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European Union Emissions Trading Scheme (EU ETS): Addressing competitiveness and carbon leakage under unilateral climate policy – impact analysis of the implementation of a Border Carbon Adjustment (BCA)

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Abstract

In order to comply with its climate change commitments, the European Commission implemented in 2005 the European Union Emissions Trading Scheme that includes the most greenhouse gases emitting sectors, mostly industrial activities. This mechanism provides an incentive for these sectors to reduce their carbon emissions by investing in cleaner technologies, and sets a cap for total European emissions. Because it consists in a unilateral climate policy, European firms have a competitive disadvantage against foreign competition. Moreover, a part of the mitigation efforts made by the European Union is wiped out by the relocation of production to climate policy-free countries. This phenomenon is known as carbon leakage and is tackled by the European Commission through important subsidies under the form of free allowances.

A potential alternative to these subsidies is a Border Carbon Adjustment that would rebalance the uneven climate costs for imports and/or exports at the European Union borders. The present paper aims at analysing the impact of a Border Carbon Adjustment on sectoral competitiveness, carbon leakage and welfare, using a static Partial Equilibrium model. Better understanding the effects of this climate measure on the market and on the environment will allow to assess its effectiveness.

Overall, it appears that while BCAs are efficient at rebalancing sectoral competitiveness and reducing carbon leakage, their effect is detrimental to European welfare, among others because of the drop in consumption. However, if the European Union wants to reach its greenhouse gases emissions mitigation target of 60% by 2040 compared to its 1990 level, it seems that it should not only base its hopes on technology improvements, but also on consumption reduction.

Table of Contents

List of Figures

Glossary

BAU	Business-As-Usual
BCA	Border Carbon Adjustment
BCA M	Border Carbon Adjustment on Imports
BCA MX	Border Carbon Adjustment on Imports and Exports
CDM	Clean Development Mechanisms
CER	Certified Emission Reduction
CL	Carbon Leakage
CLL	Carbon Leakage List
CLR	Carbon Leakage Rate
CO2eq	CO2 equivalent
COP	Conference Of Parties
CSCF	Cross Sectoral Correction Factor
EC	European Commission
EEA	European Environment Agency
EIT	Economies In Transition
EITE	Energy Intensive Trade Exposed (industries)
ERU	Emission Reduction Unit
ET	Emissions Trading
ETS	Emissions Trading Scheme
EU	European Union
EU ETS	European Union Emissions Trading Scheme
EUA	European Union Allowance (1 tonne of CO2eq)
EUTL	European Union Transaction Log
GHG	GreenHouse Gas
IPCC	International Panel on Climate Change
JI	Joint Implementation
LULUCF	Land Use, Land-Use Change and Forestry (activities)
MS	Market Share
NAP	National Allocation Plan
RMU	Removal Units (for LULUCF)
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

Introduction

Since several decades, climate experts have scientifically demonstrated the responsibility of the human activities for the acceleration of the global warming process, and have warned about its potential catastrophic consequences. Evidences of the climate disturbances such as storms, floods and droughts are becoming more frequent and more violent, not to mention that the Arctic ice pack is melting at an ever increasing pace.

Environment preservation, and more precisely climate change mitigation, is a rising concern for the international community. For example, the climate demonstration called the "Marche pour le climat" took place in Brussels on the 2nd of December 2018 and gathered about 70.000 citizens in order to put pressure on their government to take political actions in favour of environmental preservation.

In 1995, the Kyoto Protocol set the framework for fighting climate change and non-binding national objectives were set by country. In order to comply with its emissions targets, the European Union decided to implement an Emissions Trading Scheme (ETS). It includes industrial sectors representing around 40-45% of total greenhouse gases (GHG) emissions of the EU, and is the world's largest ETS (European Commission, 2015a). In short, the principle is to make industrial sectors pay for the GHG they release in the atmosphere, by putting a price on carbon as well as limiting total emissions within the EU. Carbon pricing may constitute one of the most cost-effective policies to mitigate climate change (Rabe, 2018).

Since its inception in January 2005, the EU ETS has faced some problems that will be discussed in this thesis, among which a competitiveness issue. Because of the unilateral nature of this climate policy, European firms face additional costs while their foreign competitors do not and thus European firms are disadvantaged. Moreover, there is a risk of Carbon Leakage, which is the relocation of the production outside the EU, where no climate policy is established. This implies that the European Union efforts to mitigate climate change are offset by more emissions in the rest of the world.

To solve this issue, it has been proposed to restore trade equity between domestic and foreign firms by implementing a Border Carbon Adjustment (BCA). Some notable personalities have endorsed the idea of a BCA, such as French President Nicolas Sarkozy when he said in 2009 that a border carbon adjustment is the “natural complement” of the EU ETS, and that he would lead this political battle (Discours vie publique, 2009). Besides, Nobel-prize winning economist, Paul Krugman was also favourable, arguing that BCAs are “a matter of levelling the playing field, not protectionism” (New York Times, 2009). More recently, French President Emmanuel Macron advocated the project of a BCA in a talk during his official visit in Belgium in November 2018.

In a nutshell, this thesis provides a computational framework to analyse the impacts of a BCA on the EU ETS. Using a static Partial Equilibrium model, several scenarios are created to better understand the mechanisms at work.

The first chapter is developing the theoretical framework. It explains the background of the EU ETS, how it actually works and its weaknesses. Then, the different aspects of BCAs are examined and key findings of the literature are summarised. This chapter ends with the formulation of hypotheses. The second chapter first presents the model, the methodology and the assumptions made. Next, the results are analysed in light of the hypotheses. Finally, the limitations of the model are discussed and the conclusion is presented.

1 Chapter I: Theory

The purpose of this chapter is to set the theoretical framework of the EU ETS. It will entail its history and evolution, the economics principles on which it is based and its detailed functioning. Moreover, the main weaknesses of the system will be developed, with a focus on competitiveness and carbon leakage. Subsequently, the Border Carbon Adjustment will be presented and examined in details, as it will be at the core of the model in the second chapter of the thesis.

1.1 The European Union Emissions Trading Scheme (EU ETS): history

1.1.1 Rise of climate change concerns

The Intergovernmental Panel on Climate Change (IPCC) is a group of international climate experts created by the United Nations in 1988 as a result of international attention concerning climate change. Its key role is to gather and assess scientific information on the impact of carbon emissions from human activities (Chesney, Gheyssens & Taschini, 2013). In 1990, the IPCC published its first report in which it confirmed scientifically that the anthropogenic emissions of greenhouse gases (GHG) significantly increase the concentration of GHG in the atmosphere. It also confirmed that this higher concentration is very likely to be responsible for an additional warming of the Earth's surface, inducing harmful consequences for the planet (IPCC, 2018).

The IPCC played a central role in creating an international awareness of climate change, and initiated the creation of the United Nations Framework Convention on Climate Change (UNFCCC) two years later in 1992. Since 1995, the 197 members of the UNFCCC have held Conferences of the Parties (COP) annually in order to assess the impact of the climate measures taken by the parties and the progress made towards the objectives set by the UNFCCC (UNFCCC, 2018).

1.1.2 The Kyoto Protocol

In 1995, the Parties began a negotiation process concerning precise and compelling objectives in order to reduce global emissions of greenhouse gases (GHG). Two years later, in 1997, the Kyoto Protocol (COP-3) was adopted by all the parties and only came into effect on the 16th of February 2005. It is relevant to underline the fact that the largest emitter at that time – i.e. the United States – has not ratified the Protocol and is thus not a party of it. The Kyoto Protocol has defined common but differentiated responsibilities; in other words, every country is responsible, but at different degrees, which means the efforts to be achieved will be specific to each country. This is due to the relationship between industrialization and climate change. As a result, it has been decided that only countries present in "Annex I" (see the list in Appendix 1) would have target objectives of emissions reduction. These countries can be divided into two subcategories; the developed countries and the economies in transition (EIT). The latter are composed of 14 countries from the former Soviet economies of Russia and Eastern Europe. The target objectives take the form of a ceiling that is not to be exceeded and is expressed in tonnes of CO_2-equivalent GHG emitted in the atmosphere. The Kyoto Protocol includes four GHG (i.e. carbon dioxide (CO_2) methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6)) as well as two groups of gases (i.e. hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)) (UNFCC, 2018). The emissions of these GHG are converted into CO_2 equivalent emissions (noted "CO_2eq") by using a factor of global warming potential (see Appendix 2 for a table of global warming potentials) (IPCC, 2018).

1.1.3 Three market-based mechanisms

Besides the national target objectives, the Kyoto Protocol introduced three market-based mechanisms that will foster the completion of the target objectives. These mechanisms are the “Clean Development Mechanism” (CDM), the “Joint Implementation” (JI) and the “Emissions Trading” (ET), which altogether form the carbon market (UNFCCC, 2018).

Firstly, the Clean Development Mechanism (CDM) allows a developed country to contribute to its emissions target by executing an emission-reduction project in a developing country. The developed country would therefore receive Certified Emission Reduction (CER) credits – of 1 tonne CO_2eq each – that would be deducted from their total emissions (UNFCCC, 2018).

Secondly, the Joint Implementation (JI) is very similar to the CDM, except that it concerns the implementation of an emission-reduction project between developed countries, receiving an Emission Reduction Unit (ERU) for each tonne of CO_2eq avoided (UNFCCC, 2018).

For both CDM and JI, the projects must be developed by a voluntary participation and approval of every concerned country and their outcome must lead to measurable and sustainable GHG emissions reductions compared to the current situation[1]. Furthermore, CDM and JI both allow a win-win situation as they offer developed countries more flexibility in the achievement of their emissions commitments, but also allow the country that hosts the project to benefit from foreign investment and technology (UNFCCC,

[1] According to Vlachou & Pantelias (2016), this condition is difficult to measure and led to abuses in the granting of CER credits.

2018).

Thirdly and finally, the Emissions Trading (ET) mechanism provides a framework for countries to buy and sell their CER and ERU credits so that countries that exceeded their emissions ceiling could buy credits to countries that kept their emissions below their limit. There is also another type of credit that can be traded, the Removal Unit (RMU), which concerns Land Use, Land-Use Change and Forestry (LULUCF) activities (e.g. reforestation) (UNFCCC, 2018).

1.1.4 The creation of the EU ETS

The Kyoto Protocol has set the ground rules of the common fight against climate change, thanks to a set of clear and restrictive objectives in terms of GHG emissions. As the EU needed policy instruments to meet the Kyoto Protocol commitments, the Protocol has cleared the path for the creation of the EU ETS, among other national and international initiatives (European Commission, 2015a).

In 2000, the EC presented a *Green Paper*[2] on "Greenhouse gas emissions trading within the European Union" that contained the bases of the design of the EU ETS. This paper served for the discussions that led to the creation of the first phases of the EU ETS. In 2003, the *EU ETS Directive* was adopted and the phase 1 – i.e. the pilot phase – was launched two years later. (European Commission, 2015a).

It is relevant to note that before the creation of the European carbon market, the

[2] Green Papers are "documents published by the European Commission to stimulate discussion on given topics at European level. They invite the relevant parties (bodies or individuals) to participate in a consultation process and debate on the basis of the proposals they put forward. Green Papers may give rise to legislative developments that are then outlined in White Papers." (Source: EUR-LEX https://eur-lex.europa.eu/summary/glossary/green_paper.html)

European Commission had attempted twice (in 1991 and 1995) to set up a carbon tax, but faced much opposition from several member states and a compromise has never been found. The three main controversial topics of the proposition were the impact on competitiveness of the European industry, the tax base and the competence transfer to the European level (Aykut, 2015).

1.1.5 EU objectives of emissions reductions

In 2007, the EU announced its target to reduce by 20% its GHG[3] emissions by 2020 compared to the 1990 levels. They also proposed the possibility to raise this target to 30% if there would be a comparable global commitment, but it was eventually not the case. Two years later, the EC also adopted the following long-term objective: reducing by 80-95% the emissions by 2050 compared to the 1990 levels (Climate Policy Info Hub, 2018). Therefore, the European Commission designed a roadmap that describes how the Member States would proceed to reach these low-carbon economy targets (European Climate Foundation, 2011). This roadmap includes three intermediate milestones until 2050: reductions of respectively 20% by 2020, 40% by 2030 and 60% by 2040 (Climate Policy Info Hub, 2018).

1.2 EU ETS: how it works

1.2.1 The economic theory

The concept of emissions trading has been developed by the economist and Nobel Prize Laureate R. H. Coase in 1960 in his article "The problem of social cost". Coase defines that externalities have a reciprocal nature, i.e. if the activity of an actor A harms an actor B, by preventing A to harm B, A is harmed in return because A was not allowed

[3] The GHG concerned are the six mentioned previously in the Kyoto Protocol.

to realise his activity. According to the rationale provided by Coase, the objective is thus to prevent the most harmful event to happen (Coase, 1960). Economically, the firm responsible of the externality should internalise the cost related to the damage caused through its activity as an additional production cost. Coase proposed a system that would grant property rights on resources that cause externalities and would allow to trade these rights among the different actors in order to provide an efficient allocation of resources (Coase, 1960). Furthermore, the economic efficiency of the trading scheme of pollution permits has been demonstrated theoretically by Montgomery, who showed that such system fosters efforts of emissions reductions at lower cost (Montgomery, 1972).

Figure 1 shows the economic advantage linked to emissions trading. The two curves represent the marginal abatement cost (MAC) [in €/tCO2] of firm A (left) and firm B (right) depending on their respective unitary emissions abatement. As such, a MAC links emission abatement to an emission cost (Van den Bergh and Delarue, 2014). The more a firm wants to reduce its unitary carbon footprint, the more expensive it gets. Without ETS, each firm would receive a certain abatement target from the public authority, but firm A has a lower marginal abatement cost than firm B to reach this target. The total cost of emissions reduction would then be equal to the sum of the two surfaces ABC. If we look at the situation with an ETS, firms are now allowed to trade allowances at a certain price. Abating its own emissions creates the opportunity to sell more allowances on the market or to buy less allowances on the market. Thus, an ETS provides a cost of opportunity for carbon, which will give an incentive for firms to invest in technologies such that their marginal abatement cost equals the carbon market price. Note that this opportunity cost does not depend on the free allowances received at the beginning. At this point, if a firm wants to emit one more tonne of CO2 - by increasing its production - it is cheaper to buy an allowance on the market rather than reducing its own unitary emissions. As a result, the total cost of abatement with ETS will be equal to the two surfaces ADF, and the two grey surfaces represent the advantage of each firm compared to a non-ETS situation (Venmans, 2011). An ETS fosters the low-carbon investments which are the most cost-efficient for the society (Montgomery, 1972).

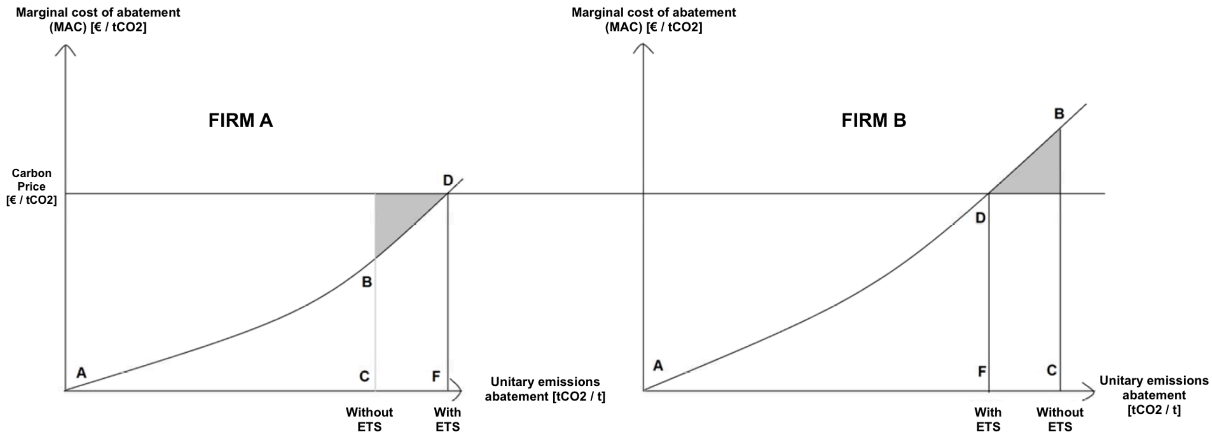


Figure 1: Economic advantage of ETS

Source: Venmans, 2011, p.6

1.2.2 The 'Cap and Trade' approach

"Cap and Trade" is a regulated market-based approach that aims at abating pollution by providing economic incentives for achieving reductions in the emissions of pollutants (Stavins, 2001) and is the underlying mechanism of the EU ETS. Nevertheless, the first cap and trade system ever implemented was the sulphur dioxide trading programme developed in the United States following the Clean Air Act of 1990 and was a source of inspiration for the European decision makers (Chevallier et al., 2009).

The principle is the following: the market authority – i.e. the European Commission – defines a ceiling (the 'cap') of emissions that is not to be exceeded for a certain period of time. The market authority then assesses the emissions that each firm is allowed to release according to its historical production volumes[4] (in tonnes of product) multiplied

[4] Forecasts are based on historical production data.

by the unitary direct emissions[5] footprint based on the EU product emissions benchmark[6]. The firms involved in the emission-trading market will either receive or have to buy on a primary market allowances – also called permits. An allowance gives the right to emit 1 tonne of CO_2-equivalent greenhouse gas (GHG) in the atmosphere. At the end of the period, each firm has to surrender a number of allowances equal to its effective annual emissions. Companies report their own emissions data to the European registry (called the European Union Transaction Log registry or EUTL). These emissions are then verified by an independent controller that is certified by the EC (Vlachou, 2014). Finally, firms will buy and sell these allowances on a secondary market depending on whether they emitted more or less than the number of allowances they received. The carbon price will be determined by the supply and the demand of the secondary market (European Commission, 2018). Because allowances are attributed a price, emissions are endowed with an opportunity cost. This means that if a firm renounces to the emission of one tonne of CO_2eq in the atmosphere – e.g. by producing less goods – it will earn a windfall profit equal to the price of one tonne of carbon by selling the allowance on the market. To this end, companies that have the possibility to reduce their emissions by investing in cleaner technologies are provided with an incentive as every tonne of CO_2eq avoided would reduce the firm's costs. As a matter of fact, the higher the carbon price, the bigger the incentive for the firms to adopt low-carbon technologies. Furthermore, market predictability is required for market actors to invest in new technologies. Uncertainties and price volatility indeed tend to delay such investments (International Energy Agency, 2007).

Moreover, it is important to highlight that since the product benchmark is based on the

[5] Direct emissions are emissions related to the combustion of fossil fuels in the production process of goods. They are opposed to indirect emissions, which are emissions linked to the electricity used for the production of goods.

[6] The EU product emissions benchmark is based on the average GHG emissions of the 10% most efficient GHG-efficient installations of the EU [in tCO2-eq per tonne of product]

performance of the 10% most GHG-efficient installations by product, only the 10% most efficient installations in each product-segment are granted enough free allowances to cover all their needs (European Commission, 2018).

Besides, since 2013, the cap defined by the European Commission (see Appendix 3) decreases by 1.74% annually in order to meet the European Union emissions target for the period 2013-2020, which consists of a total 20% reduction (Mougeot & Naegelen, 2009; European Commission 2018). In its proposition of amendment of the EU ETS Directive, the EC considered to raise the annual reduction rate of allowances for the fourth phase (2021-2030) from 1.74% to 2.20% in order to comply with the 2030 target objectives (European Commission, 2015b).

1.2.3 Scope of the EU ETS

This section aims at explaining how the EU ETS is implemented and to which extent it is applied. It will cover the geographic area, the sectors of activity and finally the greenhouse gases (GHG) that are concerned by the market.

1.2.3.1 Participating countries

To date, the EU ETS includes 31 countries: the 28 member states of the European Union – including United Kingdom – as well as Iceland, Liechtenstein and Norway. The latter non-EU countries joined the EU ETS in 2008 at the beginning of the second phase (European Commission, 2015a).

1.2.3.2 Sectors and subsectors concerned

The EU ETS comprises approximately 11.000 energy-intensive installations in power generation and manufacturing industries – e.g. the manufacturing of aluminium, steel, cement, lime, paper and chemical products (European Commission, 2018). On top of that, the aviation sector joined the market in 2012. As a result, all flights from and to the 31 countries mentioned above are also covered. An exhaustive list of the all sectors ranked by NACE code can be found in Appendix 4. Only installations reaching a certain capacity threshold are included in the scheme, e.g. power generation installations must have a rated thermal input of 20 MW (Chesney et al., 2013).

1.2.3.3 Greenhouse gases (GHG) involved

Considering the link between EU ETS and Kyoto Protocol, there is no surprise concerning the greenhouse gases included as they are the same: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) (UNFCC, 2018). As mentioned previously, the emissions of these six GHG are converted into CO2 equivalent emissions by using factors of global warming potential (see Appendix 2) (IPCC, 2018). Overall, the EU ETS is encompassing about 40-45% of total GHG emitted in the EU (European Commission, 2015a).

1.2.4 Allowances allocation rules

As mentioned before, the European Commission started the two first phases with a system where almost all allowances were distributed for free to companies. As of phase 3, the EC aimed at diminishing gradually the proportion of free allowances in favour of auctions, thus using a mix of the two methods. The two following sections are meant to explain properly these two modes of allocation and their consequences.

1.2.4.1 Free allocation rule (grandfathering)

Free allocation, also called "grandfathering", is based on the emissions levels observed in the past (Mougeot & Naegelen, 2009). Firstly, the market authority evaluates how many permits are going to be granted for each installation. In the beginning of the period, the installation receives a number of allowances. At the end of the period, the company must surrender one allowance for each tonne of CO2 that it has actually emitted. As a result, companies will trade allowances on a secondary market in order to be able to surrender the right number of allowances that they owe to comply with the regulatory authority.

Theoretically, a free allocation system does not provide any tax revenue for the market authority but allows companies to capture part of the rent by selling their surplus allowances in the form a windfall profit (Mougeot & Naegelen, 2009). However, in the case of the EU ETS, allowances were subject to VAT when sold on the secondary market, which generated some tax revenue (European Commission, 2018).

In the case of the EU ETS, grandfathering estimations are based on a EU product emissions benchmark based on the top 10% most efficient installations across the Community. Therefore, only a few installations receive enough allowances to cover their needs, while the remaining allowances have to be bought in auctions (European Commission, 2018).

1.2.4.2 Auctioning rule

Auctions follow the "polluter pays" principle as every tonne of carbon dioxide rejected in the atmosphere will require the purchase of a permit. In this case, the market authority sells allowances to companies on a primary market, and firms can trade the permits with each other on a secondary market – which is not especially based on auctions (Mougeot & Naegelen, 2009).

Counter-intuitively, auctioning does *not* impact the production output nor the emissions of the firms compared to a grandfathering system (Demailly & Quirion, 2008). This is due to the fact that pricing carbon emissions gives to allowances an opportunity cost. It is precisely this opportunity cost that will foster investments in emissions abatement technologies. The only actual difference compared to grandfathering is that industries will pay a substantial tax burden to the European Commission. Under grandfathering, the free allowances are in the form of a lump sum and can be seen as a subsidy. Its effect is to create the opportunity cost for GHG emissions without harming industrial sectors too hard (Monjon & Quirion, 2010).

Note that auctioning generates tax revenues for the market authority. As a matter of fact, total auctions revenues levied from 2012 to June 2017 were worth more than €18.3 Billion (European Commission, 2017). These revenues – at least 50% according to the EU ETS Directive – are destined to be used for climate and energy ends (European Commission, 2018).

Various possibilities exist for auctions to be organised – e.g. first or second price; oral, written or electronic; ascending or descending – and the choice of the design can have a determinant impact on the efficiency and equity of the market (Mougeot & Naegelen, 2009). However, this thesis does not intend to analyse this aspect in details.

1.2.4.3 Evolution of the EU ETS allocation rule

EU ETS is using a mix of grandfathering and auctioning; during the first phase (2005-2007), more than 95% of allowances were given for free – the rest being sold at auctions – and this percentage decreased to 90% for the second phase (2008-2012). During these two first phases, member states prepared National Allocation Plans (NAPs) defining how to distribute the free allowances among sectors and companies on a national level – with a necessary approval from the EC though (European Commission, 2015a).

In the case of the EU ETS, the number of free allowances given to installations though grandfathering is based on the *EU product emissions benchmark* which relies on the top 10% most efficient installations across the Community. Therefore, only a few installations receive enough allowances to cover their needs, while the remaining installations have to buy a part of their total emissions in auctions (European Commission, 2018).

However, in 2008 the European Commission decided that the third phase (2013-2020) would bear a transition to auctioning because it creates a more efficient incentive for firms in terms of emissions reductions as well as because it follows the transparent principle according to which the polluter pays in proportion of the pollution he created (European Commission, 2018). As a result, the electricity generation sector passed on to 100% allowances sold via auctions since 2013[7], while industrial sectors progressively had to shift toward the auctioning system: in 2013, 80% of allowances that are not destined to the Carbon Leakage List (CLL) were granted for free, with an annual decrease of

[7] Except for 8 countries which joined the EU in 2004 – Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Lithuania, Poland and Romania – and which benefit from a derogation that allows them to receive a decreasing number of free allowances until 2019 (European Commission, 2016).

7.14% in order to reach 30% in 2020 (Glowacki Law Firm, 2018). Figure 2 shows the quantity of free allowances as a percentage of the EU product direct emissions benchmark received by sector as of 2018. Moreover, another very important adjustment that came with the third phase was the suppression of the National Allocation Plans (NAPs) in favour of EU-wide allocation rules defined by the EC (European Commission, 2008).

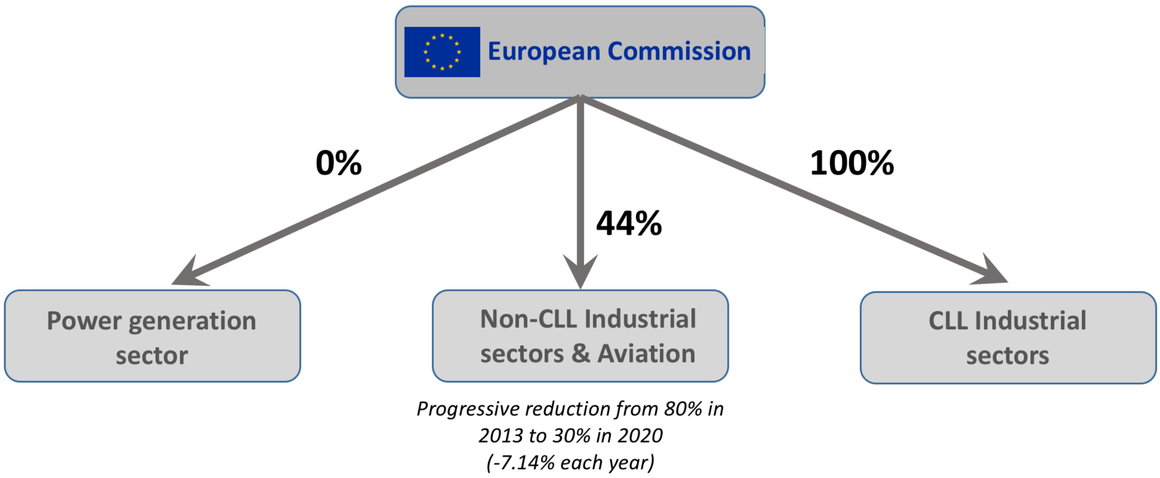


Figure 2: Free allowances received by sector as a percentage of the European product direct emissions benchmark as of 2018

Yet, there is an exception made for certain sectors which are deemed to be exposed to a risk of Carbon Leakage (CL) – i.e. the relocation of either production or investments to a region without a climate policy – are granted all their allowances for free in order to support them against non-EU competition. Foreign firms do not have to comply with the EU ETS and thus benefit from an advantage compared to European firms. The Carbon Leakage List (CLL) is the list of all sectors and subsectors that benefit from this exception toward auctioning, and is revised every 5 years. The EC defined a set of quantitative and qualitative criteria in order to define which sectors are entitled to join the CLL. However, if the supply of free allowances that is available for the CLL is lower than the sum of all the allowances that the CLL should receive, the EC planned a Cross-Sectoral Correction Factor (CSCF), which is the percentage of free allowances that will be effectively granted in this case. The CSCF is calculated as the ratio between the supply of allowances destined to the CLL and number of free allowances that the EC should ideally distribute to the sectors that face Carbon Leakage according to the relevant criteria (European Commission, 2017). For example, if the total emissions of all the CLL-sectors are of 100 Million tCO_2 in 2018, but the supply of free allowances available for the CLL for the same year is only of 90 Million, then the CSCF will be 90% and the CLL-sectors will have to purchase 10% of their allowances at auctions.

1.2.5 The carbon price

1.2.5.1 The drivers of carbon price

EU ETS allowances can be considered as a pseudo-commodity whose price is determined by its supply and its demand. On the supply side, three factors operate (Chesney et al., 2013):

(i) The emissions cap determined for the period

(ii) The banking and borrowing provisions, i.e. the possibility for a firm to retain excess allowances for future periods, while borrowing allows the firm to borrow allowances from future periods in order to use them in the current period. These provisions are restricted by the European Commission.

(iii) The offsets, i.e. alternative ways to comply with the EU ETS by surrendering Kyoto credits from Clean Development Mechanism (CDM) or Joint Implementation (JI) – respectively CERs and ERUs – but in very limited quantities defined by the EC.

The initial allocation of free allowances could also be considered as a fourth factor of supply, but this only holds if some allowances are distributed for free, which may not be the case forever.

On the other hand, allowances demand is determined by four components (Chesney et al., 2013):

(i) The emissions abatement options; when a company can decide whether or not to invest in a cleaner technology. If it does such investment, it will be able to capture a rent either by increasing its production while keeping constant its volume of emissions, or by trading the surplus allowances that resulted from the cut in its emissions.

(ii) The economic cycles; a growth period in the economy results in higher demands and goods and thus in emissions allowances. This will increase the carbon price and thus eventually encourage low-carbon investments. Inversely, bad economic situation lowers the carbon price and thus the incentives of investments.

(iii) The energy prices; when gas prices are lower than coal prices, power suppliers may use gas instead of coal (and vice versa), releasing less (or more) GHG in the atmosphere. It has a significant impact as power generation sector amounts for a great part of the CO2 emissions.

(iv) The weather conditions; it has an impact on electricity prices, and thus on the allowance price. For instance, air-conditioning is required during a hot summer, heating during a cold winter, and precipitations allow hydroelectric production.

1.2.5.2 Evolution of the EU ETS carbon price

Since the creation of the EU ETS in 2005, the price of the allowance has varied considerably from almost €0 to €27. As illustrated by Figure 3, at the very beginning, prices were slightly below €10 and rapidly reached a price over the €20. However, in April 2006, as the price had peaked at about €30, the member states reported their 2005 emissions, which were considerably lower than their forecasts. As a result, the price plunged below the €15. A few months later, the price allowances from phase 1 plummeted to a few eurocents because they could not be transferred to phase 2 according to the rules of the EU ETS at that time. The phase-2 prices rose from €15 to €27 at the end of 2008, but then fell dramatically to €10 due to the financial crisis of 2009. After recovering somewhat in 2009, the allowance value remained stable at around €15 for two years. In 2011 however, prices went down by 50%, and finally reached a low of €4 in 2012 as the phase 3 approached (Ellerman, Marcantonini & Zaklan, 2016). The beginning of this new phase was characterised by a low and stable price between €5 and €10 until beginning of 2018. The allowance indeed reached €15 in June 2018 following the opening of European discussions about future measures to rise the carbon price (Couëdic, 2018). The average carbon price by the end of 2018 was of at about €23 (Finances.net, 2018).

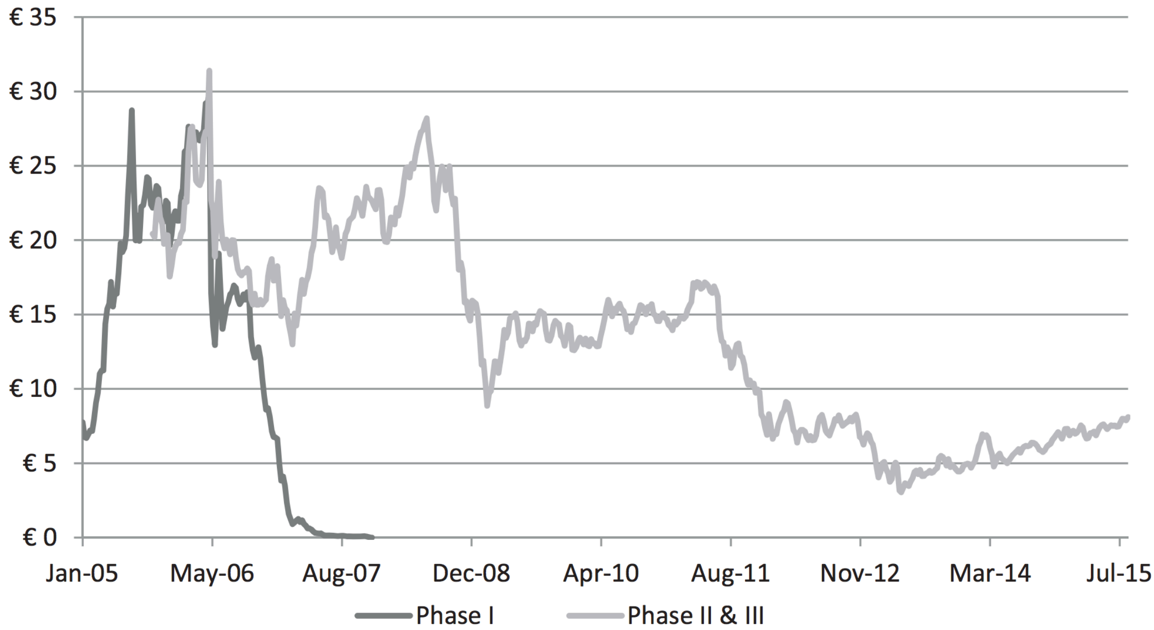


Figure 3: Futures price of permits between 01/2005 and 07/2015.

Source: Ellerman, Marcantonini, & Zaklan, 2016, p. 10

1.2.6 The emissions abatement channels

In an open economy, there exist three channels that lead to emissions reductions *in a certain region* (Demailly & Quirion, 2008). These channels are not mutually exclusive; each of them is a component of the aggregate emissions abatement in a region.

Firstly, the technological channel consists in the reduction of unitary carbon footprint through cleaner production technologies. This channel has the advantage of reducing GHG emissions while maintaining an output level constant. However, it is dependent on the gap between state-of-the-art technologies and the actual installed technology. For some sectors, there is very little room for improvement as it is impossible to reduce the carbon footprint of a good indefinitely (Demailly & Quirion, 2008).

Secondly, the consumption channel, which is simply a fall in the demand of a GHG intensive good which is generally the consequence an increase in its price (Demailly & Quirion, 2008).

Thirdly, the trade channel implies a production shift from the region having a climate constraint to a region where there is none. In this case, regional consumption remains constant while domestic production declines, and thus domestic emissions too. The outcome is positive for the regional emissions target, but from an environmental perspective, the global emissions did not decrease and may even have increased. Carbon leakage falls within the scope of the trade channel (Demailly & Quirion, 2008).

Moreover, it has been estimated that approximately one tonne of GHG out of four is due to international trade, and a non-negligible part of them is travelling from climate policy-free to climate-constrained countries (Sakai & Barrett, 2016). Peters and Hertwich (2008) even found out that industrialised countries tend to import more carbon-intensive goods than the goods they export, which makes them net importers of GHG emissions.

According to Gautam, Pandey and Madhoolika (2018), improvement in energy efficiency through policies and regulations is not sufficient to reach the global 50% emissions reduction target by 2050. They insist on the need to reduce the demand of GHG-intensive goods, as one of the carbon mitigation strategies.

1.3 The different phases

The first phase of the EU ETS was considered as the pilot phase and took place between 2005 and 2007. This 'learning-by-doing' phase allowed to analyse the price formation in the market and the deployment of the necessary infrastructure (monitoring, reporting and verification of emissions) with the aim of having the EU ETS operational for 2008. During this period, almost all allowances were distributed for free by countries to their national installations (European Commission, 2015a; 2018). Given the absence of reliable emissions data, the caps of phase 1 were estimated and exceeded emissions by far, which led to the collapse of the carbon price to almost €0 (Ellerman et al., 2016). According to a research conducted in 2017, it is not surprising that the implementation of the EU ETS followed a learning-by-doing process as the national and international situations are subject to changes. Therefore, a carbon market cannot always generate the ideal results in the very short run (Fan et al., 2017).

The second phase ran from 2008 to 2012 and comported several adjustments: three new countries – Iceland, Liechtenstein and Norway – integrated the market; the cap has been reduced by 6.5% compared to 2005; the proportion of free allocation decreased to around 90%; the penalty for non-compliance increased from €40 to €100 per allowance; the aviation sector was included to the market beginning 2012 (European Commission, 2018). Even with a lower cap which was more representative of the real emissions, the 2009 financial crisis led to a fall in production – and thus in emissions too – that was responsible for a large surplus of allowances. The price of the allowances was therefore unexpectedly low (European Commission, 2018).

The current and third phase covers the period 2013-2020 and is mostly characterised by a single harmonised European allocation plan that replaced the National Allocation Plans (NAPs) and by the transition from 100% to 0% free allocation granted to the power sector. Moreover, the third phase includes a linear reduction of its cap by 1.74% annually as shown in Figure 4 as well as a progressive shift from free allowances to the sale by auction in order to reach 30% of all allowances distributed for free by 2020 (European Commission, 2018) and ultimately intend to reach full auctioning by 2027 (van Asselt & Brewer, 2010). Figure 4 shows the number of freely allocated allowances and the verified emissions between 2005 and 2017. Note that the drop in 2013 free allocated allowances is attributed to the power sector, which represents alone about 55% of the GHG emissions of the EU ETS.

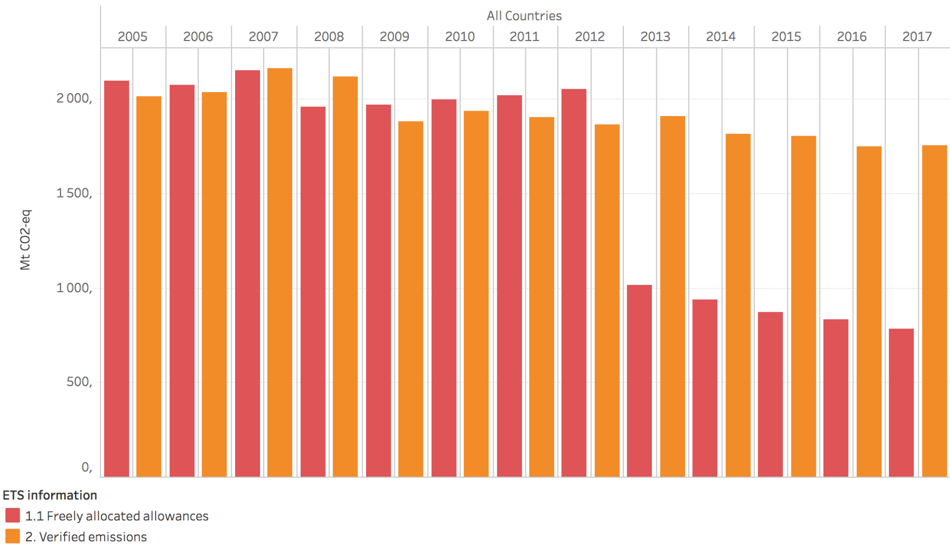


Figure 4: Evolution of free allowances and verified emissions (2005-2017)

Source: European Environment Agency (EEA)

The fourth phase, starting in 2021 and ending in 2030, is also going to comprise several adjustments that are still subject to discussions at the EU institutions (European Commission, 2018).

1.4 Weaknesses of the system

1.4.1 Sectoral competitiveness issue

As mentioned above, the fact that the EU ETS only includes installations that are located within the EU creates a distortion with the non-EU installations for sectors exposed to international trade. The unilateral nature of the EU ETS generates a cost advantage for the foreign firms. This distortion of sectoral competitiveness may lead to Carbon Leakage, i.e. relocation of production outside of the EU to the detriment of the EU industries and without any positive environmental effect.

The mechanism developed by the EC in order to support domestic production is the Carbon Leakage List (CLL), which provides free allowances (at a level of 100% of the EU emissions benchmark) for a list of sectors at risk. Carbon leakage will be developed in more details below.

1.4.2 Over-allocation

The initial National Allocation Plans (NAPs) from the two first phases resulted in a game of conflicting national interests (Spieth & Hamer, 2005). The NAPs have indeed been accused of favouritism from member states towards their own industries in the allocation process (European Commission, 2008). This is partly due to the fact that each member state had its own levels of ambition toward the emissions reduction per sector of activity. These different levels of ambitions generated over-allocation which entailed a perception of unfairness (European Commission, 2009b). Furthermore, the free allocation rule also fosters intensive lobbying activities in order to capture the rent, which also played a role in over-allocation (Dimantchev, 2015). As a matter of fact, in 2011 there was a surplus[8] of about 1 billion allowances (European Commission, 2014). The EU-wide registry that replaced the NAPs has fixed this allocation issue, but the EU ETS still suffers from it because the surplus allowances received from phase 2 were kept and still valid for phase 3. The result of this over-allocation was of course a very low carbon price – below €15 since end 2008.

1.4.3 Sensitivity to economic situation

The European Commission defines a cap of emissions for each phase, taking some market growth estimations into account, and so are the allowances distributed for free to the sectors. Given the fact that these quantities are fixed until next phase, the allowances supply is very little flexible towards economic trends that could change the carbon market context. In times of recession, such as in 2009, current allocation rule would imply an excess supply (Borkent et al., 2014). This is due to a fall of the production, thus the demand will drop, and so would the carbon prices. The EC did not make any provision to adjust the free allocation accordingly to production changes that could happen during the phase.

Moreover, in the beginning of the EU ETS, allowances were only traded among member firms, but they gradually have become an asset for investors. In other words, there has been a financial instrumentation of the carbon allowances, as more and more investors purchased them in order to optimise the diversification of their portfolio. On the bright

[8] Surplus is calculated as the difference between the total number of allowances available for compliance – i.e. from both free allocation and auctioning – and the total number of allowances used for compliance.

side, financial instrumentation improved the liquidity of the allowances, but on the other side, it also created an important sensitivity of the carbon price towards the EU publications and the rumours about future changes in the ETS policy (Atkinson, 2016). Therefore, the market became more volatile, and weakened incentives for long-term investment in low-carbon technologies.

1.4.4 Conclusion

The outcome of these weaknesses was important criticism about the poor perceived efficiency from both industrial sectors and the civil society. This thesis will focus on the competitiveness and carbon leakage aspects of the EU ETS.

1.5 Competitiveness and Carbon Leakage

Competitiveness is a concept that has a vague definition and that is, according to Krugman (1994), pointless at the macroeconomic level. However, Alexeeva-Talebi, Böhringer and Moslener (2007) argue that competitiveness at the sectoral level lies in two things; the “ability to sell” and the “ability to earn”. In the case of the EU ETS, the production cost of domestic producers of GHG-intensive sectors increases. For the sectors facing international competition, it creates a distortion as the foreign producers do not endure the same cost increase. The European companies have then two possibilities: to pass through the cost to consumers, or to bear it themselves. In the first case, they will lose market share in favour of their foreign competitors, thus reducing their ability to sell. If they choose the second option – i.e. bear the cost – they will conserve their market share to the detriment of their profit margin, which decreases their ability to earn. Therefore, on a long term perspective, capital investments may shift outside of Europe (compared to the situation without the EU ETS) after which domestic firms’ market shares are very likely to decrease both within and outside Europe. The outcome of those two options is essentially job losses in the concerned sectors and increase of GHG emissions in the non-EU countries – which is Carbon Leakage (Monjon & Quirion, 2010). For sectors not facing international competition, the cost will generally be passed through the customer, as it is the case for the power generation sector. Therefore, a carbon pricing policy on electricity generation will induce an increase of the electricity price.

Even though competitiveness and Carbon Leakage are frequently associated, they are different concepts. Carbon Leakage can be defined as a shift of GHG emissions from a region with a stricter climate policy to another region with less strict climate policy or none at all (Zaklan & Bauer, 2015). It is important to underline that this shift of emissions must be the consequence of the climate policy, and not caused by some other factor. Carbon Leakage is generally measured as the ratio of the increase in emissions outside of a region compliant with a climate policy to the reduction in emissions that occurred in this region, while considering only the emissions variations that are attributable to the climate policy (Felder and Rutherford, 1993).

It is a very difficult task to determine objectively whether a carbon-constrained sector is facing carbon leakage, as it does not operate in a vacuum. If there is a slow-down in a growing commodity market, production plants could be shut down, but that would not to be attributed to the carbon policy (Reinaud, 2008).

There exist two channels that generate Carbon Leakage: the competitiveness channel and the international fossil fuel price channel (Dröge et al. 2009). The competitiveness channel can be split into two components: operational leakage and investment leakage (Graichen et al., 2008). The former is a short- and medium-term issue that consists of the physical relocation of production from EU to countries with less environmental constraints. The investment leakage, however, has a more long-term impact and comprises a shift in the investment to outside of the climate-acting region. Investment leakage can be a dramatic issue in capital-intensive industries – e.g. production of aluminium or steel (Monjon and Quirion, 2010). Concerning the international fossil fuel price channel, it can be explained by the fact that countries which reduce their emissions must generally decrease their fossil fuels consumption, leading to a drop in their global price. The consequence is a rise of fossil fuels consumption in carbon-tax-free countries, and thus of their emissions, like two communicating vessels (Branger & Quirion, 2014a). In the framework of this thesis, the competitiveness channel will be the most relevant to observe, as the model developed does not take fuel price changes into account.

1.6 The Carbon Leakage List (CLL)

As mentioned earlier, the EC provides free allowances to the installations from sectors that are deemed exposed to a significant risk of Carbon Leakage (European Commission, 2018). This list of sectors and subsectors is called the 'Carbon Leakage List' (CLL).

In order to determine which sectors are considered as 'at risk' toward Carbon Leakage, the European Commission defined quantitative and qualitative criteria. For the quantitative criteria, there are two indicators[9]. If a sector has at least one indicator that exceeds a certain threshold, or if both indicators exceed a lower threshold, then the sector will be added to the CLL. Sectors from the Carbon Leakage List (CLL) receive free allowances equal to 100% of the EU product emissions benchmark. If the sector does not qualify for the quantitative criteria, the sector can argue and try to convince the EC that

[9] The two indicators (*ETS-cost-to-GVA ratio* and *Non-EU Trade Intensity*) are not developed here, but information can be found in the Article 10a(15-16) of the EU ETS Directive (2009).

they are exposed to Carbon Leakage in light of three qualitative criteria[10]. Note that this assessment has to be performed by taking the emissions mitigation efforts made in other countries concerning the same sector into account (European Commission, 2009a).

The first CLL was determined in 2012 before the beginning of the third phase. In October 2014, the list was revised and contained 167 sectors and subsectors. Among them, only 6 sectors were added based on the qualitative criteria abovementioned (Zaklan & Bauer, 2015).

In 2015, the sectors included in the CLL represented 97% of the industrial emissions – i.e. emissions of the whole EU ETS minus those from power generation and aviation (European Commission, 2015c). The CLL is going to be revised for the fourth phase, using new criteria that have been deemed more appropriate. However, the sectors that will be covered by this third version of the CLL amount for about 95%[11] of the non-power-sector EU ETS emissions. Therefore, it can be assumed that it will not generate any substantial variation of demand in allowances.

1.7 Border Carbon Adjustment (BCA)

The purpose of this part of the paper is to provide an overview of the findings that have contributed to a better understanding of BCAs. The two first sections explain what are BCAs and their different designs. The two following sections address their World Trade Organisation (WTO) compatibility and political feasibility. Eventually, the last section covers the impact of the measure on competitiveness, carbon leakage and welfare.

[10] These criteria are not developed in this paper but they are described in the Article 10a(17) of the EU ETS Directive (2009).

[11] Computed using emissions data from 2015 published by the European Commission (https://ec.europa.eu/clima/sites/clima/files/events/docs/0127/7_nace_eutil_installations_matching.xlsx)

1.7.1 Definition and purpose

A Border Carbon Adjustment is a measure by which a country adjusts a tax on certain products at its borders in order to match the taxes on domestically produced goods. Border *Carbon* Adjustments refer to the same concept, but their specificity is that they are related to a tax on carbon emissions.

When it comes to implement climate policies unilaterally, i.e. at a non-global level, there is a risk of free-riding behaviours (Kuik & Hofkes, 2010). Indeed, some countries have the incentive to take lax actions while some other countries strive to reduce their emissions (Carraro and Siniscalco, 1993). In the case of the EU ETS, the foreign producers benefit from a cost advantage compared to the European producers. Sectoral competitiveness between firms from inside and outside the EU has been a prominent issue for the European Commission since the creation of the EU ETS.

The aim of a Border Carbon Adjustments is to provide a correction to this distortion by re-equilibrating the environmental constraint among domestic and foreign firms. BCAs can address competitiveness issues for imports and/or exports. To do so, two methods exist - tax-based and allowances-based BCAs - and are explained in the next section.

1.7.2 Design options for a BCA

1.7.2.1 Form: Tax-based or Allowances-based BCA?

The two most relevant forms of Border Carbon Adjustments (BCA) considered in the literature are the tax-based and the allowances-based BCAs. The former is simply a tax (for imports) or a rebate (for exports) depending on the carbon content of the goods and is levied at the border. The allowances-based BCA implies that importers are integrated into the ETS (Monjon & Quirion, 2010). Importers should in this case surrender allowances at the end of the period as it is the case for domestic producers. In this system, the emissions cap determined by the European Commission would require to be increased, as it would encompass more emissions. Importers would also receive a share of the free allowances. On the other hand, a BCA on exports only would dismiss them from participating to the ETS. As a result, in the case of a BCA on imports and exports (i.e. taxing imports while rebating exports), the cap would not include emissions related to EU production anymore, but only emissions related to EU consumption. The modification of the cap in allowances-based BCAs is not discussed here, as there could be many different ways to arrange it.

1.7.2.2 Coverage: including imports and/or exports?

Without any BCA, foreign production benefits from an advantage towards domestic production. The BCA would ensure that importers must buy allowances in accordance to the carbon content of the imported products, restoring fairness between domestic and foreign firms as both products would have to comply with the climate policy.

Considering European exports under the EU ETS, domestic firms incur a carbon-related cost when exporting their products on foreign markets, where no such climate policy is in place. Therefore, a BCA would allow the domestic producer to receive a rebate for the products exported out of the EU. The idea of rebating a carbon allowance on exports can be seen as environmentally absurd because exportation does not cancel the effect of their emissions on climate change (Charnovitz, Kim & Hufbauer, 2009). However, it makes sense in a competitiveness perspective. Given that the EU is a net importer of embodied emissions, the inclusion of rebates in BCA is of lower importance for efficiency

(Böhringer, Balistreri & Rutherford, 2012). A BCA can also address both imports and exports, and is generally called a "full BCA".

1.7.2.3 Adjustment base: evaluating GHG emissions from imports

In order to apply a BCA on imported products, their carbon footprint must be assessed. This is a daunting task because outside the EU, there is barely no obligation for firms to declare emissions-related information to their own country's authorities (Monjon & Quirion, 2010).

Monjon & Quirion (2010) listed three possible manners to evaluate the carbon content of imported products. The first one implies that the importer is responsible for providing evidence of the emissions related to the imported products. The resulting administrative burden can represent a problem for small importers. The second alternative consists in computing the average emissions per tonne of imported product, but it would be a huge collection work and would require involvement from exporting countries. Thirdly, Godard (2007) and Ismer & Neuhoff (2007) suggest to use the Best Available Technology (BAT) worldwide, but it leads to different calculation methodologies. Monjon & Quirion (2010) propose to use the EU product benchmark calculated for the period 2013-2020 as a proxy of the BAT. It would thus limit both administrative costs and World Trade Organisation (WTO) disputes. However, this benchmark only takes direct emissions into account (European Commission, 2018), that leads to a distortion: emissions of imported goods would only consider direct emissions, while domestic installations would face direct and indirect emissions costs.

Because the EU ETS includes the energy sector, the electricity production is subject to the cap and trade system, and faces additional costs. Therefore, the EU product benchmark which was computed for the period 2013-2020 was only taking direct emissions into account. However, in the case carbon content from imported goods has to be evaluated by using the EU product benchmark, it would not encompass the indirect costs because the electricity used was not subject to the EU ETS.

It can be negligible for some sectors that do not face large indirect costs, but it would not solve the competitiveness issue for some others that rely tightly on electricity – e.g. aluminium production which is very electricity-intensive. Monjon & Quirion (2010) consider two alternatives to overcome this issue. Either simply use the average emissions per MWh produced in the exporting country, or, more accurately, use the marginal emission factor of power generation that was calculated by the Clean Development Mechanism (CDM) Executive Board in 2009.

1.7.3 World Trade Organisation compatibility

The following section does not aim at exhaustively discuss World Trade Organisation (WTO) compatibility, but rather to set out the legal context in which BCAs fall. Two options are considered to justify a BCA towards trade legislation; the respect of the general regime (GATT) and the use of article XX.

The general trade rules defined by the WTO allow its members to impose (resp. rebate) product taxes on imports (resp. exports) without any symmetry constraint (Charnovitz et al., 2009). However, the WTO principle contained in article III of the General Agreement on Tariffs and Trade (GATT) requires members to treat foreign goods "*no less favourably"* than comparable domestic goods (Art. III (158)). Even though a BCA would put domestic and foreign producers on the same footing, the fairness principle may not always be respected under a tax-based design; if the market price of an allowance -

which is variable - becomes lower than the tax rate inflicted to importers - which is fixed for a certain period. Therefore, Genasci (2008) and Monjon & Quirion (2011) recommend to use allowances-based BCA as they consider it provides more similar treatment between domestic and foreign goods. But there is no evidence that a tax-based BCA could not contain provisions to respect this aspect. In general, this principle would hold when using a Best Available Technology benchmark for calculating the carbon content of goods (Monjon and Quirion, 2011) and the GATT could be respected.

Another option to justify a BCA is the article XX of GATT which allows exceptions when the trade restriction is "*necessary* to protect human, plant or animal life" (Art. XX (b)) or if it ensures the « conservation of exhaustible natural resources » (Art. XX (g)). However, the acceptance of the measure following article XX remains questionable (Condon & Ignaciuk, 2013).

As a result, some authors share the opinion that BCAs are not automatically trespassing WTO rules, but that it depends on its specific design (Biermann and Brohm, 2005; Holmes, Reilly & Rollo, 2011; Sheldon, 2011). Thus, there is no guarantee in terms of WTO compatibility as it is highly difficult to assess the chances of the two options.

1.7.4 Political feasibility

In its proposal for an amendment of the Directive 2003/87/EC presented in 2015, the EU lawmaker showed his determination to better address the carbon leakage problem in the fourth phase (2021-2030) (European Commission, 2015b). Furthermore, in Article 10b of the Directive 2009/29/EC[12], the EC showed its probable willingness to include

[12] The Directive 2009/29/EC revises the EU ETS and came into force in 2013 for the third phase (2013-2020).

importers of GHG-intensive products in the EU ETS, as Article 10b mentions:

"By 30 June 2010, the Commission shall [...] submit to the European Parliament and to the Council [...] any appropriate proposals, which may include [...] inclusion in the Community scheme of importers of products which are produced by the sectors or subsectors [exposed to a significant risk of carbon leakage]" (European Commission, 2009a).

The Directive 2009/29/EC further states:

"An effective carbon equalisation system could be introduced with a view to putting installations from the Community which are at significant risk of carbon leakage and those from third countries on a comparable footing. Such a system could apply requirements to importers that would be no less favourable than those applicable to installations within the Community, for example by requiring the surrender of allowances" (European Commission, 2009a).

This shows that there is some interest from the European lawmaker concerning a possible implementation of this measure in the future.

However, there is no consensus in the economic literature on whether a Border Carbon Adjustment measure is desirable or not. On the one hand, there are those who believe that the unilateral nature of BCAs represents a second-best option to competitiveness issues, while a global policy is *the* best solution (Markusen, 1975). The other main criticism that is made against BCA is that it could undermine future co-operation on international climate agreements and foster protectionism (Houser, Bradley, Childs, Werksman & Heilmayr, 2008; Dröge et al., 2009). On the other hand, some others argue that the implementation of a BCA would leverage other countries' environmental action, and defend the idea according to which no action is worse than an individual action

(Condon & Ignaciuk, 2013). In other words, geopolitical repercussions could impede the feasibility of a BCA.

1.7.5 Effects of BCAs

Several ex-ante studies have been conducted in order to assess the impact of Border Carbon Adjustments under unilateral climate policy. Most of these studies rely on a dynamic Computable General Equilibrium (CGE) models, while a few are based on static Partial Equilibrium (PE) models.

It is relevant to highlight the fact that the majority of the models used in these studies are CGEs, which can lead to a wide range of estimations, depending on the level of sectoral and country aggregation (Caron, 2012) as well as the designs considered (Bednar-Friedl, Schinko, & Steininger, 2012; Winchester, 2012).

1.7.5.1 Effects on Competitiveness

First of all, the hypothesis according to which a unilateral climate policy reduces domestic production and increases imports in energy-intensive sectors was verified empirically. In their econometric study, Aldy and Pizer (2015) obtained a 5% output fall and a slightly lower increase of imports in the same sectors, while less energy-intensive sectors were almost not harmed. Monjon and Quirion (2011) find different output decreases when they analysed different allocation rules in the EU ETS (between -1% and -20% depending on the sectors).

Veenendaal and Manders (2008) found moderate competitiveness effects following the implementation of a BCA in their research on EU unilateral climate action. Furthermore, several studies using CGE models have shown that BCAs are not sufficient to neutralise all of the loss due to unilateral climate policy (Burniaux, Chateau & Duval, 2010; Mattoo, Subramanian & van der Mensbrugghe, 2009, Winchester, Reilly & Paltsev, 2011).

Monjon and Quirion (2011) with their Partial Equilibrium model, analysed the impacts of different types of BCA designs on four energy-intensive sectors (electricity, aluminium, cement and steel). They find that BCAs do not prevent significant output losses. According to them, free allocation is better at preserving the production of the carbon-priced region.

However, Mattoo et al. (2009) used a CGE model and considered several emissions reduction goals in the industrial countries (from 5% to 40% less than in 2005). They demonstrated relatively high output losses in energy-intensive sectors of acting countries due to the implementation of the climate policy – between 1.5% and 5% depending on the emissions reduction level. They also show that a BCA including either imports or exports is able to offset a significant part of the domestic losses, but not all of them. On the other hand, a BCA covering both imports and exports even manages to increase the total output compared to the BAU scenario for high emissions reduction goals.

Moreover, Böhringer et al. (2012) compared several models and showed that BCAs can effectively reduce competitiveness losses in *EITE*[13] industries due to unilateral climate policies. For the scenario in which there is a climate policy but no BCA, all models obtain a decrease of production for domestic EITE industries, and an increase of foreign (non-acting) production in the same industries. Considering the scenario in which there is the implementation of a BCA, the loss in domestic production in EITE industries falls from an average of 2.8% to an average of 1% over the different models.

[13] EITE stands for 'Energy Intensive Trade Exposed'

1.7.5.2 Effects on Carbon Leakage

There are currently mainly ex-ante studies on carbon leakage which led to various conclusions, while only a few ex-post studies have been conducted. As a result, the carbon leakage threat in reality remains questionable. Nevertheless, the perception of carbon leakage may be sufficient to reduce the expectations of environmental measures of stakeholders and policy makers (Monjon & Quirion, 2010). The competitiveness issue with regard to climate policy is sometimes framed as the "economy versus environment" question (Morgenstern, Pizer & Shih, 2002).

Besides, none of the existing research on sectoral carbon leakage ever indicated a leakage rate near 100%. Put differently, it is very unlikely that carbon leakage would annihilate totally an effort to abate emissions in a region (Reinaud, 2008). Carbon leakage rates due to unilateral climate policies typically range between 5% and 25% across studies, but in some studies they can be as high as 40% (Branger & Quirion, 2014b).

Some studies suggest that the implementation of a BCA would address carbon leakage concerns by dampening the shift in production to regions with less severe climate policies (Bednar-Friedl et al., 2012; Kuik & Hofkes, 2010; McKibbin et al., 2008; Winchester, 2012). When examining several models from the literature, Böhringer et al. (2012) observe that carbon leakage rates typically range between 5% and 20% without BCA, and that these rates fall between 2% and 12% overall. While it has been said earlier that Monjon and Quirion (2011) concluded that a BCA would not be able to maintain domestic production as well as free allocation would, they found that a BCA would perform well in limiting carbon leakage.

However, other authors have found moderate alleviation of carbon leakage when implementing a BCA (Böhringer et al., 2012; Branger & Quirion, 2014b). Mattoo et al. (2009) confirm this claim for aggregate emissions, but suggest that at the sectoral level, some sectors such as cement, steel and aluminium, could experience larger emissions and competitiveness effects. Kuik and Hofkes (2010) similarly found that while BCAs seem to provide satisfying results in fighting sectoral inequalities inherent to the EU ETS (especially in the iron and steel industry), they underline that this mechanism does not reduce much of carbon leakage when looking at the aggregate level. As a result, the aforementioned authors suggest that BCA is not very effective in terms of emissions reduction, and thus in terms of environment preservation.

1.7.5.3 Effects on welfare

Branger and Quirion (2014b) have compared a dozen studies on BCAs that analysed welfare variations in abating countries. It came out that all of them reported very slight welfare decreases due to the climate policy: less than 1.58% drop compared to BAU. Moreover, the improvements in welfare due to the BCA are almost imperceptible. These studies all rely on CGE models and have used income variations, i.e. variations in Gross Domestic Product (GDP), as a proxy to analyse welfare impacts of BCAs. Besides, none of these welfare estimations has taken environmental impact into account.

1.8 Conclusion

Given the absence of globally collaborated action, some countries take up their responsibility in order to curb climate change by implementing domestic climate measures. However, they create a competitiveness distortion in favour of the foreign industries, while a part of their environmental efforts is vain because of some relocation to policy-free countries.

Several studies have been conducted in order to assess how a Border Carbon Adjustment could counteract these issues. The overall conclusions are not homogenous nor straightforward. Given that the opinion is relatively divided, and that estimates are depending on the BCA designs and the model parameters, creating a model would allow to have an additional perspective on BCA effects and to analyse some indicators in more details. While the literature offers a global overview of the competitiveness aspect, this thesis would allow to have an idea of the effects of BCAs on regional market changes to better understand the mechanisms at work. With respect to welfare, authors seem to agree on its very little sensitivity both toward climate policies and BCAs. However, there has been very little attention concerning the impact on the consumers of such policies. Therefore, it would be of interest to look at this particular aspect. Furthermore, it is unfortunate that the impact on the environment is left aside from welfare considerations, while the very purpose of climate policies is to safeguard it.

1.9 Hypotheses

Based on the literature on Border Carbon Adjustments, several hypotheses are going to be tested by the means of a model. They are grouped in three categories corresponding to the three types of effects that will be analysed: emissions and carbon leakage, sectoral competitiveness and finally welfare.

Hypothesis 1.1:

"A BCA decreases carbon leakage with respect to a situation with an ETS, and a full BCA is more efficient to this extent."

Hypothesis 1.2:

"The additional global emissions mitigation due to a BCA is marginal as compared to the introduction of an ETS."

Hypothesis 2.1:

"A BCA restores some of the competitiveness loss induced by the ETS, and a full BCA is more efficient for this purpose."

Hypothesis 2.2:

"Sectors with large variation in costs due to carbon pricing are more impacted by the BCA in terms of competitiveness."

Hypothesis 3.1:

"A BCA improves the profit of European firms to the detriment of European consumers with respect to the ETS scenario."

Hypothesis 3.2:

"When integrating environmental effects into the welfare measurement, the implementation of an ETS, with or without a BCA, improves the European welfare."

2 Chapter II: Partial Equilibrium Model

2.1 Introduction

The model developed in this section is a static Partial Equilibrium (PE) of the EU ETS which comprises three industrial sectors: cement, aluminium and steel. The PE being static, there is no evolution in time, but an 'instantaneous' modification of the market equilibrium. The market simulations provided by the static PE model are not projections of the future but rather *counterfactual scenarios*. In other words, they can be seen as 'alternative present' snapshots. Several scenarios were created in order to perform an analysis of the impact of two Border Carbon Adjustment variants on sectoral competitiveness, carbon leakage and social welfare.

This chapter of the thesis will first describe and explain in details the followed methodology to build the model. Then, the results will be presented and interpreted. Eventually, limitations of the model will be developed.

2.2 Methodology

2.2.1 Model type

There are two main types of economic models; Partial Equilibrium (PE) and Computable General Equilibrium (CGE) models. The first one analyses a market by assuming that there are no mutual effects between this market and the rest of the economy, while the latter encompasses the whole economy and the various interactions between its components.

The reason why a Partial Equilibrium has been used are twofold. Firstly, a CGE is way more complex to build, and thus its results are more difficult to grasp. Of course, it makes them more exhaustive and realistic as they capture inter-sectoral and economy-wide effects. Therefore, using a PE represents a certain loss of information. In this case in particular, a CGE would have allowed to take international energy prices channel into account. However, Fischer and Fox (2009) affirm that this channel is less important when analysing anti-leakage policies. Hence, a PE is relevant to analyse competitiveness channel (Quirion, 2010). Secondly, CGE suffer from higher sectoral aggregation, i.e. some of the sectors are not isolated, as it is the case for cement and aluminium which are contained in wider clusters of the Global Trade Analysis Project (GTAP) databases that are typically used for CGE.

2.2.2 Description of the model

The model is a static PE that comprises three industrial sectors, i.e. cement, aluminium and steel, which are competing “à la Cournot” in two regions: The European Union (EU) and the Rest of the World (RoW). In the same region, firms from an industrial sector are identical and produce homogeneous goods. The sector in a region is choosing the production quantities and the prices for all the sectors’ firms, as in a cartel. Therefore, there are two actors per sector; one in each region. An overview of the model is represented on Figure 5.

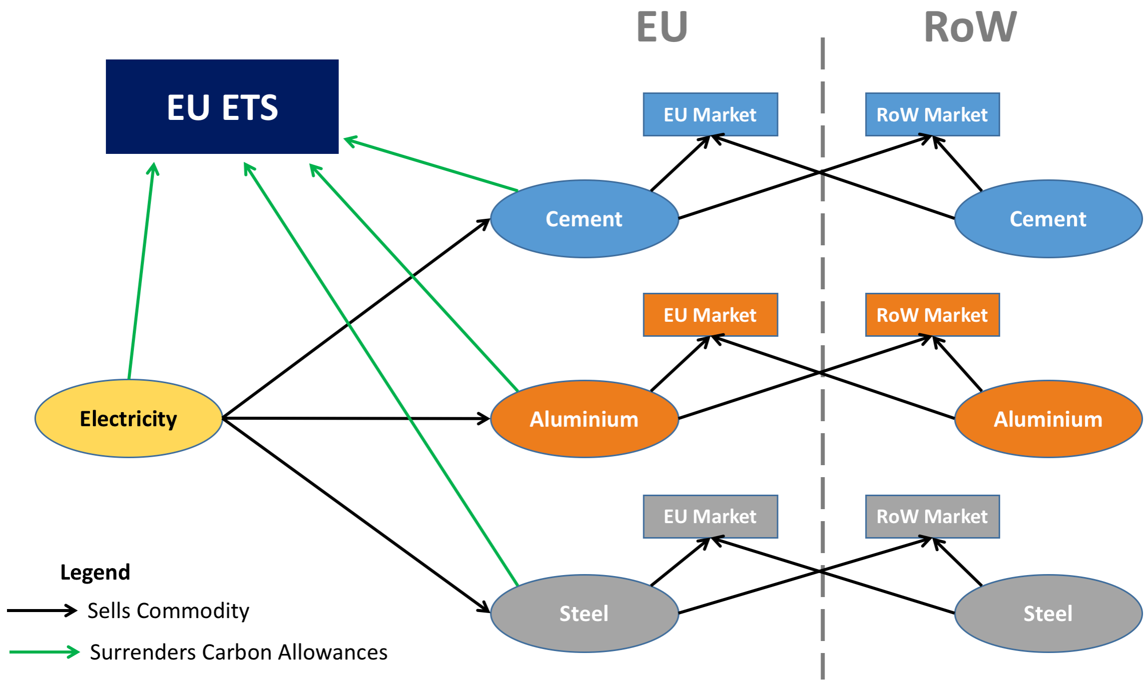


Figure 5: Overview of the model

Note that the electricity sector appears on Figure 5 in order to depict the distinction direct emissions from indirect emissions. Because the electricity sector does not suffer from international trade, it has the possibility to pass 100% of the ETS costs through to energy consumers. Therefore, when industrial sectors buy electricity, their indirect emissions will be included into the electricity price. In the model, the electricity price is embodied in the production cost.

Cement, aluminium and steel production represent together more than 45% of the emissions the industrial sectors of the EU ETS (i.e. not including electricity generation and aviation). The three sectors are deemed at risk of carbon leakage by the EC and are therefore included in the carbon leakage list explained before.

For scenarios where the ETS is implemented, each sector receives a certain amount of free allowances, and must surrender enough allowances to cover its real emissions at the end of the period. Because a carbon allowance has an opportunity cost, emissions-related costs are included in the variable production cost and free allowances are modelled as a lump sum subsidy. In short, for each tonne of commodity produced, the production cost will contain the ETS cost, i.e. the carbon price multiplied by the emissions related to the production of the commodity.

2.2.3 Model assumptions

The assumptions made to build the model are listed below by topic:

Unilateral climate policy assumption:

- The model assumes that no other country implements a climate policy outside of the European Union.

Assumptions on the three industrial sectors:

- The model assumes that firms from the same sector in a given region are symmetric and thus have the same marginal cost of production. In a region, all the firms of a sector are pooled together and define their common prices and quantities. Therefore, each sector can be seen as a cartel in this region, competing against the cartel located in the other region.

- The two varieties coming from the two regions are sold on each market and have their own price. Two products from the same variety are perfect substitutes but two products from different variety (thus region of production) are imperfect substitutes. Therefore, a Constant Elasticity of Substitution ('CES', or Armington elasticity, noted σ_s) aggregate is used to define the utility function.

- Demand functions for industrial sectors are defined by maximising the CES utility function in quantities with respect to the budget constraint (by using a Lagrangian relaxation). It is then possible to solve the underlying equations in quantities to obtain the two demand functions for domestic and foreign goods (see 2.2.6 Consumer Preferences).

- There are no economies of scale, which implies that the marginal production cost is constant with respect to output quantity.

- The model considers raw commodities, i.e. when they have not yet been subject to transformations to become final products.

- The output quantities of the sectors are not limited directly by capacity, but well indirectly by the demand functions. In the case of the European sectors, the output quantities are constrained by the emissions threshold set by the EC.

- The 3 sectors buy 100% of their electricity needs to the European Electricity sector. In other words, the firms from the 3 sectors are not assumed to generate any electricity for their own needs, which is the case in reality, especially in the aluminium sector. Moreover, the energy price is assumed constant. As mentioned before, ETS-related costs faced by the electricity sector is transferred to its clients.

ETS assumptions:

- In reality, all sectors that participate in the EU ETS must respect a unique emissions limit altogether. In the model, however, an individual emissions cap has been set for each sector in order to limit its emissions. These individual caps have been computed using the sectoral emissions levels (direct *and* indirect) observed empirically for the reference year, i.e. 2015. The electricity sector is not part of the model, but the indirect emissions are attributed to the three industrial sectors according to their electricity consumption. Because the three sectors are in the carbon leakage list, they receive 100% of free allowances based on the direct emissions benchmark. As mentioned before, it does not cover all their direct emissions needs because it is based on the top 10% best installations. On the other hand, concerning indirect emissions, no free allowance is given for free as the electricity sector is under full auctioning.

- When full auctioning is applied in the two BCA scenarios, firms must purchase an allowance for every tonne of CO2 they emit. However, the same sectoral emissions thresholds have been conserved, assuming that sectors keep similar ability to procure allowances via auctioning. This assumption leans on the reasonable belief that if the European Commission was to establish a full auctioning allocation rule, it would make provisions to preserve a certain level of output for each sector in any way. This provision would prevent most profitable sectors (in terms of carbon margin) to buy a disproportionate share of the allowances at auctions. This assumption is strong considering the fact that the European lawmaker has no incentive to let such uneven repartition of carbon permits happen. As a result, maintaining the same sectoral thresholds is not fully representative of the reality, but seems more sensible than defining an arbitrary repartition rule of carbon allowances.

- For the Border Carbon Adjustment, the import tax for a tonne of product is set as the carbon price multiplied by the direct emissions of the EU product Benchmark plus the indirect emissions linked to electricity consumption (using the European average electricity emissions intensity). For calculating the export rebate, however, sectoral average emission intensities are used so that exports are totally exempted.

- Investments in cleaner technologies are not taken into account because of the unavailability of the required data. Indeed, to consider such investments, one must collect Marginal Abatement Costs (MAC). The MACs provide, for each sector, their marginal cost increase depending on the unitary emissions abatement level, and are therefore critical for taking abating technologies into account. Unfortunately, they are complex to generate as they require an inventory of the existing technologies and a thorough investment analysis of all the potential low-carbon measures in a sector (or in a whole economy). Some consulting firms[14] specialized in the domain conduct studies to provide an estimation of these MAC and sell this valuable information.

Transport assumption:

- Transport costs within the same region is neglected, while a standard transregional transport cost of 50€/tonne has been chosen, considering a thumb rule of 1000€ per 20-foot container of 20 tonne capacity.

[14] such as the company EnerData

Emissions intensities:

- Given the complexity of gathering reliable information about real emissions intensities for RoW industries as well as the shrinking technology gap worldwide, RoW emissions intensities are assumed similar to those of European industries. Indeed, the globalisation of the economy has fostered a levelling of know-hows in energy-intensive industries, among other sectors. It has been shown that globalisation bridges the technology gap between developing countries and industrialised countries. Besides the increasing international communications means and partnerships, technology levelling can also be attributed to mergers and acquisitions (Archibugi & Pietrobelli, 2003).

- For aluminium and steel, both primary and secondary (remelting) processes were considered. Primary production always consumes much more energy per tonne of product, so the energy intensity is equal to the weighted average of the energy intensities of the two processes.

Welfare:

- A shareholdership coefficient (lambda) that multiplies the EU firms' profits has been used, as firms are not totally owned by European citizens or EU member states. The value of the lambda has been set at 0.7 in light of observations made by Dietsch (2006) concerning rate of foreign shareholdership in European firms.

- Administrative costs linked to the implementation of the ETS and of the BCA have not been taken into account in the calculations.

2.2.4 Scenarios

- Scenario 1: Business-As-Usual ('BAU')

The second scenario is the Business-As-Usual (BAU) situation, which is a representation of the market if the ETS had never been implemented. This scenario is the baseline for the analysis of the changes in competitiveness and carbon leakage.

- Scenario 2: Current situation ('ETS')

This scenario simulates the EU ETS as it currently works. The allocation rule considered is a mix between free allocation for direct emissions and full auctioning for indirect emissions. This is due to the fact that the three sectors are in the carbon leakage list and benefit from the 100% free allocation based on the direct emissions benchmark. But when it comes to their emissions related to their electricity consumption, they do not receive any because the electricity is functioning under full auctioning.

- Scenarios 3 and 4: ETS with a BCA

In the two last scenarios, full auctioning is established, meaning that each sector must buy all the allowances it requires. They also include the implementation of a BCA, but each of them with a different design:

  - Scenario 3 ('ETS BCA M'), where a tax is levied on European imports alone.
  - Scenario 4 ('ETS BCA MX'), where a tax is levied on European imports, but also gives a rebate to European exports to the rest of the world (also called 'full' BCA).

In both scenarios, a tax-based BCA is considered, and includes direct and indirect emissions. For direct emissions, the adjustment base is made by using the EU product emissions benchmark. Concerning indirect emissions, the average European GHG intensity for the production of electricity is used, i.e. 0.465 tCO_2/MWh (Zaklan & Bauer, 2015). The tax is thus computed as the carbon price multiplied by the direct and indirect emissions. For the rebate on exports, however, the EU exporter was already facing a carbon constraint based on its real emissions. Therefore, the rebate is based on the real emissions of the EU exporters so that exports are totally exempted from the carbon policy. Given that the EU product emissions benchmark is based on the average efficiency of the 10% best installations in EU, importers will be taxed more favourably than domestic firms.

2.2.5 Presentation of the sectors

Cement

Cement production is a huge industry; world total output reached 4.65 billion tonnes in 2015. The production in the European Union represents only 3-4% of this total, while China makes up half of it (CEMBUREAU, 2017).

The production of one tonne of cement emits about 0.7 tonne of CO2, among which process emissions represent roughly 95% (IEA, 2018). Worldwide, the cement sector is responsible for about 5% of global GHG emissions related to human activities (Andrew, 2018). Because the raw materials required, i.e. mostly clinker and lime, are not expensive, cement production costs are relatively low; 65 and 56 € per tonne in the EU and in the RoW respectively (Miller & Osborne, 2014). Given the very low value-to-weight ratio, cement is facing very high transportation costs, which represents a barrier to international trade (de Bruyn et al., 2008).

Aluminium

World aluminium production was of 77 million tonnes in 2015. The European Union firms are making up about 10% of the world market (European Aluminium, 2016).

The aluminium production process requires very high quantities of energy under the form of electricity (16.1 MWh/t), which amount for about one third of its production cost. The total emissions intensity is of 10 tCO2/t, among which 75% are due to electricity use. In total, aluminium production activities represent about 1% of global GHG emissions. European producers have an estimated unitary production cost of 1021€, against 969€ for their RoW competitors (Carbon Trust, 2011; Renda et al., 2014). The value-to-weight ratio of this commodity being very high, transportation costs are not significant in comparison with the production costs (de Bruyn et al., 2008).

Steel

In 2015, the steel industry produced 1.6 billion tonnes of crude steel, of which the European Union accountable for about 9%. Like in the cement sector, China produces half of the world steel supply (EUROFER, 2018).

On average, one tonne of crude steel implies 1.16 tCO2 of direct emissions and 0.14 tCO2 related to the electricity consumption (Carbon Trust, 2011). As a result, one tonne of steel emits almost two times more CO2 than one tonne of cement, and about 8 times less than one tonne of aluminium. In the world, steel is responsible for 4 to 5% of total emissions (World Steel Association, 2016). Production costs are similar around the world; 404€ in the EU and 400€ in the RoW (Carbon Trust, 2011).

2.2.6 Consumption preferences

The three sectors compete in both EU and RoW markets and goods are imperfect substitutes; consumers have different preferences for goods produced locally than for goods imported from foreign region. Even though these commodities are standardised products, the service provided by local cement producers differs from the RoW for several considerations: the price stability, security of supply, value perception, help provided for the use of their product, marketing, delivery time, etc. (Demailly and Quirion, 2008). Therefore, a Constant Elasticity of Substitution (CES) aggregate has been used to represent these preferences.

The exhaustive list of mathematical symbols used in this thesis is given in Appendix 5. In the following explanations, a focus on a single sector is made. In market r, the consumer utility function is expressed as follows:

$$u_r(Q_{rr}, Q_{r'r}) = \left(a_r\ Q_{rr}^{\frac{\sigma-1}{\sigma}} + b_r\ Q_{r'r}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \qquad \forall r \neq r'$$

Where a_r (resp. b_r) is the preference coefficient[15] of region r for a good produced in the local (resp. foreign) region, and σ is the Armington elasticity (or CES) of the sector. For quantities Q, the first index always refers to the region where the good was produced, while the second represents the market where it is sold. Hence, Q_{rr} (resp. $Q_{r'r}$) is the quantity of domestic (resp. foreign) products sold in this market r.

The budget constraint is defined as:

$$Q_{rr}\ p_{rr} + Q_{r'r}\ p_{r'r} = \alpha_r\ B_r \qquad \forall r \neq r'$$

Where α_r is the expenditure share for this sector in this region with respect to the regional budget B_r.

To derive the demand functions in a regional market, the utility function is maximised under the regional budget constraint using a Lagrangian relaxation.

$$L_r(Q_{rr}, Q_{r'r}, \lambda) = \left(a_r\ Q_{rr}^{\frac{\sigma-1}{\sigma}} + b_r\ Q_{r'r}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} + \lambda(\alpha_r\ B_r - Q_{rr}\ p_{rr} - Q_{r'r}\ p_{r'r}) \quad \forall r \neq r'$$

[15] Note that $b_r = 1 - a_r$ in each region

To maximize this Lagrangian, three First Order Conditions (FOCs) must be satisfied.

$$(1)\ \frac{\partial L_r}{\partial Q_{rr}} = 0 \qquad \forall r \neq r' \qquad (2)\ \frac{\partial L_r}{\partial Q_{r'r}} = 0 \qquad \forall r \neq r' \qquad (3)\ \frac{\partial L_r}{\partial \lambda} = 0 \qquad \forall r$$

The third FOC simply gives back the budget constraint. Solving the system formed by the two first FOCs yields the two demand functions; the first one for the domestic goods and the second one for the imported goods (Dixit & Stiglitz, 1977; Rutherford, 2002).

$$Q_{rr}(p_{rr}, p_{r'r}) = \alpha_r B_r \frac{a_r^{\sigma}\ p_{rr}^{-\sigma}}{a_r^{\sigma}\ p_{rr}^{1-\sigma} + b_r^{\sigma}\ p_{r'r}^{1-\sigma}} \qquad \forall r \neq r'$$

and

$$Q_{r'r}(p_{rr}, p_{r'r}) = \alpha_r B_r \frac{b_r^{\sigma}\ p_{r'r}^{-\sigma}}{a_r^{\sigma}\ p_{rr}^{1-\sigma} + b_r^{\sigma}\ p_{r'r}^{1-\sigma}} \qquad \forall r \neq r'$$

As a result, each sector is composed of four demand functions; one for each type of goods (either produced in EU, or in RoW) sold in each market (EU or RoW). Moreover, each demand function depends on the prices of the two products available on the same regional market.

Preference coefficients for each region are determined by the calibration of the model, using empirical data from 2015 (see Appendix 8). For some data, a time adjustment has been made to represent as best as possible the situation of the reference year.

Concerning Armington elasticities (or CES), large differences exist according to sectors and countries. Monjon and Quirion (2011) find a range of values used in the literature for several sectors. The present model has used Armington elasticities roughly equal to the mean of these intervals. These values are: 2 for cement, 2.5 for aluminium and 3 for steel.

In a nutshell, calibration is performed by tuning the preference coefficients so that they match the data, allowing the demand curves to represent realistically the market. The calibrated coefficients are the following:

- Cement: $a_E = 0.67$; $b_E = 0.33$; $a_R = 0.87$; $b_R = 0.13$
- Aluminium: $a_E = 0.55$; $b_E = 0.45$; $a_R = 0.81$; $b_R = 0.19$
- Steel: $a_E = 0.59$; $b_E = 0.41$; $a_R = 0.78$; $b_R = 0.22$

Figure 6 below represents the two demand functions of steel on the EU market, for the domestic and foreign commodities, to better visualise them.

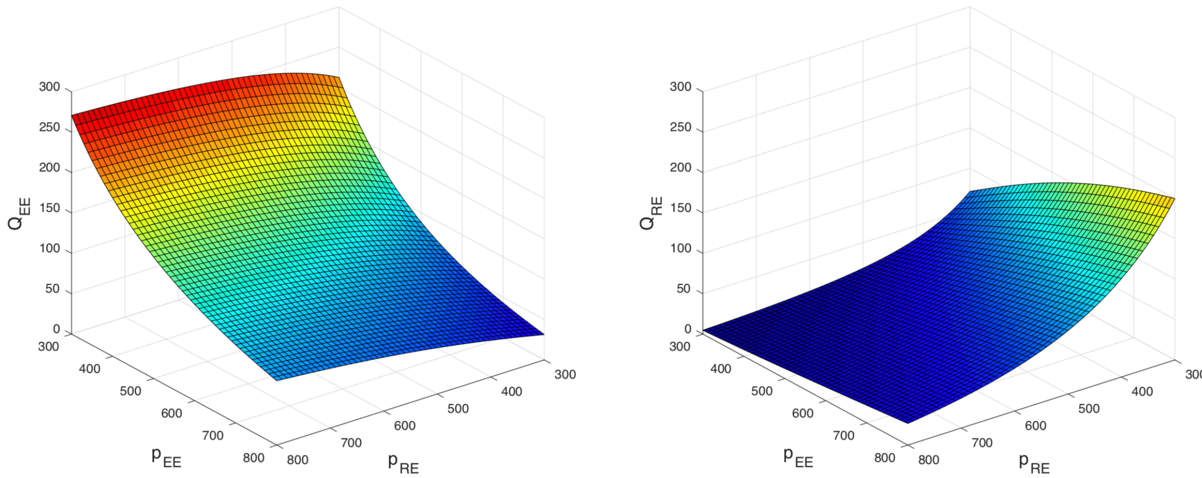


Figure 6: Demand functions for domestic (on the left) and foreign (on the right) steel and on the EU market as a function of the prices of these two goods.

2.2.7 Model resolution

2.2.7.1 Defining the carbon market price (Social Planner Equilibrium)

The first step that needs to be done is to define the carbon market price. It has been estimated as the social cost of carbon (SCC). In other words, it is equal to the cost incurred by the European society by the emission of an additional tonne of CO2. Therefore, the SCC is computed as the shadow price of the emissions constraint in a situation where a social planner[16] determines the prices of the European sectors that maximise the European welfare under the RoW profit maximisation first order conditions (FOCs), resulting in a Nash Equilibrium. In the context of public economics, a shadow price is often used to estimate the monetary value of a public good that has no market value (Smelser & Baltes, 2001).

The EU welfare (W_E) is calculated as the sum of the EU Consumer Surplus (CS_E) resulting from the consumption of domestic and foreign goods in the EU market and the EU firms' profits, for all sectors:

$$W_E = CS_E + \lambda\ \pi_E$$

$$CS_E = \sum_{s=1}^{3}\left(\int_{p_{s,EE}}^{+\infty} Q_{s,EE}\, dp'_{s,EE} - p_{s,EE}\ Q_{s,EE} + \int_{p_{s,RE}}^{+\infty} Q_{s,RE}\, dp'_{s,RE} - p_{s,RE}\ Q_{s,RE}\right)$$

$$\pi_E = \sum_{s=1}^{3}\Big((p_{s,EE} - c_{s,EE})Q_{s,EE} + (p_{s,ER} - c_{s,ER})Q_{s,ER}\Big)$$

The exhaustive mathematical expressions are developed in details in Appendix 5 and 6.

The shadow price obtained via the social planner maximisation under the European emissions constraint was of 21.7 €/tCO2. This value is the estimation of the carbon market price used in scenarios including an ETS and is noted as Beta (β).

2.2.7.2 Obtaining the market Equilibrium

In each sector, two players, i.e. EU and RoW producers, define their two prices (one in their domestic market and one for their exports) in order to maximise their own profit. When a player changes one of his prices, it will affect the strategy of his competitor, and therefore the game will stabilise when no player has any incentive to change unilaterally his prices. This situation is defined as a Nash Equilibrium. Mathematically, a system of

[16] Also called "benevolent planner"

equations is solved thanks to the software *MATLAB*. The equations are the First Order Conditions (FOCs) resulting from the profit maximisation[17] of each player depending on his prices. Hence, there are two FOCs per player which means four equations per sector:

$$\begin{cases} \dfrac{\partial \pi_{s,E}}{\partial p_{s,Er}} = 0 \\ \dfrac{\partial \pi_{s,R}}{\partial p_{s,Rr}} = 0 \end{cases} \qquad \forall s, r$$

The full model is developed in details in Appendix 5 and 7.

2.3 Analysis of the results

In this section, the results obtained by the model are presented and analysed in three parts. The first part is about the impacts of BCAs on world emissions and carbon leakage, the second focuses on their effects on sectoral competitiveness, and the third and final part concerns their repercussions on social welfare.

2.3.1 Effects on carbon leakage and world emissions

As a reminder, the carbon leakage rate (CLR) formula is:

$$CLR = \frac{\Delta e_R}{|\Delta e_E|}$$

Where Δe_R and Δe_E are variations in emissions in each region with respect to the BAU scenario.

Carbon leakage (CL) results in Figure 7 show CL rates between 38% and 68% in the ETS scenario, which is much higher than the range observed in the literature, i.e. from 5% to 40%. To put this result into context, the present model only covers three sectors

[17] The second order conditions of the individual profit maximisations are not included into the model as they are always satisfied, i.e. their second derivatives are always negative.

which are very exposed to carbon leakage, while most of the literature studies provide an average value for a wider range of sectors, among which sectors that are much less deemed to carbon leakage. Across sectors, cement has the lowest CLR, which can be explained by its lower exposure to international trade.

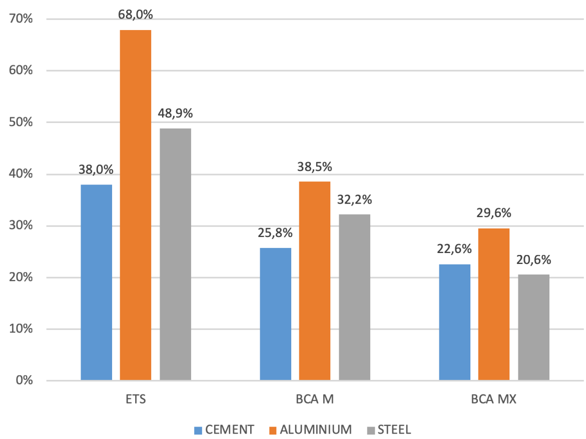


Figure 7: Carbon Leakage Rates

Implementing a Border Carbon Adjustment on imports allows to reduce CLRs overall by levelling the playing field between domestic and foreign producers in the EU market. Moreover, this reduction is even larger with a full BCA due to the rebate on EU exports. Precisely, CL rates range between 25.8% and 38.5% with an imports-based BCA, and between 20.6% and 29.6% with a full BCA. In average and for all sectors, the adoption of a BCA on imports reduces the average CLR by one third, while this rate is cut by half with a full BCA. In light of these observations, hypothesis 1.1 (*"A BCA decreases carbon leakage with respect to a situation with an ETS, and a full BCA is more efficient to this extent")* seems to hold according to the model.

BCAs seem to perform well at reducing CL when looking at these results. However, it is difficult to assess which carbon leakage rate could be acceptable. In other words, can we be satisfied with CL rates over 20%? It implies that for each emissions abatement effort made in the EU, at least a fifth of this effort is wiped out in the rest of the world. This question is not straightforward and requires to have a broader view of the situation.

Besides carbon leakage, another important aspect of a BCA is its effect on global emissions levels from the three sectors, which are shown in Figure 8. It can be seen that the EU ETS has lowered emissions by 3.5% worldwide compared to BAU. Also, BCAs appear to mitigate total emissions of industrial sectors in the world; imports-based BCA and full BCA have resulted in a global abatement of 4.9% and 5.5% respectively. The emissions reductions associated with BCAs are 40% and 57% larger than with the ETS. These variations are not negligible and lead to the rejection of hypothesis 1.2 (*"The additional global emissions mitigation due to a BCA is marginal as compared to the introduction of an ETS"*).

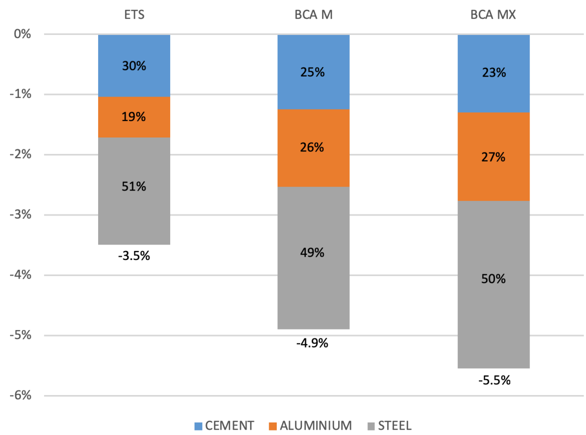


Figure 8: Variation of global emissions compared to BAU

Breaking down the emissions reductions by sector, it can be seen that steel makes up about half of them in each scenario. Cement and aluminium contribute respectively to 30% and 19% of the total diminution in the ETS, while in the BCA M and BCA MX scenarios, aluminium has a higher importance in global reduction (26% and 27%, respectively) compared to cement (25% and 23%, respectively).

2.3.2 Effects on sectoral competitiveness

On the competitiveness side, the market power relationship between EU and RoW firms must be analysed. It is important to underline that the variations in market shares (MS)

- either in terms of volume or value - that will be presented below are expressed with respect to scenario 1 (BAU) following this formula:

$$Var\ MS_i = \frac{MS_i - MS_{BAU}}{MS_{BAU}} \qquad \text{for each scenario } i$$

First of all, Figure 9 shows the variation in European producers' global market shares in terms of volume. A significant loss of overall European competitiveness between BAU and ETS can be observed, as European sectors lost on average 20.6% of their initial volume MS. More specifically, aluminium is the sector that was the most severely hit by the ETS, with a 25.4% decrease. Cement and steel experience significant losses as well, but to a lesser extent; 19.2% and 17.1% respectively. While the magnitudes of variations with respect to the BAU seem overestimated, the trends between scenarios remain interesting. Moreover, it can be seen that the variations across the ETS, BCA M and BCA MX scenarios, which are key for the analysis, are way more reasonable.

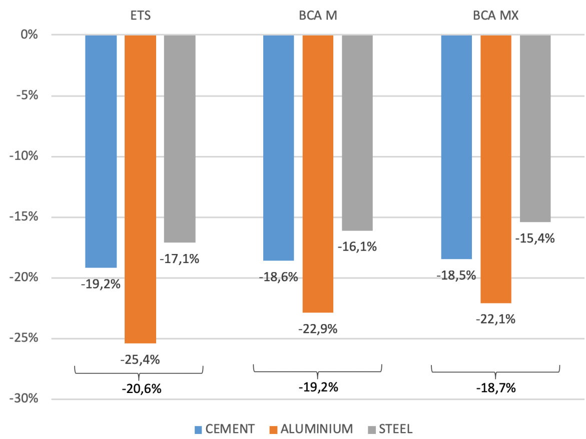


Figure 9: Variation in global Volume Market Shares of EU firms (compared to BAU)

In average, the reduction in volume MS were mitigated from 20.6% in the ETS scenario to 19.2% with a BCA on imports and to 18.7% with a full BCA. This goes along with hypothesis 2.1 ("*A BCA restores some of the competitiveness loss induced by the ETS, and a full BCA is more efficient for this purpose.*"). However, it is relevant to underline that these results show minor efficiency in rebalancing the volume market shares.

Nevertheless, it is important to underline that because of the EU ETS cap, the total production output of European sectors remains constant across scenarios ETS, BCA M and BCA MX. Therefore, variations between these three scenarios are due to output variation of RoW producers.

Because prices of domestic and foreign firms are different in the same market, the variations of their production quantities miss part of the competitiveness picture. Therefore, it is relevant to analyse the value market shares of each sector, which represent the market shares in terms of sales revenue and allow to quantify the market power balance from a different perspective. Figure 10 depicts their variation at the global level for each sector. It appears that each sector follows the same trend across scenarios as for volume market shares, which reinforces the validity of hypothesis 2.1. Nevertheless, it is interesting to note that the drop is lower in value than in volume, meaning that European firms somehow managed to increase their prices more than the RoW firms in each scenario.

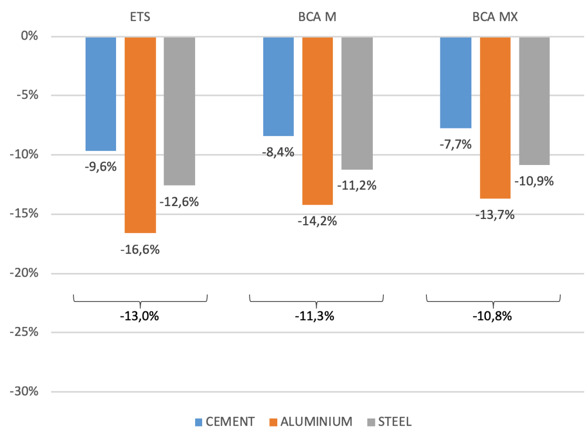
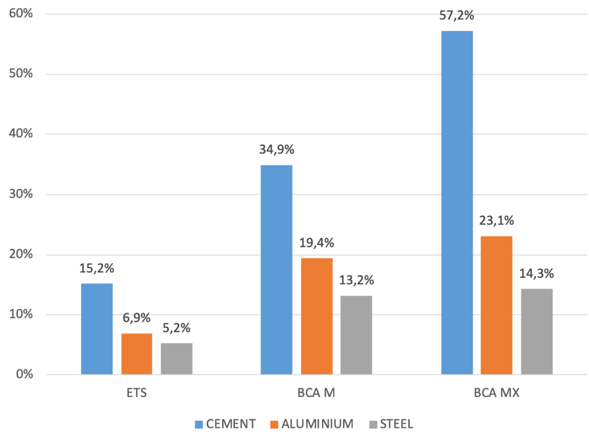


Figure 10: Variation in global Value Market Shares of EU firms (compared to BAU)

It appears that aluminium is the sector that benefits the most from the implementation of the BCAs, as it reduces the decrease in volume MS from -16.6% (ETS) to -14.2% and to -13.7% for BCA M and BCA MX, respectively. This corresponds to a mitigation of the MS losses of 2.4% for the BCA M scenario and 2.9% for the BCA MX scenario. The fact that aluminium is the sector with the largest increase in costs due to the carbon pricing (+19.1%) follows hypothesis 2.2 ("*Sectors with large variation in costs due to carbon pricing are more impacted by the BCA in terms of competitiveness*"). In comparison, these reductions are equal to 1.2% and 1.9% for cement and amount to 1.4% and 1.7% for steel which are similar. However, the carbon related cost of steel is much lower (+5.9%) than the one of cement (+15.3%). In light of this, hypothesis 2.2 does not hold anymore. The relationship between the impact of BCAs on MS and the additional carbon cost is more complex than expected and is probably the result of the combination of several factors, such as the Armington elasticity and the preference coefficients.

Price indices[18] per regional market are represented in Figure 11 and market sizes in terms of volume are shown in Figure 12. These two pairs of graphs share a symmetry, as prices and quantities are inversely proportional. They offer a good overview of market evolution throughout scenarios.



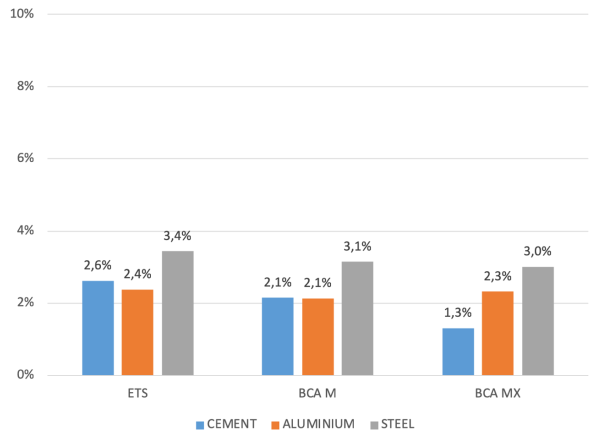


Figure 11: Variation in price index in the EU Market on the left and in the RoW Market on the right (compared to BAU)

[18] The price index of a certain market is computed as the volume-weighted average of the two prices (set by domestic firms and foreign firms) in this market.

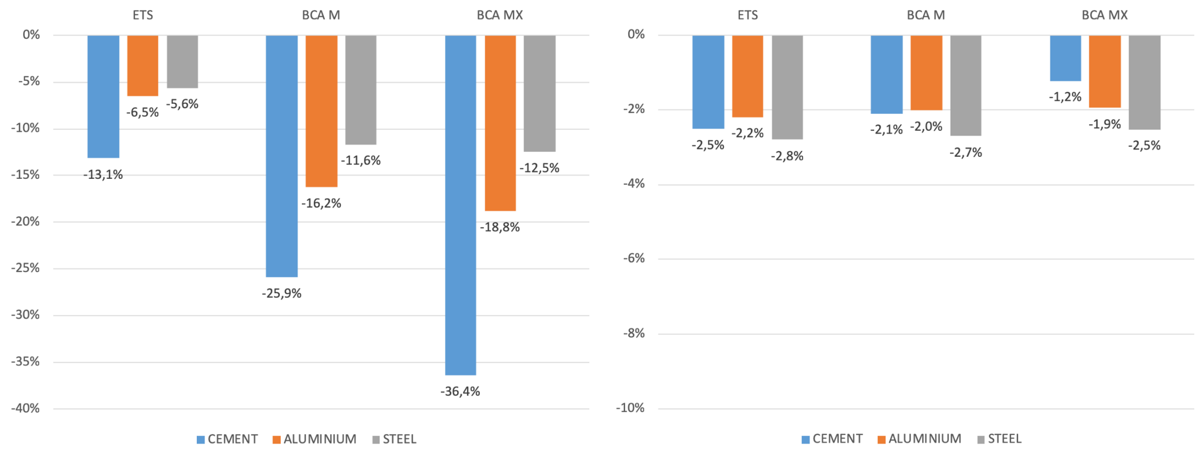


Figure 12: Variation of the EU Market size on the left and of the RoW Market size (in terms of volume, compared to BAU)

Figure 11 confirms that price indices have effectively increased due to the creation of the ETS, for all sectors and in all scenarios, both in the EU and in the RoW. The price index variations in the EU are much greater than in the RoW, which is due to a combination of two effects:

- The first one is due to the fact that European firms benefit from their domestic advantage in terms of consumers preferences (i.e. $a_{s,E}$ are comprised between 0.55 and 0.67), which implies that they are able to increase their domestic price without losing too much of their sales volume. On the other hand, the preference factor of European commodities exported to the RoW market are very low ($b_{s,R}$ range from 0.13 to 0.22), which means that they are outsiders and that a price increase would significantly cut their RoW volume sales. As a result, when European firms must reduce their output quantities because of the emissions cap, they tend to increase their domestic prices to a larger extent with respect to their export price.
- The second effect is linked to the larger volume market shares of EU firms in the EU market, which implies that their price increase is more represented in the price index.

In Figure 12 (left), all sectors experience a much higher drop in European market size when a BCA on imports is implemented as compared to the ETS scenario. It shows that when domestic producers are the only ones to be affected by the climate policy, the EU market is not shrinking too much as the increase in imports partly offsets the production drop of domestic producers. When the asymmetry is corrected thanks to the BCA, however, the EU market is subject to an important contraction. On the other hand, considering a full BCA, the EU market size is even smaller than with only imports. At first, it may sound strange that the inclusion of a rebate on exports would impact negatively the EU market size. However, in light of the fact that the European producers are limited by the emissions cap, the volumes they sell in each market are acting like two communicating vessels. It can indeed be seen by looking at Figure 13 that European producers' market shares in the two regions evolve in opposite directions between BCA M and BCA MX. Hence, this singularity may be explained by a shift of European goods from the EU market to the RoW market, leading to a drop in supply in the EU and to a rise in the average market price.

Concerning the RoW market, Figures 11 (right) and 12 (right) show smaller variations in RoW prices and market size. As mentioned above, it makes sense that the RoW is less impacted by European policies (ETS and BCA) than the EU market itself. These impacts range between -1.2% and -2.8% for market size variations, and between 1.3% and 3.4% for price indices variations.

In Figure 13, it appears that all three sectors react similarly to the two types of BCAs. For the BCA on imports, their volume MS in the EU are improved thanks to the levelling of carbon taxation, while the effect on RoW MS is negligible. When rebates on exports are added, European firms tend to reallocate a part of their production to the RoW market, which decreases their EU MS and improves their RoW MS. The European value

MS in both regions shown in Figure 14 follow the same trend as their volume counterparts, which means European firms did increase their prices to a larger extent than their RoW competitors.

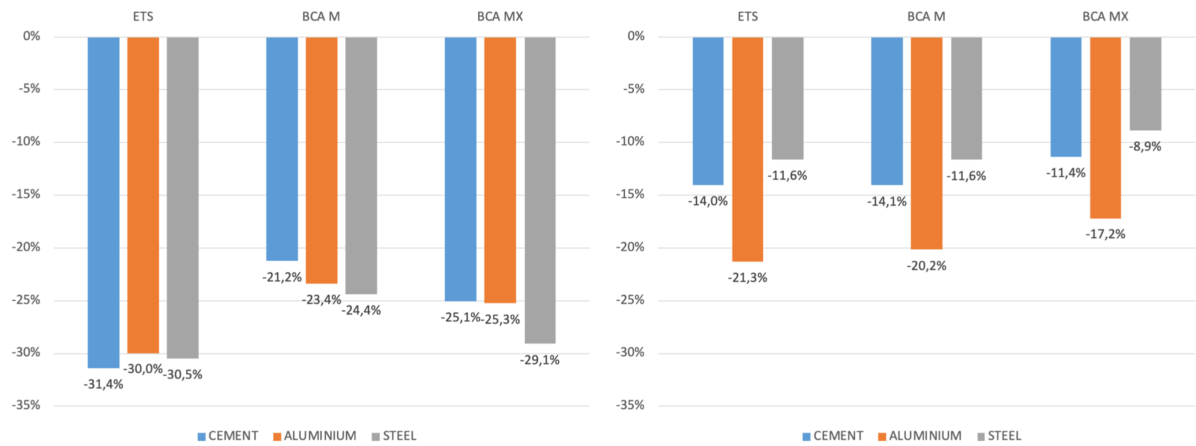


Figure 13: Variation in Volume Market Shares of EU firms in the EU market on the left and in the RoW market on the right (compared to BAU)

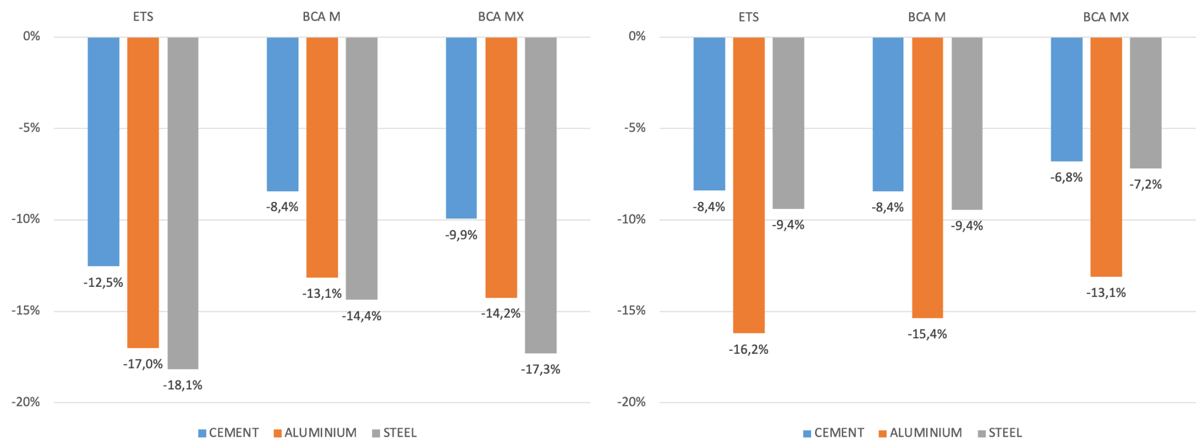


Figure 14: Variation in Value Market Shares of EU firms in the EU market on the left and in the RoW market on the right (compared to BAU)

2.3.3 Effects on social welfare

Since previous graphs have shown that BCAs generate additional price increases in the European Market as well as a fall in EU consumption, one can wonder how they impact European social welfare. As a reminder, European welfare is defined by the following equation, which may include Tax Revenue (TR) for scenarios in which the ETS is present:

$$W_E = CS_E + \lambda\, \pi_E + TR$$

Figure 15 presents a breakdown of European social welfare across scenarios. It appears that the implementation of the ETS has a negative effect on welfare, and that BCAs almost fully reduce the drop in welfare. While European firms experience a fall in their profits due to the ETS, BCAs allow to curb these profit losses. Moreover, European firms are better off with a full BCA (€81.4 billion), as they almost recover their BAU profit level (€83.2 billion). Also, the model suggests that the ETS reduces the Consumer Surplus and that both types of BCAs make this reduction greater. This trend makes sense in light of the price increases and the contraction of the European market observed previously. In conclusion, these two effects validate hypothesis 3.1 (*"A BCA improves the profit of European firms to the detriment of European consumers with respect to the ETS scenario").*

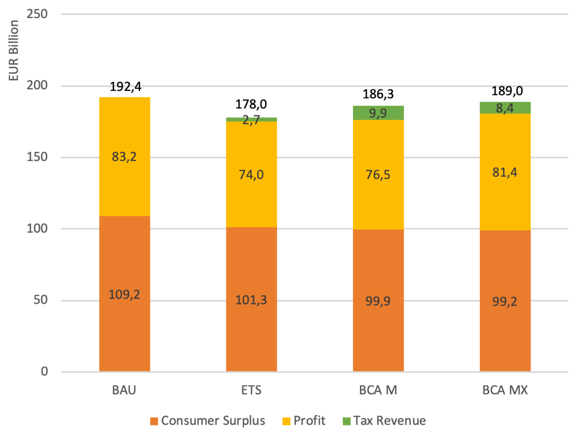


Figure 15: EU Welfare breakdown

It is also relevant to notice that because BCAs entail the end of free allowances, the underlying tax revenue is growing by a factor of 4 with an import coverage and by a factor of 3 with a full coverage. The full BCA creates thus less tax revenue as exports become free of ETS charges.

A limitation of this welfare analysis is due to the fact that it consists in a pure economic rationale, but does not take the state of the environment into account. The fact that European welfare is lower in scenarios including an ETS - with or without a BCA - than in the BAU case suggests that the European society would be better off with no climate policy at all. However, this fall in economical welfare has to be tempered by the positive impact of GHG emissions reduction. Thanks to the Social Cost of Carbon computed before (€21.7/tCO2), it is possible to estimate the ecological costs due to world emissions and thus obtain a welfare value that includes the environmental component. Scenarios with high world emissions will be penalised because of their high environmental costs. This welfare measure will be referred as the "Environment-adjusted welfare" (noted $W_{E\ env}$) in opposition to the traditional welfare presented previously.

$$W_{E\ env} = CS_E + \lambda\ \pi_E + TR - SCC(e_E + e_R)$$

Figure 16 shows the two welfare metrics for all scenarios. It can be seen that Environmental-adjusted welfare decreases for ETS and BCA M scenarios (€148.8 and €160.0 billion respectively) compared to BAU (€161.4 billion), but it increases in the case of a full BCA (€163.0 billion). Hence, the model suggests that the European society is only better off with the implementation of a full BCA, even when considering the environmental return of the climate policy, which refutes hypothesis 3.2 (*"When integrating environmental effects into the welfare measurement, the implementation of an ETS, with or without a BCA, improves the European welfare").*

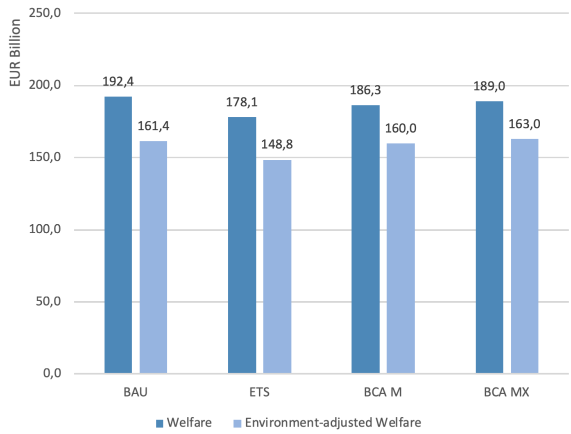


Figure 16: EU Welfare comparison

2.4 Limitations and future work

The model presented in this thesis uses assumptions that simplify the reality in order to observe the impacts of BCAs on three industrial sectors of the EU ETS. The results exposed and discussed in the previous section have several limitations, which should prompt caution.

The downturn of using a Partial Equilibrium is that the economic interactions between the three sectors and the rest of the economy (e.g. other commodities, fuel price, capital, labour or GDP) are neglected. For example, variations occurring in a certain sector have repercussions on many macroeconomic variables as well as on other sectors that are either its complements or substitutes. In short, this model observes cement, aluminium and steel sectors operating in a sort of artificial vacuum.

The model uses massive aggregation by dividing the world into the European Union and the Rest of the World, which is composed of very heterogeneous countries. It makes complex to gather data that represent the actual situation in a realistic manner. As a result, the complexity of the economic reality is maybe poorly represented in the model. A good example is the constant transport cost between regions; the approach of the model is basic as it does not take the means of transportation (e.g. by ship, train or truck) nor the distance travelled into account. Hence shipping from Belgium to the Middle East or to China is very different.

Besides, the model does not take investment carbon leakage into account, i.e. the long-term relocation of investments to no-policy regions due to a decrease in the sectoral profitability. In other words, this model neglects the weakening of industrial sectors which could lead to more carbon leakage on the long run.

Another limitation of the model is related to the use of theoretical consumption preferences by the use of the CES aggregate. Given that actual purchasing behaviours are not rational, they are complex to quantify precisely. The CES aggregate utility function is considering that consumers are not concerned about the environmental impact of their purchases. As a result, utility is monotonically increasing with consumption of goods.

Given that environment preservation becomes more and more important worldwide, consumption patterns are likely to change in the future. Part of the population would probably begin to reduce their consumption in energy-intensive products, which implies that the utility function would integrate the effects of their purchases on climate change. This will certainly be a very slow and long process as people are generally very reluctant to change their habits, even though they are aware of the negative consequences for the environment. Therefore, future work could design a model in which the utility function integrates these changes. Hence, the following paragraphs give some tracks and thoughts about it.

Mathematically, a method to express the general utility function *U(q,e)* containing this adjustment of preferences could be for example:

$$U(q,e) = u(q)\ f(e) \qquad \Leftrightarrow \qquad U(q) = u(q)\ f'(q)$$

Where *u(q)* represents the utility derived by the consumption of goods q and *f(e)* represents the state of the environment comprised between 0 and 1 and is a monotonically decreasing function with total emissions e. Note that emissions are depending on the consumption of goods q, and therefore *f(e)* can be expressed as *f'(q)*.

These two functions being multiplied, a very large consumption would be penalised by the destruction of the environment, which would moderate excessive consumption. In other words, the general utility function allows to model some sort of environmental consciousness of the society. Figure 17 below shows theoretical curves for this change in the utility function. The general utility function then loses its monotonicity and comprises a maximum. The orange lines represent a situation where consumers are more concerned about the need to preserve the environment than the blue lines.

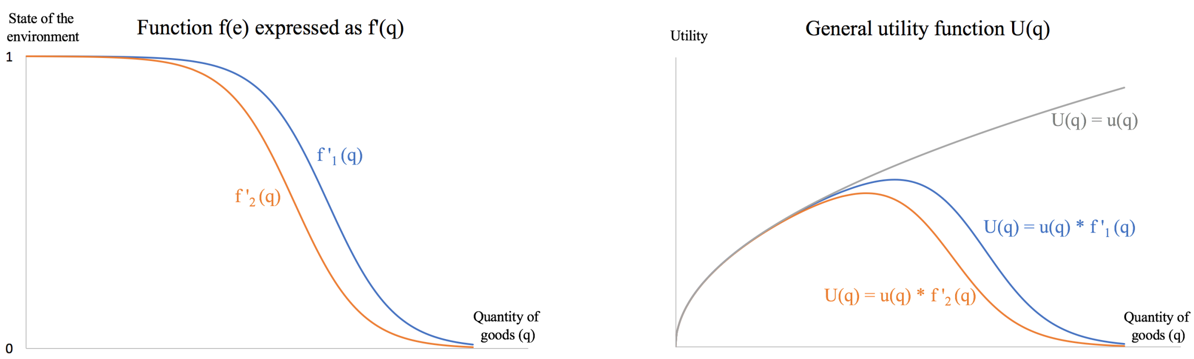


Figure 17: Theoretical adjustment of utility function

As a result, how people care about reducing global GHG emissions - i.e. their perception of ecological urgency and their willingness to take action themselves by consuming less - will impact the shape of the function f(e) and impact consumption patterns.

However, this adjustment of the general utility function is complex to implement in this model as the demand functions cannot be found analytically in the case of a Constant Elasticity of Substutition (CES) aggregate utility function.

Conclusion

Climate change is one of the biggest challenges of the 21st century, and the world is slowly understanding the urgency of the situation. As of today, the international community has failed to unite forces and define binding environmental commitments for every country. In addition to that, the rise of protectionism does not suggest that a global climate policy is about to happen. Therefore, the future implementation of a Border Carbon Adjustment (BCA) is to be considered if the European Union wants to address the competitiveness issues that are caused by the unilateral nature of the European Union Emissions Trading Scheme (EU-ETS).

A Partial Equilibrium model has been designed in order to quantify the impacts of two BCA variants (i.e. including only imports vs. including both imports and exports) on carbon leakage, competitiveness and welfare. The cement, aluminium and steel sectors were chosen as they are deemed exposed to risks of carbon leakage.

The model first confirmed the hypothesis according to which a BCA reduces carbon leakage compared to a scenario with an ETS and that the full variant generates a higher reduction. It also came out of the results that both BCA types significantly decrease global emissions, to a larger extent than the variations observed in the literature.

Moreover, it appeared that a BCA effectively restores competitiveness losses in terms of both volume market shares and value market shares, and again, the full BCA is obtaining better improvements than its counterpart. Another interesting finding is that the ETS-related increases in regional price index are much larger in the EU than in the rest of the world, which is mainly due to the fact that EU firms are better off by increasing their domestic prices, that is made possible thanks to their leader position in their domestic market. The outcome of these higher price indices is a contraction of the two regional markets. Furthermore, the model results do not allow to validate the relationship between high carbon cost increases and BCA impact on sectoral competitiveness. It seems that the way sectors are impacted depends on a combination of effects which is more complex than expected.

When looking at the welfare breakdown, it is found that the ETS reduces the Consumer Surplus and that BCAs make this reduction worse, since the European market is shrinking and its price index is on the rise. On the other hand, both BCAs improve the EU firms' profits. As a result, BCAs favour European corporate interests but are not beneficial for the European consumers. Furthermore, when integrating environmental impacts into the welfare computation, it is observed that only the implementation of a full BCA improves European welfare compared to BAU. According to this model, the implementation of the ETS is not beneficial to the European society compared to BAU.

Overall, it appears that while BCAs are efficient at rebalancing sectoral competitiveness and reducing carbon leakage, their effect is detrimental to European welfare, among others because of the drop in consumption. However, if the European Union wants to reach its greenhouse gases emissions mitigation target of 60% by 2040 compared to its 1990 level, it seems that it should not only base its hopes on technology improvements, but also on consumption reduction.

Of course, the findings of this thesis are to be considered critically in light of the limitations discussed in the dedicated section.

References

Aldy, J. E., & Pizer, W. A. (2011). *The competitiveness impacts of climate change mitigation policies*. National Bureau of Economic Research. doi:10.3386/w17705

Andrew, R. M. (2018). Global CO2 emissions from cement production. *Earth System Science Data, 10*, 195-217. doi:10.5194/essd-10-195-2018

Alexeeva-Talebi, V., Böhringer, C., & Moslener, U. (2007). *Climate and Competitiveness: An Economic Impact Assessment of EU Leadership in Emission Control Policies*. Centre for European Economic Research (ZEW), Mannheim.

Archibugi, D., & Pietrobelli, C. (2003). The globalisation of technology and its implications for developing countries windows of opportunity or further burden? *Technological Forecasting & Social Change, 70*(9), 861-883. doi:10.1016/S0040-1625(02)00409-2.

Atkinson, T. (2016). *COMMENT: In a volatile EU ETS, spare a thought for the compliance guys.* Retrieved from the website of Carbon Pulse, https://carbon-pulse.com/14915/

Aykut, S. C. (2014). Gouverner le climat, construire l'europe : L'histoire de la création d'un marché du carbone (ETS). *Critique Internationale,* (62), 39-55.

Bednar-Friedl, B., Schinko, T., & Steininger, K. W. (2012). The relevance of process emissions for carbon leakage: A comparison of unilateral climate policy options with and without border carbon adjustment. *Energy Economics, 34*, S168-S180. doi:10.1016/j.eneco.2012.08.038

Biermann, F., & Brohm, R. (2005). Implementing the Kyoto Protocol without the USA: the strategic role of energy tax adjustments at the border. *Climate Policy,* Vol. 4, 289-302.

Böhringer, C., Balistreri, E. J., & Rutherford, T. F. (2012). The role of border carbon adjustment in unilateral climate policy: Overview of an energy modeling forum study (EMF 29). *Energy Economics, 34*, 97-110. doi:10.1016/j.eneco.2012.10.003

Borkent, B., Gilbert, A., Klaassen, E., Neelis, M. L., & Blok, K. (2014). *Dynamic allocation for the EU emissions trading systems : Enabling sustainable growth : Final* *report.* Ecofys, Utrecht.

Branger, F., & Quirion, P. (2014a). Climate policy and the 'carbon haven' effect: Climate policy and the carbon haven effect. *Wiley Interdisciplinary Reviews: Climate Change, 5*(1), 53-71. doi: 10.1002/wcc.245

Branger, F., & Quirion, P. (2014b). Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? insights from a meta-analysis of recent economic studies. *Ecological Economics, 99*, 29-39. doi:10.1016/j.ecolecon.2013.12.010

Burniaux, J.-M., Chateau, J., & Duval, R. (2010). *Is there a case for carbon-based border tax adjustment: an applied general equilibrium analysis*. Paris: OECD Economics Department Working Papers no. 794.

Carbon Trust. (2011). *International Carbon Flows.* Unpublished document. Retrieved from https://www.carbontrust.com/resources/reports/advice/international-carbon-flows/

Caron, J. (2012). Estimating carbon leakage and the efficiency of border adjustments in general equilibrium — does sectoral aggregation matter? *Energy Economics, 34*, S111-S126. doi:10.1016/j.eneco.2012.08.015

Carraro, C., & Siniscalco, D. (1993). Strategies for the protection of the environment. Journal of Public Economics, 52, 309–328.

CEMBUREAU. (2017). *Activity Report 2017.* Retrieved from https://cembureau.eu/media/1716/activity-report-2017.pdf

Charnovitz, S., Kim, J., & Hufbauer, G. C. (2009). *Global warming and the world trading system* Peterson Institute for International Economics.

Chesney, M., Gheyssens, J., & Taschini, L. (2013). *Environmental finance and investments*. Berlin/Heidelberg: Springer Berlin Heidelberg.

Chevallier, J., Jouvet, P., Michel, P., & Rotillon, G. (2009). Economic consequences of permits allocation rules. *Economie Internationale, 120*(4), 77-89.

Climate Change Connection. (2018). *CO2 Equivalents*. Retrieved from https://climatechangeconnection.org/emissions/co2-equivalents/

Climate Policy Info Hub. (2014). *Overview of Climate Tragets in Europe.* Retrieved from https://climatepolicyinfohub.eu/overview-climate-targets-europe#31-eu-sets-long-term-emissions-reduction-target-fo

Coase, R. H. (1960). The problem of social cost. *Journal of lax and economics, 3*, 1-44.

Condon, M., & Ignaciuk, A. (2013). Border Carbon Adjustment and International Trade: A Literature Review. *OECD Trade and Environment Working Papers*, 2013(6). http://dx.doi.org/10.1787/5k3xn25b386c-en

Couëdic, H. (2018). *Le prix du CO2 au plus haut depuis 6 mois*. Retrieved from Le Revenu. Web site: https://www.lerevenu.com/bourse/coulisses/le-prix-du-co2-au-plus-haut-depuis-6-mois

de Bruyn, S.M., Nelissen, D., Korteland, M., Davidson, M., Faber, J., & van de Vreede, G. (2008). *Impacts on Competitiveness from EU ETS, An Analysis of Dutch Industry*. CE Delft, Delft.

Demailly, D., & Quirion, P. (2008). *Changing the allocation rules in the EU ETS: Impact on competitiveness and economic efficiency.* Fondazione Eni Enrico Mattei (FEEM), Milano.

Dietsch, M. (2006). Mondialisation et recomposition du capital des entreprises européennes. *Revue Internationale Et Stratégique, 62*(2), 53-64. doi:10.3917/ris.062.0053

Dimantchev, E. (2015). *To make European climate policy work, we need to put a carbon price on imports*. Retrieved June 11, 2018 from Energy Post Web site: http://energypost.eu/make-european-climate-policy-work-need-put-carbon-price-imports/

Dixit, A. K., & Stiglitz, J. E. (1977). Monopolistic competition and optimum product diversity. *The American Economic Review*, vol. 67, No. 3, p. 297-208.

Dröge, S., van Asselt, H., Brewer, T., Grubb, M., Ismer, R., Kameyama, Y., Mehling, M., Monjon, S., Neuhoff, K., Quirion, P., Schumacher, K., Mohr, L., Suwala, W., Takamura, Y., Voituriez, T., & Wang, X. (2009). *Tackling leakage in a world of unequal carbon prices*. Synthesis Report, Climate Strategies, Cambridge, UK.

Ellerman, D., Marcantonini, C., & Zaklan, A. (2016). The European Union Emissions trading system: Ten years and counting. *Review of environmental economics and policy, 10*(1), 89-107.

EUROFER. (2018). *Annual Report 2018*. Retrieved from http://www.eurofer.org/News&Events/PublicationsLinksList/201806-AnnualReport.pdf

European Aluminium. (2016). *EU aluminium imports dependency.* Retrieved from https://www.european-aluminium.eu/data/economic-data/eu-aluminium-imports-dependency/

European Climate Foundation (ECF). (n.d.). *A practical guide to prosperous, low carbon Europe*. Retrieved from http://www.roadmap2050.eu/

European Commission. (2008). *Questions and Answers on the Commission's proposal to revise the EU Emissions Trading System.* Unpublished document, European Union.

European Commission. (2009a). *Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community (Text with EEA relevance).* Official Journal of the European Union, L140, 63-87.

European Commission. (2009b). *Draft Commission staff working document impact assessment Accompanying document to the Commission Decision determining a list of sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage pursuant to Article 10a (13) of Directive 2003/87/EC.* SEC (2009).

European Commission. (2011). *Commission decision of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council.* Official Journal of the European Union, L130, 1-45.

European Commission. (2014*). Commission staff working document impact assessment Accompanying the document Commission Regulation (EU) No 176/2014 of 25 February 2014 amending Regulation (EU) No 1031/2010 in particular to determine the volumes of greenhouse gas emission allowances to be auctioned in 2012-2020.* SWD/2014/050 final.

European Commission. (2015a). *EU ETS Handbook*. Retrieved from https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf

European Commission. (2015b). *Proposal for Directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments*. COM/2015/0337 final – 2015/0148.

European Commission. (2015c). *Commission staff working document impact assessment accompanying the document proposal for Directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments*. SWD/2015/0135 final.

European Commission. (2017). *Report on the functioning of European carbon market*. COM/2017/0693 final. Retrieved from https://ec.europa.eu/commission/sites/beta-political/files/report-functioning-carbon-market_en.pdf

European Commission. (2018). *EU Emission Trading System (EU ETS).* Retrieved from https://ec.europa.eu/clima/policies/ets_en

European Union Emissions Trading Scheme (EUETS). (2016). *Carbon Leakage Exposure Factor (CLEF).* Retrieved from https://www.emissions-euets.com/carbon-leakage-exposure-factor-clef

Fan, Y., Jia, J.-J., Wang, X., & Xu, J.-H. (2017). What policy adjustments in the EU ETS truly affected the carbon prices? Energy Policy, 103, 145-164. doi:https://doi.org/10.1016/j.enpol.2017.01.008

Felder, S., & Rutherford, T. (1993), Unilateral CO2 reductions and carbon leakage: the consequences of international trade in oil and basic materials. *Journal of Environmental Economics and Management*, Vol. 25, No. 2, 162–176.

Finances.net (2018). *Price of CO2 European Emission Allowances*. Retrieved from http://www.finances.net/matieres_premieres/co2-emissionsrechte

Fischer, C., & Fox, A. K. (2009). *Comparing policies to combat emissions leakage: Border tax adjustments versus rebates.*

Gautam, M., Pandey, B., & Madhoolika, A. (2018). Chapter 8 - Carbon Footprint of Aluminium Production: Emissions and Mitigation. *Environmental Carbon Footprints*, 197-228.

Genasci, M. (2008). Border tax adjustments and emissions trading: the implications of international trade law for policy design, *Carbon and Climate Law Review*, 2(1): 33-42

Godard, O. (2007). *Unilateral European Post-Kyoto climate policy and economic adjustment at EU borders*. Paris: Ecole Polytechnique, Chaire du développement durable, No. DDX 07-15.

Graichen, V., Schumann, K., Matthes, F. C., Mohr, L., Duscha, V., Schleich, J., & Diekmann, J. (2008). *Impacts of the EU emissions trading scheme on the industrial competitiveness in Germany: Research report 3707 41 501. UBA-FB 001177.* Umwelt Bundes Amt (UBA), Berlin.

Grubb, M. J. (2003). The economics of the Kyoto protocol. *World Economics, 4*(3), 143-189.

Holmes, P., Reilly, T., & Rollo, J. (2011). Border carbon adjustments and the potential for protectionism. *Climate Policy*, Vol. 11, No. 2, 883-900.

Houser, T., Bradley, R., Childs, B., Werksman, J., & Heilmayr, R. (2008). *Leveling the Carbon Playing Field: International Competition and US Climate Policy Design.* Washington, D.C: Peterson Institute for International Economics and World Resources Institute.

International Energy Agency (IEA). (2007). *Climate policy uncertainty and investment risk*. Retrieved from https://www.iea.org/publications/freepublications/publication/Climate_Policy_Uncertainty.pdf

International Energy Agency (IEA). (2018). *Cement.* Retrieved from https://www.iea.org/tcep/industry/cement/

International Panel on Climate Change (IPCC). (2018). *Organization*. Retrieved from https://archive.ipcc.ch/organization/organization.shtml

Ismer, R., & Neuhoff, K. (2007). Border tax adjustment: A feasible way to support stringent emission trading. *European Journal of Law and Economics, 24*(2), 137-164. doi:10.1007/s10657-007-9032-8

Kang, S. (2010). *Carbon border tax adjustment from WTO point of view*. Second

Biennial Global Conference, Working Paper 2010/08.

Kuik, O., & Hofkes, M. (2010). Border adjustment for european emissions trading: Competitiveness and carbon leakage. *Energy Policy, 38*(4), 1741-1748. doi:10.1016/j.enpol.2009.11.048

Krugman, P. (2009). *Climate, trade, Obama.* Retrieved from https://krugman.blogs.nytimes.com/2009/06/29/climate-trade-obama/

Marcu, C., Egenhofer, C., Roth, S., & Stoefs, W. (2013). Carbon Leakage: An overview. *CEPS Special Report No 79.* Retrieved from https://www.ceps.eu/system/files/Special%20Report%20No%2079%20Carbon%20Leakage_0.pdf

Markusen, J. R. (1975). International externalities and optimal tax structures. *Journal of International Economics, 5*(1), 15-29.

Mattoo, A., Subramanian, A., van der Mensbrugghe, D., & He, J. (2009). *Reconciling climate change and trade policy*. Washington, D.C.: World Bank Policy Research Working Paper, No. 5123.

McKibbin, W. J., Wilcoxen, P. J., Braathen, N. A., Tao, T. H., & Levinson, A. (2008). The economic and environmental effects of border tax adjustments for climate policy. *Brookings Trade Forum,* 1-34.

Miller, N. H., & Osborne, M. (2014). Spatial differentiation and price discrimination in the cement industry: Evidence from a structural model. *The RAND Journal of Economics, 45*(2), 221-247. doi:10.1111/1756-2171.12049

Monjon, S., & Quirion, P. (2010). How to design a border adjustment for the European Union emissions trading system? *Energy Policy, 38*(9), 5199-5207. doi:10.1016/j.enpol.2010.05.005

Monjon, S., & Quirion, P. (2011). A border adjustment for the EU ETS: Reconciling WTO rules and capacity to tackle carbon leakage. *Climate Policy, 11*(5), 1212-1225. doi:10.1080/14693062.2011.601907

Montgomery, W. (1972). Markets in licenses and efficient pollution control programs. *Journal of economic theory, 5*(3), 395-418.

Morgenstern, R., Pizer, W., & Shih, J.-S. (2002). Jobs versus the environment: Is there a trade-off? Journal of Environmental Economics and Management 43(3): 412-436.

Mougeot, M., & Naegelen, F. (2009). La phase III du système communautaire d'échange de quotas d'émission: Comment attribuer les permis ? *Revue d'économie politique*, vol. 119(2), 165-184. doi:10.3917/redp.192.0165.

Organisation for Economic Co-operation and Development (OECD). (2018). *List of Annex I Countries*. Retrieved from http://www.oecd.org/env/cc/

Peters, G. P., & Hertwich, E. G. (2008). CO2 embodied in international trade with implications for global climate policy. *Environ. Sci. Technol.* 42, 1401–1407.

Rabe, B. G. (2018). *Can we price carbon?* Cambridge, MA: The MIT Press.

Reinaud, J. (2004). *Industrial competitiveness under the European Union Emissions Trading Scheme*. International Energy Agency, information paper.

Reinaud, J. (2008). *Issues behind competitiveness and carbon leakage. Focus on Heavy industry*. International Energy Agency, information paper.

Renda, A., Pelkmans, J., Egenhofer, C., Marcu, A., Schrefler, L. (2014). *Assessment of cumulative cost impact for the steel and the aluminium industry, final report*. Center for European Policy Studies (CEPS), Brussels.

Rutherford, T. F. (2002). *Lecture Notes on Constant Elasticity Functions*. Unpublished document, University of Colorado.

Sakai, M., & Barrett, J. (2016). Border carbon adjustments: Addressing emissions embodied in trade. *Energy Policy, 92*, 102-110. doi:10.1016/j.enpol.2016.01.038

Sheldon, I. (2011). Is there anything new about border tax adjustments and climate policy? *American Journal of Agricultural Economics, 93*(2), 553-557. doi:10.1093/ajae/aaq146

Smelser, N. J., & Baltes, P. B. (2001). *International encyclopedia of the social & behavioral sciences*. Amsterdam: Elsevier.

Spieth, W. F., & Hamer, M. (2005). The Implementation of the EU ETS Directive in the EU Member States in the Light of the German National Allocation Plan. Journal for European Environmental & Planning Law, 2(2), 112-122. doi:https://doi.org/10.1163/187601005X00174

Stavins, R. (2001). *Experience with market-based environmental policy instruments.* Fondazione Eni Enrico Mattei (FEEM) Milano.

United Nations Framework Convention on Climate Change (UNFCCC). (2018). *UNFCCC Process*. Retrieved from https://unfccc.int/process#:d8f74df9-0dbd-4932-bf3c-d8a37f8de70e

van Asselt, H., & Brewer, T. (2010). Addressing competitiveness and leakage concerns in climate policy: An analysis of border adjustment measures in the US and the EU. Energy Policy, 38(1), 42-51. doi:https://doi.org/10.1016/j.enpol.2009.08.061

Van den Bergh, K., & Delarue, E. (2015). Quantifying CO2 abatement costs in the power sector. *Energy Policy, 80*, 88-97. doi:10.1016/j.enpol.2015.01.034

Veenendaal, P., & Manders, T. (2008). *Border Tax Adjustment and the EU-ETS: A Quantitative Assessment*. The Hague: Central Planning Bureau (CPB) Document No. 171.

Venmans, F. (2011). *L'efficacité environnementale et économique du marché du carbone européen*. Bruxelles: CRISP, 5-91. doi: doi:10.3917/cris.2099.0005

Vie Publique au cœur du débat politique. (2009). *Déclaration de M. Nicolas Sarkozy, Président de la République, sur la lutte contre le réchauffement climatique notamment par la création d'une taxe carbone, à Artemare (Ain) le 10 septembre 2009.* Retrieved from http://discours.vie-publique.fr/notices/097002465.html

Vlachou, A. (2014). The European Union's Emissions Trading System. Cambridge Journal of Economics, 38(1), 127-152. doi:10.1093/cje/bet028

Vlachou, A., Pantelias, G. (2016). The European Union's Emissions Trading System, Part 1: Taking stock. *Capitalism Nature Socialism, 28(2)*, 84-102. doi: 10.1080/10455752.2016.1233287

Winchester, N. (2012). The impact of border carbon adjustments under alternative producer responses. *American Journal of Agricultural Economics, 94*(2), 354-359. doi:10.1093/ajae/aar113

Winchester, N., Reilly, J. M., & Paltsev, S. (2011). Will border carbon adjustments work? *The B.E. Journal of Economic Analysis & Policy, 11*(7).

World Business Council for Sustainable Development (WBCSD). (2016). *Cement Sustainability Initiative: Getting the Numbers Right (GNR) database*. Retrieved from https://www.wbcsdcement.org/GNR-2016/

World Steel Association. (2017). *World Steel in Figures 2016.* Retrieved from https://www.worldsteel.org/en/dam/jcr:1568363d-f735-4c2c-a1da-e5172d8341dd/World+Steel+in+Figures+2016.pdf

World Trade Organization. (1947). *General Agreement on Tariffs and Trade (GATT).* Retrived from https://www.wto.org/english/docs_e/legal_e/gatt47_01_e.htm

Zaklan, A., & Bauer, B. (2015). *Europe's mechanism for countering the risk of carbon leakage.* Deutsches Institut für Wirtschaftsforschung (DIW) Berlin.

Appendices

Appendix 1 - List of Annex I countries

Countries that are listed in Annex I to the UN Framework Convention on Climate Change:

Australia
Austria
Belarus a/
Belgium
Bulgaria a/
Canada
Croatia*
Czech Republic *
Denmark
European Union
Estonia a/
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Japan
Latvia a/
Liechtenstein*
Lithuania a/
Luxembourg
Monaco*
Netherlands
New Zealand
Norway
Poland
Portugal
Romania a/
Russian Federation a/
Slovak Republic *
Slovenia a/*
Spain
Sweden
Switzerland
Turkey
Ukraine a/
United Kingdom of Great Britain and Northern Ireland
United States of America

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a/ Countries that are undergoing the process of transition to a market economy.

*Countries added to Annex I by an amendment that entered into force on 13 August 1998, pursuant to decision 4/CP.3 adopted at COP 3.

NB: The United States figured in the Annex I, however they did not ratify the Protocol and are thus not bonded to target objectives.

Source: Organisation for Economic Co-operation and Development (2018)

Appendix 2 - Global Warming Potentials (GWP)

Greenhouse Gas	Formula	100-year GWP (AR4)
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
Sulphur hexafluoride	SF_6	22,800
Hydrofluorocarbon-23	CHF_3	14,800
Hydrofluorocarbon-32	CH_2F_2	675
Perfluoromethane	CF_4	7,390
Perfluoroethane	C_2F_6	12,200
Perfluoropropane	C_3F_8	8,830
Perfluorobutane	C_4F_{10}	8,860
Perfluorocyclobutane	$c\text{-}C_4F_8$	10,300
Perfluoropentane	C_5F_{12}	13,300
Perfluorohexane	C_6F_{14}	9,300

Note: "100-year GWP (AR4)" represents the Global Warming Potential during a century in comparison of the Carbon dioxide (which is equal to 1) according to the 4th Assessment Report (AR4) released by the IPCC.

Source: Climate Change Connection (2018)

Appendix 3 – EU ETS Cap between 2013 and 2020

Year	Annual cap *(installations)*	Annual aviation allowances put into circulation*
2013	2 084 301 856	32 455 312
2014	2 046 037 610	41 681 025
2015	2 007 773 364	48 543 026
2016	1 969 509 118	38 034 475
2017	1 931 244 873	37 833 819[14]
2018	1 892 980 627	
2019	1 854 716 381	
2020	1 816 452 135	

*Note: The number of aviation allowances put into circulation for 2017, 2018, 2019 and 2020 will depend on the outcome of the Commission's legislative proposal
Source: European Commission (2017)

Appendix 4 - Activity sectors of the EU ETS by NACE code

Activity type code	Activity
10	Aviation
20	Combustion of fuels
21	Refining of mineral oil
22	Production of coke
23	Metal ore roasting or sintering
24	Production of pig iron or steel
25	Production or processing of ferrous metals
26	Production of primary aluminium
27	Production of secondary aluminium
28	Production or processing of non-ferrous metals
29	Production of cement clinker
30	Production of lime, or calcination of dolomite/magnesite
31	Manufacture of glass
32	Manufacture of ceramics
33	Manufacture of mineral wool
34	Production or processing of gypsum or plasterboard
35	Production of pulp
36	Production of paper or cardboard
37	Production of carbon black
38	Production of nitric acid
39	Production of adipic acid
40	Production of glyoxal and glyoxylic acid
41	Production of ammonia
42	Production of bulk chemicals
43	Production of hydrogen and synthesis gas
44	Production of soda ash and sodium bicarbonate
45	Capture of greenhouse gases under Directive 2009/31/EC
46	Transport of greenhouse gases under Directive 2009/31/EC
47	Storage of greenhouse gases under Directive 2009/31/EC
99	Other activity opted-in pursuant to Article 24 of Directive 2003/87/EC
20-99	All stationary installations
21-99	All inductrial installations

Source: European Climate Foundation (2011)

Appendix 5 - Description of the mathematical symbols used in the model

Symbol	Indices	Range
s	Sector or commodity {cement, aluminium, steel}	{1,2,3}
r	Region {E, R} = {EU, RoW}	{E, R}

Symbol	Decision variables	Unit
$p_{s,rr'}$	Price of commodity s manufactured in region r and sold in market r'	[€/t]

Symbol	Parameters	Unit or Range
W_E	European Welfare	[€]
CS_E	European Consumer Surplus	[€]
$\pi_{s,r}$	Profit of firms from sector s and from region r	[€]
$c_{s,rr'}$	Extended marginal cost of production of a commodity s produced in region r and sold in market r'	[€/t]
$c^0_{s,r}$	Marginal cost of production of a commodity s produced in region r	[€/t]
$t_{rr'}$	Transportation cost from region r to region r'	[€/t]
β	Carbon market price (defined as the Social Cost of Carbon found by computing the Shadow Price of the emissions constraint in the Social Planner Equilibrium)	[€/tCO2]
$e_{s,E}$	Emissions from the European sector s	[tCO2]
θ_E	European threshold (or cap) of emissions	[tCO2]
$\theta_{s,E}$	European sectoral thresholds (or caps) of emissions	[tCO2]
d_s	Direct emissions intensity of sector s	[tCO2/t]
$d_{s,benchmark}$	Benchmark value of direct emissions intensity for sector s	[tCO2/t]
d_{elec}	Direct emissions intensity of electricity	[tCO2/MWh]
k_s	Electricity intensity of sector s	[MWh/t]
σ_s	Armington Elasticity (CES - Constant Elasticity of Substitution) for sector s	]1 ; ∞[
$Q_{s,rr'}$	Demand in market r' for commodity s produced in region r	[t]
λ	Shareholdership of the European people in the European firms	[0 ; 1]
$a_{s,r}$	Preference coefficient in the market r for a domestic good	]0 ; 1[
$b_{s,r}$	Preference coefficient in the market r for a foreign good	]0 ; 1[
$\alpha_{s,r}$	Expenditure share of the sector s of region r with respect to the regional budget ($\sum_s \alpha_{s,r} < 1 \ \forall r$)	]0 ;1[
B_r	Budget in region r (equals to the regional GDP)	[€]
gf_s	Grandfathering: number of allowances given for free to sector s	[tCO2]

Appendix 6 - Mathematical expression of the Social Planner Equilibrium

1. Model design for the Social Planner Equilibrium

$$\begin{aligned}\max_{p} \quad W_E(p) &= CS_E + \lambda\, \pi_E \qquad (1)\\ &= \sum_{s=1}^{3} \left(\int_{p_{s,EE}}^{+\infty} Q_{s,EE}\, dp'_{s,EE} - p_{s,EE}\; Q_{s,EE} + \int_{p_{s,RE}}^{+\infty} Q_{s,RE}\, dp'_{s,RE} - p_{s,RE}\; Q_{s,RE} \right) \\ &\quad + \lambda \sum_{s=1}^{3} \Big((p_{s,EE} - c_{s,EE}) Q_{s,EE} + (p_{s,ER} - c_{s,ER}) Q_{s,ER} \Big)\end{aligned}$$

such that

$$\frac{\partial \pi_{s,R}}{\partial p_{s,Rr}} = 0 \;\Leftrightarrow\; Q_{s,Rr} + (p_{s,Rr} - c_{s,Rr}) \frac{\partial Q_{s,Rr}}{\partial p_{s,Rr}} = 0 \qquad \forall s, r \qquad (2)$$

$$\pi_{s,R} = (p_{s,RR} - c_{s,RR}) Q_{s,RR} + (p_{s,RE} - c_{s,RE}) Q_{s,RE} \qquad \forall s \qquad (3)$$

$$c_{s,rr} = c^0_{s,r} \qquad \forall s, r \qquad (4)$$

$$c_{s,rr'} = c^0_{s,r} + t_{rr'} \qquad \forall s, \forall r \neq r' \qquad (5)$$

$$(p_{s,rr'} - c_{s,rr'}) Q_{s,rr'} \geq 0 \qquad \forall s, r, r' \qquad (6)$$

$$Q_{s,rr} = \alpha_{s,r} B_r \frac{a^\sigma_{s,r}\; p^{-\sigma}_{s,rr}}{a^\sigma_{s,r}\; p^{1-\sigma}_{s,rr} + b^\sigma_{s,r}\; p^{1-\sigma}_{s,r'r}} \qquad \forall s, \forall r \neq r' \qquad (7)$$

$$Q_{s,r'r} = \alpha_{s,r} B_r \frac{b^\sigma_{s,r}\; p^{-\sigma}_{s,r'r}}{a^\sigma_{s,r}\; p^{1-\sigma}_{s,rr} + b^\sigma_{s,r}\; p^{1-\sigma}_{s,r'r}} \qquad \forall s, \forall r \neq r' \qquad (8)$$

$$\frac{\partial Q_{s,RR}}{\partial p_{s,RR}} = -\alpha_{s,R}\; B_R\; a^\sigma_{s,R}\; p^{-\sigma}_{s,RR}\; \frac{a^\sigma_{s,R}\; p^{-\sigma}_{s,RR} + \sigma\; b^\sigma_{s,R}\; p^{-1}_{s,RR}\; p^{1-\sigma}_{s,ER}}{a^\sigma_{s,R}\; p^{1-\sigma}_{s,RR} + b^\sigma_{s,R}\; p^{1-\sigma}_{s,ER}} \qquad \forall s \qquad (9)$$

$$\frac{\partial Q_{s,RE}}{\partial p_{s,RE}} = -\alpha_{s,E}\; B_E\; b^\sigma_{s,E}\; p^{-\sigma}_{s,RE}\; \frac{b^\sigma_{s,E}\; p^{-\sigma}_{s,RE} + \sigma\; a^\sigma_{s,E}\; p^{-1}_{s,RE}\; p^{1-\sigma}_{s,EE}}{a^\sigma_{s,E}\; p^{1-\sigma}_{s,EE} + b^\sigma_{s,E}\; p^{1-\sigma}_{s,RE}} \qquad \forall s \qquad (10)$$

$$b_{s,r} = 1 - a_{s,r} \qquad \forall s, r \qquad (11)$$

$$e_{s,E} = (d_s + k_s d_{elec})(Q_{s,EE} + Q_{s,ER}) \qquad \forall s \qquad (12)$$

$$\sum_{s=1}^{3} e_{s,E} \leq \theta_E \qquad (13)$$

$$p_{s,rr'} \geq 0 \qquad \forall s, r, r' \qquad (14)$$

2. Explanations of equations for the Social Planner Equilibrium

(1) Objective function: Maximisation of the European welfare, which is defined as the sum of the European consumer surplus and the profits of European firms. The latter have been multiplied by a shareholdership coefficient (lambda), as a part of the firms' profits is distributed to non-European shareholders and thus do not intervene in the European welfare.

(2) RoW profit First Order Conditions: Because the equilibrium is such that each actor maximises its own gains with respect to the decisions of the other actors, these constraints make sure that the model provides a Nash Equilibrium.

(3) Profit functions of RoW sectors from which the FOCs are derived.

(4) and (5) Extended marginal costs are computed as the marginal production cost plus the transportation cost when commodities are sold to another region. Note that they are assumed constant (see 2.2.3 Model Assumptions).

(6) Budgeting constraints: they state that the profit of a sector must be positive in each market.

(7) and (8) Demand functions: as explained previously, there are two demand functions per regional market, one for the domestic product and one for the product manufactured in the foreign region (see 2.2.6 Consumption Preferences). Because firms are meeting the demand, $Q_{rr'}$ also represents the firms' output quantities.

(9) and (10) Expressions of the partial derivatives of Demand functions in the RoW market that are used in equations (2).

(11) In the same market, the sum of the preference coefficients for domestic and foreign product is equal to one.

(12) Sectoral emissions of European firms are computed as the average (direct and indirect) emissions intensity multiplied by their output quantity.

(13) Emissions constraint: the total emissions of EU firms must not exceed the emissions threshold.

(14) Non-negativity constraints for prices.

Appendix 7 - Mathematical expression of the Market Equilibrium

1. Model design for the Market Equilibrium

The Nash Equilibrium is found by solving the following system of equations :

$$\begin{cases} \dfrac{\partial \pi_{s,E}}{\partial p_{s,Er}} = 0 \;\Leftrightarrow\; Q_{s,Er} + (p_{s,Er} - c_{s,Er})\dfrac{\partial Q_{s,Er}}{\partial p_{s,Er}} = 0 & \forall s, r \\ \dfrac{\partial \pi_{s,R}}{\partial p_{s,Rr}} = 0 \;\Leftrightarrow\; Q_{s,Rr} + (p_{s,Rr} - c_{s,Rr})\dfrac{\partial Q_{s,Rr}}{\partial p_{s,Rr}} = 0 & \forall s, r \end{cases} \tag{15}$$

such that

$$\pi_{s,E} = (p_{s,EE} - c_{s,EE})Q_{s,EE} + (p_{s,ER} - c_{s,ER})Q_{s,ER} \qquad \forall s \tag{16}$$

$$\pi_{s,R} = (p_{s,RR} - c_{s,RR})Q_{s,RR} + (p_{s,RE} - c_{s,RE})Q_{s,RE} \qquad \forall s \tag{17}$$

$$c_{s,EE} = c^0_{s,E} \qquad \forall s \tag{18}$$

$$c_{s,ER} = c^0_{s,E} + t_{ER} \qquad \forall s \tag{19}$$

$$c_{s,RE} = c^0_{s,R} + t_{RE} \qquad \forall s \tag{20}$$

$$c_{s,RR} = c^0_{s,R} \qquad \forall s \tag{21}$$

$$(p_{s,rr'} - c_{s,rr'})Q_{s,rr'} \geq 0 \qquad \forall s, r, r' \tag{22}$$

$$Q_{s,rr} = \alpha_{s,r} B_r \frac{a^\sigma_{s,r}\ p^{-\sigma}_{s,rr}}{a^\sigma_{s,r}\ p^{1-\sigma}_{s,rr} + b^\sigma_{s,r}\ p^{1-\sigma}_{s,r'r}} \qquad \forall s, \forall r \neq r' \tag{23}$$

$$Q_{s,r'r} = \alpha_{s,r} B_r \frac{b^\sigma_{s,r}\ p^{-\sigma}_{s,r'r}}{a^\sigma_{s,r}\ p^{1-\sigma}_{s,rr} + b^\sigma_{s,r}\ p^{1-\sigma}_{s,r'r}} \qquad \forall s, \forall r \neq r' \tag{24}$$

$$\frac{\partial Q_{s,rr}}{\partial p_{s,rr}} = -\alpha_{s,r}\ B_r\ a^\sigma_{s,r}\ p^{-\sigma}_{s,rr}\ \frac{a^\sigma_{s,r}\ p^{-\sigma}_{s,rr} + \sigma\ b^\sigma_{s,r}\ p^{-1}_{s,rr}\ p^{1-\sigma}_{s,r'r}}{a^\sigma_{s,r}\ p^{1-\sigma}_{s,rr} + b^\sigma_{s,r}\ p^{1-\sigma}_{s,r'r}} \qquad \forall s, \forall r \neq r' \tag{25}$$

$$\frac{\partial Q_{s,r'r}}{\partial p_{s,r'r}} = -\alpha_{s,r}\ B_r\ b^\sigma_{s,r}\ p^{-\sigma}_{s,r'r}\ \frac{b^\sigma_{s,r}\ p^{-\sigma}_{s,r'r} + \sigma\ a^\sigma_{s,r}\ p^{-1}_{s,r'r}\ p^{1-\sigma}_{s,rr}}{a^\sigma_{s,r}\ p^{1-\sigma}_{s,rr} + b^\sigma_{s,r}\ p^{1-\sigma}_{s,r'r}} \qquad \forall s, \forall r \neq r' \tag{26}$$

$$b_{s,r} = 1 - a_{s,r} \qquad \forall s, r \tag{27}$$

$$p_{s,rr'} \geq 0 \qquad \forall s, r, r' \tag{28}$$

Modifications for the ETS scenario with respect to the BAU scenario :

$$\pi_{s,E} = (p_{s,EE} - c_{s,EE})Q_{s,EE} + (p_{s,ER} - c_{s,ER})Q_{s,ER} + gf_s\ \beta \qquad \forall s \qquad \text{(16 ETS)}$$

$$c_{s,EE} = c^0_{s,E} + \beta(d_s + k_s d_{elec}) \qquad \forall s \qquad \text{(18 ETS)}$$

$$c_{s,ER} = c^0_{s,E} + t_{ER} + \beta(d_s + k_s d_{elec}) \qquad \forall s \qquad \text{(19 ETS)}$$

$$e_{s,E} = (d_s + k_s d_{elec})(Q_{s,EE} + Q_{s,ER}) \leq \theta_{s,E} \qquad \forall s \qquad \text{(29 ETS)}$$

Modifications for the BCA M scenario with respect to the BAU scenario :

$$c_{s,EE} = c^0_{s,E} + \beta(d_s + k_s d_{elec}) \qquad \forall s \qquad \text{(18 BCA M)}$$

$$c_{s,ER} = c^0_{s,E} + t_{ER} + \beta(d_s + k_s d_{elec}) \qquad \forall s \qquad \text{(19 BCA M)}$$

$$c_{s,RE} = c^0_{s,R} + t_{RE} + \beta(d_{s,benchmark} + k_s d_{elec}) \qquad \forall s \qquad \text{(20 BCA M)}$$

$$e_{s,E} = (d_s + k_s d_{elec})(Q_{s,EE} + Q_{s,ER}) \leq \theta_{s,E} \qquad \forall s \qquad \text{(29 BCA M)}$$

Modifications for the BCA MX scenario with respect to the BAU scenario :

$$c_{s,EE} = c^0_{s,E} + \beta(d_s + k_s d_{elec}) \qquad \forall s \qquad \text{(18 BCA MX)}$$

$$c_{s,RE} = c^0_{s,R} + t_{RE} + \beta(d_{s,benchmark} + k_s d_{elec}) \qquad \forall s \qquad \text{(20 BCA MX)}$$

$$e_{s,E} = (d_s + k_s d_{elec})(Q_{s,EE} + Q_{s,ER}) \leq \theta_{s,E} \qquad \forall s \qquad \text{(29 BCA MX)}$$

2. Explanations of equations for the Market Equilibrium

First of all, the mathematical expressions are given for the BAU scenario. Then, modifications (equations using BAU equation numbers but specifying the scenario to which it refers) and additions (new equation numbers) made to the mathematical model are provided for the ETS, BCA M and BCA MX scenarios.

(15) The system is composed of the First Order Conditions (FOC) of profit maximisation of each firm from each sector from each region. There are four FOCs per sector, as mentioned previously.

(16) and (17) Profit functions of sectors by region from which the FOCs are derived.

(18) to (21) Extended marginal costs are computed as the marginal production cost plus the transportation cost when commodities are sold to another region. Note that they are assumed constant (see 2.2.3 Model Assumptions).

(22) Budgeting constraints: they state that the profit of a sector must be positive in each market.

(23) and (24) Demand functions: as explained previously, there are two demand functions per regional market, one for the domestic product and one for the product manufactured in the foreign region (see 2.2.6 Consumption Preferences). Because firms are meeting the demand, $Q_{rr'}$ also represents the firms' output quantities.

(24) and (26) Expressions of the partial derivatives of Demand functions that are used in equations (15).

(27) In the same market, the sum of the preference coefficients for domestic and foreign product is equal to one.

(28) Non-negativity constraints for prices.

Modifications referring to the ETS scenario with respect to the BAU scenario

(16 ETS) The profit of European firms now includes the free allowances received from the European Commission. Because these allowances have an opportunity cost, they are multiplied by the carbon market price and are assimilated to a subsidy.

(18 ETS) Addition of the ETS cost to the extended marginal cost of European firms for products sold in the EU market.

(19 ETS) Addition of the ETS cost to the extended marginal cost of European firms for products sold in the RoW market.

(29 ETS) Emissions constraint: the emissions of European sector must not exceed the emissions threshold of this sector.

Modifications referring to the BCA M scenario with respect to the BAU scenario

(18 BCA M) Addition of the ETS cost to the extended marginal cost of European firms for products sold in the EU market.

(19 BCA M) Addition of the ETS cost to the extended marginal cost of European firms for products sold in the RoW market.

(20 BCA M) RoW firms now face an additional cost due to the BCA when they sell products to the EU.

(29 BCA M) Emissions constraint: the emissions of European sector must not exceed the emissions threshold of this sector.

Modifications referring to the BCA MX scenario with respect to the BAU scenario

(18 BCA M) Addition of the ETS cost to the extended marginal cost of European firms only for products sold in the EU market.

(20 BCA M) RoW firms now face an additional cost due to the BCA when they sell products to the EU market.

(29 BCA M) Emissions constraint: the emissions of European sector must not exceed the emissions threshold of this sector.

Appendix 8 - Data by sector

	Cement	Aluminum	Steel
Production cost (€/t) c_E^0/ c_R^0	65/56	1021/969	404/400
Sources	Miller & Osborne (2014)	Carbon Trust (2011)	Carbon Trust (2011) ; Renda et al. (2014)
Sigma (-)	2	2.5	3
Sources	Monjon & Quirion (2011)	Monjon & Quirion (2011)	Monjon & Quirion (2011)
Direct emission-intensities (tCO2/t)	0.69	2.50	1.16
Sources	WBCSD (2016) ; IEA (2018)	Carbon Trust (2011)	Carbon Trust (2011)
Indirect emission-intensities (tCO2/t)	0.05	7.49	0.14
Sources	IEA (2018)	Carbon Trust (2011)	Carbon Trust (2011)
EU product (direct) emissions benchmark (tCO2/t)	0.650	1.514	0.984
Sources	European Commission (2011)	European Commission (2011)	European Commission (2011)
Quantities (M t) $q_{EE}/q_{ER}/q_{RE}/q_{RR}$	134.8/17.2/32.5/4482.8	6.9/6.7/0.8/62.5	126.7/35.7/21.1/1437.4
Sources	CEMBUREAU (2017)	European Aluminium (2018)	EUROFER (2018) ; World Steel Association (2016)