A GREEN DEAL ON STEEL

THE IMPACT OF THE EU EMISSIONS TRADING SYSTEM AND AN EU BORDER CARBON ADJUSTMENT MECHANISM ON THE EU STEEL MARKET

BY
EMMA EIERMANN

CAPSTONE SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR A
MAJOR AND DEGREE IN
GOVERNANCE, ECONOMICS AND DEVELOPMENT
BACHELOR OF SCIENCE

LEIDEN UNIVERSITY COLLEGE THE HAGUE
UNIVERSITEIT LEIDEN
2021

WORD COUNT: 10496

Abstract

This paper addresses how a carbon price in the EU alongside an EU border carbon adjustment mechanism (ETS BCA carbon price) may influence, (i) the volume of steel, (ii) the technology mix, (iii) the associated greenhouse gas emissions and (iv) the region mix (shares of EU and non-EU steel) consumed in the EU market. To answer this, I develop a scenario that implements an ETS BCA carbon price of €50 per ton of emissions for the EU steel sector. I use a stylized graphical derivation based on data from the literature to reconstruct the current state of the EU steel sector. My results indicate that an ETS BCA carbon price reduces emissions primarily by increasing the share of green steel in the market by 24%, and to a lesser extent due to an overall volume decrease. Emissions from steel consumed in the EU decrease by 31%. Overall steel volume consumed in the EU decreases by 10%. The new region mix is 85% EU steel and 15% Foreign steel from an initial 78% and 22%, respectively, meaning that within the overall volume decrease, 2% can be traced back to a volume decrease supplied by EU producers and 8% to a volume decrease supplied by Foreign producers. The absolute volume supplied by EU producers decreases by 3%. This suggests that an ETS BCA carbon price is a viable tool for policymakers to reconcile environmental and economic concerns. It decreases emissions effectively without decreasing the volume produced by EU steel producers – hence employment and GDP –significantly.

Keywords**:** CO_2 emissions reduction, iron and steel industry, European Union, carbon price, border carbon adjustment.

Table of Contents

List of Figures

List of Tables

List of Appendices

Glossary

Abbreviations	**Synonyms**	**Explanation**
Emissions	Carbon	Carbon and emissions are abbreviations that refer to emission of carbon dioxide (CO2) and carbon dioxide equivalents (CO_2-e). I express the absolute emissions in terms of million metric tons (mt-CO_2).
Emission intensity		Indicates the emissions in tons per ton of steel produced (t-CO_2/t-steel).
Dirty steel	Dirty production process, dirty technology	Steel technology with high emission intensity.
Green steel	Green production process, green technology	Steel technology with low emission intensity.
Foreign		Regions that export steel to the EU. Calculations for Foreign are based on the five largest exporters to the EU as of 2019: Turkey, Russia, South Korea, China, and India (in that order).
EU	European Union	Includes all 28 members of the EU as of 2019.
EU ETS	EU Emissions Trading Scheme	The carbon price market in the EU.
EU BCA	EU Border Carbon Adjustment Mechanism	The carbon import tariff levied by the EU on steel from Foreign.
ETS BCA carbon price	EU ETS carbon price alongside an EU BCA	Abbreviation for the implementation of the EU ETS alongside an EU BCA. Expressed in € per ton of emissions (€/t-CO_2).
Technology mix	Share of green versus dirty production process	Refers to the share of green versus dirty steel within the total steel volume supplied to the EU market.
Region mix	Share of Foreign versus EU supply	Refers to the share of Foreign versus EU steel supply within the total steel volume supplied to the EU market.
Steel types		I use this abbreviation to refer to the steel categories resulting from the two-by-two combinations of technology and region: EU green steel, EU dirty steel, Foreign green steel, and Foreign dirty steel.
PED		Abbreviation for own-price elasticity of demand
PES		Abbreviation for own-price elasticity of supply

Acknowledgements

I am very thankful for how much the process of writing this capstone taught me–lessons that go beyond academic knowledge. I would also like to thank my supervisor, Mr Zetland, for providing me with opportunities to grow and giving me the freedom to pursue a topic I genuinely care about. As this is the culmination of my education at LUC, I would like to seize the moment to express my gratitude to this institution and community that I am honoured to belong to.

But more than all, I would like to express my gratitude to my family. Thank you to my mother Anna for always supporting me, to Martin, to Thomas, to Emine, Inci, Micha, Helen, Mex, Jorge, Muckel, Elsa, Malchen–and last but not least: thank you, David. Thank you for everything!

Dedicated to my siblings Muckel, Elsa, and Malchen

1. Introduction

We need to reduce global carbon dioxide and carbon dioxide equivalents emissions (hereafter, emissions) to limit global warming's adverse impacts (United Nations 2019). However, many regions shy away from the necessary emission mitigation costs (Bellora et al. 2020). Only a few regions are committed to reducing emissions substantially, one of them being the European Union (hereafter, EU) (Bellora et al. 2020). The EU aims for carbon neutrality by 2050 and has set the first step in that direction by introducing the European Green Deal plan (ÖGfE 2020).

An important aspect of this plan is to reduce emissions in the iron and steel sector (hereafter, steel sector) as the steel sector produces 6 to 10% of global emissions and approximately 4% of EU emissions (Medarac, Moya, and Somers 2020; Roland Berger Consultancy 2020). To reduce emissions in the EU steel sector, the EU puts a price on its emissions to incentivize steel producers to emit less (Directive 2003/87/EC 2003). The EU Emissions Trading System (hereafter, EU ETS) determines this price on emissions in the EU (hereafter, ETS carbon price) (Directive 2003/87/EC 2003).

However, foreign steel-producing countries less committed to reducing emissions could significantly hamper the EU's efforts (Branger and Quirion 2014). This is because the steel produced in the EU (hereafter, EU steel) is subject to an ETS carbon price. In contrast, steel produced in non-EU countries and exported into the EU market (hereafter, 'Foreign' steel from 'Foreign') is not (Branger and Quirion 2014).[1][2] If the ETS carbon price increases sufficiently to significantly reduce emissions, the EU steel supply may decline because EU steel may become relatively more expensive to produce than Foreign steel. This may offer Foreign steel a

---

[1] South Korea and China – countries that export steel into the EU – are two exception because they also established a carbon price (Hasanbeigi et al. 2019).

[2] When I refer to Foreign steel producers, I do not mean every non-EU steel producer. I instead refer to the part of the Foreign steel producers who supply to EU steel market.

competitive advantage which may drive EU steel producers out of the market, resulting in a shift of economic activity in the steel industry from the EU to abroad. Moreover, Foreign steel emits more per ton than EU steel (see Section 6.3). Therefore, EU emissions savings through an ETS carbon price for the steel sector can be offset by additional Foreign emissions if steel production relocates from the EU to abroad. This phenomenon is called carbon leakage (Cosbey et al. 2019).

Consequently, the EU Commission considers introducing a border carbon adjustment mechanism (EU BCA) to shield its steel sector from competitiveness losses while reducing emissions effectively (Zachmann and Mcwilliams 2020).[3] The EU BCA is an import tariff that puts the same carbon price on imported steel as EU steel (ÖGfE 2020). Without an EU BCA, the EU could not implement an ambitious ETS carbon price on steel because competitiveness losses and carbon leakage would undermine its efficacy (Branger and Quirion 2014a and references therein). Furthermore, BCAs make it possible to achieve the same global emissions decrease as without a BCA at significantly lower costs for the domestic, carbon-pricing region (Mathiesen and Mœstad 2004). A BCA could ensure that steel from every region consumed in the EU market is subject to equally stringent environmental constraints (Branger and Quirion 2014). Therefore, it could provide a level playing field for Foreign and EU producers in the EU market (Branger and Quirion 2014).

However, it is not well researched how an EU ETS carbon price alongside an EU BCA (hereafter, ETS BCA carbon price) would impact the share of high-emissions steel (hereafter, dirty steel) versus low-emissions steel (hereafter, green steel) consumed in the EU. These two types are produced using different technologies (hereafter, dirty and green technology) (Abdul Quader et al. 2016). Hereafter, I refer to the share of green versus dirty steel within the total steel

---

[3] I note that there are different kinds of accounting for emissions at the border. I consider the type of BCA which is most likely to be introduced in the EU (Felbermayr, Peterson 2020).

volume supplied to the EU market with ‘technology mix’. Following the ETS BCA carbon price, green steel may become significantly less costly to produce than dirty steel, thus increasing green steel supply. The ETS BCA carbon price may induce producers in the EU and in regions that export dirty technology steel into the EU to switch to the green technology to avoid high carbon pricing. Moreover, it is not well researched how the ETS BCA carbon price would impact the share of EU versus Foreign steel supplied to the EU steel market (hereafter, region mix).

For these reasons, this thesis examines: **How would an EU ETS carbon price alongside an EU BCA in the steel sector change (i) the volume, (ii) the technology mix, (iii) the associated emissions and (iv) the region mix consumed in the EU steel market?** To answer these questions, I model a scenario that implements an ETS BCA carbon price of €50 per ton of emissions on the steel sector using basic economic tools. The study's heart is a stylized graphical representation of the carbon price effects, which I develop based on the literature's estimates.

This study's broader purpose is to inform policymakers on whether it is useful to consider an ETS BCA carbon price for the steel sector to decrease emissions while shielding the EU steel industry. Suppose emission reductions were driven by a higher decrease in Foreign producers' supply since Foreign steel is more emissions-intensive than EU steel (see Section 6.3). In that case, a BCA would equal the playing field and volume supplied by EU producers may not decrease significantly. These changes are measured with the variable (iv) region mix. Suppose that emission reductions are not mainly caused by a reduction in total volume supplied by EU steel producers but by a shift from dirty to green technology. This would be favourable for EU policymakers because this shift in technology would maintain employment and GDP while decreasing emissions sustainably (Godden 2018). On the contrary, a decrease in volume produced by EU steel producers goes hand in hand with decreased employment in the steel sector and a reduction in GDP (Godden 2018). Moreover, a shift to newer, green technology may offer a competitive advantage for the steel sector in the long run. This may be the case because green steel may offer a competitive advantage in a future in which more and more regions commit to carbon neutrality and establish a carbon price (Bellora et al. 2020).

My results indicate that an ETS BCA carbon price reduces emissions primarily by increasing the share of green steel in the market by 24%, and to a lesser extent due to an overall volume decrease. Emissions from the EU steel sector decrease by 31%. Overall steel volume consumed in the EU decreases by 10%. Within the overall volume decrease, 2% can be traced back to a volume decrease of EU producers and 8% to a volume decrease of Foreign producers. This is because Foreign producers' steel becomes more costly since it is more emissions-intensive and because steel supply from Foreign producers is more responsive to price changes. My thesis suggests that an ETS BCA carbon price on the steel sector is a viable tool for policymakers to reconcile environmental and economic concerns. It decreases emissions effectively without decreasing the volume produced by EU steel producers – hence employment and GDP – significantly.

This research question is important to investigate for at least three reasons. First, steel is an integral intermediary good for numerous products. It is currently not sufficiently substitutable by other materials and remains essential in many industries for the foreseeable future (Roland Berger Consultancy 2020). Therefore, the transition to lower-emissions steel could be an important pillar for a modern low-emissions economy. Second, the steel sector is also one of the most carbon-intensive industries worldwide, accounting for 23% of the manufacturing industry's emissions in the EU (Felbermayr and Peterson 2020; Pardo and Moya 2013). Reduced emissions in the steel sector could contribute to the EU's carbon neutrality commitment and global efforts to limit global warming. Lastly, this research is very topical because the EU Commission plans to propose an EU BCA in 2021 (Felbermayr and Peterson 2020). Moreover, €50 is a likely ETS carbon price for 2025-30 (Argusmedia 2020; Carbon Tracker Initiative 2020; Reuters 2020). As such, my model could represent and contribute valuable insight into understanding how the EU market may look in a few years from now.

My study divides into 10 Sections. Following this introduction, I provide some contextual information about the steel industry and the EU's carbon pricing instruments. Section 3 provides an overview of the conceptual frameworks and a brief explanation of the most important economic concepts relevant to the study. Section 4 concerns the existing literature relating to the research question. Section 5 explains the research design. Section 6 presents relevant data about the steel industry and discusses their weaknesses. Section 7 expounds on the economic and environmental implications of implementing an ETS BCA carbon price of €50 per tonne of emissions. Section 8 presents the results, followed by a discussion of the limitations and broader implications of the thesis in Section 9. Section 10 follows with the conclusion, implications of the results for policymakers and suggestions for further research.[4]

2. Background

2.1. Steel technology

For simplicity, I only consider the blast-furnace/basic-oxygen-furnace production process (hereafter, 'dirty' technology) and the electric-arc-furnace production process (hereafter 'green' technology). Both require iron ore, a reagent and energy (Roland Berger Consultancy 2020). In the first step, the reagent strips the oxygen from the iron ore to create iron (Roland Berger Consultancy 2020). Then, the iron is melted to steel (Roland Berger Consultancy 2020). The

---

[4] I aim at reaching a general audience which has no in-depth knowledge of economics. Thus, I write in non-technical language where possible. More technical explanations are in the appendices.

emissions stem mostly from the iron ore reduction process and partially from the energy required for melting (Roland Berger Consultancy 2020). The emission intensity measures the amount of emissions emitted by producing one ton of steel (t-CO_2/t-steel)**.**

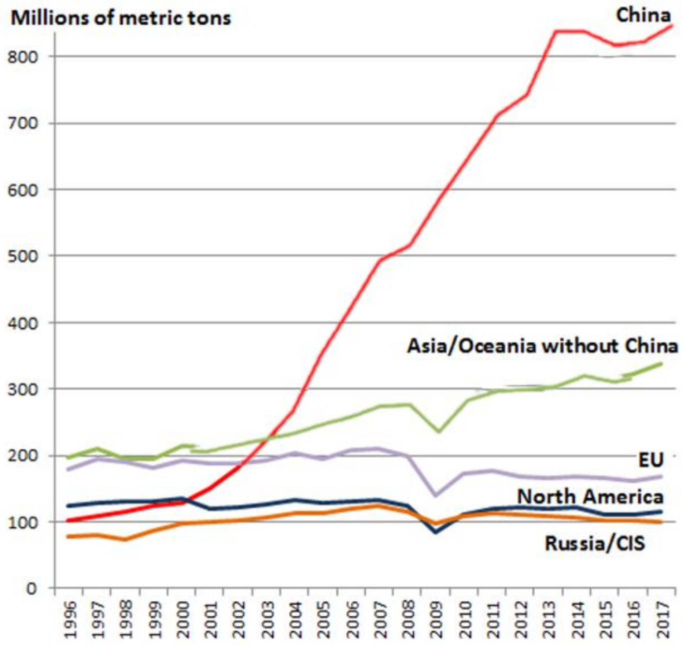
The dirty technology uses coking coal as a reagent and energy source, which is the main reason for its high emission intensity (Hasanbeigi and Springer 2019). The green technology uses mostly natural gas as a reagent and electricity as an energy source (Hasanbeigi and Springer 2019). Furthermore, the share of scrap – the technical term for recycled steel – can, for technical reasons, be higher in the green technology than in the dirty technology (Mayer, Bachner, and Steininger 2019). Recycled steel only needs to be remelted, so its emission intensity is lower, and its use in producing new steel decreases overall emissions of steel production (Roland Berger Consultancy 2020). For these reasons, the green technology emits less than the dirty technology (see Section 6.3). Furthermore, dirty steel – excluding carbon prices – is less costly to produce than green steel (see Section 6.7).

Additionally, I concern only with crude steel. Crude steel is the first steel product upon solidifying the melted steel (Ispat Guru 2018). Hence, I exclude any downstream or upstream activities in my definition of steel, such as the mining and trading of iron ore, and the transformation of steel into its final form after its production.

2.2.Global and EU steel production

The EU steel industry is responsible for 1.3% of the EU's GDP and directly employs 320.000 people (Godden 2018). Thus, it is important to EU policymakers to ensure its continuation (Godden 2018). Figure 1 presents steel production by region over time and puts the EU's steel production into perspective. China's production increased significantly, whereas the EU's decreased by 20% from 2007 to 2017 (Tatasteel 2019). Simultaneously, steel exports into the EU increased continuously (Tatasteel 2019). In 2020, the EU was the largest net importer of steel worldwide (EUROFER 2020b). The reason for the decrease in EU production is significantly higher production costs of EU producers – especially for raw material, labour and energy – compared to Oceania and Asia (Medarac, Moya, and Somers 2020).

Figure 1**.** Steel production by region



Source: Richter (2018) adjusted by the author based on data from Worldsteel

2.3.EU carbon pricing instruments

The EU imposes a carbon price on its producers by pricing emissions under the EU ETS (Directive 2003/87/EC 2003). This directive requires steel producers to hold one EU ETS emission allowance for every ton of carbon emitted (Directive 2003/87/EC 2003). In turn, an EU BCA for the steel sector is an import tariff levied by the EU on steel products manufactured in

Foreign countries less committed to mitigating climate change (ÖGfE 2020). If the EU intents to design a BCA that adheres to its commitments under international trade law, then the carbon tariff for Foreign steel must equal the ETS carbon price (Monjon and Quirion 2011a). Therefore, I implement a carbon price of €50 on both EU and Foreign producers. The former pay via the EU ETS while the latter pay via the EU BCA. For example, a ton of EU steel emits 1.38 tons of emissions on average (see Section 6.3). Hence, an EU producer must pay on average 1.38 x €50 = €69/ton of steel. Foreign steel has an average emission intensity of 1.55 t-CO_2/t-steel (see Section 6.3), requiring Foreign steel producers to pay 1.55 x €50 = €77.50/ton as a carbon import tariff at the EU's border if they export steel into the EU.

3. Conceptual frameworks

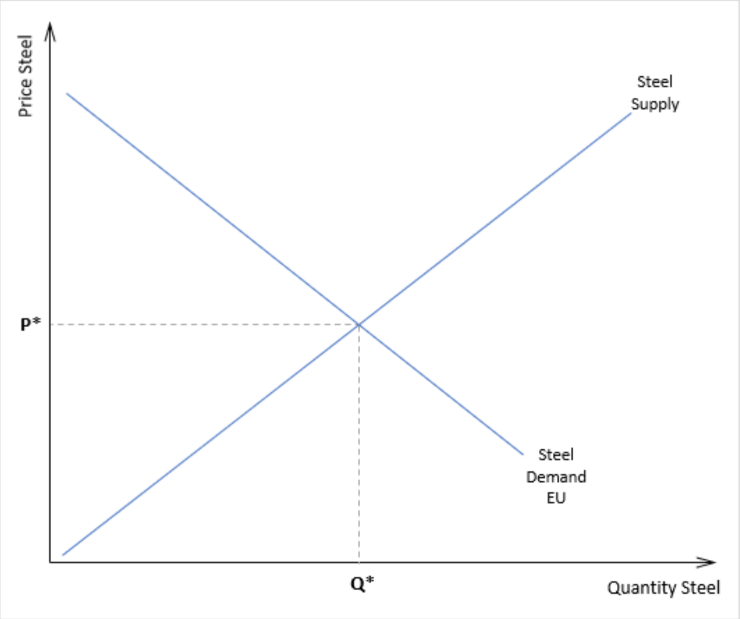
3.1. Overview of emission reduction possibilities via carbon pricing

Carbon pricing is widely regarded as the most effective climate policy to reduce emissions (Stern and Stiglitz 2017). There are four canonical ways to reduce emissions from the steel sector via a carbon price. Hereafter, I refer to them under changes in steel production processes. The first is a decrease in the volume demanded and supplied. The second is a change in the technology mix that supplies the EU market due to the carbon price. If the carbon price is sufficiently high to significantly offset the advantages of dirty steel production, the technology mix may change. The third way is energy efficiency improvements. This could entail an increased use of scrap or a fuel-shift from fossil-based to renewable energy. This could also entail energy efficiency retrofitting of old steelmaking facilities or a change from dirty to greener machinery via input substitution. The latter is achievable by substituting capital for emissions. This means that producers can invest capital and therefore reduce emissions. The fourth way is investment and technological breakthrough in steel production technologies. I consider the first and second option.

3.2.Outlining relevant economic concepts

One of the key tools I use to explain the steel market dynamics is stylized graphs illustrating steel market equilibria in different scenarios. Therefore, I will explain the basic principles of a graphical analysis by illustrating the EU steel market equilibrium in this Section. My reasoning requires the assumption that all producers are profit maximisers, which I assume throughout the study. Furthermore, the steel market is competitive. This means that every producer can enter the market and that a single producer cannot influence the price, called price-taking behaviour (Goodwin et al. 2015). Moreover, throughout the analysis, I use comparative statics, meaning that while studying the effect of certain dynamics, I keep ‘all other things equal’, or *ceteris paribus*. Notably, I assume that the demand curve is constant before and after the BCA.

Figure 2**.** Stylized figure of the EU steel market



Source: author

In Figure 2, the x-axis denotes the quantity of steel supplied and demanded. The y-axis denotes the price of steel supplied and demanded. The upward sloping curve is the inverse steel supply curve. The line tells us that the higher the price, the higher the quantity of steel produced for a given production cost. The downward-sloping curve is the inverse demand curve. It tells us that the quantity demanded increases the lower the steel price. The point where both curves meet is the quantity Q* supplied and consumed at price P*. This point is called ‘market equilibrium’ (Goodwin et al. 2015).

Another important economics term relevant to my paper is ‘margin’. Here, margin refers to the cost of a next additional ton of steel produced. In the competitive steel market, producers in the market sell steel until the marginal cost equals the market price (Goodwin et al. 2015). If, for example, the marginal cost of producing the 1000th ton of steel is €486 and the market price is €486, they will produce 1000 tons of steel. If the next ton's marginal cost over the previous 1000 tons of steel is €487, and the market price is €486, they will not produce this additional ton because they would make negative profits on it. Each producer supplies until the supply curve meets the demand curve. At this point, price equals marginal cost.

A last economic concept relevant to my paper is elasticities. These measure how responsive one economic factor (for example, steel demand) is to another (for instance, the price of steel) (Goodwin et al. 2015). If the demand for a good is relatively irresponsive to price changes, it is price-inelastic (Goodwin et al. 2015). For example, steel demand is relatively inelastic because steel is an essential basic material with many applications (Hebling et al. 2019; Winters 1995). Nonetheless, a steel price increase reduces steel demand somewhat, an effect measured by the own-price elasticity of demand (PED) (Goodwin et al. 2015). Likewise, producers reduce their output if the price of steel decreases, measured by the own-price elasticity of supply (PES) (Goodwin et al. 2015).

4. Literature review

This Section summarizes the literature concerning two dynamics: first, whether carbon prices change the steel industry’s emissions, and if so, by how much; and second, which specific change reduces emissions. The latter could be any of the four ways described in Section 3.1.

I draw on two strands of literature. The first strand focuses on the BCA’s effectiveness in decreasing carbon leakage. Thus, the first strand contains emissions reductions numbers as intermediary values, but they are not chiefly concerned with changes in steel production processes. The second strand focuses on both dynamics and assumes a closed economy or a global carbon price. A ‘closed economy’ means that they do not consider the rest of the world (RoW) and assume that only domestic steel supplies the domestic market (Baldwin and Wyplosz 2019).

I am aware of only two papers, Gielen and Moriguchi (2002b) and Mathiesen and Mœstad (2004), which explore the impact of a domestic carbon price *alongside* a BCA on not only emissions reduction but changes in steel production processes. However, they consider different regions – Japan and all industrialized countries, respectively – and steel technology and steel markets have changed considerably since their publication (Bellora et al. 2020). Therefore, their results may not be transferable to the present EU steel market.

There are two reasons for this scarcity of papers with the same focus as mine. Firstly, prior research focused on proving the effectiveness of BCAs in reducing competitiveness losses and carbon leakage instead of delivering a detailed account of their impact on steel production processes and the domestic market. Secondly, that the EU Commission considers a BCA is a very recent development, only recently attracting in depth evaluation of its effectiveness and practicability (see for example Bellora et al. 2020; Felbermayr and Peterson 2020; ÖGfE 2020; Zachmann and Mcwilliams 2020).

Table 1 presents the results from the literature, which I explain further in this paragraph. Studies that assume a closed economy are comparable to mine because they also put a carbon price on all steel supplying the market. Even though they cannot distinguish between the carbon price's foreign and domestic effects, the results should indicate the trajectory I can expect. I include studies investigating the Japanese, Canadian and US markets because the steel market structure and emission intensity in these countries are similar to the EU’s, meaning that here too, the results are comparable to mine (Hasanbeigi and Springer 2019; Worldsteel 2018). Surprisingly, some papers did not indicate the total volume decrease. Because of spatial limits, I present a downsized table that only lists studies whose results I can compare to mine. A detailed version is in Appendix A.

Additionally, all studies use very complex econometric models and consider more variables than I do. For example, many studies consider up to nine different steel technologies (see, for example, Pardo and Moya 2013) or up to 26 different scenarios (see, for example, Kuramochi 2016). Moreover, Schumacher and Sands (2007) and Hidalgo et al. (2005) also consider a carbon price in the electricity sector. This affects their results because green steel requires much more electricity and hence generates more electricity costs than dirty steel (Hidalgo et al. 2005).

Table 1. Summary literature review

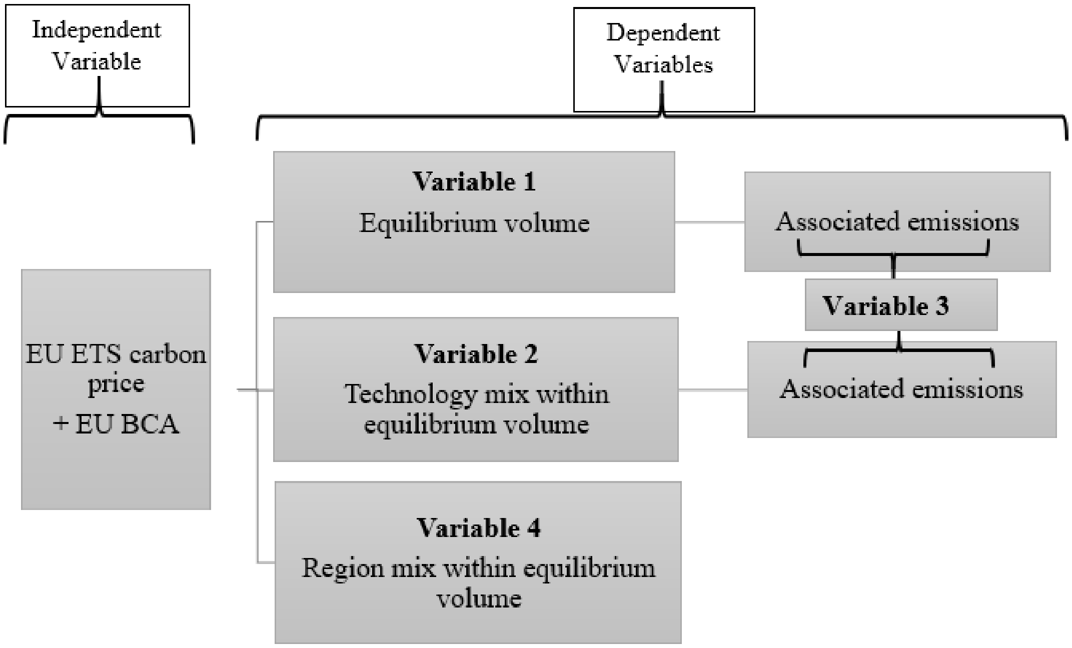
Region	Relation to RoW	Paper	Driving force behind emissions reduction	Volume change	CO_2 Price	CO_2 Change
EU (27)	Closed economy	Pardo and Moya (2013)	Shift dirty to green, energy efficiency of green and dirty steel through innovative breakthrough technologies	-	€100	-24%
EU (15)	Global carbon price	Hidalgo et al. (2005)	Retrofitting of dirty technology, no shift from dirty to green because of increasing prices of electricity	-1,4%	€28	-4%
Japan	Closed economy	Kuramochi (2016)	Increased scrap use, fuel shift in dirty technology	+8%	€98	-12%
Canada	Closed economy	Talaei et al. (2020)	Shift dirty to green	-	€50	-13%
Germany	Closed economy	Lutz et al. (2005)	Shift dirty to green, technology innovation, fuel shift within technology	-0,4%	€73	-9%
Germany	Closed economy	Schumacher and Sands (2007)	Shift dirty to green, fuel shift within technology	-2%	€50	-11%
US	Closed economy	Ruth and Amato (2002)	Shift dirty to green, increased scrap use	+0,4%	€47	-23%
East Asia	Closed economy	Vercoulen et al. (2018)	Shift dirty to green	-	€90	-60%
Japan	Global carbon price	Gielen and Moriguchi (2002a)	Energy efficiency, increase of scrap, shift dirty to green	-2%	€40	-31%
Japan	Including BCA	Gielen and Moriguchi (2002b)	Decreased volume, energy efficiency, increase of scrap, shift dirty to green	-13%	€20	-25%
Industrialized countries	Including BCA	Mathiesen and Mœstad (2004)	Shift dirty to green	-2,4%	€22	-8%
Industrialized countries	Including BCA	Böhringer, Balistreri, and Rutherford (2012)	-	-	€93	-21%
EU (27)	Including BCA	Monjon and Quirion (2011b)	-	-7%	€47	-28%
EU (27)	Including BCA	Alexeevi-Taleba et al. (2012)	-	-	€56	-22%
Average		14 studies			€58	-23%

In summary, the academic literature finds that, on average, the steel industry's carbon pricing decreases emissions by 23% for a carbon price of €58, however with great varieties in the literature’s results. About the EU, the lowest impact of a carbon price is found by Lutz et al. with a 9% decrease in emissions and a 0.4% decrease in volume considering a €73 carbon price over 15 years for the German steel sector (2005). Monjon and Quirion find the highest impact with a 28% decrease in emissions and a 7% decrease in volume with a €47 carbon price over the same period as Lutz et al. for the EU steel sector (2011b). Emissions reductions in East Asia are more significant. This may be because the room for improvement is higher as steel in this region tends to be emissions-intensive (Hasanbeigi and Springer 2019). The driving force behind emissions reduction in most of these studies is the shift from dirty to green steel technology rather than a significant volume decrease.

5. Research design

For answering the research questions of the study, I use the design depicted in Figure 3. Thus, I investigate the impact of the ETS BCA carbon price, as the independent variable, on four dependent variables: (i) the equilibrium volume, (ii) the technology mix within the equilibrium volume of steel, (iii) change in associated emissions and (iv) region mix within the equilibrium volume of steel. Using the results for the first two dependent variables, I can calculate the change in emissions (iii) associated with the equilibrium volume and the respective technology mix.

Figure 3. Research design



Source: author

The change in shares in my second variable can occur either via a shift in the capacity utilization rate of steelmaking facilities or new steel producers entering the market. The capacity utilization rate defines as the share of potential economic output that a steelmaking facility realizes (Federal Reserve Bank of St. Louis 2021). For example, green steelmaking facilities' capacity utilization rate may increase after introducing the ETS BCA carbon price, whereas that of dirty steelmaking facilities may decrease. Furthermore, I do not consider EU steel producers who supply to abroad in this study.

My research method deviates from the literature cited in Section 4 because I do not have the resources to remodel their methodologies. I started with my knowledge of basic economic concepts and developed my research method from that. This explains the lack of references to the methodology of previous research in this Section. However, even complex economic models are built on the same basic economic tenets as mine. Therefore, the results of my thesis should not deviate significantly from those of previous research.

In terms of research methods, I employ a market equilibrium analysis, using quantitative data from the literature (see Section 6). The study's heart is a stylized graphical representation of the effects of the ETS BCA carbon price on the EU steel market which I develop based on the literature’s estimates regarding inputs, elasticities, and market quantities and prices. I use the basic economic concepts outlined in Section 3.2 to investigate the ETS BCA cabon price implications. I examine how the EU steel market changes in three points in time. First, before the implementation of the ETS BCA carbon price, also called the initial situation. The second is the short run after the implementation of the ETS BCA carbon price. The third is the long run after the implementation of the ETS BCA carbon price. I define the short run as the timeline in which capacity utilization can change. However, no new steel producers can enter the market. In the long run, there is entry of new firms.

The following dynamics could occur after introducing the ETS BCA carbon price: First, if the ETS BCA carbon price decreases equilibrium volume, emissions may decrease significantly. In this case, the emissions reductions (variable 3) pertain to dependent variable 1: equilibrium volume. Second, if the ETS BCA carbon price is sufficiently high to offset the advantage of dirty steel production, emissions may decrease significantly at the expense of dirty steel. This means that the emissions reduction would pertain to dependent variable 2: technology mix within the equilibrium volume. Third, regarding dependent variable 3, Foreign supply and emissions could decrease by more than those of EU steel because Foreign steel is more emissions-intensive. This could also indicate that even if volume should decrease significantly overall, the decrease in EU steel volume, and thus employment and GDP, may not be significant. On the other hand, EU supply and emissions could decrease more than Foreign's, because the share of green technology in Foreign is higher (see further in Section 6.1).

5.1.Contribution to the literature

Previous research on the impacts of carbon pricing on the steel sector *with a focus on the EU* has been limited to:

First, research on the impact of both the ETS and BCA carbon price on a) associated emissions and b) volume.

Second, research on the impact of the ETS carbon price on a) associated emissions, b) volume, but also on c) the production process.

Previous research on BCAs has shown that an EU BCA on steel decreases emissions and volume. Previous research on the impacts of the ETS carbon price on the steel sector shows that it decreases emissions by shifting from dirty to green steel, assuming a closed economy. I attempt to combine both strands of literature by researching the effects of the ETS and BCA carbon price on not only volume and associated emissions but also on technology shifts.

Therefore, the contribution of my study to the existing literature is twofold. First, it contributes to understanding the impact the ETS BCA carbon price may have on the technology mix, region mix and associated emissions of all four steel types. By the four "types" of steel I mean the categories of steel resulted from the two-by-two combinations of technology and region: EU green steel, EU dirty steel, Foreign green steel, and Foreign dirty steel. This has not yet been investigated empirically for the EU. Second, my thesis may confirm or cast doubt on previous research by investigating the overall decrease in the steel sector's volume and emissions under a given carbon price.

6. Data

This Section gathers the data I use to remodel the EU steel market – the technology mix, steel emission intensity, absolute emissions, steelmaking capacity constraints, steel costs and prices, carbon price, elasticities and equilibrium volumes for each steel type. If not explicitly mentioned otherwise, the data pertains to the EU steel sector's current state before introducing the ETS BCA carbon price. In the last Section, I summarize the data and model the graphical representation of the EU steel sector's current state. I show the ETS BCA carbon price effects in Section 7.

6.1. Technology mix

Table 2 presents an overview of the technology mix in the world, the EU, and the weighted average for Foreign based on data from 2017.

Table 2. Technology mix in the world, EU and Foreign, in %

	Share of world production	**Share of production in EU**	**Share of production in Foreign**
Dirty	74%	60%	52%
Green	25%	40%	48%
Other	1%	0%	0%

Source: Worldsteel (2018)

Surprisingly, the share in green steel is higher in Foreign than in the EU. Yet, both technologies are less emissions-intensive in the EU compared to Foreign (see Section 6.3). The primary reasons green technology is not quite as developed as the dirty technology are twofold. First, its higher production costs (excluding carbon pricing), and second, that green technology steel only recently became sufficiently competitive to dirty technology in quality (Elkader et al. 2015; Medarac, Moya, and Somers 2020; Steelonthenet.com 2020b). Additionally, steelmaking facilities are built for decadelong utilization, indicating path-dependency in the steel industry's infrastructure (OECD 2020b). The current technology mix may be due to a lock-in effect.

6.2. Region mix and volume in the EU steel market

Overall steel consumption in the EU is 157 million metric tons (hereafter, mt), of which EU producers supply 123 mt, and Foreign producers supply 34 mt (Medarac, Moya, and Somers 2020). I only found detailed data that includes the country of origin of the steel exports to the EU for a subset of the total imports into the EU (EUROFER 2020b). In this subset, the five largest Foreign producers exported 17 mt into the EU (EUROFER 2020b). Throughout this study, I base my projections for Foreign on these five biggest exporters to the EU, namely China, India, Turkey, Russia and South Korea (EUROFER 2020b). I scaled the 17 mt tons on which I have the data up to 34 mt using the coefficient 1.96.[5] This is an important step because I use average weighted production costs and emission intensities of all five countries for Foreign in this study. Therefore, I must know the share of the total imported volume that each Foreign producer supplies. Furthermore, I assume that steel consumption divides between both technologies based on the region's respective technology mix from Section 6.1. This gives the following volumes for each steel type. Table 3 presents the region mix and volumes in the scaled-up depiction based on data from 2019. The region mix is 22% Foreign, 78% EU steel. Table 4 presents the volume exported of the five countries that constitute Foreign to the EU, based on data from 2019.

---

[5] The exact calculations are in an Excel sheet I can of course provide.

Table 3. Region mix and volume of the EU steel market by steel type, in mt

	Volume EU	**Volume Foreign**	**Volume per technology**
Dirty	73	18	91
Green	50	16	66
Total	123	34	157
Region mix	78%	22%	100%

Source: Calculations of the author based on EUROFER (2020b); Medarac, Moya, and Somers (2020)

Table 4. Volume Foreign steel exports to the EU, in mt

Region	**Turkey**	**Russia**	**South Korea**	**China**	**India**	**Foreign total**
Volume	11	8	6	5	4	34

Source: Calculations of the author based on EUROFER (2020b); Medarac, Moya, and Somers (2020)

6.3. Emission intensity

Table 5 shows the weighted average emission intensity for each steel type per ton of steel produced based on data from 2003-2015. I use these values to calculate the realized carbon costs for each steel type (Section 6.8) and the overall absolute emissions of the steel consumed in the EU market (Section 6.4). I retrieved the values for Foreign from Hasanbeigi and Springer (2019). Since there is no consistent emission intensity data for the EU, I calculate it as the weighted average of the major steel-producing EU countries' emission intensities, namely France, Spain, Germany, Italy and Poland (Godden 2018). Hasanbeigi et al. (2019) 's values are coherent with the emission intensity values from other studies.[6]

Table 5. Average emission intensity by steel type, in t-CO_2/t-steel

	Emission intensity EU	**Emission intensity Foreign**	**Emission intensity per technology**
Dirty	1.9	2.2	1.96
Green	0.6	0.84	0.66
Average	1.38	1.55	1.41

Source: Hasanbeigi and Springer (2019)

The emission intensities between producers that use the same technology differ due to the source of energy used and the plant's efficiency. EU plants tend to be more energy-efficient, and the energy, especially the electricity mix, tends to be less emissions-intensive than the mix in Foreign (Hasanbeigi and Springer 2019).

6.4. Absolute emissions in the EU steel market

I calculated the steel sector's absolute emissions by multiplying the volumes of each steel technology of both regions with their respective emission intensity. Table 6 shows the absolute

---

[6] Dahlmann et al. (2015); Hasanbeigi et al. (2016); Moya and Pardo (2013); Schumacher and Sands (2007); Vercoulen et al. (2018); Xu et al. (2015); Zhang et al. (2018); Sanin and Sourisseau (2019)

emission values of the steel sold in the EU market in mt-CO_2. The values are coherent with the values of other studies.[7]

Table 6. Absolute emissions of EU steel market by steel type, in mt-CO_2

	Emissions EU	**Emissions Foreign**	**Emissions per technology**
Dirty	140	39	179
Green	29	14	43
Total	169	53	222

Source: Calculations of the author based on EUROFER (2020b); Hasanbeigi and Springer (2019); Medarac, Moya, and Somers (2020)

6.5. Capacity constraints in the EU steel market

Capacity constraints define the maximum amount of steel that each producer can supply (Chalabyan, Mori, and Vercammen 2018). Because no new steel producers can enter the market in the short-run, the capacity constraints put an upper bound to supply of steel in the EU in the short run. Thus, the capacity constraints values calculated in Table 7 may constrain the volumes supplied by any steel type in the short-run after implementing the ETS BCA carbon price. I assume an average capacity utilization rate of 75% to calculate these values. This means that each steel firm produces currently on average 75% of what it could produce. This concords with the values published by Hijikata (OECD 2020b), Chalabyan, Mori, and Vercammen (2018), and the Federal Reserve Bank of St. Louis (2021).

---

[7] For example, Hidalgo et al. (2005) considering the current development of the EU steel industry, Moya and Pardo (2013), Tatasteel (2019).

Table 7. Maximum capacity by steel type, in mt

	Maximum capacity EU	Maximum capacity Foreign	Maximum per technology
Dirty	92	22	114
Green	62	20	82
Total	154	42	196

Source: calculations of the author based on Hijikata (OECD 2020b), Chalabyan, Mori, and Vercammen (2018), and the Federal Reserve Bank of St. Louis (2021)

6.6.Elasticities

Steel demand is inelastic, with estimated own-price elasticities ranging from -0.6 to -0.2 (Demailly and Quirion 2008; Farr and Lord 2003; Giuliodori and Rodriguez 2015; World Bank 2015). The most used value is a PED of -0.3, which Winters calculated for the EU steel market (1995). A PED of -0.3 means that a 10% increase in steel prices decreases demand by 3%.

The only estimates for a PES I found are 1.2 and 0.7 for green and dirty steel, respectively (OECD 2003). This means that a price increase of 10% leads to a percentage increase in output of 12% and 7%, respectively. Green technology is more elastic, mainly because it has a more flexible cost structure (OECD 2003). Studies using the gravity trade model find that iron ore has a high trade elasticity (from -1.1 to 1.96) with respect to distance (Head and Mayer 2014 and references therein; Lundmark 2018; Robertson and Robitaille 2017; Sohn 2001). I assume that the steel trade must behave similarly. Since this means that the trade volume reacts more sensitively to price changes the higher the distance between to trading countries is, I gauge that the own-price elasticity of supply for Foreign importing into the EU is +0.4 higher than the PES for EU producers supplying to the EU market. Thus, I gauge the elasticities presented in Table 8., EU dirty steel is inelastic, the others are elastic.

Table 8. Elasticities by steel type

	Elasticity EU	**Elasticity Foreign**
Dirty	0.7	1.1
Green	1.2	1.6

Source: author based on Head and Mayer (2014); OECD (2003); Winters (1995)

I use these elasticity values to determine the slope of linear demand and supply curves (see the calculations in Appendix C). Several weaknesses pertain to this. First, I use these elasticities because I lack the actual marginal costs data. With marginal cost data, I would have the exact slope of the supply curves. Second, to simplify the analysis, I assume linear curves, even though the literature estimates are based on constant elasticity functions which result in convex or concave curves, respectively. Third, because the elasticity along a linear curve varies, I simply place myself on that part of the curve where the elasticity corresponds approximately to the elasticities taken from the literature, i.e. on the inelastic part for the demand curve and the elastic or inelastic part for the supply curve (see Appendix C). Fourth, I assume that the steel market exhibits the same trade elasticities as the iron ore market. Lastly, I assume an arbitrary value for the additional increase in the elasticity of supply values for Foreign steel.

6.7. Steel costs and prices

Table 9 presents the initial price in the EU steel market along with the initial costs for each steel type. The production costs consist mainly of energy, labour and raw material costs (Medarac, Moya, and Somers 2020). The initial costs are weighted averages. They also include the initial carbon costs and transport costs of €27 for Foreign costs. Appendix B contains the exact cost calculations. In the Appendix, I calculate the costs based on Medarac, Moya, and Somers (2020). I disentangle the carbon costs from the overall production price to not double count the carbon price already in place. I base my transport costs on data from Miao and Fortanier (2017) and the OECD (2020a).

Table 9**.** Initial price and production costs by steel type, in €/ t-steel

	Initial costs EU	**Initial costs Foreign**	**Total**	**Initial Price**
Dirty	€487	€422	€479	€486
Green	€483	€466	€474	

Source: calculations of the author based on Medarac, H., Moya, J.A. and Somers (2020); Miao and Fortanier (2017); OECD (2020a); Steelonthenet.com (2020); MEPS (2020); Stahlpreise (2020).

Surprisingly, green EU steel is already cheaper than dirty EU steel. The reason for that EU steel already includes an ETS carbon price of €1 for green steel and €9 for dirty steel (Medarac, Moya, and Somers 2020).

6.7.1. The gravity model of trade

I outlined in Section 3.1 that price equals cost because the steel market is competitive. The costs of EU producers are plausible because they approximately equal the current price.[8] In contrast, Foreign costs are too low compared to the market price. If Foreign costs were that low, they would supply a significantly higher share of the market than 22%. However, this is not the case – the volumes supplied from Foreign that one would expect at these costs are "missing".

The gravity model of trade can explain this phenomenon. It tells us that the steel imports into the EU depend on the foreign country's size and, most importantly, distance (Robertson and Robitaille 2017). According to the model, bilateral trade volumes decrease proportionally to Foreign's distance and increase proportionally to Foreign's GDP (Sohn 2001). Empirical studies for the steel and basic metal industry strongly support the gravity model hypotheses (Head and Mayer 2014; Lundmark 2018; Robertson and Robitaille 2017). They show that steel trade tends to fall with distance because the transaction costs γ, such as organizational, political, cultural, transport time costs, and market access barriers, increase with distance (Sohn 2001).

The EU steel market clears at €486 with an imported volume of 34 mmt (see Section 6.1). This means that the Foreign costs (€466 for green and €422 for dirty) plus the transaction costs γ must approximately equal €486 at the imported volume of 34 mmt. I attempt to make γ tangible by 'monetizing' the value in my marginal cost structure. I assume that these costs γ are unit costs. This means that I add them on top of the marginal costs for each unit of steel. I add a unit cost of €10.50 and €48 for Foreign green and dirty steel, respectively (see Appendix C).

---

[8] The real market, competitive or not, always deviates from the perfectly competitive market in economic theory, explaining the minor discrepancies.

The ‘missing’ trade and lack of transaction costs information are the most significant weaknesses of my data. It may be improbable that green and dirty steel have different transaction unit costs since the transport distance is the same. However, it is not inconceivable that the transaction costs for dirty steel are higher, because it may involve more negotiations costs to accept dirty steel in the EU. Nonetheless, there is a lack of data for the transaction costs γ, explaining the ‘missing trade’. Another explanation could be that Medarac, Moya and Somers’ cost data is not reliable.

6.8.The carbon price

This is the only value in Section 6, which is not currently part of the EU steel market and will only play a role once the ETS BCA carbon price is implemented. In 2019, the price for an emissions allowance averaged at approximately €25 per ton of emissions (ICAP 2020). Considering the EU’s reinforced mitigation efforts and the European Green Deal adopted in 2020, carbon prices are expected to rise to €32-65 per ton of emissions in 2030 (Argusmedia 2020; Carbon Tracker Initiative 2020; Reuters 2020). To avoid competitiveness losses and carbon leakage, to date, the steel industry has been granted free allowances by the EU (Sanin and Sourisseau 2019). Due to this free allocation, the steel sector was previously only marginally affected by the EU ETS (Verde 2020 and references therein). In 2019, the effective emissions cost varied between €0.80 and €9 for each ton of steel produced in the EU (Medarac, Moya, and Somers 2020). I assume €50 because it is approximately the mean of the forecast interval. I furthermore assume that the steel industry will not receive free allowances after the introduction of the BCA.

6.9.Summary data: current EU steel market

Table 10 summarizes the data characterizing the initial situation of the market. The emission intensity data refer to 2009 to 2015, while other values are from 2017 and 2019.

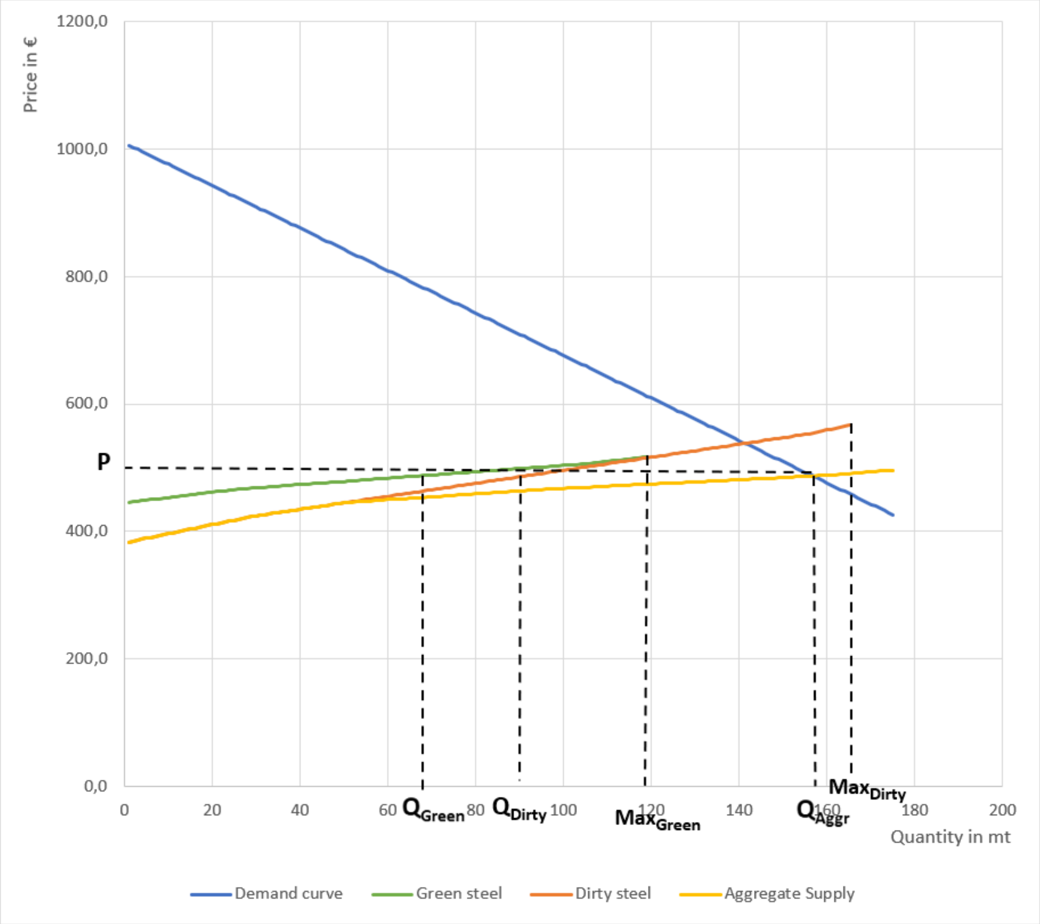
Table 10. Summary of EU Steel market before the ETS BCA carbon price

	Costs	**Price**	**Technology mix**	**Volume**	**Region mix**	**Emissions**	**Emission intensity**
	t-steel /€	t-steel /€	%	mt		mt-CO_2	t-CO_2/ t-steel
Dirty EU	€487		60%	73		140	1.90
Green EU	€483		40%	50		29	0.60
Steel EU Total	-		100%	123	78%	169	1.38
Dirty Foreign	€422		52%	18		39	2.20
Green Foreign	€466		48%	16		14	0.84
Steel Foreign Total	-		100%	34	22%	53	1,55
Dirty Total	€474		58%	91		179	1.96
Green Total	€479		42%	66		43	0.66
Steel Total	€476	€486	100%	157	100%	222	1.41

Source: author

Using the data from this Section, I derive Figure 4. Figure 4 illustrates the EU steel market's initial equilibrium before the ETS BCA carbon price, differentiating between steel types.

Figure 4**.** EU steel market before the ETS BCA carbon price



Source: author[9]

Dirty steel (orange supply curve) is cheaper than green steel (green supply curve), illustrating the costs calculations in Section 6.7. The aggregation of the two supply curves gives the aggregate supply curve (yellow). The EU steel market price P (€486) and total EU steel volume $Q_{\mathbf{Aggr}}$ (157 mt) emerges where the aggregate supply curve meets the demand curve (blue line). Green technology producers stop producing at point $Q_{\mathbf{Green}}$ (66 mt), while dirty technology producers produce until point $Q_{\mathbf{Dirty}}$ (91 mt), as calculated in Section 6.2. Point $Q_{\mathbf{Aggr}}$ (157 mt) equals the total quantity produced by both green ($Q_{\mathbf{Green}}$) and dirty steel producers ($Q_{\mathbf{Dirty}}$). $Max_{\mathbf{Green}}$ (119

---

[9] I derived this graph in MS Excel. Please contact me for a detailed overview.

mt) indicates the maximum capacity of green steel, as calculated in Section 6.5. $\text{Max}_{\textbf{Dirty}}$ indicates the maximum capacity of dirty steel (165 mt). The elasticities from Section 6.6 determine the slope of the curves.

Appendix C explains how I derived Figure 4 using the data in Section 6. It also contains the desegregation on the four steel types. In the Appendix, I derive the inverse demand and supply functions using the elasticity values from Section 6.6. I calibrate the cost of the first ton of steel (the intercepts of the supply curves with the y-axis) such that I obtain supply curves that are consistent with the technology mix from my data (Section 6.1). All steel types had to supply their respective quantity at the market price of €486 (hence marginal cost of €486) since this is the EU market steel price. For the EU values, I ensured that they reflect the average costs I discerned in Section 6.7. For Foreign, this is not the case. This means that the average costs of my marginal cost structure for Foreign in the graph are far apart from the average production costs from Section 6.7. This has mostly to do with the 'missing trade' that I attempt to make up for. Nonetheless, I calibrate the cost curve so that they accurately represent the cost difference between green and dirty steel.

7. Results

This Section presents the economic and environmental impact of the carbon price, first in the short run, then in the long run, followed by a summary of the results.

7.1.The short-run

First, production costs increase depending on their emission intensity, calculated in Table 11. The initial costs increase by €50/ton of emissions for each ton of steel. As such, I multiply each steel type's emission intensity by €50, as illustrated in Section 2.3. The EU costs increase by less than the corresponding Foreign costs for two reasons. Firstly, EU steel is less emissions-intensive than Foreign steel (see Section 6.3). Secondly, EU steel already includes an ETS carbon price (Medarac, Moya, and Somers 2020).

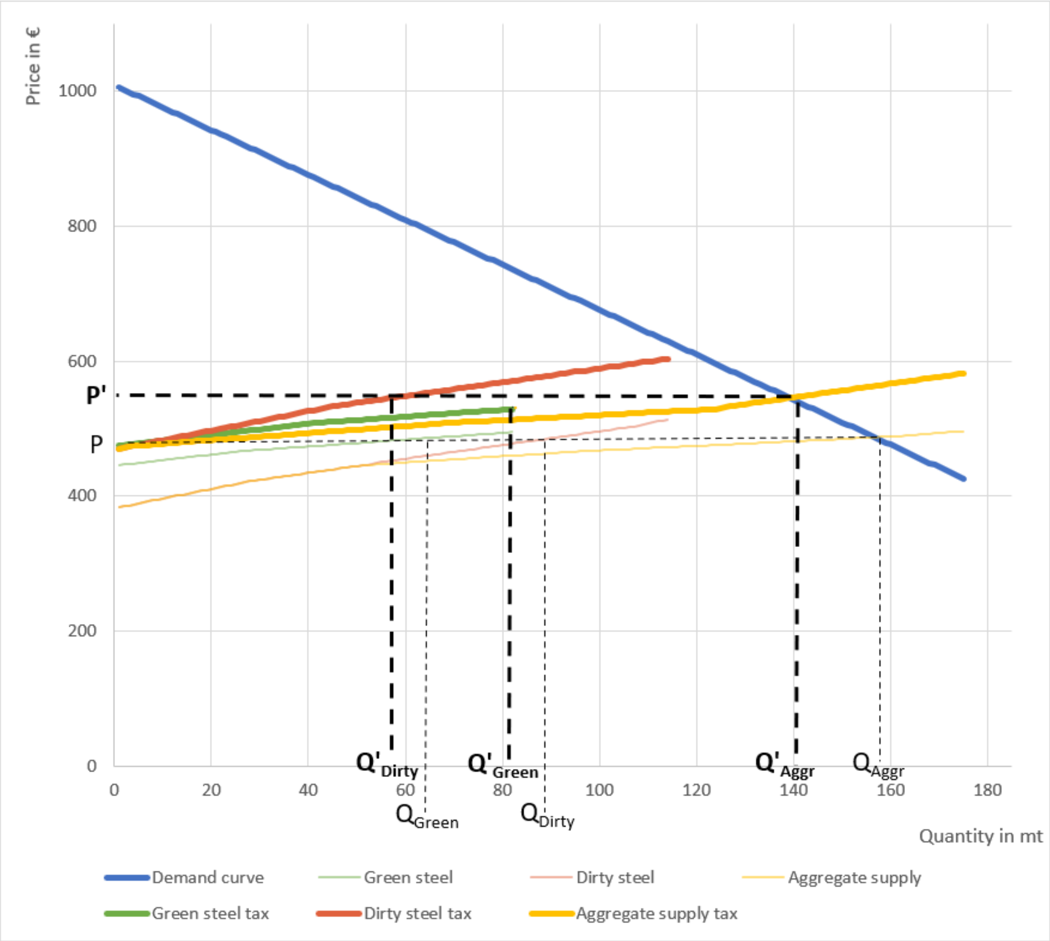
Table 11. Costs before and after the ETS BCA carbon price and initial price, in €

	Green EU	**Dirty EU**	**Green Foreign**	**Dirty Foreign**	**Green total**	**Dirty total**	**Initial Price**
Initial costs	€483	€487	€466	€422	€474	€479	**€486**
New costs	€512	€574	€508	€531	€510	€565	
Change in costs	6%	18%	9%	26%	8%	18%	

Source: calculations of the author based on Medarac, H., Moya, J.A. and Somers (2020); Miao and Fortanier (2017); OECD (2020a); Steelonthenet.com (2020); MEPS (2020); Stahlpreise (2020).

Figure 5 depicts the EU steel market after implementing the ETS BCA carbon price in the short-run. The thin curves represent the market before and the thick curves the market after the ETS BCA carbon price.

Figure 5. EU steel market in the short-run



Source: author

A few dynamics are noteworthy:

1. The increase in costs shifts the supply curves to the left. Dirty steel supply shifts more to the left than green steel supply. Dirty steel is on average more expensive than green steel under the ETS BCA carbon price.
2. The equilibrium quantity decreases from $Q_{\mathbf{Aggr}}$ (157 mt) to $Q'_{\mathbf{Aggr.}}$ (139 mt). The price increases from P (€486) to P' (€546). The new equilibrium emerges at P' and $Q'_{\mathbf{Aggr}}$.
3. The quantity supplied by the dirty technology decreases from $Q_{\mathbf{Dirty}}$ (91 mt) to $Q'_{\mathbf{Dirty}}$ (57 mt). The quantity supplied by the green technology increases from $Q_{\mathbf{Green}}$ (66 mt) to

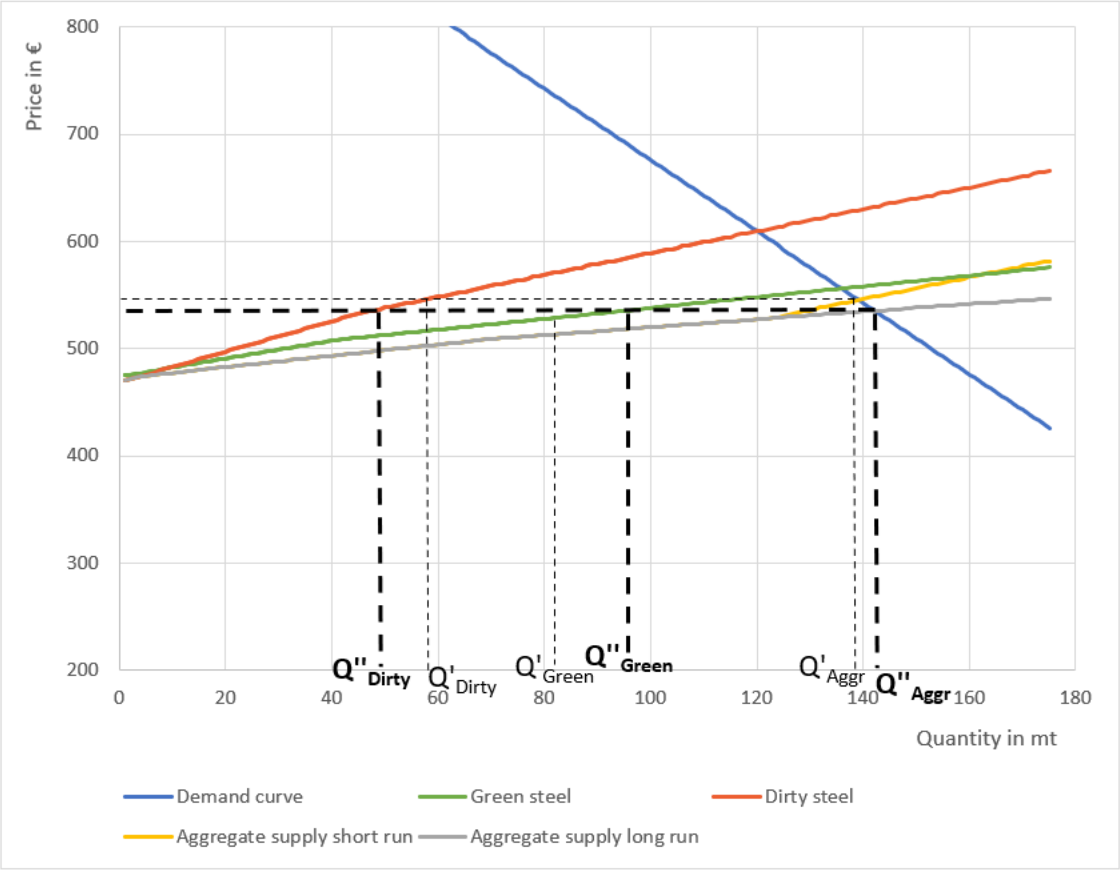
Q’$_{\textbf{Green}}$ (82 mt). This is because after the carbon price, dirty steel becomes more expensive than green steel.

4. After the carbon price, green steel producers produce at maximum capacity. The capacity of green steel stops before the green steel supply curve crosses the horizontal line at the market price. This means that green steel producers stop producing at a marginal cost lower than the market price.

7.2. The long-run

In the long-run, new steel producers enter the market until the marginal costs equal the market price. This could be any of these four producer groups: first, green steel producers who supply elsewhere but ramp up their production from 75 to 100% capacity utilization rate to supply to the EU market; second, green steel producers who previously supplied elsewhere but decide to supply the EU market now; third, dirty steel producers who were driven out of the market by the carbon price or fourth, entrepreneurs who build a new green steelmaking facility. Eventually, green steel producers' capacity utilisation may decrease back to their initial capacity utilization rate while more new green steel producers enter the market. Figure 6 illustrates this. The green steel supply curve is not constrained anymore and crossed by the horizontal line at the equilibrium price.

Figure 6. The EU steel market in the long-run



Source: author

Compared to the short-run, the market price decreases by €10 to €536, and the quantity supplied increases by 3 mt to 142 mt. Moreover, the share of green steel within that volume increases from Q’**Green** (82 mt) to Q’’**Green** (94 mt), and the share of dirty steel decreases from Q’**Dirty** (58 mt) to Q’’**Dirty** (48 mt).

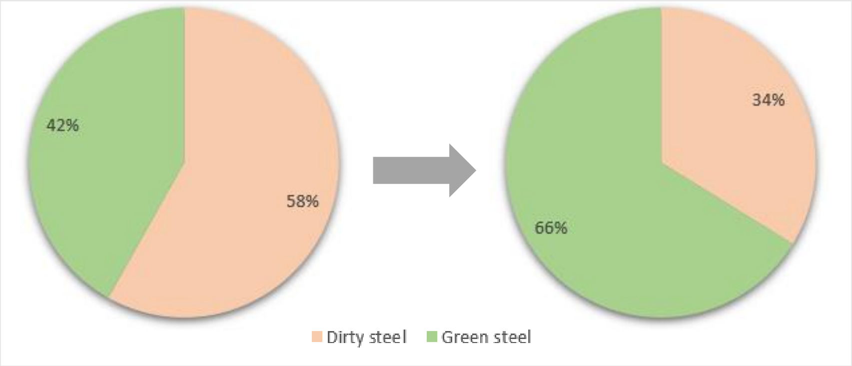
Moreover, steel producers may decide to undergo energy efficiency improvements in the long-run. To recall from 3.1, this is one of the four canonical ways in which a carbon price can induce emission reductions. I assumed that producers could only switch from dirty technology with the average “fixed” emission intensity of their region to green technology with their region's fixed emission intensity that I calculated in Section 6.3. Suppose I relax this assumption and allow for energy improvements within a steelmaking facility. In that case, producers could substitute away from producing many emissions by using capital to switch to more energy-efficient machinery. The input substitution elasticity measures how easy this switch from high-emission to low-emission machinery is. The higher the substitution elasticity, the likelier the switch. I calculated this elasticity value and compared it with the literature, which is inconclusive. My calculations indicate a weak substitution for EU producers and a very low substitution for Foreign producers. This means that it is likely that a few EU dirty producers will become more energy efficient within their technology in the long-run. Very few Foreign dirty producers will switch. This technological substitution results in further emission reduction. I omitted this part for space reasons, but details are in Appendix D.

7.3. Summary results

Summarizing, I can distinguish three emissions-reducing sources: (i) a decrease in volume, (ii) an increase in the share of green steel caused by a change in the capacity utilization rate and new green steel producers entering the market and – as calculated in Appendix D – (iii) energy efficiency improvements through a weak input substitution from emissions to capital within steelmaking facilities. I will, however, not discuss the third source in the following because of space limits.

The driving force behind the emissions reduction is the change in the technology mix. If the volume decreased, assuming the initial technology mix, a 10% volume decrease would lead to an emissions reduction of 10%. However, due to the change in the technology mix, the emissions reduction is 31%. This shows that the technology mix change is the driving force behind the reduction. Moreover, if the mix remained constant, the decrease in volume would be higher. Figure 7 illustrates the change in the technology mix from before to after the ETS BCA carbon price. The share of green steel increases by 24%.

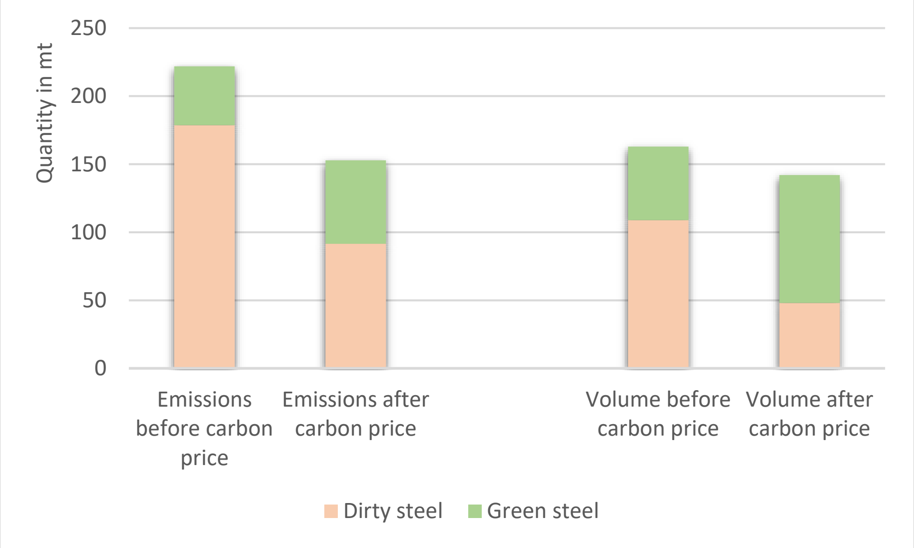
Figure 7. Technology mix before and after the ETS BCA carbon price



Source: author

Overall, the volume decreases, and prices increase by 10%. The dirty steel volume decreases by 47%, whereas the green steel volume increases by 43%, as depicted in Figure 8.

Figure 8. Emissions and volume before and after the ETS BCA carbon price



Source: author

Comparing the changes in steel production of EU and Foreign producers; the volume supplied by EU producers decreases by 3%, whereas the supply by Foreign producers decreases by 35%. The new region mix is 85% EU steel and 15% Foreign steel from an initial 78% and 22%, respectively, meaning that within the overall volume decrease, 2% can be traced back to a volume decrease of EU producers and 8% to a volume decrease of Foreign producers. The decrease in Foreign is so drastic that dirty Foreign steel is wholly driven out of the market. The decrease in Foreign is higher than in the EU for two reasons: Firstly, Foreign steel becomes more costly than EU steel because it is more emissions-intensive. This is the case for both green and dirty steel, however, particularly for dirty Foreign steel, which increases significantly in costs compared to EU steel. Secondly, the Foreign supply curves are more elastic, thus more responsive to price changes than EU steel. Table 12 shows the effects of the ETS BCA carbon price in detail.

Table 12. Summary EU steel market after the ETS BCA carbon price

	Technology mix		**Volume**			**Emissions**		
	Initial	**New**	**Initial**	**New**	**Change**	**Initial**	**New**	**Change**
	%		mt		%	mt-CO$_2$		%
Dirty EU	60%	39%	73	47	-36%	140	89	-36%
Green EU	40%	61%	50	73	+46%	29	44	+48%
Steel EU Total	100%	100%	123	120	-3%	169	133	-21%
Dirty Foreign	52%	0%	18	0	-100%	39	0	-100%
Green Foreign	48%	100%	16	22	+38%	14	18	+29%
Steel For. Total	100%	100%	34	22	-35%	53	18	-66%
Dirty Total	58%	34%	91	47	-48%	179	92	-49%
Green Total	42%	66%	66	95	+44%	43	61	+42%
Steel Total	100%	100%	157	142	-10%	222	153	-31%

Source: author

8. Discussion

8.1. Comparison with the academic literature

To recall from Section 4, previous studies ‘averaged’ at an emissions decrease of 23% considering a carbon price of €58. According to my results, the decrease in volume and emissions (variable 1 and 2) are at the upper end but within the range priorly found in the literature. Thus, my thesis supports previous literature’s results. My findings are similar to the results of Monjon and Quirion. They find an emissions decrease of 28% and a volume decrease of 7% considering carbon price of €47 in the EU (27) market (Monjon and Quirion 2011b). Gielen and Moriguchi find a 13% volume and 25% emissions decrease considering a €22 carbon price in the Japanese steel sector (2002a). Alexeevi-Taleba et al. also find comparable values with a decrease in emissions of 22% considering a carbon price of €56 for the EU’s energy-intensive sectors (2012). Ruth and Amato (2002), Pardo and Moya (2013) and Mathiesen and Moestad (2004) find similar values for comparable non-EU regions. The latter three are also concerned with a detailed account of the driving force behind the emission reductions. They all find that a shift in the technology mix from dirty to green is the primary cause behind the emission reduction, as do I.

However, none of the papers considering a BCA deal with the shares of foreign and domestic supply within the domestic market (dependent variable 3). Instead, most focus on global emission levels. As such, I cannot compare these values to the previous literature. Referring to dependent variable 3, there is anyways one caveat to my Foreign versus EU results. As I have pointed out throughout the study, the data for Foreign on which I base my analysis is rickety. This relates to the ‘missing trade’ phenomenon. Therefore, the results for Foreign steel must be viewed with caution. Yet, the results for EU producers seem plausible.

8.2.Limitations of the paper

This Section discusses the most critical limitations of the paper with reference to the research design and the paper as a whole.

8.2.1. Limitations of the research design

Economic modelling is always prone to lead to distortions of reality because it requires simplifying assumptions. Yet, assumptions are necessary to make any economic analysis manageable. Similarly, my analysis and, hence, my results are subject to the validity of several assumptions.

First, BCAs are proven to be efficient in theory but are associated with great difficulties when put into practice (ÖGfE 2020; Zachmann and Mcwilliams 2020). Economic, theoretical modelling does not take these into account.

Second, the assumption that all producers are rational profit-maximizing actors is a weakness. It may be that not every steel producer wishes to maximize their profits at any cost (such as by firing employees or depressing wages). Consumers may not be interested in the cheapest steel either. As we saw in Section 6.7, Foreign – ‘cheap’ – steel is associated with high transaction costs, such as cultural, political and market access barriers, which are not considered in the price. Moreover, participants in the steel market may also have non-standard preferences, such as social preferences. Thus, they may be intrinsically motivated to reduce emissions and decide to deal in green steel despite higher costs and prices.

Third, I do not model the consumers' behaviour, and I take the demand side as given. Moreover, I assume that the demand curve stays fixed between the before-carbon price and after-carbon price scenarios. Yet, this may not be the case. For example, consumers could improve what is referred to as light-weighting, i.e. using less steel with the same effect (Demailly and Quirion 2008).

8.2.2. Considering the rest of the world

My study's most significant limitation is that I do not consider the impact of the ETS BCA carbon price on global emissions levels and exporting EU steel producers. Non-EU or even global emissions levels could increase significantly for two reasons. First, dirty EU producers driven out of the EU market may decide to export their steel abroad. Following the same logic, dirty Foreign producers driven out of the EU market could sell their steel to non-EU countries. For example, Böhringer et al. examine this case and found a 2% emissions increase in non-EU countries due to an ETS BCA carbon price (2012).

8.2.3. Considering the interaction with competing sectors

Another limitation is that I do not account for the fact that the steel market is interrelated with other competing sectors which could also bear the EU ETS price. Hence, I ignore secondary effects of an ETS carbon price on, for example, the electricity-generating sector. Since green steel requires more electricity than dirty steel, green steel may again increase relatively in price compared to dirty steel (see section 2.1.). Carbon pricing costs in the energy sector could also increase transport costs and costs of production of steel further.

Moreover, under a comprehensive ETS carbon price on emissions-intensive sectors, steel will become more expensive than low-emissions sectors. Therefore, another limitation is that I do not consider that consumers may substitute steel with lower-emissions products where possible, decreasing overall steel volume further.

8.3. Broader implications of the study

My findings are likely transferable to other regions because the steel market structure is mostly similar worldwide (Worldsteel 2018). Emissions reductions in Asia and Oceania may be higher than those suggested by my results because steel there is more emissions-intensive (see Section 6.3). Hence, there is more room for improvement. My study indicates that a global carbon price on steel could reduce emissions in the global steel industry by 31%. The steel industry is responsible for 7 to 10% of global emissions. It follows that global emissions may decrease by 2-3% when a global carbon price on steel of €50 is introduced.

Furthermore, a few other sectors could likely have similar emissions reductions if they obeyed a carbon price. They must have two features to achieve similarly significant reductions: they must be emissions-intensive, and they must have readily-available alternative technologies to which producers can switch. An example of this is the electricity sector, where actors can switch from fossil-fuel-based to renewable electricity generation (Schumacher and Sands 2007). Other sectors with a high emissions reduction potential are the cement, chemical and aluminium sectors (Kuik and Hofkes 2010; Monjon and Quirion 2011a).

8.4. Future steel technology developments

To recall from Section 3.1, the fourth canonical way to reduce emissions is developing breakthrough technologies. Nearly carbon-neutral steel technology using hydrogen is a technically proven production method currently being developed for production on a global scale by all major EU steel producers (McKinsey & Company 2020; Roland Berger Consultancy 2020). The Swedish producer SSAB expects to sell its first hydrogen-based steel in 2026 (SSAB 2020). Emissions reduction in the steel industry under a carbon price will be even more significant in the near future when hydrogen-based steel technology is rolled out for mass-scale production. With few investment cycles left until the 2050 carbon neutrality goal, the EU steel industry will turn to hydrogen-based solutions once the technology is ready for mass-scale production (Roland Berger Consultancy 2020).

9. Conclusion

This thesis addressed the research question: How would an ETS BCA carbon price in the steel sector change (i) the volume, (ii) the technology mix, (iii) the associated emissions and (iv) the region mix consumed in the EU steel market? My results indicate that an ETS BCA carbon price reduces emissions primarily by increasing the share of green steel in the market by 24%, and to a lesser extent due to the overall volume decrease. Emissions decrease by 31%. Overall steel volume consumed in the EU decreases by 10%. The new region mix is 85% EU steel and 15% Foreign steel, meaning that within the overall volume decrease, 2% can be traced back to a volume decrease of EU producers and 8% to a volume decrease of Foreign producers.

9.2. Policy lessons

The results indicate that an ETS BCA carbon price on the steel sector is a viable tool to decrease emissions effectively without significantly decreasing the volume produced by EU steel producers, and thus employment and GDP. The carbon pricing income could partially flow back to finance the rebate for EU producers exporting abroad. The remaining income could be used to mitigate the carbon price’s adverse effects, such as unemployment. The EU steel sector directly employs 320.000 people, and a decrease in volume of 3% supplied by EU producers indicates a proportional decrease in employment (Godden 2018). Thus, the carbon pricing revenue could help structurally unemployed steelworkers transition into another field. The carbon pricing income could also be used to help dirty steel producers switch to green steel. It could also flow into further research and development of hydrogen-based steel. This may be useful because if the EU steel industry were the first to introduce carbon-neutral, mass-scale steel technology, this could offer a significant competitive advantage compared to non-EU steel producers. This may help secure employment, a strong steel industry and a contribution to carbon neutrality in the long run.

9.3. Research suggestions

Future research could mitigate my study's limitations by investigating the change in global emissions from the steel sector or considering interaction with competing sectors. It could also consider the role of the EU exporting producers, the impacts of a BCA carbon price rebate mechanism at the EU’s border, or the practical feasibility of an EU BCA. Finally, efforts could be directed at understanding how policymakers can contribute best to the steel industry's transition to hydrogen-based carbon-neutral steel technology. For example, researchers could research which carbon price is *sufficient* to make the new carbon-neutral technology economically competitive.

10. Bibliography

Abdul Quader, M, Shamsuddin Ahmed, S Z Dawal, and Y Nukman. 2016. "Present Needs, Recent Progress and Future Trends of Energy-Efficient Ultra-Low Carbon Dioxide (CO 2) Steelmaking (ULCOS) Program." *Renewable & sustainable energy reviews* 55: 537–49.

Alataş, Sedat. 2020. "Towards a Carbon-Neutral Economy: The Dynamics of Factor Substitution in Germany." *Environmental Science and Pollution Research* 27(21): 26554–69. https://doi.org/10.1007/s11356-020-08955-2.

Alexeeva-Talebi, Victoria, Böhringer Christoph, Andreas Löschel, and Sebastian Voigt. 2012. "Implications on Competitive Consequences of Climate Change Policies: The Role of Border Carbon Adjustment in Unilateral Climate Policy." *Energy economics* 34.

Argusmedia. 2020. "EU ETS Price €32-65/t under 2030 Scenarios." https://www.argusmedia.com/en/news/2142240-eu-ets-price-3265t-under-2030-scenarios (November 28, 2020).

Baldwin, Richard, and Charles Wyplosz. 2019. "The Economics of European Integration." *The McGraw-Hill Education* 6th editio.

Bellora, Cecilia et al. 2020. *Trade-Related Aspects of Carbon Border Adjustment Mechanisms*. Brussels: European Parliament.

Böhringer, Christoph, Edward J Balistreri, and Thomas F Rutherford. 2012. "The Role of Border Carbon Adjustment in Unilateral Climate Policy: Overview of an Energy Modeling Forum Study (EMF 29)." *Energy economics* 34: S97--S110.

Branger, Frédéric, and Philippe Quirion. 2014. "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.

Branger, Frédéric, Philippe Quirion, and Julien Chevallier. 2016. “Carbon Leakage and Competitiveness of Cement and Steel Industries Under the EU ETS: Much Ado About Nothing.” *The Energy journal (Cambridge, Mass.)* 37(3): 109–35.

Carbon Tracker Initiative. 2020. “EU Carbon Prices Could Double by 2021 and Quadruple by 2030.” https://carbontracker.org/eu-carbon-prices-could-double-by-2021-and-quadruple-by-2030/ (November 20, 2020).

Chalabyan, Avetik, Lapo Mori, and Steven Vercammen. 2018. “The Current Capacity Shake-up in Steel and How the Industry Is Adapting.” *McKinsey* (January): 1–2. https://www.mckinsey.com/~/media/McKinsey/Industries/Metals and Mining/Our Insights/The current capacity shake up in steel and how the industry is adapting/The-current-capacity-shake-up-in-steel-and-how-the-industry-is-adapti.

Cosbey, Aaron, Susanne Droege, Carolyn Fischer, and Clayton Munnings. 2019. “Developing Guidance for Implementing Border Carbon Adjustments: Lessons, Cautions, and Research Needs from the Literature.” *Review of environmental economics and policy* 13(1): 3–22.

Costantini, Valeria, Francesco Crespi, and Elena Paglialunga. 2018. “Capital–Energy Substitutability in Manufacturing Sectors: Methodological and Policy Implications.” *Eurasian business review* 9(2): 157–82.

Dahlmann, Peter et al. 2015. “Steel’s Contribution to a Low-Carbon Europe 2050: Technical and Economic Analysis of the Steel Sector’s CO2 Abatement Potential.” *Iron and Steel Technology*.

Demailly, Damien, and Philippe Quirion. 2008. “European Emission Trading Scheme and Competitiveness: A Case Study on the Iron and Steel Industry.” *Energy economics* 30(4): 2009–27.

Directive 2003/87/EC, 2003. 2003. DIRECTIVE 2003/87/EC OF THE EUROPEAN

PARLIAMENT AND OF THE COUNCIL Directive 2003/87/EC of the European Parliament and the Council of 13 October 2003 on the EU Emissions Trading Scheme (EU ETS) , 2003 O.J. (L0087). https://eur-lex.europa.eu/legal-content/ *Directive 2003/87/EC*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32003L0087 (January 10, 2021).

Elkader, M A et al. 2015. “Influence of the Direct-Reduced Iron Percentage in the EAF Charge Mix on EAF Operation Parameters.” *Steel Research International*: 13–22.

EUROFER. 2020a. *Economic and Steel Market Outlook 2020-2021*. https://www.eurofer.eu/assets/Uploads/REPORT-Economic-and-Steel-Market-Outlook-Quarter-2-2020.pdf.

———. 2020b. 44 The European Stee Association *Steel in Figures*. https://www.eurofer.eu/assets/Uploads/European-Steel-in-Figures-2020.pdf.

Exchangerates.org. 2021. “US Dollar to Euro Spot Exchange Rates for 2019.” https://www.exchangerates.org.uk/USD-EUR-spot-exchange-rates-history-2019.html (January 26, 2021).

Farr, W Ken, and Richard A Lord. 2003. “Collusion and Financial Leverage: An Analysis of the Integrated Mill Steel Industry.” *Financial Management* 32(1).

Federal Reserve Bank of St. Louis. 2021. “Capacity Utilization: Manufacturing: Durable Goods: Iron and Steel Products.” https://fred.stlouisfed.org/series/CAPUTLG3311A2S (January 17, 2021).

Felbermayr, Gabriel, and Sonja Peterson. 2020. *Economic Assessment of Carbon Leakage and Carbon Border Adjustment*. Brussels: European Parliament.

Gielen, Dolf, and Yuichi Moriguchi. 2002a. “CO2 in the Iron and Steel Industry: An Analysis of Japanese Emission Reduction Potentials.” *Energy Policy*.

———. 2002b. “Modelling CO2 Policies for the Japanese Iron and Steel Industry.”

Environmental Modelling & Software 17(5): 481–95.

Giuliodori, David, and Alejandro Rodriguez. 2015. “Analysis of the Stainless Steel Market in the EU, China and US Using Co-Integration and VECM.” *Resources policy* 44: 12–24.

Godden, Doug. 2018. *The Impact of the European Steel Industry on the EU Economy*. Oxford Economics and EUROFER.

Goodwin, Neva et al. 2015. *Microeconomics in Context*. Routlege.

Hasanbeigi, Ali et al. 2016. “Comparison of Carbon Dioxide Emissions Intensity of Steel Production in China, Germany, Mexico, and the United States.” *Resources, Conservation and Recycling*.

Hasanbeigi, Ali, and Cecilia Springer. 2019. *How Clean Is the U.S. Steel Industry?* Global Efficiency Intelligence.

Head, Keith, and Thierry Mayer. 2014. “Gravity Equations: Workhorse,Toolkit, and Cookbook.” In *Handbook of International Economics*,.

Hebling, Chris et al. 2019. “Eine Wasserstoff-Roadmap Für Deutschland [in German].” *Fraunhofer Institut*.

Hidalgo, Ian, Linda Szabo, Jorge Carlosciscar, and Aaron Soria. 2005. “Technological Prospects and CO Emission Trading Analyses in the Iron and Steel Industry: A Global Model.” *Energy (Oxford)* 30(5): 583–610.

ICAP. 2020. “ETS Prices.” *International Carbon Action Partnership*. https://icapcarbonaction.com/en/ets-prices (November 28, 2020).

Ispat Guru. 2018. “Crude Steel.” https://www.ispatguru.com/crude-steel/ (November 26, 2020).

Kuik, Onno, and Marjan Hofkes. 2010. “Border Adjustment for European Emissions Trading: Competitiveness and Carbon Leakage.” *Energy Policy*.

Kuramochi, Takeshi. 2016. “Assessment of Midterm CO2 Emissions Reduction Potential in the

Iron and Steel Industry: A Case of Japan.” *Journal of Cleaner Production* 132: 81–97.

Lagomarsino, Elena. 2020. “Estimating Elasticities of Substitution with Nested CES Production Functions: Where Do We Stand?” *Energy Economics* 88: 104752. http://www.sciencedirect.com/science/article/pii/S0140988320300918.

Lundmark, Robert. 2018. “Analysis and Projection of Global Iron Ore Trade: A Panel Data Gravity Model Approach.” *Mineral Economics* 31(1): 191–202. https://doi.org/10.1007/s13563-017-0125-8.

Lutz, Christian, Bernd Meyer, Carsten Nathani, and Joachim Schleich. 2005. “Endogenous Technological Change and Emissions: The Case of the German Steel Industry.” *Energy Policy* 33(9): 1143–54.

M. Huang, Y. He. 2006. “Modelling Energy Consumption and Economic Growth: An Empirical Study for China Stat Decis [in Chinese].” 11.

Ma, Hengyun, Les Oxley, John Gibson, and Bonggeun Kim. 2008. “China’s Energy Economy: Technical Change, Factor Demand and Interfactor/Interfuel Substitution.” *Energy Economics* 30(5): 2167–83. http://www.sciencedirect.com/science/article/pii/S0140988308000273.

Malfa, E. 2017. “Steel Made in Europe: The Backbone of Sustainability.” In *2017 12th International Conference for Internet Technology and Secured Transactions (ICITST)*,.

Mathiesen, Lars, and Ottar Mœstad. 2004. “Climate Policy and the Steel Industry: Achieving Global Emission Reductions by an Incomplete Climate Agreement.” *Energy Journal*.

Mayer, Jakob, Gabriel Bachner, and Karl W Steininger. 2019. “Macroeconomic Implications of Switching to Process-Emission-Free Iron and Steel Production in Europe.” *Journal of Cleaner Production* 210: 1517–33. http://www.sciencedirect.com/science/article/pii/S0959652618335224.

McKinsey & Company. 2020. “Decarbonization Challenge for Steel.” *McKinsey*. https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel# (November 22, 2020).

Medarac, Hussein, Jan A. Moya, and Julia Somers. 2020. Publications Office of the European Union. *Production Costs from Energy-Intensive Industries in the EU and Third Countries.* https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/production-costs-energy-intensive-industries-eu-and-third-countries.

MEPS. 2020. “Europe Steel Prices | MEPS International Ltd.” https://www.meps.co.uk/gb/en/products/europe-steel-prices (November 20, 2020).

Miao, Guannan, and Fabienne Fortanier. 2017. “Estimating Transport and Insurance Costs of International Trade.” https://www.oecd-ilibrary.org/content/paper/8267bb0f-en.

Monjon, Stéphanie, and Philippe Quirion. 2011a. “A Border Adjustment for the EU ETS: Reconciling WTO Rules and Capacity to Tackle Carbon Leakage.” *Climate Policy: Consuming and producing carbon: what is the role for border measures?* 11(5): 1212–25.

———. 2011b. “Addressing Leakage in the EU ETS: Border Adjustment or Output-Based Allocation?” *Ecological Economics*.

Moya, José Antonio, and Nicolás Pardo. 2013. “The Potential for Improvements in Energy Efficiency and CO2 Emissions in the EU27 Iron and Steel Industry under Different Payback Periods.” *Journal of Cleaner Production*.

OECD. 2003. *Environmental Policy in the Steel Industry: Using Economic Instruments*.

———. 2020a. “International Transport and Insurance Costs of Merchandise Trade (ITIC).” https://stats.oecd.org/Index.aspx?DataSetCode=MTC# (December 2, 2020).

———. 2020b. *Latest Developments in Steelmaking Capacity*. https://www.oecd.org/industry/ind/latest-developments-in-steelmaking-capacity-2020.pdf.

ÖGfE. 2020. “How to Implement a WTO-Compatible Full Border Carbon Adjustment as an Important Part of the European Green Deal How to Implement a WTO-Compatible Full Border Carbon Adjustment as an Important Part of the European Green Deal.” *Österreichische Gesellschaft für Europapolitik*.

Pardo, Nicolás, and José Antonio Moya. 2013. “Prospective Scenarios on Energy Efficiency and CO2 Emissions in the European Iron & Steel Industry.” *Energy*.

Peterson, Everett B; 2007. “Economic and Environmental Effects of Border Tax Adjustments.” *Fraunhofer ISI InstituteSystems and Innovation Research*.

Quirion, Philippe, and Stéphanie Monjon. 2012. “How to Design a Border Adjustment for the European Union Emissions Trading System?” *SSRN Electronic Journal*.

Recycling Today. 2020. “The Growth of EAF Steelmaking.” https://www.recyclingtoday.com/article/the-growth-of-eaf-steelmaking/ (November 26, 2020).

Reuters. 2020. “Analysts Sharply Raise EU Carbon Price Forecasts on Tougher Climate Goals.” https://www.reuters.com/article/us-eu-carbon-poll-idUSKBN2711HK (November 28, 2020).

Richter, Wolf. 2018. “Who Dominates Global Steel Production & Trade?” *Wolf Street*. https://wolfstreet.com/2018/06/01/who-dominates-the-steel-trade-that-trump-just-hit-with-tariffs/ (January 6, 2021).

Robertson, Peter E, and Marie-Claire Robitaille. 2017. “The Tyranny of Distance and the Gravity of Resources.” *The Economic record* 93(303): 533–49.

Roland Berger Consultancy. 2020. *The Future of Steelmaking – How the European Steel Industry Can Achieve Carbon Neutrality*. https://www.rolandberger.com/publications/publication_pdf/rroland_berger_future_of_steelmaking.pdf.

Ruth, Matthias, and Anthony Amato. 2002. “Vintage Structure Dynamics and Climate Change Policies: The Case of US Iron and Steel.” *Energy Policy*.

Sanin, Maria-Eugenia, and Sylvain Sourisseau. 2019. “Pervasive EUAs Free Allocation : The Case of the Steel Industry.” *Centre D’etudes des Politiques Economiques de l’univsersité d’Evry*.

Schumacher, Katja, and Ronald D Sands. 2007. “Where Are the Industrial Technologies in Energy–Economy Models? An Innovative CGE Approach for Steel Production in Germany.” *Energy economics* 29(4): 799–825.

Sohn, Chan-Hyun. 2001. “A Gravity Model Analysis of Korea’s Trade Patterns and the Effects of a Regional Trading Arrangement.” *Korea Institute for International Economic Policy* Working Pa: 1–35.

SSAB. 2020. 5 *Annual Report 2019*. https://mb.cision.com/Main/980/3057172/1209497.pdf.

Stahlpreise. 2020. “Aktuelle Stahlpreise pro Tonne, Stahlpreisentwicklung [in German].” https://www.stahlpreise.eu/ (November 30, 2020).

Steelonthenet.com. 2020a. “Cargo Transport Freight Shipping Costs of Iron, Ore, Coal & Steel.” https://www.steelonthenet.com/freight.html (November 30, 2020).

———. 2020b. “Electric Arc Furnace Technology Quality Trends.” https://www.steelonthenet.com/kb/eaf-technology-trends.html (December 2, 2020).

Stern, Nicholar, and Joseph E Stiglitz. 2017. World Bank *High-Level Commission on Carbon Prices*.

Talaei, Alireza et al. 2020. “Potential for Energy Efficiency Improvement and Greenhouse Gas Mitigation in Canada’s Iron and Steel Industry.” *Energy Efficiency* 13(6): 1213–43. https://doi.org/10.1007/s12053-020-09878-0.

Tanaka, Hidetoshi. 2014. “Resources Trend and Use of Directly Reduced Iron in Steelmaking

Process." *Kobelco Technology Review* 64(1): 2–7.

Tatasteel. 2019. *European Union Steel Imports Report*. https://legacy.trade.gov/steel/countries/pdfs/imports-eu.pdf.

U.S. Energy Information Administration (EIA). 2019. "The Basic Metals Industry Is One of the World's Largest Industrial Energy Users - Today in Energy -." https://www.eia.gov/todayinenergy/detail.php?id=38392 (January 5, 2021).

United Nations. 2019. *UN Climate Action Summit 2019*. https://www.un.org/en/climatechange/un-climate-summit-2019.shtml.

Vercoulen, Pim et al. 2018. "Decarbonizing the East Asian Steel Industry in 2050: An Analysis Performed with FTT(Future Technology Transformation)-Steel Model." (October). http://wwwecono.meijo-u.ac.jp/discussion/dp_0008.pdf.

Verde, Stefano F. 2020. "The Impact of the EU Emissions Trading Scheme on Competitiveness and Carbon Leakage: The Econometric Evidence." *Journal of economic surveys* 34(2): 320–43.

Wang, Xiaolei, and Boqiang Lin. 2017. "Factor and Fuel Substitution in China's Iron & Steel Industry: Evidence and Policy Implications." *Journal of Cleaner Production* 141: 751–59. http://www.sciencedirect.com/science/article/pii/S0959652616314743.

Winters, L Alan. 1995. "Liberalizing European Steel Trade." *European economic review* 39(3): 611–21.

World Bank. 2015. *Carbon Leakage : Theory, Evidence and Policy Design*. World Bank, Washington, DC.

Worldsteel. 2018. "Steel Statistical Yearbook 2018." *WorldSteel Association* 1(November): 121. https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html.

Xu, Wenqing et al. 2015. "Material Flow Analysis of CO2 Emissions from Blast Furnace and

Basic Oxygen Furnace Steelmaking Systems in China." *Steel research international* 86(9): 1063–72.

Zachmann, Georg, and Ben Mcwilliams. 2020. "A European Carbon Border Tax: Much Pain, Little Gain." *Bruegel* Policy Con(March).

Zhang, Qi et al. 2018. "Comprehensive Assessment of Energy Conservation and CO2 Emissions Mitigation in China's Iron and Steel Industry Based on Dynamic Material Flows." *Applied Energy*.

Appendices

A. Detailed literature review

Table A1 on the following page gives a detailed overview of the literature.

Table A1. Detailed literature review

Region	Sector	Relation to RoW	Model	Time line	Paper	Driving force behind emission reduction	Volume change	CO_2 price	CO_2 change
EU (27)	Steel	Closed economy	Computable general eq. (CGE)	2010-2030	Pardo and Moya (2013)	Shift dirty to green, energy efficiency of green and dirty steel through innovative breakthrough technologies	-	€100	-24%
EU (15)	Steel and electricity	Global carbon price	Global partial equilibrium	1997-2030	Hidalgo et al. (2005)	Retrofitting of dirty technology, no change from dirty to green technology because of increasing prices of electricity	-1,4%	€28	-4%
Japan	Steel	Closed economy	CGE	2010-2030	Kuramochi (2016)	Increased scrap use, fuel shift in dirty technology	-	€98	-12%
Canada	Steel	Closed economy	Partial eq. (PE)	2010-2050	Talaei et al. (2020)	Shift dirty to green	-	€50	-6%
Germany	Steel and energy	Closed economy	Econometric multi-sector eq.	2005-2020	Lutz et al. (2005)	Shift dirty to green, technology innovation, fuel shift within technology	-0,4%	€73	-9%
Germany	Steel and Electricity	Closed economy	CGE	2005-2020	Schumacher and Sands (2007)	Shift dirty to green, fuel shift within technology	-2%	€50	-11%
US	Steel	Closed economy	PE	2002-2020	Ruth and Amato (2002)	Shift dirty to green, increased scrap use	+0,4%	€47	-23%
East Asia	Steel	Closed economy	FTT	2015-2050	Vercoulen et al. (2018)	Shift dirty to green	-	€90	-60%
Japan	Steel	Global carbon price	Partial foresight (STEAP)	2000-2020	Gielen and Moriguchi (2002a)	Energy efficiency, increase of scrap, shift from dirty to green	-15%	€40	-49%
Japan	Steel	Including BCA	Partial foresight (STEAP)	2000-2020	Gielen and Moriguchi (2002b)	Decreased volume, energy efficiency, increase of scrap, shift from dirty to green	-13%	€20	-41%
EU (27)	Steel, non-metallic minerals, non-ferrous metals	Including BCA	CGE	2020	Alexeevi-Taleba et al. (2012)	-	-	€56	-22%
Industr. countries	Steel, non-metallic minerals, non-ferrous metals	Including BCA	CGE	2004-2020	Böhringer, Balistreri, and Rutherford (2012)		-	€93	-21%
EU (27)	Steel	Including BCA	PE		Monjon and Quirion (2011b)		-7%	€47	-28%
EU (27)	Steel	Excluding BCA	PE	2020	Monjon and Quirion (2011a)	-	-7%	€20	-21%
EU (27)	Steel	Including BCA	PE	2005-2020	Monjon and Quirion (2011b)	-	-7%	€47	-28%
Industr. (Annex B)	Steel	Including BCA	global static partial eq.(SIM)	1995	Mathiesen and Mæstad (2004)	Shift dirty to green	-2,4%	€22	-8%
EU (15)	Steel	Excluding BCA	CGE		Peterson (2007)	-	-0,4%	€13	-5%

Here and throughout the study, I convert US dollars into euros using the 2019 average exchange rate of USD 1 = EUR 0.8931 (Exchangerates.org 2021). Most studies compare the emission reduction change to a business-as-usual scenario over a timespan of several decades. Most studies assume that overall steel consumption increases over that time span. For example in the case of Kuramochi (2016), this results in an increasing volume compared to the steel market before the carbon price (hereafter also called initial situation) because steel consumption increases by more than can be 'offset' by the carbon price-induced price increase. Furthermore, I compare the emissions and volumes from the initial situation to the final point in time instead of comparing the reductions with the business-as-usual scenario, unless otherwise indicated.

Most studies consider a progressively increasing carbon price over time. I inserted the final carbon price they considered. If a paper comprised several scenarios, I chose the scenario most comparable to mine. Suppose studies did not consider international trade throughout their study and did not specify their relationship to the rest of the world (RoW). In that case, I assume that they assumed a closed economy. This means that they did not consider international trade and assume that only domestic steel supplies the domestic market. However, some papers did not explicitly stated that assumption. Yet, they also did not mention carbon leakage or international trade in any way.

B. Calculation production costs

I calculated the prices using hot-rolled coil as a proxy of flat products and wire rod as a proxy of long products, as also done in Medarac, Moya, and Somers (2020). I then took the average of those to receive an average price for the green and dirty technology. Projections for Foreign are based on production costs of the five biggest exporters into the EU, namely China, India, Turkey, Russia, and South Korea. The initial production costs are the average weighted costs from

January until October to avoid a distortion of the costs due to the Covid-19 induced recession (Medarac, Moya, and Somers 2020). The carbon price was disentangled from the overall production price to not double count the carbon price already in place.

Additionally, the average transportation costs from the Foreign regions to the EU were included as they were not considered in the production costs estimated by Medarac, Moya, and Somers (2020). The CIF-FOB margin is, in plain words, the difference between average costs per unit and average costs per unit, including transport costs ((Miao and Fortanier 2017). I calculated the transport costs by taking the average CIF-FOB margin from the five countries that I am basing Foreign on from the OECD statistics for iron and steel products (Miao and Fortanier 2017). The average ratio between both is 6,45% (OECD 2020a). The average costs for foreign steel are €442 (see Table B1). 6,45% of that equal €27 transport costs. However, estimates of transport costs differ significantly, and in these calculations, the transport costs are the weakest point that would require more attention (Miao and Fortanier 2017; Steelonthenet.com 2020a). I then take the average of Foreign dirty and green steel to calculate the transport costs not to have two different transport costs for green and dirty technology.

The following Table presents production costs for each steel type All values are averages in € per ton of steel, and the data is from January to October 2019. The following Table B1 shows a summary of these calculations. The specific costs for each steel type are presented in Table B2 that follows after Table B1. The values for Foreign in Table B1 are the averages for Foreign in the columns “Green average” and “dirty average” in Table B2.

Table B1. Summary production costs for each steel type, 2019

	Initial costs	Transport costs	Initial costs excluding initial carbon price, including transport costs	Carbon price	New production costs
Green EU	€483	-	€482	€30	€512
Dirty EU	€487	-	€479	€95	€573.5
Green Foreign	€439	€27	€466	€42	€507.5
Dirty Foreign	€395	€27	€422	€110	€531

Source: Calculations from the author based on (Medarac, Moya, and Somers 2020; Miao and Fortanier 2017; OECD 2020a; Steelonthenet.com 2020a)

Table B2 presents the initial production cost, excluding the initial carbon price. The EU, China, and South Korea have an initial carbon price. Because I do not have the carbon prices for steel for China and South Korea, I assumed that the carbon prices are the same as in the EU (€1 for green, €8.5 for dirty steel), as you can see in Table B2.

Table B2. Detailed costs in the EU and Foreign, 2019

Region	Green long steel	Green flat steel	Green average	Dirty long steel	Dirty flat steel	Dirty Average
EU	€480	€485	€483	€508	€466	€487
Turkey	€413	€467	€441	€409	€427	€417.5
Russia	€390	€469	€429	-	€374	€374
South Korea	€440	-	€440	€371	€381	€367.5
China	€395	€468	€431	€404	€402	€403
India	€380	€451	€424	€420	€402	€411

Source: Medarac, H., Moya, J.A. and Somers (2020)

C. Deriving the graphical representation

To calculate the new price, I need values for the supply curves and the demand curve.[10] However, I could not find any data on exact marginal cost curves in the steel industry. Therefore, I assume the PED to be the slope of the function.

To preserve the spirit of the literature's values, I assume to be on the part of the curve that is inelastic or elastic, respectively. Because the elasticity along a linear curve varies, I place myself on that part of the curve where the elasticity corresponds approximately to the elasticities taken from the literature, i.e. on the inelastic part for the demand curve and the elastic part for the supply curve, respectively (Goodwin et al. 2015). Although the above-mentioned elasticity values are estimated based on constant elasticity demand and supply functional forms, it is still useful to apply these values to derive the slopes of the linear curves, because they still reflect these elasticities on the relevant portions. The flatter the function, the larger the portion of the curve that is elastic. Hence, the slope of the curve reflects the elasticity taken from the literature. Conversely, the steeper the linear function, the larger the portion of the curve that is inelastic. As a result, it is more likely to have everything happening on the curve’s portion, where the elasticity corresponds approximately to that from the literature.

This is not entirely correct because these estimates from the literature are based on constant elasticity (resulting in a convex or concave curve). However, the values that came up using the inverse function of the constant elasticity values (for example for the demand curve: $(Q)=D(Q)=a*Q_D$^(PED)) where difficult to interpret. Hence, I decided to take a linear function using the estimates from the literature.

---

[10] Please contact me if you want to see the excel sheet in which I constructed the graph.

The demand curve:

The demand curve can be derived using the inverse demand function

$$P(Q)=D(Q)=a-(1/PED)*Q_D$$

With
$P(Q)=D(Q)$:= price and demand as a function of quantity
a:= intercept with y-axis
PED:=own-price elasticity of demand
Q_D:= Quantity demanded

The PED is inelastic (constant PED -0.3). If we plug that in we, have the function

$$P(Q)=D(Q)=a-(1/0.3)*Q_D$$

$$P(Q)=D(Q)=a-(3.33)*Q_D$$

I know that the demand curve in the market before the carbon price meets the aggregate supply curve at Price €486 and Quantity 157. Hence, I took a random number for the coefficient a that would yield a demand function that also entails the value 486.

$$P(Q)=D(Q)=1009.3-(1/0.3)*Q_D$$

The supply curves:

In the market before the carbon price, we have five different supply curves. Firstly, supply for dirty and green steel from the EU. Secondly, the supply of dirty and green steel from Foreign. Lastly, the aggregate supply curve is then the sum of the values of the other four supply curves. That the supply curve is upward sloping means that I assume that the marginal costs increase. The supply curve can be derived using the inverse supply function

$$P(Q)=S(Q)=b+(1/PES)*Q_D$$

With
$P(Q)=S(Q)$:= price and supply as a function of quantity
b:= intercept with y-axis
PES:=own-price elasticity of supply
Q_D:= Quantity demanded

The PES’s are elastic. The values differ for each steel type.

For EU Green technology:

$$p(Q)=S(Q)=b+(1/1.2)*Q_D.$$

$$p(Q)=S(Q)=445+(0.83)*Q_D.$$

For EU Dirty Technology:

$$p(Q)=S(Q)=b+(1/0.7)*Q_D.$$

$$p(Q)=S(Q)=382+(1.4)*Q_D.$$

As you can see, EU dirty starts with a very much lower inframarginal cost curve than EU Green. I had to tweak the inframarginal cost curves so that each steel type's quantity was the quantity I calculated at the initial marginal cost and price of €486. The average costs from my graph for the first 100 tons for Green EU is €487, the same value as in the literature. The average costs from my graph for the first 150 tons for Dirty EU is €490. The average costs from the literature are the average costs per steelmaking firm. Green steelmaking facilities have lower capacity (up to 100 mt), whereas dirty steelmaking facilities have a higher capacity (up to 150 mt) (OECD 2020b; Recycling Today 2020). Therefore, these values are more or less comparable with the average weighted costs calculated in Section 6.7. The cost differences proportions of the steel types still reflect the proportions that I calculated in Section 6.7. I also had to tweak the inframarginal cost for Foreign. In Foreign, I assume that the inframarginal costs equal the average costs and therefore adjust the transaction costs accordingly.

To recall from Section 6.7, Foreign values include the transaction costs γ.

For Foreign green technology:

$$p(Q)=S(Q)=b+\gamma+(1/1.6)*Q_D$$

$$p(Q)=S(Q)=466+9.5+(0.625)*Q_D$$

For Foreign dirty technology:

$$p(Q)=S(Q)=b+\gamma+(1/1.1)*Q_D$$

$$p(Q)=S(Q)=422+48+(0.9)*Q_D$$

The “tweak” and making up of the inframarginal cost is the biggest drawback of my study. Because I had to make the data “fit” with my graph (the total volume supplied green and dirty Foreign steel had to equal the EU market price) the costs for Foreign applied in my graph do not reflect the costs that I calculated under Section 6.7. Additionally, the “missing trade” problem made it worse. Thus, the results for Foreign steel must be viewed with caution. On the other hand, the results for EU producers seem plausible. However, also these contain a more or less made up inframarginal cost value. To approach reality better, I would need marginal cost data, or at least more reliable transaction cost data. However, this would go beyond the scope of a capstone, so I must rely on somewhat imprecise data.

Implementing the carbon price:

Due to the carbon pricing, all supply curves increase proportionally depending on the steel's emission intensity in costs. The supply curve for green steel from Foreign, including a carbon price of €42 looks like this:

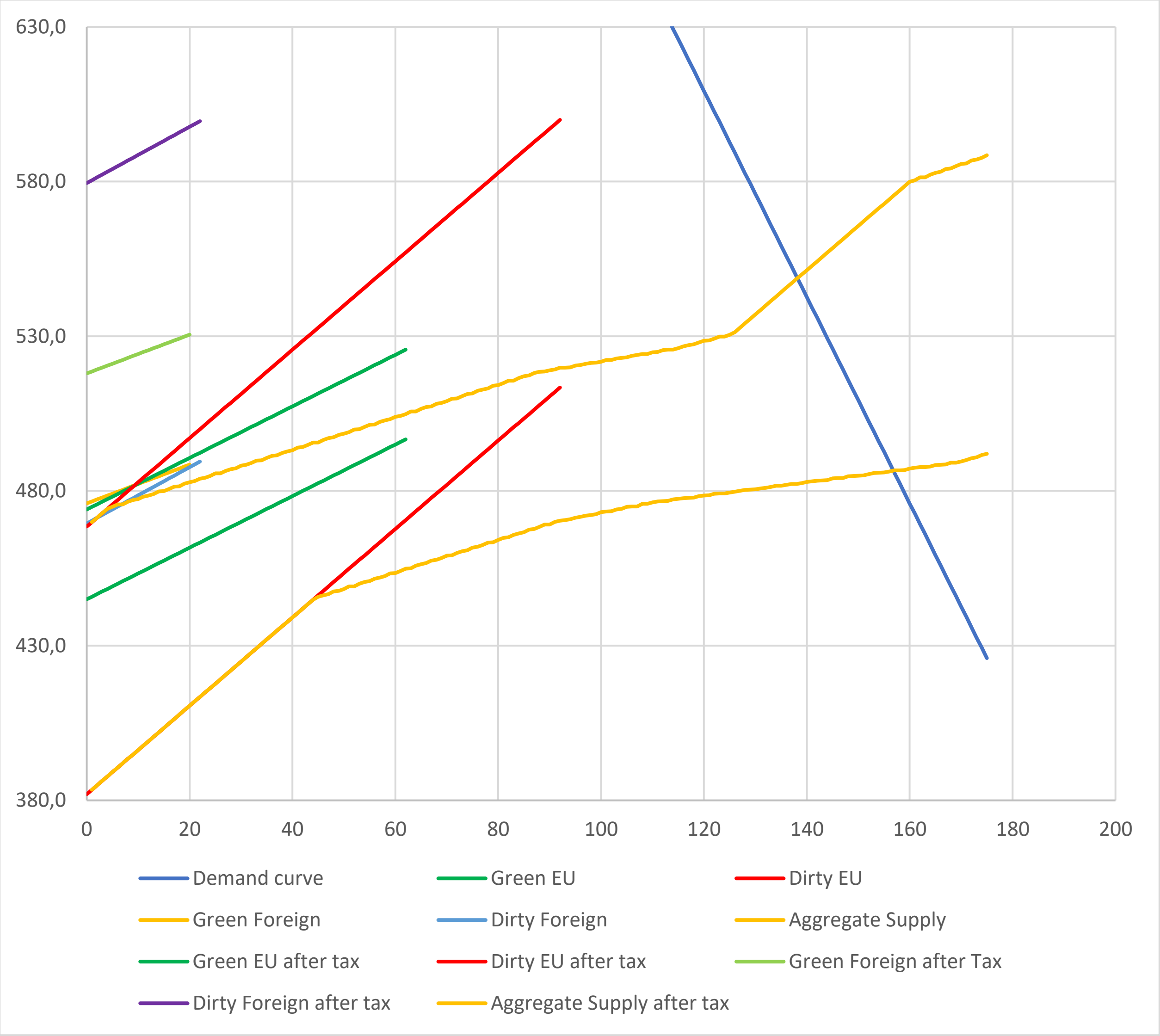
$$p(Q)=S(Q)=42+466+9.5+(0.625)*Q_D$$

The aggregate supply curve is then the sum of the values of the other four supply curves.

The new price estimate:

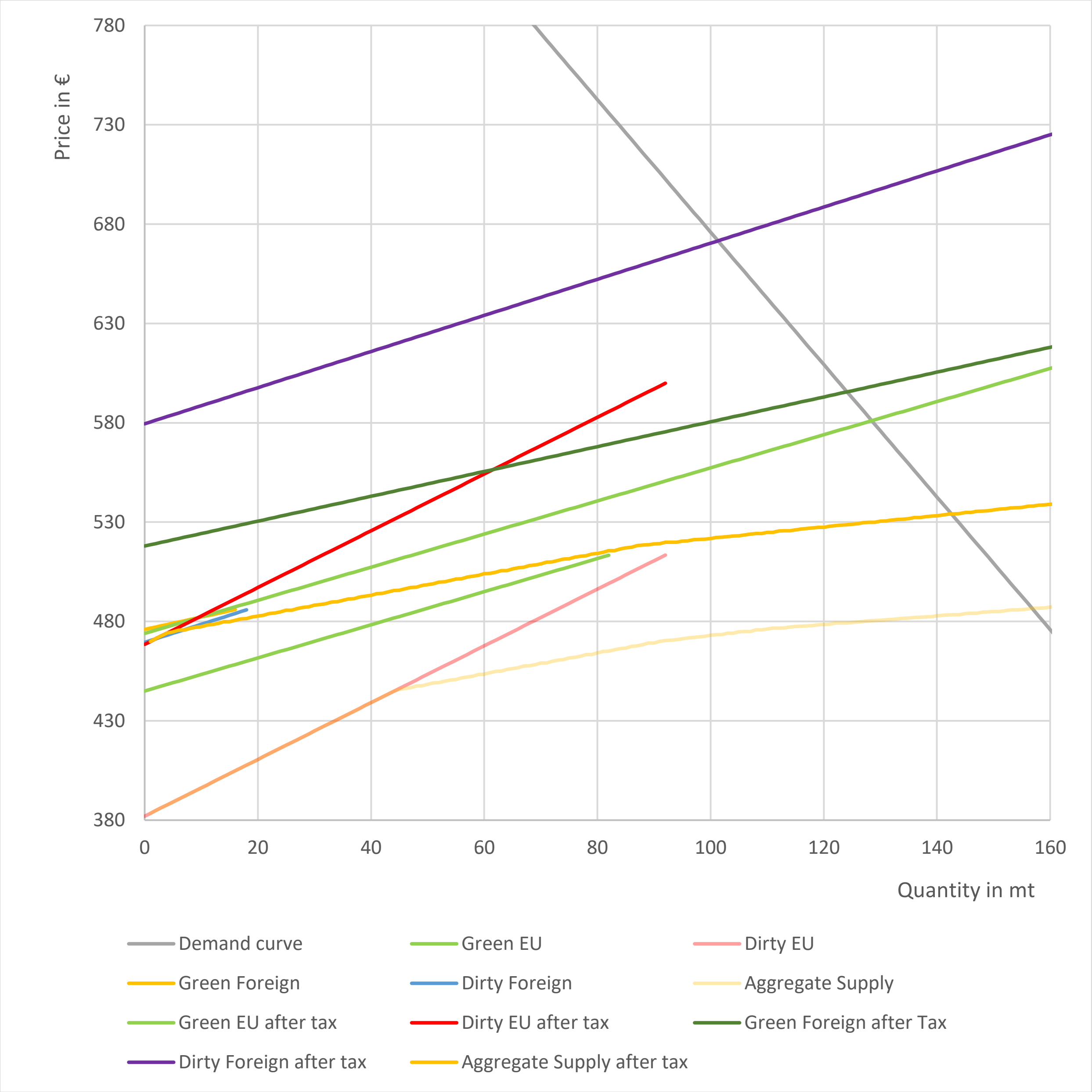
The new price is where the aggregate supply curve after implementing the price and the EU demand curve meet. This is where the price of EU demand and the price of aggregate supply after-carbon price are equal. Because the curves are presented in discrete numbers, there is no exact value for that. The market clears at a price of €536 with a quantity of 142 mt.

Figure C1. Graph in the short run



Source: author

Figure C2. Graph in the long run



Source: author

Even in this enlarged graph, it is difficult to discern the values for Foreign before the implementation of the carbon price.

I also cross-checked this using the elasticities of supply and demand from the literature. According to the PED of -0.3, the demand for steel in the EU decreases by approximately 3% from 157 mmt to 152 mmt, assuming the new equilibrium price and an own-price elasticity of demand of -0.3. According to the literature's own-price elasticity of supply values, supply of steel to the EU market decreases by 11% from 157 to 140 million tons supplied. Dirty steel decreases by 14 % and green steel by 7% because dirty steel increase more in costs than green steel.

Since I already lack the marginal cost data, I try to approach actual values as much as I can using the data that I have. For example, Demailly and Quirion estimated a cost-pass through rate of 75% (2008). This means that the increased carbon price costs are passed on to the consumer’s price by 75%. The average weighted increase in costs is €66. According to Demailly and Quirion, €49 are passed through to the consumers. I reach this value with a price of €536, which is a price increase of €50 and a cost-pass through rate of 76%.

D. Input substitution away from emissions to capital

The input substitution away from emissions to capital explains how much producers are inclined to replace the dirty technology machinery with the green technology machinery in a steelmaking facility. I explain this, starting with outlining basic economic concepts relevant to this Section.

A production function tells you what “inputs” and how much of these inputs you need to produce a good. In simple terms, the good steel requires the inputs energy and capital. Energy can also be framed as the input factor “emissions”. This is because energy is emissions-intensive. Therefore, the factor emissions is the inverse of the factor energy because energy input determines emissions. Emissions *must* be emitted to produce steel. Hence, emissions is a valid factor in the production function. This means that Steel (*S*) is produced from the two factors, emissions and capital. For simplicity, I assume that the steel technology only involves two production factors, carbon emissions (C) and capital (K).

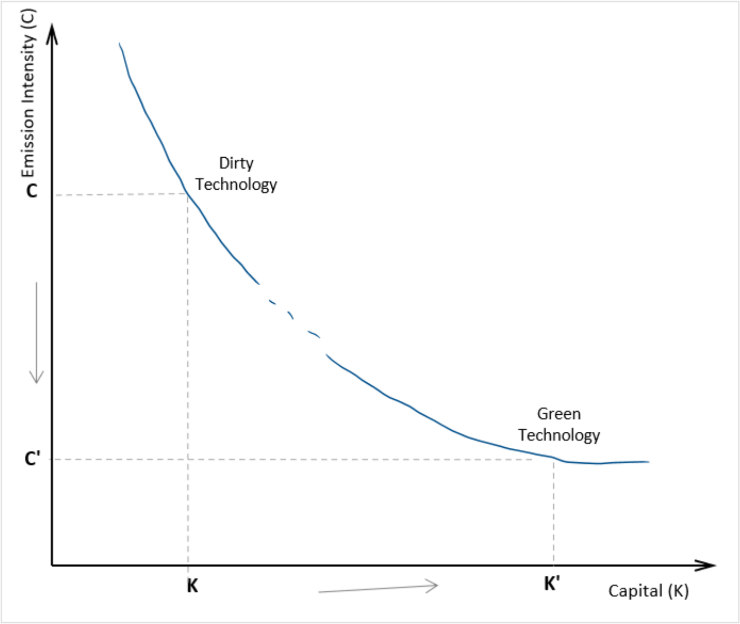
Therefore, the production function to produce steel is

$$S(C,K),$$

with S (steel) and our two inputs C (emissions) and K (capital). I decided to take emission instead of energy as a factor because I, firstly, already have the data for emissions. Secondly, because this study is framed in terms of emissions. Bringing in another factor would complicate it unnecessarily. Each producer has two choices on how much of each input he wants to use to produce steel. The producer can either produce dirty steel or green steel. The connection between emissions and capital on the one hand and green and dirty technology, on the other hand, is as follows:

In the scenario here, I am referring to the dirty producers who consider switching to green technology. Dirty technology producers have high emissions and low capital expenditure. If they were to switch towards green technology, emissions would be low, but capital expenditure for the new plant would be high. Figure D1 below depicts this. The more we move along the x-axis away from 0, the more capital the producers use. The more we move along the y-axis away from 0, the more emissions the producers emit. A producer can either produce at around **C/K** (dirty technology) and emit a lot of emissions. Or, the producer can switch to at around **C'/K'** (green technology) where he does not emit a lot of emissions. C (emissions) become more expensive relative to K (capital) when we introduce a carbon price. Therefore, producers may be more inclined to switch to the lower emission production process. The input substitution process – from high emissions and low capital to low emissions and high capital – becomes more likely.

Figure D1. Stylized figure of the input substitution away from emissions to capital from the perspective of dirty steel producers



Source: author

The line in the middle is dashed because it is never utilized because of technological constraints. Both technologies cannot produce at the emission levels of the dashed line. The range of emissions for the dirty technology is 4 to 1,9 tons of emissions per ton of steel (Hasanbeigi and Springer 2019). The range of green technology emissions is 1,5 to 0 tons of emissions per ton of steel (Hasanbeigi and Springer 2019; Roland Berger Consultancy 2020).

My elasticity calculations

I calculate this value myself. In summary, I derive this formula

$$\sigma=[(K/C)_{green} - (K/C)_{dirty}]/ (K/C)_{dirty} / [(P_C/P_k)_{green} - (P_C/P_k)_{dirty}]/ (P_C/P_k)_{dirty}$$

with

$$\sigma = \text{Marginal rate of technical substitution (MRTS)}$$

K= capital expenditure, P_K = price for capital (real interest rate)

C = emissions, $P_{C\,=}$ price for emissions (carbon price)

I derive this formula by assuming that the input markets emissions and capital are competitive. Therefore, I can retain that the ratio of the marginal products equals the ration of the input factors. The formula tells me that the higher the price for carbon, all other values equal, the more likely it is that producers will switch from dirty to green technology. Plugging in the data I receive the following values:

EU= 0.8809

Foreign= 0.0883

In simple terms, this MRTS value indicates how easy hence how likely it is for dirty technology producers to switch to green technology.

Brief Literature Overview: Input Substitution Elasticities

There are also a few studies that concern with input substitution as I do. On the level of the steel industry, factor-substitution research is only available for China. Other studies concern several OECD (including EU) countries, but only on the basic metal industry level. The basic metal industry comprises iron and steel, but also aluminium, copper, and other intermediate metal goods (U.S. Energy Information Administration (EIA) 2019). I only consider the steel industry because many studies found that policies of the different industrial and manufacturing sectors are too heterogenous to find a sensible common elasticity value (Alataş 2020; Costantini, Crespi, and Paglialunga 2018). Policy should be designed specifically for each sector because of the heterogeneity of the industrial structure and technological advancement. Inducing technological change makes only sense when there are already technologies available (Alataş 2020; Lutz et al.

2005). Table D1 summarises the literature on input-substitution. Please note that the literature only uses energy and capital rather than emissions and capital as inputs. However, as I explained before, energy and emissions are the inverse of each other. Followingly, both inputs can be used in the substitution calculations.

Table D1. Summary elasticities of technological input substitution for the steel and basic metals industries[11]

Time Period	**Region**	**Industry**	**Paper**	**Factors of Production**	**Methodology/estimation method**	**Substitution elasticity**
2020	EU and Foreign	steel	My calculations	Emission, capital	Unconstrained optimization MRTS calculation assuming competitive input and output markets	**EU= 0.8809** **Foreign = 0.0883**
1978–2000	China	steel	Zheng and Liu (2004)	energy-capital substitution	A range of production functions and assumptions about technical progress	1.003
1978-2002	China	steel	Huang and Me (2006)	energy-capital substitution	using a second-order Constant Elasticity of Substitution production function	0.685
1995-2004	China	steel	Ma et al. (2008)	energy-capital substitution	two-stage translog cost function	0.8034
1985-2011	China	steel	Wang and Lin (2017)	Energy-capital substitution	trans-log cost function	0.870472
1978-2007	China	steel	Smyth et al. (2011)	Energy-capital substitution	trans-log production function, production function approach by means of ridge regression	1.0082
-	12 OECD countries	basic metals	Van der Werf (2008)	Energy-capital substitution	Two-level CES production function	0.88
-	14 OECD countries	basic metals	Okagawa and Ban (2008)	Energy-capital substitution	CES	0.29
-	Brazil, India, South Korea, USA	basic metals	Roy et al. (2006)	Energy-capital substitution	Translog AES	1.9
1990-2008	21 OECD countries, including 12 EU countries[12]	basic metals	Costantini, Crespi, and Paglialunga (2018)	Energy-capital substitution	Translog AES	0.25

---

[11] I did not add a bibliography for this literature review in the Appendix. Please contact me if you are interested in the full version of this.

[12] Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portu-gal, Spain, Sweden, UK and USA.

A value between 0 and 1 means that the inputs do not substitute easily. A value lower to 0 reflects very weak substitutability. A value closer to one reflects a weak substitutability of inputs. In that case, a carbon price may affect the current steel industry structure marginally. A value greater than 1 means that the inputs substitute easily.

Despite much research devoted to measuring the elasticity of substitution of capital with energy or emissions, there is no consensus on its exact value (Costantini, Crespi, and Paglialunga 2018; Lagomarsino 2020, and references therein) This appears to be also true for the steel industry. The estimates vary significantly. Three of our papers find a strong substitution, four papers find a weak substitution, and three papers find a very weak substitution. Followingly, the results are inconclusive.

Interpretation

In the literature review, I showed that the values from previous literature are inconclusive. Moreover, my calculations' values must be considered with caution because the data that my calculations are limited on one specific data and not on a thorough database.

Nonetheless, my calculations show that in the EU, capital for emissions is only a weak substitute. In Foreign, the substitution process is almost negligible. The elasticity value for EU producers (0,88) is somewhat higher than that of Foreign producers (0,08). The values indicate that EU producers are more inclined to change their technology than Foreign producers. This means that the EU producers are more responsive to the carbon price than Foreign producers.

Unfortunately, I cannot compare my values with the literature values since they vary greatly. However, the values for countries I included in Foreign range from 0,68 to 1,9 in the academic literature. This indicates that my calculations may underestimate the substitution value. My values for Foreign are also perplexing since, first, Foreign producers have more room for improvement, second, green technology CAPEX costs are significantly lower in Foreign as they are in the EU, and third, the change in carbon price is higher than in the EU and hence represent a higher change in prices than for EU producers.

In summary, my calculations indicate a weak substitution for EU producers and a very low substitution for Foreign producers. This means that it is likely that a few EU dirty producers will become more energy efficient within their technology in the long-run. Very few Foreign dirty producers will switch. This technological substitution results in a further emission reduction of what the graphical representation of the EU steel market indicates.