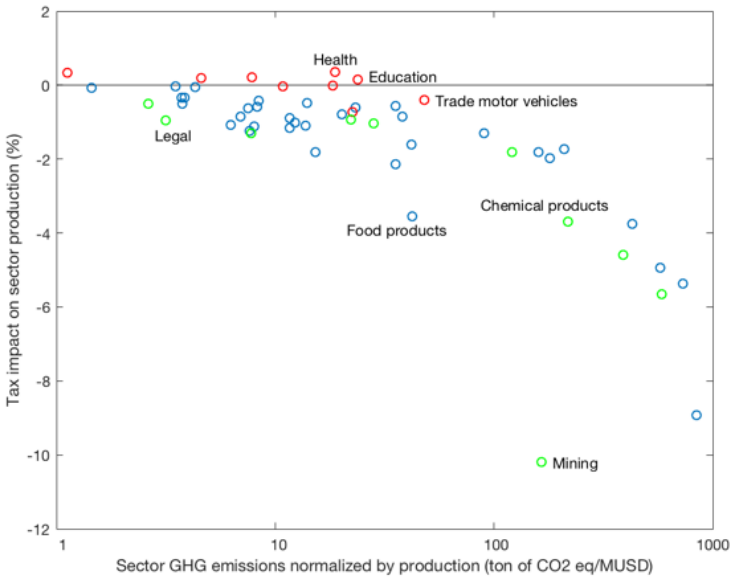



Figure 8: GHG emissions intensity of production and impact of the tax on production for French sectors

Note: The top-10 and bottom-10 sectors in terms of DownMeasure are plotted respectively in red and green. The point *Coke and refined petroleum products* has been removed from this plot for better readability, as well as *Activities of households* since it does not emit GHG.

# 6 Robustness

## 6.1 Financial markets

To have a clearer view of the mechanisms involved by perfect risk-sharing, we consider an alternative specification of the model where there are no international financial markets and country-blocks are in financial autarky. In this set-up, country $A$ household's total resources only consist in labour income $w_A L_A$, firms' profits $\Pi_A$ and the lump-sum transfer $T_A$. The household's program is then:

$$\max_{\{C_{jA}\}} C_A = \left( \sum_{j=1}^{N} \gamma_{jA}^{\frac{1}{\rho}} C_{jA}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \tag{45}$$

$$\text{s.t. } \sum_{j=1}^{N} P_j(1+\kappa_{jA})C_{jA} = w_A L_A + \Pi_A + T_A \tag{46}$$

Similarly to the complete markets case, the first order conditions are the equations (22), and the consumption price index is defined as above in equation (24). The country-specific budget constraint (46) replaces the perfect risk-sharing condition to solve the model.

To define the equilibrium under financial autarky, the three equations (23) and (30) are replaced by the household budget constraint (46) for each of the three country blocks. The equilibrium equation for $C_A$ below becomes:

$$C_A = \frac{w_A L_A + \sum_{j \in \mathcal{S}_A} \tau_j P_j Q_j + \sum_{i \in \mathcal{S}_B} \sum_{j=1}^{N} \zeta_{ji} P_j Z_{ji}}{\sum_{j=1}^{N} \gamma_{jA} P_A^{\rho} (1 + \kappa_{jA})^{-\rho} P_j^{1-\rho}} \tag{47}$$

The financial autarky assumption changes the results in a non-negligible fashion. The negative impact on aggregate value added significantly shrinks (sometimes becoming positive) and is more spread across all countries, including the ones that do not implement the tax which fare worse in financial autarky than in complete markets. Also, the sign of the impact on consumption switches, implying that the implementation of the tax increases consumption in the taxed countries. This is related to the evolution of relative prices and to the redistribution of the tax proceeds. In financial autarky, France's real exchange rate (RER) appreciates more strongly after the implementation of the tax, reflecting the substantial increase of the relative price of French goods due to the tax. With our perfect competition assumption, the tax is fully passed through to the final consumer. It is partially paid by French consumers, but also by foreign consumers when they buy French goods, and foreign producers whose technology involves French intermediate inputs. Hence, in the case of a tax in France only, the tax proceeds redistribution increases the French household's real budget constraint by 2.12%, allowing for an increased consumption despite this relative price increase of her consumption basket. This can be linked to the results discussed in Corsetti et al. [2008], where the authors study the impact of a positive productivity shock on consumption and show that with a low enough trade elasticity in financial autarky, the income effect dominates the substitution effect. Here, we also have relatively low elasticities, implying a strong income effect in financial autarky, but we consider a tax shock instead of a productivity one. Our tax shock goes in the same direction as a negative productivity shock, yet it also involves redistribution of the tax proceeds to the French household, which enhances the income effect and impacts positively the French household's consumption in financial autarky.

With a tax in France only, France's RER appreciate significantly, implying an increase in real imports by 2.74%. In that case, imported goods become relatively cheaper, and the French household's budget constraint is relaxed, allowing her to consume more in general, including more imported goods. Similarly, when the tax is implemented in the whole EU, real total imports of the RoW decrease by 9%, which is mainly a consequence of the stronger appreciation of the RER of France and the RoEU with respect to the RoW (-13.7% and -12.8% respectively).

The impact on the most affected sectors in the countries where the tax is implemented is similar with complete markets and under financial autarky (see Figure 9 in Appendix B). Less impacted sectors in those countries (mostly services sectors) become even less or sometimes positively affected in financial autarky: this is related to the aggregate consumption increase that affects the overall domestic demand for all taxed sectors more than in complete markets. The decrease in sectoral value added in countries that do not implement the tax is on average larger under financial autarky. Overall, the complete markets assumption tends to smooth the impacts on sectoral real value added, compared to the financial autarky where impacts are more contrasted and dispersed.

### 6.2 Calibration

Since there is considerable uncertainty surrounding the values of the elasticity parameters, we do robustness checks on each of them, namely $\sigma$, $\epsilon$, $\theta$, $\rho$ and $\varphi$. Results are presented in Figures 10 to 14 in Appendix C.

In general, results appear fairly robust to the choice of elasticities, especially at the world level. In most cases, the higher the elasticities, the less the aggregate value added is impacted. Higher elasticities allow indeed an optimal reallocation of resources given the new tax and minimise the impact of the tax distortion at the world level. This is however not always true at the level of country blocks: the impact of a tax in France tends to be larger and more negative with higher elasticity across intermediate inputs, and this tends to be true for the rest of Europe when an EU-wide carbon tax is implemented. Indeed, at the country-level, higher elasticities may lower the demand for French (resp. RoEU) local products in favour of products from the RoW.

One key parameter for the results is the elasticity of substitution across energy types ($\sigma$): the higher this elasticity, the smaller the impact on real value added in the country where the tax is implemented (see Appendix Figure 10). Indeed, with higher elasticity, both producers and consumers are able to substitute away from the taxed, hence more expensive fossil fuels towards cheaper, non-taxed electric energy. The same mechanism alleviates the burden of the whole world when the elasticity increases. However, since most of oil production comes from the rest of the world, more substitution away from oil will slightly deteriorate the RoW value added outcome.

A similar logic – although with smaller implications for the results – applies for the elasticities across labour, energy and intermediate inputs $\theta$ and across consumption goods $\rho$. The higher the elasticity $\theta$, the more producers are able to substitute non-taxed labour for taxed energy or intermediate inputs in the rest of Europe, so that they are able to limit the increase in intermediate input costs, keep price levels lower and the demand for their good higher (see Appendix Figure 12). A higher $\rho$ also allows domestic consumers in the taxed country to substitute away from taxed, more expensive goods towards cheaper, less taxed goods, redistributing more optimally their demand across sectors (see Appendix Figure 13).

The diagnosis is somewhat different for substitution across intermediate inputs. A higher elasticity $\epsilon$ is detrimental to the taxed country (see Appendix Figure 11). Producers in all countries are indeed substituting away from the more expensive goods, produced in the taxed country, towards goods from countries not implementing the tax. This decreases the demand for goods produced in the taxed country and penalizes that country.

Changing the consumption smoothing parameter $\varphi$ also moderately affects the impact of the carbon tax on aggregate value added (see Figure 14 in Appendix). A higher smoothing parameter somewhat alleviates the impact of the tax in the taxed countries, but increases it in the rest of the world. Indeed, more risk-averse households are more willing to share their country-specific risk internationally, so that the tax's negative effect is more evenly spread across countries.

Last, we change the size of the tax by adjusting the price of the ton of $CO_2$ (up to 200 euros, see Appendix Figure 15). The results show that the impact on real value added is fairly linear with the size of the tax. A linear approximation wouldn't therefore be very far off, especially for the aggregate world value added. It would nevertheless somewhat underestimate the impact on French real value added of a small carbon tax.

# 7 Conclusion and way forward

This paper uses a multi-sector, multi-country static general equilibrium model to simulate and analyse the quantitative impact of a carbon tax on real value added and production both at the aggregate and sectoral levels. On the production side, the shock is propagated through global input-output chains. Demand responds to changes in relative prices and is impacted by international trading in financial securities. For a tax corresponding to a price of 100 euros per ton of carbon dioxide equivalent, distributed across sectors in proportion to their initial emissions, aggregate value added in France and in the European Union is found to decline by 1.2% and 0.05% respectively when the tax applies in France only, and 1.5% and 2% respectively when the tax applies in the whole EU. The sectoral impacts reflect both their own emissions and the emissions indirectly embedded in their production processes. In France, they range from a negligible impact to a fall of -20% in the *Coke and refined petroleum* sector when the tax is only applied in France.

Our model still has some limitations, besides the simplifying assumptions regarding labour supply and the absence of capital. First, another layer of substitution could be added across goods or services of the same sector but produced in different countries. The corresponding intuition is that it may be easier to substitute, say European coal for French coal than to substitute French gas for French coal. Second, we introduce sector-specific taxes in such a manner that they add up to proxy taxes on goods' embodied emissions, but it is clear that an implementation at the sector level based on average emissions in a given year, irrespective of firms' specificities and efforts to reduce their own emissions, is somewhat unrealistic. Yet, we believe that our exercise remains useful as it gives a reasonable approximation for large enterprises, and thus for aggregate effects. Last, the absence of endogenous technological adjustments in the economy is not fully satisfactory when it comes to energy transition. This is why we consider our results to be best suited for medium run simulations.

Despite these shortcomings, the model proposed in this paper is particularly well suited to study other topical issues related to the low-carbon transition, like the magnitude of cross-border carbon leakages, or the economic impact of border tax adjustments on the carbon content of imports. This will be the subject of future work.

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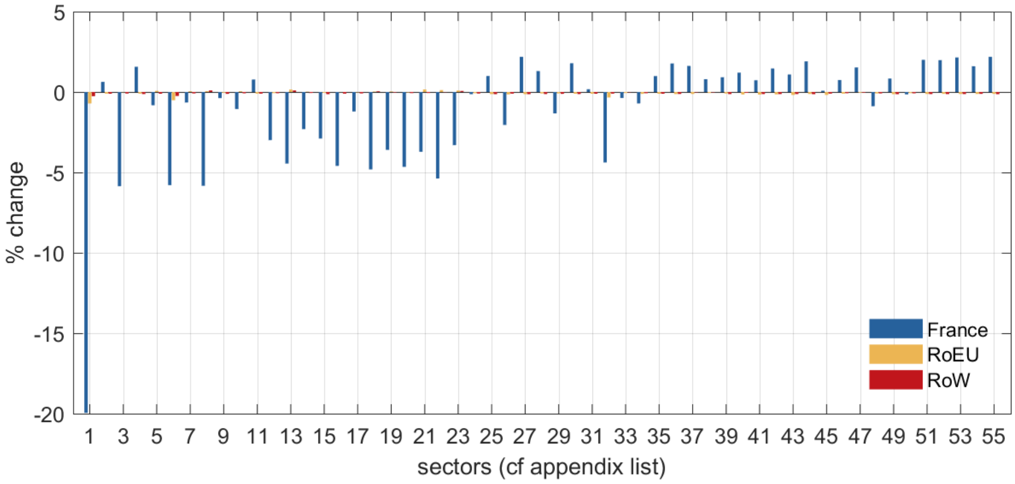
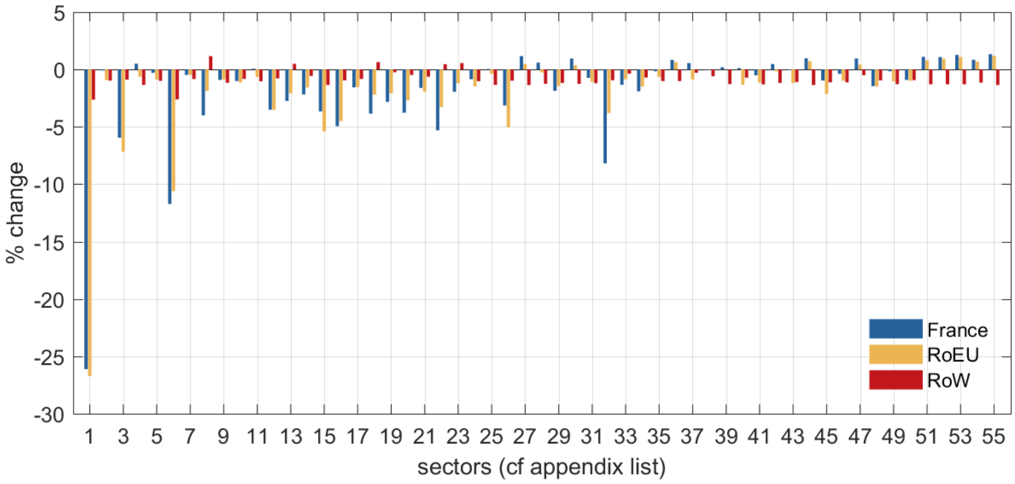
# Appendix A Sectors

| | |
|---|---|
| 1 | Manufacture of coke and refined petroleum products |
| 2 | Electricity, gas, steam and air conditioning supply |
| 3 | Crop and animal production, hunting and related service activities |
| 4 | Forestry and logging |
| 5 | Fishing and aquaculture |
| 6 | Mining and quarrying |
| 7 | Manufacture of food products, beverages and tobacco products |
| 8 | Manufacture of textiles, wearing apparel and leather products |
| 9 | Manufacture of wood, products of wood and cork, except furniture; manufacture of articles of straw and plaiting |
| 10 | Manufacture of paper and paper products |
| 11 | Printing and reproduction of recorded media |
| 12 | Manufacture of chemicals and chemical products |
| 13 | Manufacture of basic pharmaceutical products and pharmaceutical preparations |
| 14 | Manufacture of rubber and plastic products |
| 15 | Manufacture of other non-metallic mineral products |
| 16 | Manufacture of basic metals |
| 17 | Manufacture of fabricated metal products, except machinery and equipment |
| 18 | Manufacture of computer, electronic and optical products |
| 19 | Manufacture of electrical equipment |
| 20 | Manufacture of machinery and equipment n.e.c. |
| 21 | Manufacture of motor vehicles, trailers and semi-trailers |
| 22 | Manufacture of other transport equipment |
| 23 | Manufacture of furniture; other manufacturing |
| 24 | Repair and installation of machinery and equipment |
| 25 | Water collection, treatment and supply |
| 26 | Sewerage; waste treatment and disposal; materials recovery; remediation and other related services |
| 27 | Construction |
| 28 | Wholesale and retail trade and repair of motor vehicles and motorcycles |
| 29 | Wholesale trade, except of motor vehicles and motorcycles |
| 30 | Retail trade, except of motor vehicles and motorcycles |
| 31 | Land transport and transport via pipelines |
| 32 | Water transport |
| 33 | Air transport |
| 34 | Warehousing and support activities for transportation |
| 35 | Postal and courier activities |
| 36 | Accommodation and food service activities |
| 37 | Publishing activities |
| 38 | Motion picture, video and television production, sound recording, music publishing; programming and broadcasting |
| 39 | Telecommunications |
| 40 | Computer programming, consultancy and related activities; information service activities |
| 41 | Financial service activities, except insurance and pension funding |
| 42 | Insurance, reinsurance and pension funding, except compulsory social security |
| 43 | Activities auxiliary to financial services and insurance activities |
| 44 | Real estate activities |
| 45 | Legal and accounting activities; activities of head offices; management consultancy activities |
| 46 | Architectural and engineering activities; technical testing and analysis |
| 47 | Scientific research and development |
| 48 | Advertising and market research |
| 49 | Other professional, scientific and technical activities; veterinary activities |
| 50 | Administrative and support service activities |
| 51 | Public administration and defence; compulsory social security |
| 52 | Education |
| 53 | Human health and social work activities |
| 54 | Other service activities |
| 55 | Activities of households as employers; goods- and services-producing activities of households for own use |

# Appendix B Robustness: Financial Autarky



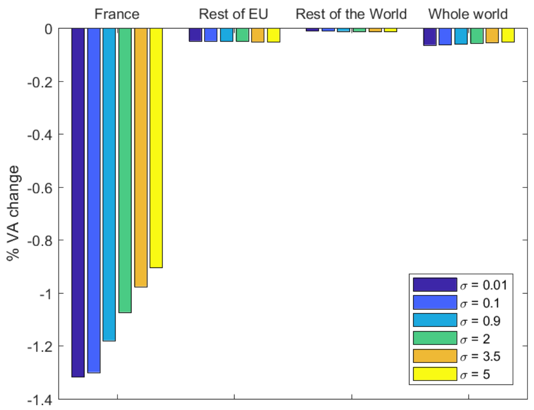

(a) Tax in France only



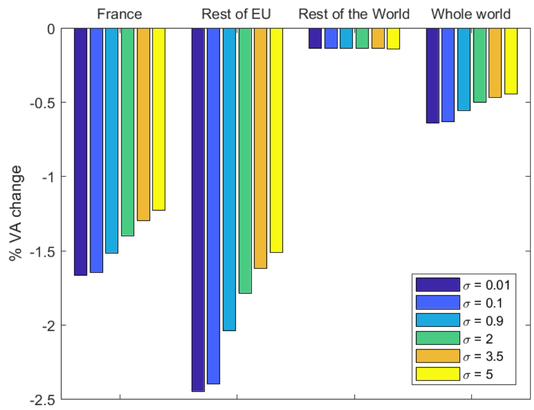

(b) Tax in France and the rest of the European Union

Figure 9: Impact on real sectoral value added (% change) in financial autarky

# Appendix C Robustness: Calibration

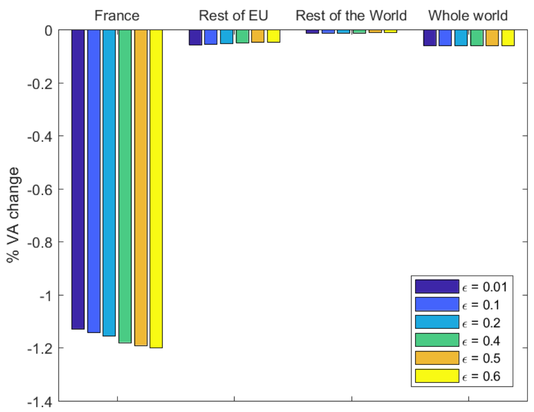



(a) GHG tax in France only

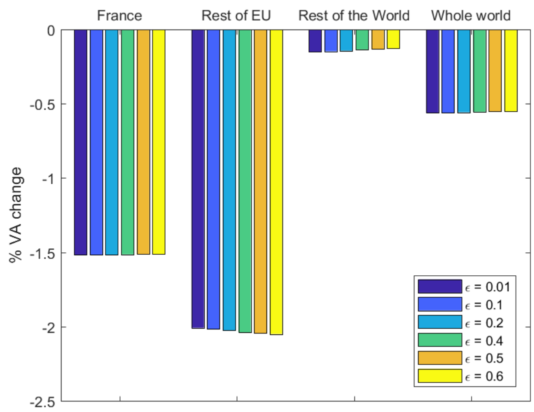



(b) GHG tax in France and the rest of the EU

Figure 10: Impact on real value added (% change), varying the elasticity $\sigma$ of substitution across energy types

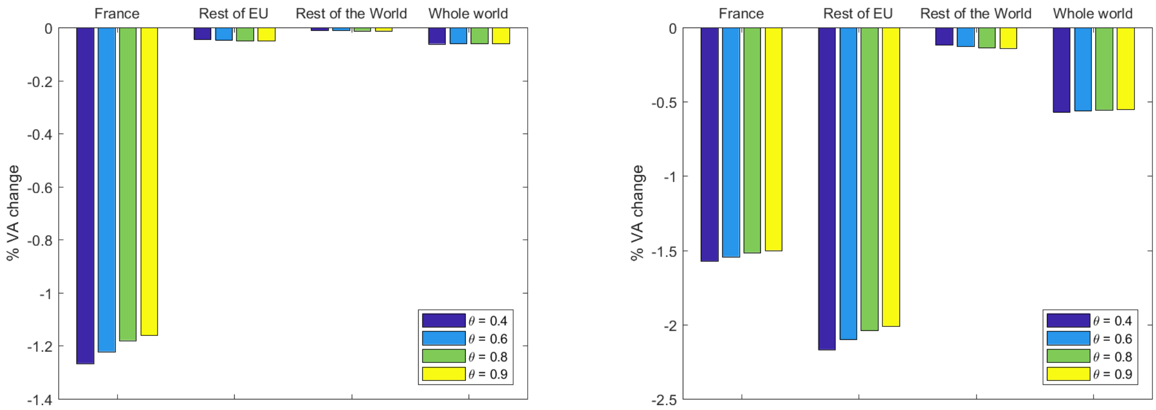



(a) GHG tax in France only




(b) GHG tax in France and the rest of the EU

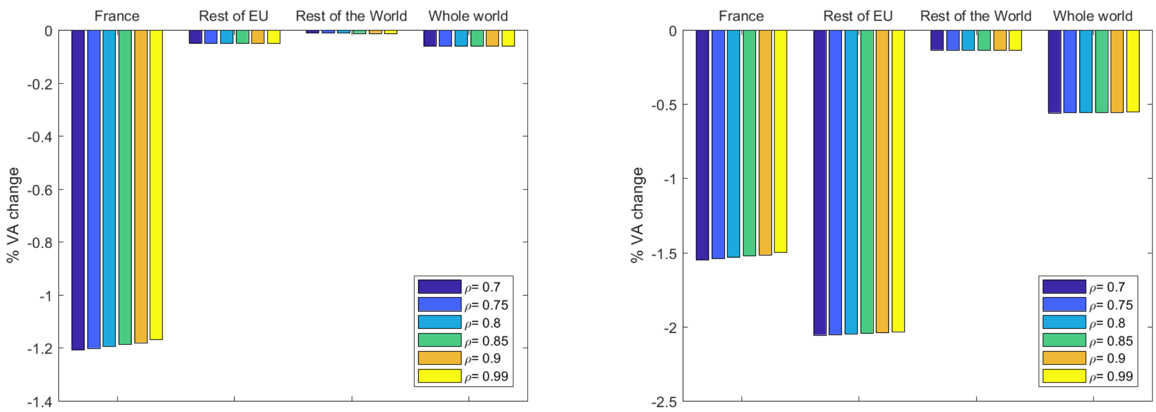
Figure 11: Impact on real value added (% change), varying the elasticity $\epsilon$ of substitution across intermediate inputs




(a) GHG tax in France only

(b) GHG tax in France and the rest of the EU

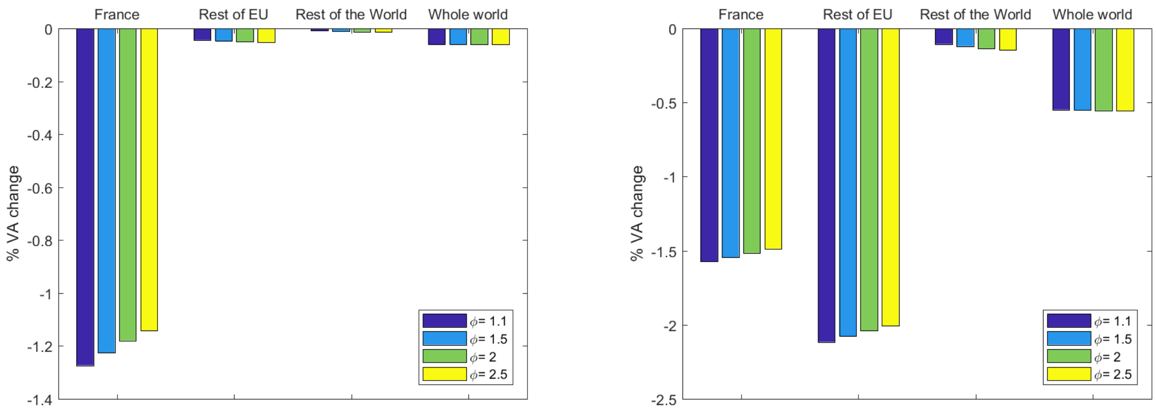
Figure 12: Impact on real value added (% change), varying the elasticity $\theta$ of substitution across labour, energy and intermediate inputs




(a) GHG tax in France only

(b) GHG tax in France and the rest of the EU

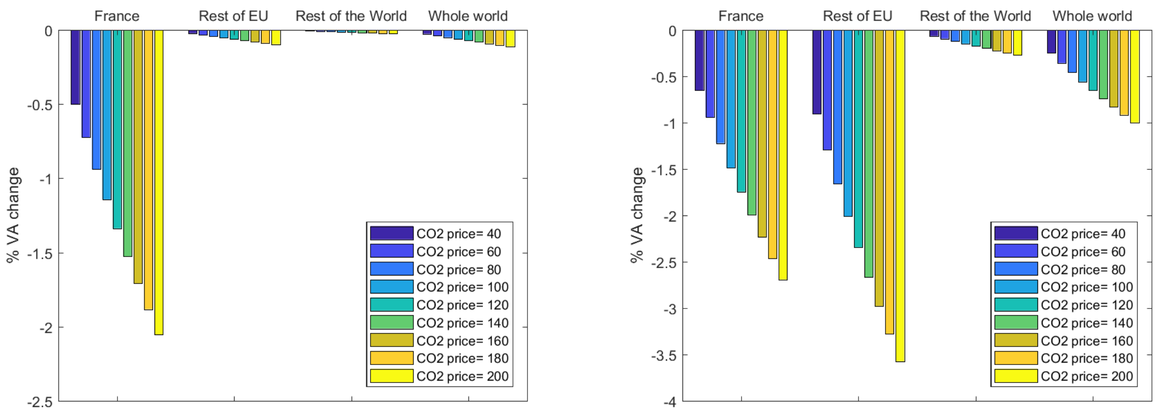
Figure 13: Impact on real value added (% change), varying the elasticity $\rho$ of substitution across consumption goods




(a) GHG tax in France only

(b) GHG tax in France and the rest of the EU

Figure 14: Impact on real value added (% change), varying the consumption smoothing parameter $\varphi$




(a) GHG tax in France only

(b) GHG tax in France and the rest of the EU

Figure 15: Impact on real value added (% change), varying the price of carbon