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WORKING PAPER

The influence of a carbon tax on cost competitiveness

Bastien DUFAU [1*]

Difficulties to adopt an international price of carbon has highlighted one of the most important objectives of countries: preserve their industries' competitiveness.
This article follows this idea and aims to evaluate the multisectoral and international impact of an energy shock. More precisely, the focus is made on a carbon tax and its impact on unit cost of production. In this article, the focus is made on a way to go through the limits of the input-output analysis by endogenizing technical coefficients. Using a flexible cost function permits to remove the non-substitution hypothesis and allows all sectors to optimize their demand of inputs. We use a Generalized Leontief (LG) implicit cost function in our input-output model. We show that this implicit cost function matches with the price input-output model in physical data.
Finally, we study the impact of a carbon tax (40€/tCO2 or 80€/tCO2) at a European level. A cost competitiveness analysis shows that Poland would be mainly impacted by the tax, unlike the other European countries that maintain their competitiveness at the international level at the lower rate of tax. A strong heterogeneity among countries and industries stresses the necessity to focus negotiations on the recycling of the product of the tax.
Then we compare the impact of the tax in France and in Germany and find a little impact on France's competitiveness contrary to Germany. Nevertheless, if the tax is adopted at the European level, the French Manufacturing sector would be more impacted by the indirect effect of the tax through intermediate consumption.

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[1] Climate Economics Chair, Palais Brongniart, 28 Place de la Bourse, 75002 Paris

KEYWORDS

Input-Output analysis | Competitiveness | Carbon tax | Multisectoral analysis | Energy | Flexibles functional forms

1. Introduction

1.1. Energy, CO_2 and competitiveness issues in Europe

The United States' withdrawal from the Paris agreement on climate change mitigation in 2017, after the drop of the carbon tax project in 2014 by the European Union, drew the attention to the difficulties to come to an international agreement on climate change.

These difficulties are mainly based on the high cost of reduction of CO2 emissions for countries under the agreement that make free-riding incentive stronger than incentive to cooperate (Barrett, 1994). In the case of a carbon tax, additional cost incurred by a firm located in a country under the international environmental agreements (IEA) could be seen as a competitive disadvantage compared with a firm located in a country that doesn't respect the IEA. Therefore, an IEA has nothing to do but induce small trade penalties on non-participants to remain stable (Nordhaus, 2015). These penalties aim to compensate the higher taxation into the IEA but are politically not easy to set up as they seem to be protectionist measures and lead to an economic war.

These difficulties have led some regions at a local level within a country, or some countries at a national level or a group of countries at an international level to act on their own, adopting unilateral measures. Nevertheless, it increases risks for a loss of cost-competitiveness or of purchasing power. It is a major political choice, not always approved by the population. In France, for instance, the "Gilets Jaunes" movement protesting against the national carbon tax led the French government to give up the rise of the tax and stressed the fact that a national agreement is also difficult to be set up.

On the other side, adopting national measures of carbon reduction allows each country to choose how to set up the measures in order to limit negatives outcomes for the economy. In fact, each industry, depending of its exposure to CO_2 emissions, could be more or less exposed to these measures. That is why national measures seem to be a good compromise between the necessity to reduce CO_2 emissions and the economical constraints of each country.

A national carbon tax makes polluting firms less competitive by increasing their price, including a new combination of inputs, mainly non energy inputs. As the carbon tax allows polluters to choose the cost minimizing abatement strategy, its effect also differs from an industry to another. Differences accrue from the energy consumed, the ability to substitute energy with other inputs and also the ability to replace less competitive commercial partners. Indeed, it is often forgotten that there is a huge content of energy embodied in intermediate consumption. An increase in energy price due to a carbon tax would make some partners more or less competitive than before the tax. That is why we need to make the distinction between the energy directly used by an industry and the energy indirectly used, also called the embodied energy. This effect is often neglected whereas European industries are highly impacted by an increase in intermediate products' prices resulting from a carbon tax (Bordigoni *et al*., 2013). We go further in this study, first by simulating the impact of a carbon tax in different scenarios of taxation (applicated unilaterally by a sole European country, or by European countries in a whole). We compare effects of this unilateral carbon tax on unit cost of production in major countries around the world. Then, while the previous analysis is made under the assumption of perfect complementarity between inputs, we introduce here substitutability between intermediate inputs. In our study all industries could optimize their cost function. As an increase in energy prices leads to a new combination of inputs, we have to combine the underlying cost function of the input-output analysis with a flexible cost function.

To consider the overall impact of the tax, an analysis based on input-output methodology, at 6 sectors level, is undertaken. The use of international input-output tables (WIOD[1]) makes it possible to take into account the effect of embodied energy.

This study presents results on the previous issues. First, it sheds light on indirect carbon tax effects in all sectors and how it reduces a country's competitiveness. Secondly, taking into account of substitution between inputs gives a complete overview of the impact of a carbon tax on all European sectors country by country. A significant increase in unit cost of production occurs in Poland or in Germany contrary to countries like France. This approach may push European countries to increase their fiscal collaboration to make.

This quantitative study of short-term impact, based on multiple carbon tax scenarios in industries of major global countries, can be helpful to design future carbon pricing policies respecting cost-competitiveness. In the analysis, our assumptions of carbon tax (40$ and 80$/tCO2) follow those permitting to reach the goals of the Paris Agreement.

1.2. Review of CO_2 taxation

According to the World Bank, carbon pricing has become popular since a few years. This seems to be the consequence of the Paris Agreement as, since 2015, twenty-two new carbon pricing initiatives have been implemented leading, to more than 70 the total of national (46 in 2019) or subnational initiatives (28 in 2019)[2]. Whereas China national ETS (launched in 2020) and EU ETS (launched in 2005) cover a high share of global annual CO_2 emissions, these initiatives result in a too weak carbon pricing to achieve the minimal price range needed to be consistent with the Paris Agreement. The Carbon Pricing Leadership Coalition

[1] A full description of the database is available on the website: http://www.wiod.org/home

[2] World Bank & Ecofys. Carbon Pricing Watch. State and Trends of Carbon Pricing 2019.

calculates[3] that achieving the goals of the Paris Agreement requires carbon price between 40$ and 80$/t$CO_2$ by 2020. Today, only carbon tax initiatives achieve the minimal range, and only three initiatives go further (Sweden carbon price is at 127$/t$CO_2$, Switzerland and Liechtenstein carbon price at 96$/t$CO_2$).

While several countries covered by our study have implemented a carbon pricing initiative (Korea, China, EU for ETS and Canada, France, Poland, Mexico, Japan, Spain, UK for carbon tax) only the French carbon tax reaches the range with a 50$/t$CO_2$ price. Unfortunately, the French protestation against the tax highlights the difficulties to increase the price level which reduces the purchasing power of consumers and the competitiveness of industries.

1.3. Earlier literature on competitiveness and a carbon tax

Many studies on the impact of a carbon tax have been proposed, using different approaches of the academic literature. Three criteria seem essential to analyze an overall impact of a shock on energy prices: (i) the first criterion is to study the impact of the tax at an international level. With the globalization of economic exchanges and the geographical fragmentation of the value chain, the impact of a unilateral shock in a major country will spread in its commercial partners, and their commercial partners; (ii) the second criterion is to take into account embodied energy in intermediate consumption. In industry, expenses in intermediate consumption are far more important than expenses in energy. This situation could lead expenses in embodied energy to be more important than expenses in energy directly used; (iii) the third criterion is to take into account substitution between inputs.

Studying the effects of energy prices on competitiveness usually relies on the estimation of the impact of a carbon tax on trade. When the focus is made on bilateral trade, the academic literature generally leads to similar results. Aldy and Pizer (2011) propose a supply demand model where supply is shared between US and the Rest of the World. They find that energy-intensive manufacturing industries are more likely to experience a decline in production (5%) and an increase in net imports (1%) than less-intensive industries in US under a $15 carbon tax. Bordigoni (2012) uses gravity equations to highlight that exports of iron and steel decrease by 1.9% and exports of paper articles decrease by 0.9% whereas electricity prices increase by 10%. Bureau *et al.* (2013) find similar results, namely that an increase of 10% of the price of French electricity (resp gas) would lead to a decrease of 1.9% (resp 1.1%) of the value of exportations. Sato and Dechezleprêtre (2015) found that a variation of 10% in the energy prices between two country-sectors increases imports by 0.2%. These studies find a significant effect of energy prices on competitiveness, but they only focus on bilateral trade and doesn't take into account the first criterion.

To fulfill the first two criteria, the use of multi-regional input-output (MRIO) models, that are increasingly developing, seems more relevant as it is the best way to take account of, at the same time, embodied energy through intermediate consumption and trade flows. The emergence of consistent data at the international level has promoted their development and many sources such as the World Input Output Database (WIOD), the Global Trade Analysis Project (GTAP), Exiobase[4] or OECD input-output databases are now available and good sources for MRIO models, especially on environmental issues (Nakano *et al.,*2009; Hertwich *et al*., 2009). Studies using input-output models can evaluate the additional effect of embodied energy on sectoral prices. Mongelli *et al.* (2009) use an intensity vector for each sector multiplied by a tax rate of 20€/tCO_2 to assess the percent price increase for each sector in Italy. The percent price increase is less than 0.6% for 90% of the sectors. Bordigoni and Leblanc (2012) use a MRIO on European manufacturing industries to compute a vector of embodied energy and simulate the effect of a 20€/tCO_2 tax rate. It results that most of the tax burden is supported by only a few industries and that the competition distortion may be as important among European countries than with non-European producers. For the high majority of sectors, the tax impact induced by higher inputs' prices stands for more than a half of the total tax impact. Unfortunately, these studies are mainly short-run analysis and consider that industries cannot reduce their emission neither substitute their inputs. To solve this and introduce substitution between inputs, the best way to do is to use flexible functional forms for the cost function.

Diewert (1971) initiated studies of the production structure based upon the idea of flexible coefficient of production. Flexible cost functions enable to provide estimations of substitution between more than two factors of production and result from KLEM production functions. This flexibility has become primordial since the oil crisis in the 70's and the resulting need to differentiate substitution between capital, labour, energy and raw materials (Arthus and Peyroux, 1981). The study of KLEM or multifactor cost functions using a Translog function (Christensen *et al*., 1971; Berndt and Wood, 1975; Griffin and Gregory, 1976; or more recently Reynès and Yeddir-Tamsamani, 2009) or generalized Leontief cost function (Woodland 1975, Morrison 1988) found a significant substitution between energy and at least one of the other inputs. It justifies the need to take substitution into account in order to analyze a shock in energy prices. In the context of a carbon tax, it seems fundamental to consider all levels of substitution as political choices may have a strong impact on energy-related practices. The major limit in the use of functional forms is the impossibility to take into account energy embodied in intermediate inputs (second criterion).

Taking into account the second and third criteria together is challenging[5] and studies attempting to do it are relatively rare (except Hudson and Jorgenson, 1974). This is particularly apparent when one wants to analyze the ability of firms to gain competitiveness at the international level. In this article we propose a

[3] https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices

[4] https://www.exiobase.eu/index.php

[5] Computable general equilibrium models could be appropriate, nevertheless they present two major weakness: they are long-term oriented whereas the impact of a carbon tax on competitiveness is more short-term or medium-term oriented. Moreover, computable general equilibrium models usually rely on less flexible cost functions such as CES functions.

model that takes into account the three criteria to analyze the impact of a carbon tax. With a focus on the producer's side, this study aims at developing a many-country, many sectors input-output model with short-term substitution between all intermediate consumptions.

2. Input-Output models

2.1. Critical review of input-output models

Since the popularization of input-output models by Leontief (1936, 1951), the last decades have seen many studies implementing and developing IO models. Studies were interested in the geographical use of IO models first. Single Regions IO models (SRIO) use a national table of technical coefficients in conjunction with an adjustment procedure designed to capture some of the characteristics of the regional economies and create regional technical coefficient tables (Miller, 1957). Multi-Regional IO models (MRIO) extends classic national IO coefficients to a larger scale including differences in foreign industries (Timmer *et al*., 2014, Ottaviano *et al*., 2014) and are becoming more widely used while international trade increase and international policies, particularly within the UE, are developing. With the emergence of energy and environmental concerns, IO studies focused on a way to evaluate non-monetary embodied inputs such as energy or CO2 (Bullard and Herendeen, 1975, Proops, 1976, Mongelli *et al*., 2009).

Input-output analysis relies on strong assumptions of constant return to scale and fixed technical coefficient (no substitution of inputs in the short run). Classical models studying the effect of a shock with a Leontief model finds new prices indexes as a solution. These models implicitly rely on a two periods approach (Mesnard, 2013): a base time period (all prices are normalized to one) that serves as a common reference for all base year index prices and a current time period where prices have been shocked. The model calculates new prices indexes after the shock as the difference between the base time period and the current time period. This difference occurs only because of the assumption that technical coefficients are fixed. If technical coefficients were not fixed, producers would be considering optimizing their input allocation after the shock and the new price indexes would simply become new base year price indexes. This incompatibility between input-output analysis and substitution of inputs lead us to use another version of input-output analysis that is not concerned with this problem, the Leontief production-prices model based on physical/volume data[6]. In that case coefficients and prices pertain to the same time period and the model finds prices as solution (Mesnard, 2013).

2.2. Model presentation

Our study is based on a multi-regional input-output model. This is a complete MRIO model with multi-directional trade. Our main contributions are to use a set of 6 aggregated major sectors in 7 European countries and 11 international countries (countries and sectors' lists are provided in **Appendix A**), but also to take into account substitutability between inputs in each industry. The model includes the *Manufacturing* and an *Energy* (combining the *Mining and Quarrying* industry, the *Coke, refined petroleum and nuclear fuel* industry and the *Electricity, gas and water supply* industry) sector. In every country, aggregation of industries is the same and follows the same aggregation than the one used by Inklaar et Timmer (2012) to construct relative prices[7]. Different energy intensities, the use of intermediate products, or importation structures lead to high variations in the impact of a carbon tax. In order to identify the most and less penalized sectors for the design of a national or European policy, it is necessary to consider these variations between sectors and countries.

Numerous MRIO databases have been developed in the last decades while the most popular are certainly WIOD (World Input-Output Database from the European Commission, Timmer et al., 2015), GTAP (Global Trade Analysis Project- Aguiar *et al.*, 2019) or ICIO (Inter-Country Input-Output from the OECD[8]). We choose to use data from WIOD because many satellites' accounts (Socio Economic accounts, Environmental accounts) are available. Although we use aggregated data, we examine the whole productive economy (final consumers are not included).

Countries analyzed in the model represent almost 80% of world GDP during the considered period (1995-2007). In the model, the focus is made on CO_2 emissions but countries with the strongest level of emissions are not necessary countries with the strongest GDP. Whereas USA and China represent the highest GDP and the highest CO_2 emission levels (almost 50% of the total), many rich countries such as European countries (France or Germany in particular) pollute much less than poorer countries such as India or Russia. Studying CO_2 emissions inside European countries (**Fig. 1.**) reveals a strong heterogeneity. Germany and UK are the most emitting countries in particular because of their *Energy* sector more dependent on fossil fuels. As the focus is made on CO_2 emissions in sectors, we can notice that more than 50% of total emissions are coming from the *Energy* sector and 25% from the M*anufacturing* sector.

[6] Difference between the Leontief model and the Leontief production-prices model is that the first one uses monetary data (currency units) and the second uses physical data (for more details, see **Appendix B**).

[7] All 34 industries are aggregated into 6 major sectors.

[8] https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm

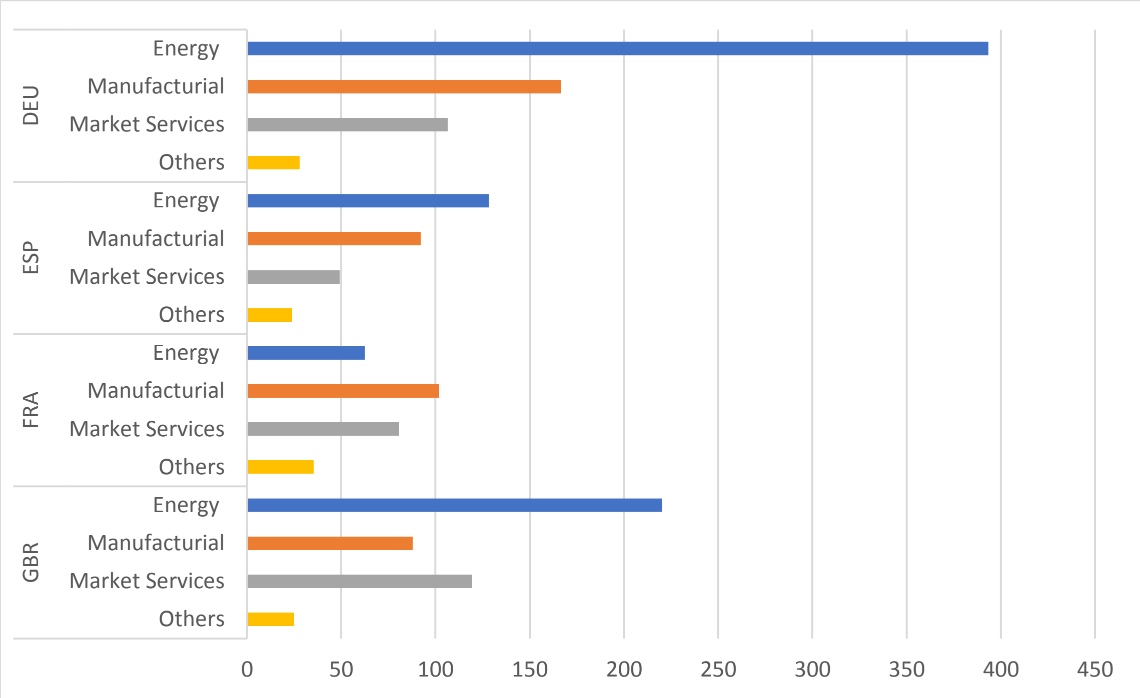


Fig. 1. CO2 emissions in Gg CO2-eq. (Mt)

Nevertheless, these ratios are very different among countries. If we take a closure attention to the share of CO_2 emissions, we see important differences from a country to another (for example in France *Market services* pollutes more than *Energy* sector.

Contrary to many studies on the potential short-term costs of a carbon tax for industries, the focus is made on the mid-term. Behavioral reactions of industries happen (and are implicitly taken into account with the use of an implicit flexible cost function) but the mid-term is too short to allow substitutions with capital. Industries can change their direct or indirect exposition to the tax by substituting inputs or labour. This configuration is relevant to identify the most threatened sectors and countries by a carbon tax. Another issue on this carbon tax stand on the way of its application. We choose to apply the tax only on local production. This explains why we do not retain the idea of a boarder tax which is often called by political opinions. The focus is then made on national or European sectors and the effect of this carbon tax on their unit cost of production. We allow sectors to substitute inputs if their price increases: Most polluting sectors will suffer from a highest increase of prices and their production will be less demanded by other sectors. At the opposite, final consumers have no impact on the reaction of sectors to the tax (non-substitution theorem; Samuelson, 1954) in this kind of model.

Data sources and details of our model database are described in **Appendix A**. Input-output, socio-economic and CO_2 emission are taken from the WIOD database. PPP and aggregation of industries are taken from the GGDC database. In **Appendix D** we explain the aggregation of industries and prices.

3. Methodology

3.1. Adjustment of unit costs of production after a carbon tax

In the common language, a Leontief model is said to rely on fixed technical coefficients but in fact we should use the expression of fixed cost shares in total cost of producing. That is why a Leontief cost function is implicit to a physical input-output model (**Appendix C**).

In order to introduce substitutability in the system we need to change the implicit Leontief production function into another one with flexibility. We choose to use the generalized Leontief production function for two reasons. Firstly, the use of Shephard's Lemma (1953) leads to flexible technical coefficients (Appendix E). Flexible technical coefficients permit the use of an input-output model with data in physical units. Secondly, solving Input-output models in physical units leads to equilibrium prices (**Appendix B**).

Our model stands on three steps. On the first step a shock in energy prices (modelized by a carbon tax) leads to new equilibrium prices. We calculate these new prices solving the equation:

$$P = C.P + C_L.W + C_k.R + \tau.CO_2$$

Where P represents the vector of production prices, W the vector of wages and R the vector of capital prices. C, C_L and C_k are respectively the matrix of technical coefficients, labour coefficients and capital coefficients all in monetary terms. τ represents the tax rate in \$/tCO_2 and CO_2 is the level of CO_2 directly emitted by industries. With the linearity assumption of input-output analysis, we obtain:

$$P = (I - C)^{-1}(C_L.W + C_k.R + \tau.CO_2)$$

On the second step, we consider that we enter in a new period: prices are reported in the new production plans of industries. We consider that industries work under a static price expectation (Tinbergen, 1930). We consider that industries operate under a short term generalized Leontief cost function (Morrison, 1988) with labour considered as the only quasi-fix factor (Kratena, 2005)[9].

$$G(y, P, x_k) = y\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\alpha_{ij}p_i^{\frac{1}{2}}p_j^{\frac{1}{2}} + \sum_{i=1}^{n}\delta_{it}p_i t^{\frac{1}{2}} + \sum_{i=1}^{n}p_i\gamma_{it}t\right) + y_j^{\frac{1}{2}}\left(\sum_{i=1}^{n}b_{ik}p_i x_k^{\frac{1}{2}} + 2\sum_{i=1}^{n}\gamma_{itk}p_i t^{\frac{1}{2}}x_k^{\frac{1}{2}}\right) + \sum_{i=1}^{n}p_i\gamma_{ik}x_k$$

The use of Shephard's Lemma (1953) yields new technical coefficients[10]:

$$c_{ij} = \sum_{j=1}^{n}\alpha_{ij}p_i^{\frac{-1}{2}}p_j^{\frac{1}{2}} + \delta_{it}t^{\frac{1}{2}} + \gamma_{it}t + \sum_{i=1}^{n}b_{ik}x_k^{\frac{1}{2}} + 2\sum_{i=1}^{n}\gamma_{itk}t^{\frac{1}{2}}x_k^{\frac{1}{2}} + \sum_{i=1}^{n}\gamma_{ik}x_k$$

On the third step we re-iterate the first step with these new technical coefficients. We obtain new equilibrium prices consecutively to an input substitution. Finally, these equilibrium prices are re-injected in the implicit cost function to calculate a unit cost for each sector (**Appendix D**).

3.2. Effect of disaggregation on estimated results

Crossed prices relationships between industries and countries lead us to adopt a weak level of disaggregation. We aggregate international industries twice.

We decided to aggregate the prices coming from the 34 industries into prices of 6 sectors (**Appendix A**) while retaining the assumption of constant return to scale and under this assumption the unit cost equals the unit price (**Appendix E**). With these aggregated prices, the cost function finally includes the intermediate prices $\bar{P}$ of the 6 major sectors.

For an industry j, the cost function becomes:

$$G_j(\bar{P}, y, t, x_k) = y_j\left(\sum_{i=1}^{n_2}\sum_{j=1}^{n_2}\alpha_{ij}\bar{p}_i^{\frac{1}{2}}\bar{p}_j^{\frac{1}{2}} + \sum_{i=1}^{n_2}\delta_{it}\bar{p}_i\, t^{\frac{1}{2}} + \sum_{i=1}^{n_2}\bar{p}_i\gamma_{tt}t\right)y_j^{\frac{1}{2}}\left(\sum_{i=1}^{n_2}b_{ik}\bar{p}_i x_k^{\frac{1}{2}} + 2\sum_{i=1}^{n_2}\gamma_{tk}\bar{p}_i t^{\frac{1}{2}}x_k^{\frac{1}{2}}\right) + \sum_{i=1}^{n_2}\gamma_k\bar{p}_i x_k$$

Shephard lemma (1953) allows to deduce the demand $\bar{x}$ in each aggregate input and associated technical coefficients:

$$\bar{c}_i = \frac{\bar{x}_i}{y_j}$$

Using Shephard lemma (1953) in the aggregated price function $\bar{P}$ gives us the demand x_i and the associated technical coefficient $c_{i/\bar{p}}$. Where $c_{i/\bar{p}} = \frac{x_i}{\bar{x}}$ represents the share of demand of good i in the demand to the major sector $\bar{x}$. We then deduce true technical coefficients:

$$c_{ij} = \frac{x_i}{y_j} = \frac{\bar{x}}{y_j} * \frac{x_i}{\bar{x}} = \bar{c}_i * c_{i/\bar{p}}$$

Moreover, for each country, we adopt an international price for all goods imported from the same industry. This choice reduces the flexibility of the cost function but is essential. For each country, the price of an industry i good p_i^c is calculated as the geometric mean of all industries i prices abroad, weighted by $w_{i,t}^{mc}$ the share of imports form the different foreign countries on the total of all imports of good i (**Appendix D**). All estimations are made with international prices $\tilde{p}_{i,t}^m$.

Thus, we deduce the true technical coefficients $c_{ij}^c(P, t, x_k)$ from international technical coefficient$\tilde{c}_{i,j}^m$:

$$c_{ij}^c(P, t, x_k) = \tilde{c}_{i,j}^m(\tilde{P}^m, t, x_k) * w_{i,t}^{mc} * \frac{\tilde{p}_{i,t}^m}{p_i^c}$$

3.3. Cost increase analysis

We decided to apply 6 scenarii using different levels of tax or considering different countries setting a tax. Results of each scenario can then be compared with results obtained with a business as usual scenario in order to assess the effect of the tax.

Concerning the level of the tax, we choose the two extremities of the range that permits to achieve the goals of the Paris agreement, *i.e.* a carbon price between 40\$ and 80\$/tCO_2.

[9] The estimation procedure is described in **Appendix F.**

[10] We use *c* to denote technical coefficients in physical term whereas *a* is used to design monetary coefficients as presented in Miller and Blair (2009).

Concerning the countries supporting the tax, we choose first to apply the tax in European countries because the European Commission debate the idea to add a carbon tax to the existing EU ETS. Six countries (France, Germany, Italy, Netherlands, Poland and Spain) are submitted to the tax but not UK[11] as it is no longer part of the European Union. This scenario put the emphasis on the debate of the recycling of the tax. Although recycling of the tax is not studied here, identifying which national sectors would be the most affected by the tax would be very helpful during political negotiations on the subject.

The two remaining scenarios consist to apply the carbon on France or Germany only. Undertaking these scenarios has many issues. First, as adopting a European carbon tax currently seems complicated from a political point of view, many European countries are (aims at) developing their own taxation of carbon. Whereas a unilateral tax reduces competitiveness of a country, it also facilitates the setup of the tax in order to limit the negative effects on the economy. Knowledge of national and international impacts of the tax is a key issue to preserve national competitiveness in this period when majority of European countries are losing market shares since the 2000's. Second, a comparison of the European scenario versus national scenarii allows to distinguish, for France or Germany, the share of national incoming cost increase in the international one. Third, we can analyze the impact of the tax on non-European partners, that could be of a strong magnitude in future international negotiations.

4. Results

4.1. European cost competitiveness after a carbon tax

The input-output analysis developed in this study can be used to assess which industries in Europe would bear the largest loss of competitiveness. To this end we analyze the variation of unit costs after the tax.

4.1.1. With a tax of 40\$/tCO$_2$

[11] Since UK is no longer part of the UE, it seems more relevant to remove it from taxed countries.

Country	Agriculture	Energy	Construction	Manufacturing	Market services	Non-market services
France	**0.49%**	**1.27%**	**0.30%**	**0.80%**	**0.30%**	**0.19%**
	46.0	*59.0*	*50.9*	*76.7*	*77.1*	*57.9*
Germany	**1.21%**	**2.80%**	**1.35%**	**1.30%**	**0.96%**	**0.70%**
	52.1	*70.3*	*61.4*	*74.4*	*64.2*	*69.2*
Italy	**0.77%**	**3.36%**	**0.88%**	**1.22%**	**0.59%**	**0.51%**
	42.8	*58.0*	*38.2*	*54.6*	*66.6*	*85.1*
Netherland	**0.93%**	**2.51%**	**0.64%**	**0.97%**	**0.85%**	**0.53%**
	11.2	*37.5*	*69.3*	*34.7*	*58.5*	*42.3*
Poland	**1.15%**	**3.80%**	**1.71%**	**2.20%**	**1.69%**	**0.98%**
	21.8	*39.4*	*34.7*	*43.1*	*47.8*	*20.7*
Spain	**1.10%**	**3.63%**	**1.10%**	**1.38%**	**0.80%**	**0.56%**
	35.5	*51.4*	*51.1*	*89.6*	*61.1*	*70.1*

(asymptotic t-ratios in italic)

Table 1. Effects of a 40$/t$CO_2$ European carbon tax

This section summarizes results of a 40$/t$CO_2$ carbon tax applied on the emissions of European industries. While the model regroups European and non-European countries, as the tax is set up only on European countries, the focus is made in this section on the variation of unit cost of production among all sectors in these countries (**Table 1.**).

Poland is the only country that seems to be really suffering from the tax. In Poland, increase in unit costs are for each industry at least two times more important than this increase in other countries. Excepting for the *Energy* sector, unit costs' increases are limited to 2.2%. This result follows the conclusion of Bordigoni *et al.* (2012) who find that Eastern Europe countries would be the most impacted by a carbon tax. This is not a surprise as Poland is strongly dependent on coal.

Unsurprisingly, the *Energy* sector is, in every country, the most impacted sector while the *Non-market services* sector is the less impacted one. European manufacturing is the second most impacted sector. Though, these sectors are strongly spared by the tax as, with the exception of Poland, the increase in unit costs never exceed 1.4%. These results are reassuring regarding the capacity of European manufacturing's competitiveness to adapt to a carbon tax.

France industries are clearly the less impacted in every case. Contrary to Germany, France benefits from its electrical mix based on nuclear energy that limits CO_2 emissions. Nevertheless, the lower increase in unit costs in France than in Germany doesn't seem enough to fill the gap of competitivity between these two countries.

We conclude that a tax of 40$/t$CO_2$ has a relatively small impact on unit costs of production in the majority of European countries. This level of tax permits to respect the Paris Agreement while preserving industrial competitiveness.

4.1.2. With a tax of 80$/t$CO_2$

A higher level of carbon tax increases incentives to reduce carbon emissions then increases the probability to reach the objectives of Paris Agreement. We have first to notice that a Leontief cost function is non-linear in prices, which explains that variations don't follow exactly proportionality rules (Table 2.).

Country	Agriculture	Energy	Construction	Manufacturing	Market services	Non-market services
France	**0.98%**	**2.52%**	**0.60%**	**1.59%**	**0.59%**	**0.37%**
	45.9	*59.0*	*50.9*	*77.0*	*77.1*	*57.8*
Germany	**2.37%**	**5.48%**	**2.65%**	**2.55%**	**1.88%**	**1.38%**
	52.2	*69.6*	*61.2*	*74.3*	*63.2*	*68.9*
Italy	**1.51%**	**6.54%**	**1.74%**	**2.41%**	**1.17%**	**1.00%**
	42.9	*57.9*	*38.2*	*54.9*	*66.7*	*85.1*
Netherland	**1.89%**	**5.27%**	**1.30%**	**1.97%**	**1.73%**	**1.09%**
	11.3	*37.8*	*69.5*	*34.9*	*58.6*	*41.8*
Poland	**2.37%**	**7.74%**	**3.54%**	**4.44%**	**3.51%**	**2.27%**
	22.0	*39.1*	*35.2*	*43.6*	*48.1*	*19.9*
Spain	**2.17%**	**7.04%**	**2.16%**	**2.71%**	**1.57%**	**1.10%**
	35.7	*51.0*	*51.1*	*90.4*	*60.9*	*70.0*

(asymptotic t-ratios in italic)

Table 2. Effects of an 80$/t$CO_2$ European carbon tax

The *Energy* sector suffers from a strong increase of unit costs in each European country (with the exception of France) with increases from 5.5% to 8%. Other non-services sectors begin to feel the effect of the tax with increases of their units cost by 1.5 to 4.5% in each country. *Manufacturing* sector is the most impacted and its competitiveness would be strongly penalized as it is already on the decline. Once again, Poland is highly impacted and France is protected due to its non-emitting nuclear power plants. These differences of impact between sectors, and even mostly between countries, put forward the necessity to smartly redistribute the products of the tax. This aspect of the tax is often forgotten whereas it is a critical point to the success of a common taxation. Besides, after Poland it is Spain that reduces the most its cost competitiveness. Spain has been one the most impacted European country during the 2010's crisis. A stronger loss of competitiveness compared to other European partners seems to be difficult to accept without any redistribution of the earnings of the tax.

These increases in unit costs in European countries have no significant effects on their international's partners.

4.2. Competitiveness effect on non-European countries

Effects of a European carbon tax spread among non-European countries through intermediate consumption.

We can see that the spread of an 80$/t$CO_2$ European carbon tax has only few impacts on competitiveness among European partners (**Table 3**.) [12].

More than 75% of trade of European countries is with other European countries. This particularity limits the diffusion of the tax effects outside Europe and does not penalize non-European countries. We choose to consider UK like a non-European country in this study. Since Brexit, UK is no longer part of European Union but still has the particularity to have strong commercial relationships with European countries compared to other non-European countries, at least under the current trade agreements. This particularity enables a better understanding of the international diffusion of the tax. Indeed, we can notice that UK, and to a less extent Russia or Turkey, are the most impacted countries by the tax. Geographical proximity looks highly correlated with the diffusion of the tax though the impact remains very weak. Cost increases' in UK are around 0.2% in all sectors. It is much less than in taxed countries (from 2 to 6 times lower than France) but much more than in other countries (near 6 times more than USA in every sector).

[12] We do not present results with the lower tax level because they are of too small magnitude.

Country		Agriculture	Energy	Construction	Manufacturing	Market services	Non-market services
Australia		**0.06%**	**0.05%**	**0.07%**	**0.08%**	**0.04%**	**0.03%**
		15.7	*9.4*	*15.1*	*10.2*	*58.9*	*76.9*
Brazil		**0.04%**	**0.10%**	**0.04%**	**0.06%**	**0.04%**	**0.04%**
		18.1	*37.4*	*17.1*	*26.3*	*37.6*	*43.3*
Canada		**0.11%**	**0.20%**	**0.13%**	**0.11%**	**0.07%**	**0.06%**
		18.8	*8.6*	*16.8*	*7.9*	*60.8*	*86.8*
China		**0.03%**	**0.05%**	**0.08%**	**0.09%**	**0.05%**	**0.04%**
		63.4	*40.7*	*1.3*	*40.1*	*39.2*	*42.7*
United Kingdom		**0.23%**	**0.40%**	**0.34%**	**0.24%**	**0.20%**	**0.16%**
		49.5	*38.5*	*81.0*	*73.6*	*71.1*	*96.7*
India		**0.03%**	**0.07%**	**0.07%**	**0.10%**	**0.05%**	**0.01%**
		29.5	*43.2*	*1.8*	*44.7*	*41.2*	*15.1*
Japan		**0.03%**	**0.02%**	**0.03%**	**0.04%**	**0.02%**	**0.02%**
		19.6	*13.8*	*3.7*	*2.8*	*61.5*	*65.9*
Korea		**0.03%**	**0.13%**	**0.06%**	**0.08%**	**0.05%**	**0.04%**
		56.7	*23.2*	*5.9*	*3.7*	*54.9*	*56.5*
Mexico		**0.06%**	**0.17%**	**0.08%**	**0.09%**	**0.05%**	**0.04%**
		23.5	*38.6*	*24.0*	*32.3*	*28.8*	*30.9*
Russia		**0.15%**	**0.11%**	**0.15%**	**0.22%**	**0.08%**	**0.13%**
		43.3	*22.0*	*29.0*	*24.2*	*37.7*	*7.2*
Turkey		**0.04%**	**0.16%**	**0.06%**	**0.20%**	**0.06%**	**0.08%**
		10.8	*41.3*	*26.8*	*45.0*	*39.5*	*20.4*
USA		**0.06%**	**0.07%**	**0.06%**	**0.05%**	**0.03%**	**0.03%**
		14.8	*9.3*	*14.4*	*8.1*	*55.5*	*81.8*

(asymptotic t-ratios in italic)

Table 3. Effects of an 80$/t$CO_2$ European carbon tax on non-European partners

4.3. Comparative analysis of carbon tax impacts on carbon emitting sectors

In **Fig. 2.** we compare the share of CO_2 emission by sector in each European country with the share of unit cost increase by sector in those countries. With perfect proportionality between levels of emissions and of costs, a sector emitting 50% of carbon emissions of a country would concentrate 50% of the increase of unit costs. In this study, input substitution allows us to analyze the diffusion of the tax in intermediate consumption. Some sectors are more exposed than others to the embodied carbon tax. Because their share of carbon emissions is very small, we regroup *Non-market services, Construction and Agriculture* in an aggregated sector named *Others*. We first note that whatever the level of the carbon tax, the share of increase in unit costs is hardly the same in every sector.

Regarding the results we see that in every country, the share of carbon emissions from *Others* sector is less than 10%. It implies that the direct impact of the carbon tax on costs should be less than 10% with perfect proportionality. Nevertheless, the share of the increase in unit costs is between 20% and 45% in every country. That means that the indirect effect of the tax is stronger in this sector. The carbon tax embodied in *Others* sector's inputs lead to a higher increase of costs than in other sectors. Finally, the *Others* sector is the most penalized by the tax in every country regarding to their level of emissions. This is more pronounced in Germany but even more especially in the UK. The increase in unit costs is similar in the *Others* sector and in *Energy* in UK whereas around 50% of total carbon emission are coming from *Energy*. With a more in-depth view we remark that it is the *Construction* sector which concentrates the majority of the indirect impact of the tax. A *contrario*, the *Manufacturing* and *Market services* sectors are less impacted by the indirect effect of the tax. It leads to a lower increase in unit costs compared to their level of carbon emissions.

These differences are explainable by the nature of intermediate consumption in each sector. The *Others* sector's intermediate consumption may be composed in majority of inputs coming from the more taxed sectors. The proportion of highly taxed inputs is superior in this sector than in *Manufacturing* or *Market services*, it explains that *Others* sector is the most impacted by the diffusion of the tax.

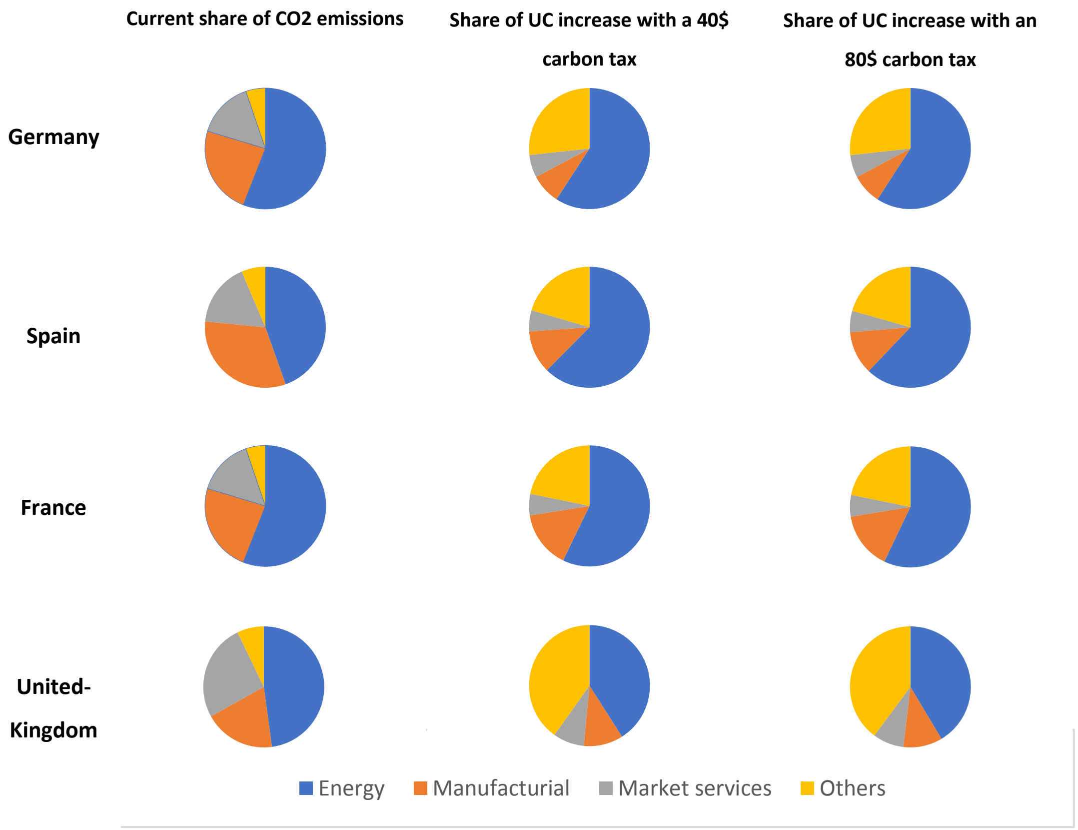


Fig. 2. Comparison of share of emissions and share of increase in unit costs by country

4.4. Impact of a unilateral carbon tax

The difficulties to find an international agreement on carbon taxation lead many countries to make their own taxation in order to achieve the objectives of the Paris agreement. In this section the focus is made on the difficulties encountered by European countries to adopt a common tax on carbon emissions. The failure of negotiations led some European countries to adopt their own taxation device. The same procedure than in the previous subsection is conducted for a unilateral taxation in France or in Germany. The major point of this section is to analyze the sustainability of a unilateral carbon tax in terms of cost competitiveness, **Tab.4.** reports the increase in unit costs for each case[13].

[13] We only keep the 80$/tCO2 carbon tax in this section.

	Agriculture		Energy		Construction		Manufacturing		Market services		Non-market services	
Pays	***French tax***	***German tax***	***French tax***	***German tax***	***French tax***	***German tax***	***French tax***	***German tax***	***French tax***	***German tax***	***French tax***	***German tax***
China	**0.00%**	**0.02%**	**0.00%**	**0.02%**	**0.01%**	**0.04%**	**0.01%**	**0.04%**	**0.00%**	**0.02%**	**0.00%**	**0.02%**
	63.4	*63.4*	*40.7*	*40.7*	*1.3*	*1.3*	*40.1*	*40.1*	*39.2*	*39.2*	*42.6*	*42.6*
France	**0.76%**	**0.10%**	**2.14%**	**0.18%**	**0.48%**	**0.05%**	**1.05%**	**0.24%**	**0.50%**	**0.04%**	**0.30%**	**0.03%**
	45.9	*46.1*	*59.0*	*59.1*	*50.9*	*50.9*	*76.8*	*76.5*	*77.1*	*77.2*	*57.9*	*58.1*
Germany	**0.07%**	**1.88%**	**0.09%**	**4.60%**	**0.06%**	**2.15%**	**0.09%**	**1.97%**	**0.06%**	**1.48%**	**0.05%**	**1.06%**
	52.0	*52.1*	*70.8*	*69.8*	*61.6*	*61.3*	*74.4*	*74.2*	*64.9*	*63.5*	*69.6*	*69.0*
Italy	**0.10%**	**0.16%**	**0.49%**	**0.56%**	**0.10%**	**0.20%**	**0.14%**	**0.28%**	**0.06%**	**0.12%**	**0.06%**	**0.11%**
	42.6	*42.6*	*57.9*	*57.9*	*38.3*	*38.3*	*54.3*	*54.3*	*66.5*	*66.5*	*85.0*	*85.0*
Netherland	**0.09%**	**0.19%**	**0.12%**	**0.32%**	**0.06%**	**0.17%**	**0.08%**	**0.21%**	**0.10%**	**0.20%**	**0.05%**	**0.12%**
	11.1	*11.1*	*37.2*	*37.2*	*69.1*	*69.2*	*34.6*	*34.6*	*58.3*	*58.3*	*42.7*	*42.6*
Poland	**0.03%**	**0.20%**	**0.03%**	**0.21%**	**0.03%**	**0.22%**	**0.07%**	**0.43%**	**0.03%**	**0.22%**	**0.02%**	**0.15%**
	21.6	*21.7*	*39.5*	*39.5*	*34.2*	*34.3*	*42.6*	*42.6*	*47.5*	*47.6*	*21.4*	*21.4*
Russia	**0.01%**	**0.06%**	**0.01%**	**0.05%**	**0.01%**	**0.07%**	**0.02%**	**0.10%**	**0.01%**	**0.03%**	**0.01%**	**0.05%**
	43.3	*43.3*	*22.0*	*22.0*	*29.0*	*29.0*	*24.2*	*24.2*	*37.6*	*37.7*	*7.2*	*7.2*
Spain	**0.07%**	**0.12%**	**0.08%**	**0.19%**	**0.10%**	**0.17%**	**0.12%**	**0.20%**	**0.04%**	**0.07%**	**0.03%**	**0.06%**
	35.4	*35.4*	*51.5*	*51.5*	*51.0*	*51.0*	*88.8*	*88.9*	*61.2*	*61.2*	*70.0*	*70.0*
Turkey	**0.00%**	**0.01%**	**0.02%**	**0.04%**	**0.01%**	**0.02%**	**0.02%**	**0.07%**	**0.01%**	**0.02%**	**0.01%**	**0.02%**
	10.8	*10.8*	*41.3*	*41.3*	*26.8*	*26.8*	*44.9*	*44.9*	*39.5*	*39.5*	*20.3*	*20.3*
United Kingdom	**0.03%**	**0.06%**	**0.04%**	**0.08%**	**0.05%**	**0.12%**	**0.03%**	**0.06%**	**0.03%**	**0.05%**	**0.02%**	**0.05%**
	49.5	*49.5*	*38.6*	*38.6*	*81.0*	*81.0*	*73.5*	*73.5*	*71.0*	*71.0*	*96.8*	*96.8*
USA	**0.01%**	**0.02%**	**0.01%**	**0.02%**	**0.01%**	**0.03%**	**0.01%**	**0.02%**	**0.00%**	**0.01%**	**0.01%**	**0.01%**
	14.8	*14.8*	*9.3*	*9.3*	*14.4*	*14.4*	*8.1*	*8.1*	*55.5*	*55.5*	*81.8*	*81.8*

(asymptotic t-ratios in italic)

Tab. 4. Impacts of a unilateral carbon tax of 80\$/tCO_2 on unit costs.

Germany is more impacted by a unilateral 80\$/tCO_2 carbon tax than France, which is not surprising regarding their level of emissions; German industries total emissions being 2.5 times that of France. Apart the *Energy* sector, French sectors escape the impact of the tax. The increase of unit costs doesn't exceed 1% and lets us imagine that French competitiveness would not be damaged by the tax. France's most damaged partners are Spain and Italy. Nevertheless, with an average of 0.1% increase of their unit costs, the diffusion of the tax doesn't damage their competitivity.

The important amount of carbon emission in Germany implies a more important impact of the tax on unit costs for this country. Contrary to France where the increase of unit costs does not exceed 1% (except for the *Energy* sector), Germany's unit costs are increasing on average by 2% (and 4.6% in the *Energy* sector). The *Manufacturing* sector which is key in the German economy, is damaged by a 2% increase in unit costs while its competitors are exempt of the diffusion of the tax. It is Poland that suffers the most of the German tax. German manufacturing goods have a large share in Poland's imports. As the German *Manufacturing* sector emits a lot of carbon, the German carbon tax increases the prices of Poland's intermediate inputs. In general, all sectors are more impacted by the German tax than the French tax but the increase remains low. Because German unit costs are already high, this increase could damage its competitiveness. The ability of German industries to improve their non-cost competitiveness would be a key issue to reduce the impact of the tax.

5. Implications of the implementation of a carbon tax

The debate on the implementation of a carbon tax has two main issues. First issue is about the price of carbon permitting to achieve the goals of the Paris Agreement. Estimations of a price between 40\$ and 80\$/tCO_2 are generally used. Second issue is about who applies the tax. A global agreement would certainly be the more equitable but does not seem feasible on the short run. That is why some countries or group of countries decided to price carbon on their own. It has moved the debate from who is paying the tax to the potential implementation of a border adjustment to preserve competitiveness.

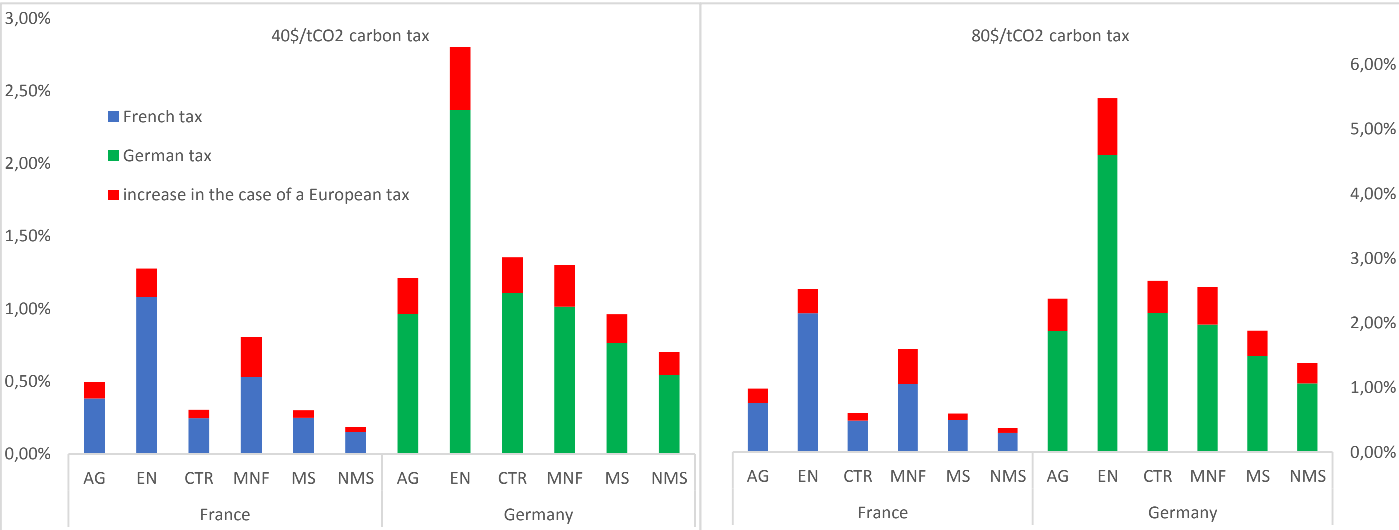
5.1. National versus international impact of the carbon tax

It is useful to distinguish to what extend a European carbon tax would increase unit costs more than a unilateral national tax. Indeed, the high level of trade between European countries contribute to spread the tax through intermediate consumption. To go further, a tax in a country A impacts units cost in a country B through intermediate consumption; The increase in unit costs in country B is reported in its exports toward other countries. Finally, the initial tax has indirect impacts all along the international supply chain. We analyze here these international effects, by comparing the increase in unit costs (**Tab.5.**) in France and Germany with the two scenarios of the European carbon tax.

We note that in every country, each sector is differently impacted by the European tax. French sectors look less impacted by the European tax than German ones, excepted the *Manufacturing* sector. This lower effect of the European tax in France can be explained by many factors. A lower share of "made in Europe" imports of intermediate consumption could first explain the strongest resistance of France. French sectors import more from extra-European countries that do not suffer the impact of the tax. Another explanation stands in the nature of French imports that could be less carbon intensive than German imports. Indeed, French *Energy* sector, mostly based on nuclear energy, is less emitting than in German's. Moreover, France imports few electricity from the European's electricity market contrary to Germany what make France more independent from the level of CO_2 embodied in European electricity.

	40$/tCO2 carbon tax		80$/tCO2 carbon tax	
	France	Germany	France	Germany
Agriculture	0.11%	0.25%	0.22%	0.50%
Energy	0.19%	0.43%	0.38%	0.88%
Construction	0.06%	0.25%	0.12%	0.50%
Manufacturing	0.28%	0.29%	0.54%	0.58%
Market-services	0.05%	0.20%	0.10%	0.40%
Non-market services	0.03%	0.16%	0.07%	0.32%

Tab. 5. *Additional* increase in unit costs due to a European taxation



AG : Agriculture ; EN : Energy ; CTR : Construction ; MNF : Manufacturing ; MS : Market services ; NMS : Non-market Services

Fig. 3. Increase in unit costs. National versus European tax.

We can first note that if the level of the tax doubles, all unit costs are multiplied by a coefficient in the range [1.96; 2.05][14]. Managing the level of the tax has few effects on the differences of impact between countries. We can also notice that except in the *Manufacturing* sector, the European carbon tax increases the loss of competitiveness of German sectors compared to French sectors (**Fig. 3**.). German sectors are then more exposed to the European carbon tax than France sectors because of three reasons:

- the direct effect, they are more CO_2 emitting;

- the national indirect effect, their national partners are more CO_2 emitting;

[14] This coefficient reaches 2.31 in Poland.

- the international indirect effect, their European partners are more CO_2 emitting.

These cases show that a European carbon tax tends to increase unit costs by 20% more than a national carbon tax. This increase is mainly due to the quantity of carbon embodied in the international supply chain of intermediate goods. The case of the German sectors which are more impacted by the European tax than French sectors is the perfect illustration of the difficulties that await European political leaders to make all countries accept a common taxation. The temptation for each country to make its own national carbon tax offers the opportunity to act faster than at the European level. Indeed, countries who would be the most impacted by the tax, like Poland, want to limit the adoption of such a tax that would penalize them more than others. Moreover, a national carbon tax is built under the consideration of the specificities of the national economy. Characteristics of the tax become a national political choice.

Nevertheless, promoting a national carbon tax instead of a European carbon tax remains objectionable for many reasons. First it increases the risk of free riding inside the EU. Moreover, it will increase carbon leakage, inside EU itself, toward free riders. This makes all national contributions useless by simply relocating GES emissions in other European countries. Then, it would increase differences of environmental performances among countries what risks to reduce the ability of countries to build a common agreement on the mid/long run. Finally, it increases the willingness of virtuous countries to adopt a boarder tax against free riders inside EU itself.

5.2. Implications for the implementation of a European border adjustment

Increases in unit costs due to a carbon tax are limited in most sectors but accentuate the loss of competitiveness of European industries. Among European countries and sectors, those that trade massively with non-EU countries would benefit from imported inputs that have not been taxed. It will encourage carbon leakage and increase importations from non-taxed countries what could strongly limit the expected impact of the tax.

To preserve UE from these non-expected impacts and from the loss of competitiveness, a border adjustment project has taken a central place in the European Commission. The major issue of the debate on the border adjustment relies on the ability to preserve the competitiveness of industries that export outside the EU.

If the border tax is only calculated on the basis of the final producing sector, it will not take into account CO_2 embodied into imports. This non-taxed indirect CO_2 will still threaten the European industry competitiveness. Moreover, the border adjustment will increase the price of imported intermediate goods in Europe and accentuate the increase of European prices. At a lower extend, it still encourages carbon leakage.

A carbon tax calculated on total carbon embodied increases the loss of competitiveness of European industries on international markets. Indeed, European exports are triply penalized compared to non-EU countries: The carbon tax directly increases the global cost of production while the border adjustment increases the cost of intermediate goods. Moreover, non-EU country could also reply to the border tax with other taxes on EU exports what would triply penalize European industries.

This carbon tax has also strong benefits for European countries. First it discourages carbon leakage from Europe. Then it preserves competitiveness of European industries on the local market because European industries are more virtuous than non-EU one[15]. At the same level of taxation (EU carbon tax versus border adjustment), inside Europe, European industries are less penalized than their non-EU competitors. It protects low carbon industries on their local market and contribute to the emergence of new ones. Finally, this European protection would encourage more emitting industries and countries to reduce their emissions.

All these points justify the necessity to make the adoption a European carbon tax concomitant to the set-up of a border adjustment.

6. Conclusion

GHG emissions are currently the focus of key debates in countries, within the European Union or at the international level. An international carbon tax is one of the major economic instruments required to fight against GHG emissions but it has a negative effect on competitiveness if not adopted by all countries at the same time. Competitiveness is one of the major concerns for policy makers in Europe. It explains that a European carbon tax is a real threat for European industries which already suffer from international competitiveness.

This study is relevant to emphasize the difficulties to build a European carbon taxation device taking into account national specificities. Results from the input-output analysis are used first to simulate the distributional impact of a 40\$/tCo_2 and an 80\$/tCO_2 European carbon tax on all European and non-European sectors. Results show that a European carbon tax has different impacts among countries (Poland is the most impacted) and among sectors (*Energy* and *Manufacturing*). Although a 40\$/tCo_2 carbon tax seems sustainable for the majority of sectors, an 80\$/tCo_2 tends to impact more severely competitiveness. Heterogeneity among European countries leads to a potential heterogeneity of unit costs' increases among European countries and sectors. If there is no border tax, countries that trade massively with non-EU countries benefit from imported inputs goods that have not been taxed. Among European countries, sectors importing from partners less impacted by the tax are improving their competitiveness compared to their European competitors. These problems of

[15] https://resources.ecovadis.com/fr/accueil/comparatif-de-la-performance-rse-des-entreprises-francaises-avec-celle-des-pays-de-l-ocde-et-des-brics-2 (in French)

heterogeneity have limited the adoption of a European carbon tax so far and countries have to act by making their own level of taxation. Building a national carbon tax allows each country to adapt the specificity of the tax to its national competitivity. Indeed, we have shown that the effects of the tax are different among national sectors. Recycling the tax on most impacted industries could attenuate the loss of competitiveness. Finally, the spread of the tax through intermediate goods is weak in the case of a national carbon tax, even if the tax is of 80$/t$Co_2$. That means that a country taxing unilaterally its industries would not deteriorate its partners' competitiveness. Then, adopting the tax at the European level accentuate by more than 20% the increase in unit costs compared to the same level of tax at the national level. In some sectors (French *Manufacturing* for example) this accentuation reaches 50%. The high level of trade among European industries tends to accentuate the indirect effect of the tax by increasing the costs of intermediate goods all along the supply chain.

Finally, the indirect effect of the tax is stronger in C*onstruction* or in *Agriculture* than is other sectors. We have shown that despites carbon emissions are very low in these sectors, they are relatively more impacted by the tax than others. It means that *Construction* and *Agriculture* are the most exposed to the tax through intermediate consumption. All these points are crucial to take into account for the design and negotiations of national, European or international environmental policies.

7. Appendix

Appendix A. Data sources

Input-output tables data are based on World Input-Output Database (WIOD – Timmer et al., 2015), a project funded by the European Commission. The database is a set of harmonized supply and use tables, alongside with data on international trade in goods and services. These two sets of data have been integrated into sets of intercountry (world) input-output tables. Extensive satellite accounts with environmental and socio-economic indicators (WIOD SEA) are also included. Input-output tables are covering 40 countries (Table A1.) and a model for the rest of the world for the period 1995-2011. Input-output data from EU countries are provided annually while those from non-EU countries are provided every 5 years. To construct annual database for these countries, WIOD uses a RAS method with data on growth, inflation and other economic variables.

We decided to keep 18 over the 40 countries of the database to make our model. These countries represent around 80% (82% in 1995, 79% in 2007) of world GDP. Regarding at the heterogeneity of all other countries, we decided to not create a 19th country regrouping the rest of the world because it is not possible to model a single comportment for these countries altogether.

Table A1

List of countries in WIOD Database and list of countries in our study

Euro zone		Europe non-EZ	TAFTA	Dvpd Asia	Row
Austria	Belgium	Bulgaria	**Canada**	**China**	**Australia**
Cyprus	Estionia	Czech Republic	**Mexico**	**Japan**	**Brazil**
Finland	**France**	Denmark	**United States**	**Korea (South)**	**India**
Germany	Greece	Hungary		Taiwan	Indonesia
Ireland	**Italy**	Latvia			**Russia**
Luxembourg	Malta	Lithuania			**Turkey**
Netherlands	**Poland**	Sweden			
Portugal	Romania	**United Kingdom**			
Slovak Republic	Slovenia				
Spain					

<u>Legend:</u> Data in bold are those that have been selected within our database. We keep major countries from the database to keep homogeneity in the panel estimation. All 18 selected countries represent around 80% of world total GDP. All 7 selected European countries represent 80% of European GDP.

Data for the 34[16] industries are classified according to the International Standard Industrial Classification revision 3 (ISIC Rev. 3). All values are given in a common currency, current Dollar. Socio-economic indicators contain data on capital, labour or input prices indexes. Data on capital are not available for some countries after 2007. We then decided to use data for the period 1995-2007.

[16] There normally are 35 industries. But there are no data for *Households with employed persons* (P) in each database then we left it of our study.

To improve the quality of our estimation results, we aggregated the 35 industries into 6 major sectors (Table A2). Some price index data are missing in *Government* or *Motor vehicle & fuel trade.* We replaced this data by a weighted mean of all other *Non-market services* industries for *Government* and by *Wholesale trade* and *Retail Trade* for *Motor vehicle & fuel trade.*

Table A2

Hierarchy of industries as part of major sectors.

Major sector	Agriculture		Energy		Construction		Manufacturing		Market services		Non-market services	
	Industry name	*Industry code*	*Industry name*	*Industry code*	*Industry name*	*Industry code*	*Industry name*	*Industry code*	*Industry name*	*Industry code*	*Industry name*	*Industry code*
Industries	Agriculture, forestry & fishing	AtB	Mining & quarying	C	Construction	F	Food, beverage & tobacca	15t16	Motor vehicle & fuel trade	50	Real estate	70
			Coke & refined petroleum	23			Textile products	17t18	Wholesale trade	51	Government	L
			Utiliteis	E			Leather & footwear	19	Retail trade	52	Education	M
							Wood products	20	Hotels & restaurants	H	Health	N
							Paper, printing & publishing	21t22	Land transport	60		
							Chemical products	24	Water transport	61		
							Rubber & plastics	25	Air transport	62		
							Non-metallic mineral products	26	Transport services	63		
							Basic & fabricated metal	27t28	Post & telecommunications	64		
							Machinery	29	Financial services	J		
							Electrical & optical equipment	30t33	Business services	71t74		
							Transport Equipment	34t35	Other services	O		
							Other manufacturing	36t37				

Appendix B. Input-output price model in physical units

Input-output models (Leontief, 1936) can be represented in two different forms. The more common is to fill tables with monetary values. A less known approach is to fill tables with physical units. These tables are more complicated to build but present the advantage to perfectly match with the entire microeconomic theory. Indeed, the later distinguishes prices and quantities which is not the case with tables in monetary values. The physical approach thus relies on uses prices instead of price index. This difference is crucial if one wants to make an international study where PPP have to be taken into account (what is not possible with price index).

Input-output models (Leontief, 1936) can also be studied in two different forms. The more common form is oriented towards the study of shock on the Demand side: How production will react to a shock in final demand? The other form, that will be used here, is oriented towards the study of a shock on the Supply side: How prices (or price index) will react to a shock in value added costs[17]?

An analysis of the input-output price model in physical units aims to calculate prices resulting from a shock in value added. Following Miller and Blair (2009) notation, we denote C the matrix of technical coefficient in physical units, v_c the technical coefficient of value added. We can calculate input prices corresponding to these levels with the equation:

$$p = (I - C')^{-1} v_c$$

Appendix C. Choice of the implicit cost function in input-output models.

We have seen in Appendix B. that there exist four different ways to use input-output models, based on 2 differences:

[17] Labour price in general.

- the quantity or demand side model (prices are fixed, quantities vary) versus the price or supply side model (quantities are fixed, price vary)

- monetary units (technical coefficients in value are fixed ($a_{ij} = \frac{z_{ij}}{C_j}$)[18]) versus physical units (technical coefficients in physical units ($c_{ij} = \frac{x_{ij}}{y_j}$)[19] are fixed).

Analysis of an implicit Cobb-Douglas cost function:

$$\ln C_j\left(x_j, p_i\right) = b_o + \sum_{i=1}^{n} a_{ij} \ln(p_i)$$

Using Shephard's Lemma[20] leads to fixed technical coefficient:

$$a_{ij}^{*} = \frac{x_{ij} * p_i}{y_j * p_j} \quad \left(or \quad a_{ij}^{*} = \frac{z_{ij}}{C_j} \right)$$

It matches with the model in monetary units. If prices are exogeneous then $\frac{s_{ij}}{q_j}$ is fixed too; it also matches with the supply side model in physical units.

Analyze of an implicit Leontief cost function:

$$C_j\left(y_j, p_i\right) = y_j \sum_{i=1}^{n} a_{ij} p_i$$

Using Shephard's Lemma leads to:

$$c_{ij}^{*} = \frac{x_{ij}}{y_j}$$

It matches with the model in physical units. If prices are fixed, then we have:

$$a_{ij} = c_{ij}^{*} * \frac{p_i}{p_j} = a_{ij}^{*}$$

The Leontief cost function also matches with the model in monetary units if prices are exogeneous.

All possibilities are reported in Table E1.

Table E1.

Matching of cost function with input-output analysis

	Quantity Model	Price Model
Monetary units	Cobb-Doublas Leontief	Cobb-Douglas
Physical units	Cobb-Doublas Leontief	Leontief

Choice of the implicit cost function

We have seen that the best model to use in this study is the supply-side model in physical units. This model matches with an implicit Leontief cost function.

The Leontief cost function is a particular case of the Generalized Leontief cost function with a constraint on inputs substitution ($a_{ij} = 0 \; if \; i \neq j$):

$$C(y, p) = y \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} p_i^{\frac{1}{2}} p_j^{\frac{1}{2}}$$

Removing the constraint of non-substitution of inputs consists in adopting a Generalized cost function. It permits to go through the limits of the input-output analysis by endogenizing technical coefficients.

Appendix D. Generalized Leontief cost function with quasi-fixed capital and quality of estimation

The choice of an implicit flexible cost function for each industry, consistent with Leontief input-output modelling, leads us to choose between a Translog form (Christensen et al. 1971) and a Generalized Leontief form (Diewert, 1973). While the Translog form is the most famous in the literature, we chose to use the Generalized Leontief form that better matches with the Leontief input-output price model. In order to focus our study on the short term, we used a

[18] With z_{ij} the demand of input i in value (monetary units), C_j the total cost of industry j.

[19] With y_j is the production of industry *j* in physical units and x_{ij} is the demand of input *i* in physical units.

[20] Demonstration is proposed in Berndt & Wood (1975) with a Tranlog cost function or in Diewert (1973).

Generalized Leontief cost function with capital as a quasi-fixed input (Morrison, 1988). Accordingly, each industry in our database admits an implicit cost function of the form (Kratena, 2005):

$$G(y,P,x_k) = y\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\alpha_{ij}p_i^{\frac{1}{2}}p_j^{\frac{1}{2}} + \sum_{i=1}^{n}\delta_{it}p_i t^{\frac{1}{2}} + \sum_{i=1}^{n}p_i\gamma_{it}t\right) + y_j^{\frac{1}{2}}\left(\sum_{i=1}^{n}b_{ik}p_i x_k^{\frac{1}{2}} + 2\sum_{i=1}^{n}\gamma_{itk}p_i t^{\frac{1}{2}}x_k^{\frac{1}{2}}\right) + \sum_{i=1}^{n}p_i\gamma_{ik}x_k$$

The cost function in each industry depends on all input prices p_i $(i = 1, \dots, n)$ of our database, but also on crossed prices $(p_i * p_j)$, on time t, on hourly wages[21] and on capital x_k. Because our model encompasses many sectors and many countries, it leads each industry to trade with 6 different industries in 18 different countries. The huge number of coefficients to estimate reduces too much the number of degrees of freedom and severely degrades the quality of our estimation results. Therefore, for each country, we adopt an international price for all goods imported from the same industry in order to preserve the number of degrees of freedom. This choice reduces the flexibility of the cost function but is essential. For each country, the price of an industry *i* good is calculated as the geometric mean of all industries *i* prices abroad, weighted by the share of imports form the different foreign countries on the total of all imports of good *i*. With $\tilde{p}_i^m$ the international price for industry i in a country m and $p_{i,}^c$ the price of an industry *i* in a country c, we have:

$$\tilde{p}_i^m = \prod_{c=1}^{M} p_i^{c^{w_i^{mc}}}$$

where:

$$w_{i,t}^{mc} = \frac{1}{2}\left(\frac{\sum_{j=1}^{N} z_{ij,t}^{mc}}{\sum_{j=1}^{N}\sum_{c=1}^{M} z_{ij,t}^{mc}} + \frac{\sum_{j=1}^{N} z_{ij,t-1}^{mc}}{\sum_{j=1}^{N}\sum_{c=1}^{M} z_{ij,t-1}^{mc}}\right)$$

$z_{ij,t}^{mc}$represents the demand of industry *j* from a country m to the industry i in a country c in a year *t*.

All estimations are made with international prices. We can easily deduce "true" technical coefficients from international technical coefficients calculated by the model:

$$\frac{\partial G_j^m(y_j, \tilde{P}^m, t, x_k)}{\partial p_i^c} = \frac{\partial G_j^m(y_j, \tilde{P}^m, t, x_k)}{\partial \tilde{P}^m} * \frac{\partial \tilde{P}^m}{\partial p_i^c}$$

with:

$$\frac{\partial \tilde{P}^m}{\partial p_i^c} = w_{i,t}^{mc} * \frac{\tilde{p}_{i,t}^m}{p_i^c}$$

Thus, we deduce the true technical coefficients (in physical units):

$$c_{ij}^c(P,t,x_k) = \tilde{c}_{i,j}^m(\tilde{P}^m,t,x_k) * w_{i,t}^{mc} * \frac{\tilde{p}_{i,t}^m}{p_i^c}$$

Appendix E. Industry Price Aggregate

Input prices have been constructed from price indexes of the SEA and Purchasing Power Parities (PPP) of the GGDC Productivity Level Database (Inklaar et Timmer, 2014). This database provides data on relative prices and labor productivity across countries and industries among WIODs. Different levels of PPP are proposed and we chose to use PPP of the 35 industries to aggregate industries' prices in our model into 6 major sectors.

We choose to use a Generalized Leontief Cost function with a quasi-fix input, capital, as the implicit cost function in each sector. We decided to aggregate the prices coming from the 34 industries into prices of 6 sectors to simplify the cost function. We retain the assumption of constant return to scale and under this assumption the unit cost equals the unit price. Thus, the aggregated price function $\bar{P}$ is consistent with a Generalized Leontief cost function (Diewert, 1973) and is a quadratic mean of order *r (*with *r=1):*

$$\bar{P} = \sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}p_i^{\frac{1}{2}}p_j^{\frac{1}{2}}$$

Diewert (1976) shows that there is an *exact*[22] aggregate price index for this functional form:

$$P_1(p^0,p^1;x^0,x^1) = \left(\sum_{i=1}^{n}(p_i^1/p_i^0)^{\frac{1}{2}} M_i^0\right)\left(\sum_{k=1}^{n}(p_k^0/p_k^1)^{-\frac{1}{2}} M_i^1\right)^{-1}$$

[21] We consider labour like an intermediate input in our notations.

[22] *Exact* price indexes reflect changes in the cost function between an initial price vector p_0 and final vector p_1, at constant utility.

Where M_i^j represents the share of good *i* in total cost at period *j*.

This *exact* price index calculates the price variation of the aggregate each year. To construct series of aggregated input prices in each industry for the entire period we start with the PPP of major sectors available in the GGDC database. Then, we apply the *exact* price index using the methodology of chained prices to calculate our series of prices:

$$I_{p_{t+1}} = P_{t+1}(p^{t+1}, p^t, q^{t+1} q^t) * I_{p_t}$$

With these aggregated prices, the cost function finally includes the intermediate prices $\bar{P}$ of the 6 major sectors. For an industry *j*, the cost function becomes:

$$G_j(\bar{P}, y, t, x_k) = y_j \left(\sum_{i=1}^{n_2} \sum_{j=1}^{n_2} \alpha_{ij} \bar{p}_i^{\frac{1}{2}} \bar{p}_j^{\frac{1}{2}} + \sum_{i=1}^{n_2} \delta_{it} \bar{p}_i \, t^{\frac{1}{2}} + \sum_{i=1}^{n_2} \bar{p}_i \gamma_{tt} t \right) y_j^{\frac{1}{2}} \left(\sum_{i=1}^{n_2} b_{ik} \bar{p}_i x_k^{\frac{1}{2}} + 2 \sum_{i=1}^{n_2} \gamma_{tk} \bar{p}_i t^{\frac{1}{2}} x_k^{\frac{1}{2}} \right) + \sum_{i=1}^{n_2} \gamma_k \bar{p}_i x_k$$

Appendix F. Procedure estimation

In general, there are two ways to estimate flexible functions:

- Estimating jointly the cost function and the demand equations (or share equations)
- Estimating share equations alone.

Some authors recommend to estimate only share equations because they contain all the information on perturbations (Berndt, 1991). In our case, Generalized Leontief cost function with quasi-fixed factors proposed by Morrison (1988) presents the particularity to have the same number of coefficients to estimate in both cases. For this reason, a join estimation adds more information to our system of equations and increases its quality.

Estimation is made using the method of Seemingly Unrelated Regression (SUR, Zellner, 1962).

The model is estimated using panel data and the choice as been made that first order coefficients in the share equations vary across countries. We then use national intercept dummy variable in the share equations.

Homogeneity between the same sector in every country is rejected by Hsiao test (1986). This is not surprising because there are huge disparities between countries of our panel. This leads us to pool some group of countries separately.

Group 1: Germany, France, Italy, Spain and UK.

Group 2: Japan, Korea, Canada, Australia and US.

Group 3: Netherland, Poland and Turkey.

Group 4: Brazil, Mexico and Russia.

Group 5: China and India.

Estimation for all these groups are accepted by Hsiao test. We found parameter estimates that are considerably different from one group to another which is consistent with the fact that their socioeconomic conditions are extremely different.

Significance of estimated changes in unit costs are calculated using the delta method[23]. This method permits to calculate the estimated asymptotic covariance matrix and to deduce asymptotic t-values for each estimated unit costs equation.

[23] More information on Green (2011).

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