Carbon leakage in the Steel Sector Accounting for Induced Technological Change and Spillover Effects

A Theoretical Analysis

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Abbreviations

Abbreviation	Meaning
BCA	Border Carbon Adjustments
BF-BOF	Blast Furnace and Basic Oxygen Furnace
CBAM	Carbon Boarder Adjustment Mechanism
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EC	European Commission
EITE	Emission Intensive and Trade Exposed Goods
EGD	European Green Deal
EU ETS	European Union Emissions Trading System
GE	General Equilibrium
GJ	Gigajoule

Abstract

This analysis investigates the relationship between unilateral climate policy and the risk of carbon leakage in the steel sector. A simple analytical macroeconomic model is employed to highlight the various parameters influencing the magnitude of carbon leakage. An extended version of the model allows for assessing the impacts of induced technical change and technological spillover effects on the industry's carbon leakage. A numerical illustration using sector-specific parameters shows that the leakage rate within the steel sector is 27%. Accounting for induced technological change and spillover effects reveals that higher rates of innovative activity reduce the risk of carbon leakage within the sector. In the presence of technological spillover effects under the assumption that the rate of technological change is 0.8, the carbon leakage rate reduces to 5%. The impact of induced technological change on carbon leakage in the steel industry implies that a global industrial network empowering the expansion of new technologies has the potential to decrease the industry's overall emissions.

1 Introduction

Economies and industrial sectors worldwide are undergoing essential transformations driven by the urgency of addressing climate change. However, the thorny dispute of reaching uniform global climate agreements has led to unilateral climate policies forming across regions. Research on environmental policy reveals that differences in abatement efforts across regions can cause undesirable side effects of carbon leakage. Stringent climate actions undertaken by one region may shift emission-intensive commodities away from the policy area to regions with less strict climate policy (see for example Burniaux & Martins, 2000, 2012; Babiker, 2005).

Contrary to the negative side effect of carbon leakage, climate policy can induce innovation of new carbon-saving technologies (Hoel, 1991; Sue Wing, 2006; Nordhaus, 2002). If these innovations spillover to unregulated regions, this could significantly reduce the risk of carbon leakage and overall emissions (Coe & Helpman, 1995; Coe et al., 1997). Previous studies show that ignoring the technological change in modeling can lead to underestimates of the effectiveness of unilateral climate policy and overestimates of carbon leakage (Di Maria & Smulders, 2005; Gerlagh & Kuik, 2014).

So far, little research has been undertaken to analyze the relationship between unilateral climate policy and carbon leakage in heavy industries. The steel industry is globally one of the most energy-intensive and trade-exposed sectors and accounts for approximately 8% percent of the world's total carbon emissions (IEA, 2021b). Hence, this analysis focuses on the risk of carbon leakage in the steel sector and the impact of induced innovation and technological spillover effects on the steel industry's carbon leakage rate. While earlier investigations indicate that the effects of induced technological change reduce the risk of carbon leakage, it is expected that this analysis will reveal a similar result within the steel industry. The open question is whether accounting for induced innovation has a large or small impact on carbon leakage in the steel sector. For this reason, this study aims to quantify the magnitude of the effect on carbon leakage when accounting for induced technological change in the steel industry.

The European Union (EU) has undertaken ambitious climate strategies and implemented the European Union Emissions Trading System (EU ETS) as a critical tool to achieve an industrial decarbonization transition in the power and manufacturing sectors in the region. The EU ETS is the world's first primary carbon market and remains the largest (European Parliament, 2003). The EU aims to become the world's first climate-neutral continent by 2050 as a part of the European Green Deal (EGD) Fit-For-55 strategy (European Parliament, 2022). Until now, the ambitious climate actions undertaken by the EU have not been met by similar actions by other large countries or world regions. Research focusing on the EU's unilateral reduction strategies, (see for example Gerlagh & Kuik, 2014), shows that an uneven playing field is created in international trade by which energy-intensive and trade exposed (EITE) sectors in the EU will be disadvantaged and subject to carbon leakage.

Carbon leakage can be defined as the displacement of economic activities or investment patterns that cause carbon emissions to shift away from a policy area to another region with less stringent mitigation rules (IPCC, 2007). A critical channel of carbon leakage has been detected to occur via international trade in energy-intensive commodities, known as the 'energy channel' (Felder & Rutherford, 1993). In this way, the stringent emissions regulation in the EU increases production costs for producers covered by the EU ETS. It decreases the demand for carbon-energy goods in the EU, and this leads to a fall in global prices for these goods, causing an advantage for non-EU producers to utilize more carbon energy in production. Consequently, the emissions reduction undertaken by the EU can be partially or entirely offset by an emissions increase in regions outside the EU. The risk of carbon leakage can therefore undermine regional abatement efforts reducing the effectiveness of environmental policies (Rutherford, 1992).

To protect the competitiveness of EU producers and avoid carbon leakage, the EU has to date, given support treatment through the allocation of free emission allowance to the heavy industry, including the steel sector (European Parliament, 2011). In the current phase (phase 4) of the EU ETS covering the period 2021-2030, the steel sectors can receive allowances equivalent to 100% of the relevant benchmark for free, making it hard to obtain an emissions reduction in the industry (European Parliament, 2011). In order to achieve the EU's climate goals, the European Commission seeks to phase out free emission allowances in the long run, and steel producers in the EU are therefore deemed to be at significant risk of carbon leakage.

Research supports that stringent climate policies can also lead to innovation and diffusion of new carbon-saving technologies. As discussed by Hoel (1991), it is essential to consider that differences in abatement efforts across regions could induce incentives for innovation of new technologies that mitigate the cost of abatement. If these technologies spillover to unregulated regions, this could eliminate a significant fraction of carbon leakage and potentially reduce overall emissions (see Gerlagh & Kuik, 2014). In virtue of technological change and technological spillover effects, it is ambiguous whether an emissions reduction in one region will be offset by increased emissions in other parts of the world (Golombek & Hoel, 2004).

The steel industry's carbon leakage rate and its determinants are investigated in this analysis using an analytical model and econometric parameters from related literature. An extended version of the analytical model accounting for induced technological change and spillover effects is used to evaluate the impact of innovative activity on the steel sector's carbon leakage. The structure of the paper is as follows. Section 2 provides a brief literature review of previous findings on carbon leakage and induced technological change. Section 3 describes the basic analytical framework for analyzing carbon leakage under asymmetric climate policy action. Subsequently, the model is extended to account for induced technological change and technological spillover effects. Section 4 gives a detailed description of the steel sector to enhance the understanding of how the model can be applied to analyze carbon leakage in the steel industry. Section 5 includes an assessment of the economic parameters of the analytical model for sensitivity analysis. Following this, the carbon leakage is numerically illustrated in the steel industry, and the effect of induced technological change is investigated. Finally, section 6 discusses the results and concludes.

2 Literature Review

Previous literature on the topic addressed the relationship between unilateral climate policy and the risk of carbon leakage. Estimates of the size of carbon leakage have been done with Computable General Equilibrium (CGE) models using the Kyoto Protocol to demonstrate a unilateral climate agreement. Leakage rates reported in the literature range from 2% to 40% (see for example Burniaux & Martins, 2000). In one study by Babiker (2005) the leakage rate is as high as 130% for one particular scenario. These studies show great inconsistency in the estimates of carbon leakage. Different assumptions in modeling regarding the integration of international markets, substitution and supply elasticities, and market structure give rise to different results.

In a study by Burniaux & Martins (2012) a simplified general equilibrium model (GE) characterizing a static two-country environment with multiple goods was used to calculate carbon leakage. The model captures the main interactions between energy and non-energy markets at a global level. Their analysis assumes that unilateral carbon abatement action is taken by a large group of countries, such as the Annex I group, based on the parties' commitment to the Kyoto Protocol. Their results revealed that the most critical parameter influencing the magnitude of carbon leakage is the price elasticity of coal supply. They showed that an integrated international coal market with a high value of price elasticity for coal supply results in a low rate of carbon leakage. However, if coal supply is inelastic with a supply elasticity below one, carbon leakage could reach 40%. Furthermore, the authors discuss the importance of the shape of the production function. Allowing for higher inter-factor and inter-fuel substitution elasticizes in production resulted in high carbon leakage even if the coal supply is elastic.

In contrast to the many models lumping individual industries into aggregates, Mathiesen & Mœstad (2004) analyzed the implications of the Kyoto Protocol on carbon leakage, focusing on the world steel sector. They used the Steel Industry Model (SIM) based on a static numerical equilibrium framework covering ten regions and three different steel-producing technologies. The model predicts carbon leakage within the steel industry to be as high as 53%. One of the significant findings in their analysis emphasizes the importance of adequately capturing the features of a specific industry while analyzing policy impacts. They found that the industry's carbon leakage reduces to 26% when accounting for factor substitution within a specific production technology and to some extent by switching between existing steelmaking technologies. The authors discuss that environmental taxes may speed up restructuring in the steel industry, but they do not consider substitutability in production by switching to new steelmaking technologies.

Many studies focus on induced technological change and the effect of technological spillover effect. For example, Sue Wing (2006); Nordhaus (2002) develop frameworks of induced technological change in models for climate policy analysis. In addition, studies support the occurrence of technological spillover effects (see for example Coe & Helpman, 1995; Coe et al., 1997). In contribution to the theoretical literature on carbon leakage Di Maria & Smulders (2005) are highlighting the role of directed technical change caused by changes in relative prices due to unilateral emissions regulation. In this analysis, the authors construct a modeled economy with two identical regions, with one region imposing a binding cap on emissions. The model departs from a CES aggregate production function allowing for innovative response in energy production due to the implementation of the unilateral emissions constraint. They show that accounting for the effect of technological change always reduces the risk of carbon leakage. Gerlagh & Kuik (2014) build on this framework by assuming that technological change can freely spillover from one region to another. The authors further assume that technological change is induced by climate policy. In their study, they use the EU's abatement target for 2020 as an example of a unilateral attempt to reduce emissions. By testing their model against actual data using a multi-region, multi-sector CGE model, they found that technological spillover effects can lead to minor or even negative rates of carbon leakage. These findings imply that leakage rates found in earlier literature disregarding innovative activities and spillover effects might be overestimated.

Studies of technological spillover effects are often based on aggregate representations of the economy. More recent studies focus on the effect of technological spillovers on the sector level. For example, Sijm et al. (2007) focuses on energy-intensive manufacturing, wind power, and biomass and bio-energy industries. In another study by Huang & Lv (2021) the authors assessed the emissions reduction potential of technology spillover in the electricity sector and Yang et al. (2021) investigated the relationship between technology spillover effect on CO_2 emission reduction in the transport sector.

3 Analytical Model of Carbon Leakage

An analytical model of carbon leakage presented by Gerlagh & Kuik (2014) is considered to analyze carbon leakage occurring in the steel industry. The model builds on the original work of Di Maria & Smulders (2005) and Van der Werf & Di Maria (2008), capturing carbon leakage via the energy channel. The macroeconomic framework derives the carbon leakage rate from the regional demand for carbon-energy inputs in energy-intensive goods sectors and the related carbon-energy elasticities. In this section, the analytical model is described.

3.1 Basic Model of Carbon Leakage

The model capture carbon leakage via the energy channel for carbon-energy inputs used in the production of energy-intensive commodities. A fully integrated carbon-energy market is assumed with one global price for the carbon-energy input. The regional structure of the model is straightforward and divides the world into two regions with subscript $i = A, B$, region A and B. The regions are assumed to be identical but differ in size and emissions regulation. The parameter θ describes the share of region A in the world economy, and $(1-\theta)$ describes the share of region B. Furthermore, it is assumed that in region A, the regulators have decided to implement a production-based tax on carbon-energy input τ to reduce carbon emissions. Region B remains unregulated in this modeled economy. For simplicity, the model only takes sectors producing energy-intensive commodities into account. All firms producing carbon-intensive commodities are considered price takers in a competitive market to allow for market equilibrium. The global price for carbon-energy input is described within the model. In contrast, the prices for other production inputs such as capital, labor, and non-energy inputs are given. In unison, it is assumed that a perfect international world market exists to produce the carbon-energy input.

The two regions are connected via the carbon-energy market. The total world supply of carbon energy is denoted by E and equals the total world demand. The total world demand for carbon-energy is put together by both regions carbon-energy use E_i. It is equal to the price of carbon-energy p multiplied by the price elasticity of carbon-energy supply ψ.

$$\theta E_A + (1-\theta)E_B = \psi p \tag{1}$$

The regional demand for carbon energy is proportional to each region's output Y_i of energy-intensive goods. The regional carbon-energy demand depends on the elasticity of substitution between carbon-energy input and other production factors σ and on the price difference between the final good's price q_i and the price for the carbon-energy input p. The implementation of the emissions tax τ in the region A is added to the input price of carbon-energy use in the region A and results in an additional production cost.

$$E_A = Y_A + \sigma(q_A - p - \tau) \tag{2}$$

$$E_B = Y_B + \sigma(q_B - p) \tag{3}$$

The regional demand for the energy-intensive goods Y_i depends on the final good's price q_i and the price elasticity of demand for the energy-intensive goods ε.

$$Y_A = -\varepsilon q_A \tag{4}$$

$$Y_B = -\varepsilon q_B \tag{5}$$

Final prices for energy-intensive goods in each region depend on carbon-energy input price multiplied by the factor share of carbon-energy input in production in value added α. In region A the emissions tax is added to the final good price and passed on to the consumers of the emission-intensive good. Given the assumption that all factor prices are constant, the price for carbon-energy input is the only price impacting the final good price.

$$q_A = \alpha(p + \tau) \tag{6}$$

$$q_B = \alpha p \tag{7}$$

Equation (1)-(7) determine the seven variables $Y_A, Y_B, p, q_A, q_B, E_A$ and E_B as a function of τ. The equations are all linear, and the emissions tax τ is proportionate to the size for size with the share of carbon-energy use in production in the regulated region A. Thus, the carbon leakage rate (LR) can be defined as the absolute emissions increase in region B divided by the absolute emissions decrease in region A.

$$LR = -\frac{(1-\theta)}{\theta}\frac{E_B}{E_A} \tag{8}$$

Rearranging equation (8) using equation (1)-(7) to substitute for regional carbon-energy use E_A and E_B gives following expression for the carbon leakage rate. For the derivation of the carbon leakage rate, see Appendix A.

$$LR = 1 - \frac{\psi}{[\psi + (1-\theta)(\alpha\varepsilon + \sigma\ (1-\alpha))]} \tag{9}$$

The derived leakage rate depends on the regional size parameter θ, price elasticity of carbon-energy supply ψ, factor share of carbon-energy input α, price elasticity of demand for energy-intensive good ε and elasticity of substitution between carbon-energy and other factors in production σ. Inserting estimated values for the economic parameters from related literature indicates the real-world carbon leakage rate. Changes in parameter values can influence the magnitude of carbon leakage. The extent to which differences in parameter values affect the leakage rate is assessed in section 5. The leakage rate seizes carbon emissions in percentage leaking from region A to region B as an adverse effect due to the implementation of the emissions tax in region A. In the following sections, the leakage rate in equation (9) will be referred to as the basic carbon leakage rate.

3.2 Extended Model of Carbon Leakage with Technological Change and Spillover Effects

To analyze the impact of technological change on carbon leakage Gerlagh & Kuik (2014) extended the above basic carbon leakage model to account for technological spillover effects. The model is based on the concepts of induced technological change concerning climate policy analysis described by Nordhaus (2002) and Sue Wing (2006). By investing in innovation, sectors can improve production technologies and the productivity of their resources. In market economies, investment decisions are fundamentally made on the private sector level, and the decisions about inventive activity depend on private sector incentives (Nordhaus, 2002). Incentives to develop new technologies can arise following a change in factor prices. In induced technical change models, producers are incentivized to improve factor productivity, especially for production factors with a high share of value added. Climate policies that reduce carbon emissions encourage emission-intensive sectors to develop new carbon-saving technologies due to increased production costs. Innovation that facilitates substitution of carbon-energy inputs in production can moderate the abatement cost of climate policies and move industries towards cleaner production (Sue Wing, 2006).

In the basic carbon leakage model, σ represents the elasticity of substitution between carbon-energy input and other input factors in production. In the extended model, it is assumed that factor substitution arises in two different ways. One way is by switching between factors for a given capital stock with a fixed technology. The second way is by switching factors for a capital stock that involves multiple technologies or by developing new technologies following a change in factor prices. Hence, the parameter σ represents the elasticity of substitution, including technological change. The share of the substitution possibility arising from technological change alone is denoted by γ and is assumed to be in the range $\gamma \in [0, 1)$. The substitution possibility not related to technological change is denoted μ. The elasticity of factor substitution can be described as follows:

$$\sigma = \frac{\mu}{(1-\gamma)} \tag{10}$$

Equation (10) can be rewritten as $\mu = (1-\gamma)\sigma$ to get an expression for the share of the substitution not related to technological change. This share represents the possibility of switching between carbon-energy intensive and less carbon-energy intensive production methods using energy-saving equipment for the benchmark technology within a sector. The share of the substitution related to technological change γ makes it possible to switch between input factors by developing new production technologies. It is assumed that technology is non-rival and that innovation is shared across regions allowing for technological spillover.

The analytical background for the extended model with induced technological change and international technological spillover effects is based on a CES production function. Output is denoted Y and depends on an input vector X_i, a technology vector ζ_i, and the elasticity of substitution σ.

$$Y = \left(\sum_i \zeta_i (X_i)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{11}$$

The first order condition of the production function with respect to X_i becomes:

$$\frac{p_i}{q} = \zeta_i \left(\frac{X_i}{Y} \right)^{-\frac{1}{\sigma}} \tag{12}$$

The production function can be altered to incorporate induced technology denoted by vector A_i, which denotes the current level of technology in sector i. For a given technology, the elasticity of substitution is reduced to $(1-\gamma)\sigma$. The altered production function with a constant technology becomes:

$$Y = \left(\sum_i (A_i X_i)^{\frac{(1-\gamma)\sigma-1}{(1-\gamma)\sigma}} \right)^{\frac{(1-\gamma)\sigma}{(1-\gamma)\sigma-1}} \tag{13}$$

Taking the first order condition of the altered production function with respect to X_i gives:

$$\frac{p_i}{q} = A_i^{\frac{(1-\gamma)\sigma-1}{(1-\gamma)\sigma}} \left(\frac{X_i}{Y} \right)^{-\frac{1}{(1-\gamma\sigma}} \tag{14}$$

The first-order conditions require the equations for relative prices to be equal. Setting equation (12) and (14) equal to each other gives an expression for induced technological change:

$$A_i = (\zeta_i)^{\frac{(1-\gamma)\sigma}{(1-\gamma)\sigma-1}} \left(\frac{X_i}{Y}\right)^{\frac{\gamma}{(1-\gamma)\sigma-1}} \tag{15}$$

Rearranging equation (15) gives an expression for A_i, which can be set to represent the level of technology H_i.

$$H_i \equiv A_i^{\ 1-(1-\gamma)\sigma} = A_i^{\ 1-\mu} \tag{16}$$

Using the above simplification for A_i makes it possible to derive the optimal level of technology H_i and the level of inputs X_i for a given level of output and for given prices (p_i, q):

$$H_i = \zeta_i^{\ \mu} \left(\frac{X_i}{Y}\right)^{\gamma} \tag{17}$$

$$X_i = \left(\frac{Y}{H_i}\right) \left(\frac{p_i}{q}\right)^{-\mu} \tag{18}$$

The derived levels include induced technological change and can be integrated into the basic carbon leakage model. Technological change enters the model via the regional demand for carbon-energy inputs and affects the amount of carbon energy used in each region. Comparable to the basic model, regional carbon energy demand in the extended model depends on the price difference and the emissions tax p, q_i, τ and the included parameter for induced technological change H_i. Since $\mu = (1-\gamma)\sigma$, an additional possibility to substitute the carbon-energy input for other production factors arises due to induced technological change. Following the log-linear transformation of equations (17) and (18) as demonstrated by Gerlagh & Kuik (2014) gives:

$$H_i = \gamma \left(Y_i - E_i\right) \tag{19}$$

The expression for H_i is the available input-saving technology dependent on the carbon-energy input and parameter γ. The regional demand with induced technological change can then be written as:

$$E_A = Y_A - H_A + \mu(q_A - p - \tau) \tag{20}$$

$$E_B = Y_B - H_B + \mu(q_B - p - \tau) \tag{21}$$

The induced technological change replaces a fraction of the classical substitution and will in itself not have an impact on carbon leakage. Only when allowing for technological spillover to producers outside the policy area can new technologies affect the magnetite of carbon leakage. A final assumption about the international uptake of technological change is needed. Here technologies can freely spillover from one region to another, and the model assumes that the technological spillover is symmetric. The available level of global technology, H, can therefore be defined as the weighted average of changes in production structures in both regions.

$$H = \gamma \left[\theta(Y_A - E_A) + (1-\theta)(Y_B - E_B)\right] \tag{22}$$

By using equations (20), (21), and (22), the new carbon leakage rate with induced technological change and spillover effects can be derived. For simplicity, expressions for $b > 0$ and $c > 0$ can be substituted into the calculation.

$$b = \varepsilon\alpha + \frac{\mu}{1-\alpha} \qquad c = \frac{1-\alpha}{1-\gamma}\,\mu\gamma \tag{23}$$

The derivation of the new carbon leakage rate is presented in Appendix B and becomes:

$$LR = 1 - \frac{\psi}{[\psi\,(\frac{b+\theta c}{b+c}) + b\,(1-\theta)]} \tag{24}$$

The new leakage rate is more complex and depends on the parameter of induced technological change γ. Accounting for induced technological change and international technological spillover effects impacts the carbon leakage rate. If there is no technological change $\gamma = 0$ and $c = 0$. In this case, technological spillover does not affect carbon leakage, and the new leakage rate equals the old leakage rate. A higher level of induced technology in the economy increases γ and the substitutability of carbon energy in production due to new technologies. As a result, the carbon leakage rate declines. When γ is close to one, the possibility to substitute due to new production methods has reached its full potential. The expression for c, is dependent on γ and increases as $\gamma \to 1$. In equation, (24), the c enters the denominator and causes the new leakage rate to decrease as γ increases.

4 The Steel Industry

The above analytical model captures carbon leakage and accounts for induced technological change from emission-intensive sectors, such as cement, petrochemicals, and metals. The model is constructed to estimate carbon leakage on an aggregate level covering multiple sectors of the economy. Alternatively, the model is applied in this analysis to quantify the potential risk of carbon leakage within a specific sector. Since this paper focuses on the steel industry, this section provides an overview of the steel sector to enhance the understanding of how the model can be adapted to fit on a single sector level. By narrowing down the production structure and the inputs utilized in the steel manufacturing process, the risk of carbon leakage and the impact of technological spillover effects in the industry can be analyzed with the analytical model.

4.1 Raw Materials

Steel comprises iron, carbon, manganese, and small amounts of other elements such as silicon, phosphorus, sulfur, and oxygen. Essential raw materials needed in the steelmaking process include iron ore, coal, limestone, and recycled steel (Worldsteel, 2021). Iron ore is heated and melted in furnaces where most of the oxygen and other impurities are removed using coal and limestone. Recycled steel is used as a complementary input in the steelmaking process but can also exclusively function as the primary input to make new crude steel (Eurofer, 2020). The global production of crude steel reached about 1.9 billion tonnes in 2020. The global production used about 2 billion tonnes of iron ore, 1 billion tonnes of metallurgical coal, and 575 million tonnes of recycled steel (Worldsteel, 2021).

4.1.1 Iron Ore

Iron is the main component of steel, and iron ore is an essential resource in production. Most iron ore is extracted in opencast mines established in around 50 countries. The extracted iron ore is commonly transported to devoted ports by train and then shipped to steel plants worldwide. The most prominent iron ore mining sights are based in Australia and Brazil, representing two-thirds of the total global exports. Other major extracting countries are China, the US, and Russia. Iron ore is one of the most abundant metallic elements on earth, and 98% of the iron ore mined globally is used to make steel. The earth's crust is estimated to contain 5% iron ore, and the world's total reserve is estimated to exceed 800 billion tonnes containing more than 230 billion tonnes of pure iron (Worldsteel, 2021).

4.1.2 Coal

Iron only occurs as iron oxides in the earth's crust, and the ores must be converted or "reduced" to pure iron using carbon. The predominant source of this carbon is coking coal (Worldsteel, 2021). Coking coal is mined and carbonized in a series of coke ovens before it is used in the iron reduction process. The purifying process of coal eliminates impurities and produces coke made out of almost pure carbon. Coke is used as the primary heating fuel and reducing agent in the steelmaking process (World Coal Association, 2020). The minded metallurgical coal used in the steel industry represents around 15% of world consumption. Coal is an accessible resource almost all over the world, and active mining activity takes place in over 70 countries. The largest reserves exist in the US, China, Russia, Australia, and India.

Of these countries, Australia is the biggest exporter of mined metallurgical coal, and China is the country producing the most coking coal in the world (Worldsteel, 2021).

4.1.3 Steel Scrap

Steel is recyclable, and the availability of scrap steel as a raw material is becoming crucial for the industry. Steel is one of the most recycled materials in the world, and the overall recycling rate is currently estimated to be about 85% (World Coal Association, 2020). Steel scrap is collected from demolished structures, end-of-life vehicles, machinery, and the yield losses in the manufacturing process of steel (Worldsteel, 2021). The magnetic properties of steel make it easy to separate from waste and impurities. The properties of steel remain unchanged no matter how many times it is recycled. Steel is 100% recyclable, which makes it a very beneficial resource. The extracted iron ore can therefore be used repeatedly in production. All production methods can use steel scrap as input, and most new crude steel contains recycled components. Some steel products contain up to 100% recycled material (World Coal Association, 2020).

4.2 Production Routes

Two main methods, often referred to as production routes, have been established to produce steel. The dominating route is the integrated steelmaking process combining a blast furnace and a basic oxygen furnace, known as the BF-BOF route. The second route is based on an electric arc furnace and is shortened and referred to as the EAF route. The main difference between the two routes is the type of raw materials they require and the plant configuration. Other steelmaking technologies and combinations of production routes have also been established but stand for a small share of the total world production and will not be discussed here (Eurofer, 2020).

4.2.1 The BF-BOF Route

The BF-BOF route is used to create new or 'virgin' steel using iron reduction, and around 70% of the global steel supply is produced via this route. The industry's blast furnaces are highly energy-intensive and utilize raw materials such as iron ore, coal, limestone, and recycled steel (Worldsteel, 2021). In the first step of the process, iron ore is reduced in the blast furnaces, which operate on the principle of chemical reduction. In the reduction process, the blast furnace is fed with iron ore and carbon (supplied as coke) to serve as a so-called reducing agent. Small quantities of fluxes minerals such as limestone are also added to collect impurities. Air heated to about 1200°C is blown into the blast furnace, causing the coke to burn. The heated coke produces carbon monoxide, which reacts with the embodied oxygen in the iron and forms carbon dioxide. This way, the iron ore is separated from its oxygen and converted into elemental iron. During the process, the heat melts the separated iron, and the molten mass, also called pig iron, can be drained off (World Coal Association, 2020).

Carbon is necessary for the chemical reduction of processing iron ore, and immense amounts of carbon dioxide are produced as a by-product. Due to the chemical process, CO_2 emissions are unavoidable in the current steel-making process (Eurofer, 2020). Coke-based reduction is the dominating technique used to make steel, and the method takes place in thousands of blast furnaces worldwide. For each tonne of steel produced in the conventional BF-BOF route, between 1.5 and 3 tonnes of carbon dioxide are released into the atmosphere (Hasanbeigi & Springer, 2019).

Since iron is brittle and not easy to form, it must be turned into steel. The transformation is done in a second step and takes place in the basic oxygen furnace called the converter. The molted iron is passed on to the converter, where hot air is blown into the system to burn unwanted elements. When this process step is over, the iron has turned into steel (Eurofer, 2020). On average, this route uses 1,370 kg of iron ore, 780 kg of metallurgical coal, 270 kg of limestone, and 125 kg of recycled steel to produce 1 tonne of crude steel (Worldsteel, 2021). Finally, the liquid steel can be formed using casting and rolling operations to obtain final steel products with the desired shape. The steel products are typically delivered as plates, coils, sections, or bars (Eurofer, 2020).

4.2.2 The EAF Route

Based on the electric arc furnace, the second route produces steel using mainly recycled scrap steel and electricity. Other sources of metallic iron, such as sponge iron, direct-reduced iron (DRI), or hot metal, can also be used in the EAF route. Additives, such as alloys adjust to the desired chemical composition. About 30% of steel is produced using the EAF route (Worldsteel, 2021). The heat for melting the metal in the EAF comes from an electric arc that arises when graphite electrodes make contact with the metal. Arc temperatures can go as high as 3,500°C, while the molten metal temperature is about 1,800 degrees. The formation process of casting and rolling is similar to the BF-BOF route (Eurofer, 2020).

On average, the steelmaking process via this route involves around 710 kg of recycled steel scrap, 580 kg of iron ore, 150 kg of coal and 90 kg of limestone, and 2.3 GJ of electricity to produce 1 tonne of crude steel. Using recycled steel in production allow for a significant reduction in energy and raw material use. Production based on scrap can save around 1,400 kg of iron ore, 740 kg of coal, and 120 kg of limestone for every tonne of steel scrap made into new steel. However, steel products have a long lifespan and remain in use for decades before they can be reclaimed. Compared to iron ore, for which the extraction can be adjusted to the steel demand, the global availability of scrap is closely related to the levels of past steel production, average product lifespan, and the efficiency of recycling programs. Therefore, the expansion of steel production using scrap is restrained by the accessibility of recycled steel products. Thus, there is insufficient recycled steel to meet the growing demand using the EAF steelmaking method alone. Demand is met through the combined use of both the BF-BOF and the EAF production route (Worldsteel, 2021).

5 Economic Parameter Analysis

In order to visualize and capture the main mechanisms determining carbon leakages, this section assesses the sensitivity of the leakage rate concerning the values of the different parameters. The results found using the analytical model rely upon the size and the directional impact of the various parameters specified [1]. Excessively high (low) estimates of the parameter values may bring about under (over) estimation of the impact of climate policy. Therefore, the value of these econometric parameters should be carefully considered and justified using empirical evidence.

Regarding the share of carbon-energy use in production α, the steel sector has continuously made efforts to increase energy efficiency and reduce its environmental impact by using less carbon. Producing one tonne of steel today requires about 40% less energy than 60 years ago (Worldsteel, 2022). In the short to medium run (the next five to ten years), further improvements in energy efficiency can be achieved by improving operational technologies and implementing energy management systems (IEA, 2021a). For example, some of the coke used in the reduction process of iron ore can be replaced by adding alternative carbon sources into the blast furnace, such as pulverized coal, oil, and tar/pitch (IEA Bioenergy, 2021). Pulverized coal has more narrowly defined qualities than coke, and using one tonne of pulverized coal replaces 1.4 tonnes of coking coal (Worldsteel, 2021).

Due to expanded transporting possibilities, och infrastructure, coal, and oil used for heating furnaces and mill motors are increasingly replaced by liquefied natural gas, natural gas, and electric power, which gives a less emissions-

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[1] To see the directional impact of the econometric parameter on the carbon leakage rate, the first order conditions of Eq. (9) with respect to each parameter is presented in Appendix C.

intensive production (Jernkontoret, 2018). Nevertheless, steel production is highly dependent on coal, which meets 75% of its energy demand. In the past few years, the energy intensity of steelmaking has shown little improvement (IEA, 2021a). In Europe, steelmakers have reduced the amount of required carbon as far as possible within the thermodynamic limits of the process (Eurofer, 2020). However, the potential emissions reduction and energy efficiency improvements will soon be exhausted (IEA, 2021a). As a result, the carbon-energy share in production varies across producers and regions (EU JRC Technical Report, 2020). However, with the existing steelmaking technologies, the carbon-energy share will remain fairly constant.

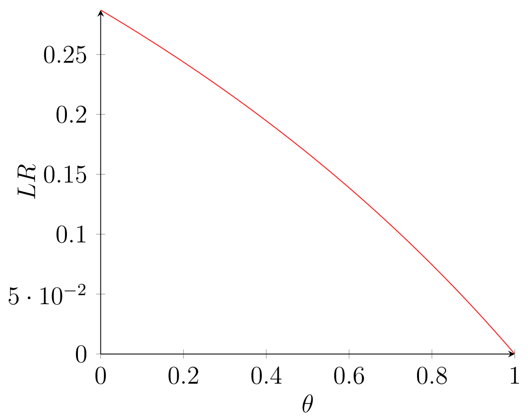

Figure 1: EU's share of global steel production and the leakage rate

The share that the EU's steel production makes up of global steel supply matters for the magnitude of carbon leakage. The EU is the world's second largest steel producing region and stands for around 8% of the world's total steel supply (Worldsteel Statistical Yearbook, 2020). If more countries were to implement carbon emissions abatement measures comparable to the EU ETS system, the competitive advantage of using coal in steel production outside the EU would decrease. As a result, the risk of carbon leakage can be significantly decreased if the fraction of countries adopting emissions regulation increases.

As can be seen in Figure 1, the larger is the share of EU's steel production in the global market or put differently if the policy area expands, the smaller the potential risk for carbon leakage becomes, $\frac{\partial LR}{\partial \theta} < 0$. If $\theta = 1$, all countries worldwide have implemented similar emissions abatement efforts, and all steel producers face similar abatement costs. In this case, there is no risk of carbon leakage. Notably, the policy area needs to be relatively large for the risk of carbon leakage to be substantially reduced. The likelihood of a high carbon leakage when few steel producers face a carbon restriction supports the importance of a worldwide climate coalition to reduce emissions.

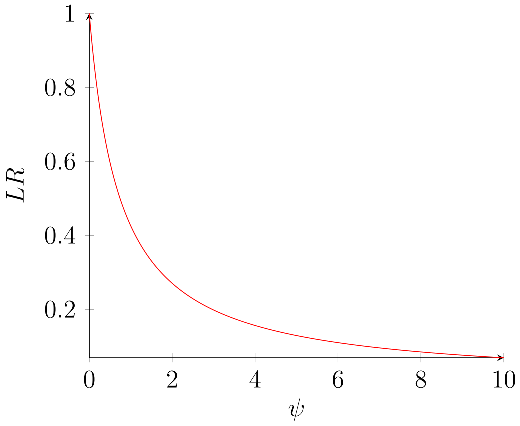

Figure 2: Elasticity of coal supply and the leakage rate

The set of elasticity parameters making up the derived carbon leakage rate in equation (9) can be translated into steel sector-specific parameter values. The first elasticity parameter in the model is the price elasticity of carbon-energy supply which can be translated into the price elasticity of coal supply in the steel sector. In the multi-sector analysis of carbon leakage by Gerlagh & Kuik (2014), the authors assumed the value of elasticity carbon-energy supply to be 2. In a study by Golombek et al. (1995) the price elasticity of coal supply corresponds to this value. The authors of this study investigated the optimal carbon tax under incomplete international climate agreements assuming that the cooperating region was the members of the OECD. The elasticity of coal supply is considered relatively high since existing coal reserves are enormous, and the extraction can be done at a low cost. A higher coal price, therefore, promote coal supply.

The values of the coal supply elasticity appear to be the most influential parameter determining leakage rate in the steel industry. Figure 2 shows that the more responsive the coal supply is to changes in coal price, the lower carbon leakage will be, $\frac{\partial LR}{\partial \psi} < 0$. A high value of the coal supply elasticity moderately decreases the magnitude of carbon leakage, and a value close to 10 makes the risk of carbon leakage very small. As the coal price decreases due to the more stringent emissions regulation and the decreasing demand for coal in the EU, an incitement for steel producers in countries not covered by the EU ETS arise to take advantage of the lower coal price. This price advantage increases the demand to utilize more coal in production outside the EU, leading to more emissions.

The strength of this mechanism depends on the structure of the international carbon market. The decision made by coal extractors to either meet the demand or leave the coal in the ground is fundamental to the magnitude of carbon leakage. Compared to oil which can be considered a homogeneous international commodity, coal is more restricted in its application scope. There exist wide varieties of coal which are suitable for different purposes. In addition, coal is a bulky material, and transportation is difficult and costly. Therefore, it is more challenging to trade coal internationally, and domestic demand for coal may not be shifted easily across different users (Burniaux & Martins, 2012).

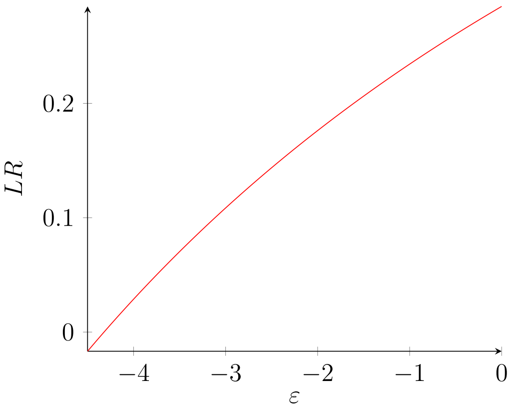

Figure 3: Elasticity of crude steel demand and the leakage rate

The second elasticity parameter in the model is the price elasticity of demand for energy-intensive goods. This sector-specific analysis can be comparable to the price elasticity of demand for crude steel. Steel is used in multiple aspects of the economy, foremost in engineering and construction. The lack of suitable substitutes and a growing economy make it difficult to bypass the use of steel. Due to this, the steel demand is considered to be relatively inelastic.

Karlson (1983) early empirically estimated the price elasticity of steel demand for US steel plants using a behavioral and econometric model of spatial firms. The study resulted in the price elasticity of steel demand being -0.3. Studies analyzing trade and policy aspects of EU steel markets have been relying on the same value for the price elasticity of steel demand (see Winters, 1995; Mathiesen & Mœstad, 2004). A more recent study by Fernandez (2018) presents new evidence of heterogeneous demand patterns across regions based on the long-run specification for 1980–2015. For example, South America's had the most price-elastic steel demand whit a value of -0.18. North America and the EU revealed price elasticity of steel demand of -0.065 and -0.025, respectively. Although these studies reveal variations in the empirical estimates, the results are consistent because the steel demand is found to be negative and relatively low.

Figure 3 demonstrates that higher values of the price elasticity of steel demand increase the leakage rate $\frac{\partial LR}{\partial \varepsilon} > 0$. However, minor adjustments in the elasticity of demand for crude steel will have a limited impact on carbon leakage. For the magnitude of carbon leakage to be considerably reduced, the demand for crude steel needs to be very responsive to price changes, which has empirically not been proved. Therefore, a value for the price elasticity around -4.5 would be needed to reduce the risk of carbon leakage to zero.

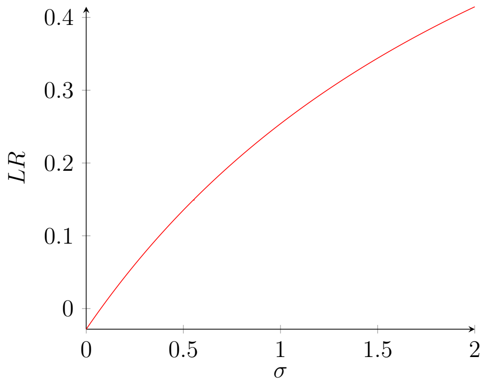

Figure 4: Elasticity of factor substitution and the leakage rate

The model's last elasticity parameter is the substitution elasticity between carbon-energy input and other factors of production. In the steel sector, this implies how other input factors in production can substitute coal use. The substitution possibility between inputs in production also appears to be an essential factor in determining the magnitude of carbon leakages. In Figure 4, it can be seen that a lower substitution elasticity in the production process tends to decrease leakage $\frac{\partial LR}{\partial \sigma} > 0$.

Higher substitutability between the coal input and other factors in production effectively allows for an emissions reduction in the EU. Conversely, producers outside the EU react stronger to the price decrease of coal, followed by the stringency of the EU emissions regulation, and demand for non-EU steel producers for coal increases. This increase in coal demand compensates for a large part of the saved coal in the EU and contributes to carbon leakage.

Thus, changes in the input structures can significantly influence the risk of emissions shifting across producers facing different emissions regulations.

As insufficient research exists about factor substitution within the steel industry, the substitution possibility between coal and other inputs will be translated into the more general substitution possibility between energy inputs and non-energy inputs in this analysis. In a study by Papageorgiou et al. (2017), the authors used data from 26 countries from 1995 to 2009 and estimated elasticizes for two production functions separately. One for the electricity sector and one for non-energy industries such as the steel industry provided a theoretical argument on how these elasticizes relate to the economy-wide elasticity of substitution between energy and non-energy inputs. Following their research, coal represents the energy input, and non-energy inputs represent other factors such as capital, labor, and raw materials. For the non-energy industries, the authors estimated this elasticity to be close to unity, with a value of 1.082.

5.1 Carbon Leakage in the Steel Industry

Carbon leakage in the steel industry raises a concern that regional emissions reduction could be partly or fully offset by increasing emissions from steel producers in other parts of the world with laxer emission regulation. Considering that the EU ETS is the first major carbon market in the world and remains the biggest one (European Parliament, 2003), the EU can demonstrate a regional attempt to reduce carbon emissions. Hence, in this analysis, EU steel production represents the regulated region of the analytical model while the rest of the world's steel producers represent the unregulated region.

In this illustrative case, it is assumed that the EU will further tighten its carbon emission regulations and revise the EU ETS to cover emission-intensive sectors. In this scenario, EU steel producers must bear the full cost of emissions linked to production without allocation of free emissions allowances. In order to numerically assess the risk of carbon leakage in the steel sector, the derived carbon leakage rate in equation (9) is applied using the steel sector specific parameter discussed in the previous section.

The model focuses on carbon leakage occurring through the energy channel and the market for carbon energy. In the steel industry, coal is the primary carbon-energy input used in production, causing carbon emissions. Around 86% of the emissions occurring via the BF-BOF route comes from the preparation and usage of coal (Mathiesen & Mœstad, 2004). Therefore, this analysis assumes that carbon leakage in the steel industry arises via the market for coking coal followed by the unilateral carbon abatement policy in the EU. The leakage rate in equation (9) depends on the share of carbon-energy inputs in production in value added and can be translated into the coal use in the steelmaking process. However, the composition of raw materials in production, including iron ore, coal, scrap, limestone, and oxygen, varies across the production routes and steel plants. In the lack of appropriate assessments of the share of coal in value added in steel production, the energy cost will serve as an indicator for coal use in this analysis.

The energy costs usually represent between 11% and 20% of the total costs for the different production routes and regions (EU JRC Technical Report, 2020). Since the blast furnace based on iron reduction using carbon is the most widespread method to produce steel worldwide, energy use related to the BF-BOF route will be used as a benchmark to analyze the steel sector's carbon leakage. The reduction process in the blast furnace is a core element in the steelmaking process requiring large amounts of energy in such a way that energy use can serve as an indicator for the share of carbon-energy use (coal) in steel production.

In 2020 the European Commission's joint research center provided a technical report on the production costs of the iron and steel industry and third countries. The report revealed that EU steel plants had the third highest energy costs among the world's steel producers and reached on average 17% of total production costs based on the BF-BOF route. The range of energy costs amongst EU plants was extensive, making EU producers gain an advantage over non-EU facilities with higher energy costs and become more competitive with non-EU producers with lower energy costs (EU JRC Technical Report, 2020). Therefore, the average energy cost of 17% in the EU will be used to represent the share of carbon-energy input in steel production in this analysis.

The parameter for the price elasticity of coal supply will take a value of 2 in this analysis based on the findings by Golombek et al. (1995). The estimated value of -0.3 for the price elasticity of demand for steel by Karlson (1983) has been used as a reference value in previous literature. Although more recent research indicates that steel demand may be even more inelastic, this value will be used as a base case even in this analysis. Ultimately, the elasticity of factor substitution within the steel production will be assumed to be 1.082, as previously noted from the study by Papageorgiou et al. (2017). A summary of the econometric parameters used to calculate the steel sector's carbon leakage is presented in Table 1.

Economic parameters of the basic carbon leakage model			
Parameter	Description	Value	Source
θ	EU's share of global steel production	0.08	Worldsteel Statistical Yearbook (2020)
α	Share of energy cost in production	0.17	EU JRC Technical Report (2020)
ψ	Price elasticity of carbon supply	2.0	Golombek et al. (1995)
ε	Price elasticity of crude steel demand	-0.3	Karlson (1983)
σ	Elasticity of factor substitution in production	1.082	Papageorgiou et al. (2017)

Table 1: Overview of economic parameters in the steel industry

Inserting the parameter values into the expression for the carbon leakage rate, equation (9), makes it possible to calculate the carbon leakage for the steel industry. Due to a unilateral emissions reduction in the EU, the carbon leakage becomes LR=0.27. Meaning that if the EU were to cut its emissions unilaterally and included EITE sectors in the EU ETS, then around 27% of the emissions reduction in the steel industry would be offset by emissions increase by steel producers in the non-EU countries.

5.2 The Impact of Technological Change and Spillover effects

The extended carbon leakage model allows for examining carbon leakage in the steel industry, accounting for technological change and technological spillover effects. As described in the extended model, the CES production function incorporates substitutability between different energy-intensive inputs and the possibility to substitute energy inputs for other factors in production, such as capital and labor. It is assumed that the substitutability is partially linked to technological change and partially to classical factor substitution.

In the steel industry, this exemplifies the possibility of substituting carbon energy within the integrated steel mills and, to some extent, shifting between steelmaking technologies. Given that the steelmaking process has two primary sources of carbon emissions, the combustion of carbon-intensive fuels and the industrial process. Reducing combustion emissions is more manageable than reducing emissions from the chemical process and can be done by improving energy efficiency or using energy from renewable sources. On the contrary, emissions reduction in the chemical process of producing steel requires a switch to a new production process.

In recent years, steel producers worldwide have started to make plans and set targets to achieve deep emissions reductions. Many projects have been initiated to develop new steelmaking technologies enabling the fossil-free production of steel. Nevertheless, the necessary technologies are not available at a large scale and yet have to transform the sector. Continued efforts on these and other innovative projects will be essential to fully commercialize these technologies in the coming decade (IEA, 2021a).

The decarbonization measures in the EU will likely encourage steel producers to move ahead with the development of new technologies to reduce the abatement cost of reducing emissions linked to production. As coal is the primary source of emissions in the steelmaking process, the revised carbon emission pricing of the EU ETS will increase the unit cost of coking coal. Consequently, coal as an input will take up a greater share in value added in production, and innovation will be directed towards carbon-energy saving technologies to decrease the coal's cost share. Once carbon-reducing technologies are available, coal use in the EU decreases, and the new technologies can spillover and be adopted by steel producers outside the EU, leading to further reductions in coal use on a global level.

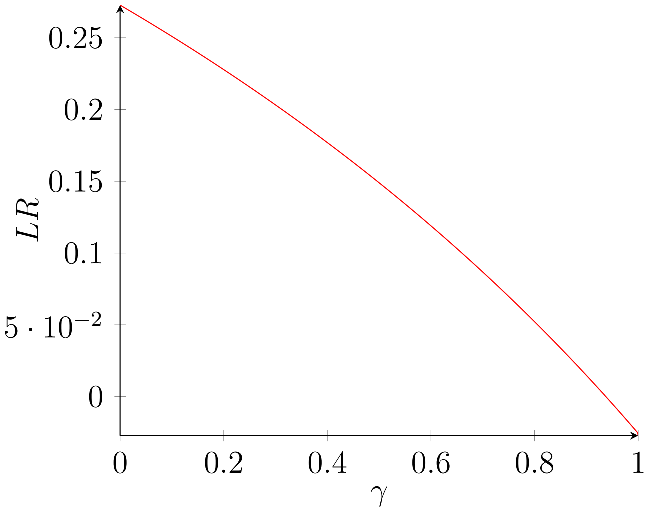

Figure 5: Effect of induced technological change on the leakage rate

New technologies enable steel producers to substitute coal use in production. Figure 5 shows to what degree the share of the substitution possibility related to technological change, γ, influences the carbon leakage rate. A higher rate of induced technological change and international technological spillover decreases the risk of emissions leaking to non-EU regions. The effect on carbon leakage is moderate for low values of γ. As γ increases, the effect accelerates, and as $\gamma \to 1$ the risk of carbon leakage becomes negligible. The transition from low to high values of γ and the effect on carbon leakage is illustrated in Table 2.

Technology transition	
γ	Leakage rate
0	27%
0.05	26%
0.1	25%
0.2	22.5%
0.3	20%
0.4	17.5%
0.5	15%
0.6	11.5%
0.7	8.4%
0.8	5%
0.9	1.2%
1	0%

Table 2: Different rates of induced technological change

The mechanism can be explained as follows. In the case that technological change is nonexistent, $\gamma = 0$, it becomes apparent that carbon leakage of 27% corresponds to the rate found using the basic carbon leakage model. In this case, the possibility of substituting coal in production arises entirely via classic factor substitution. As the emissions regulation in the EU is tightened, the reactive response of innovating new carbon-saving technologies increases among EU steel producers, and an innovation transformation is set in motion. However, few new technologies are being established at the start of the technological transition, and the possibility of substituting coal in production due to new production methods is limited. Therefore, the uptake of new technologies in the sector is initially expected to be low. With a low rate of induced technological change, producers outside the EU still face an advantage in utilizing more coal in production. Therefore, the risk of carbon leakage will still be substantial. For example, allowing for a low substitution possibility related to technological change of $\gamma = 0.05$ only reduces the risk of carbon leakage with 2%.

Over time, the innovative response continues and increases the possibility of substituting coal in production due to new production structures. The carbon-saving technologies have become more profitable, and new installations can compete with old production methods. Spillover effects cause more and more steel plants to adopt the new production technologies and the advantage of using coal in production decreases. In the later stage of the technological transformation, a higher rate of technological change can be assumed, and for $\gamma = 0.8$, the risk of carbon leakage is considerably reduced to 5%. In the end stage of the technological transition $\gamma \to 1$, a very high share of the substitution possibility of coal lies within the switch to new technologies. The advantage of utilizing more coal outside of the EU vanishes, and technology transition result in zero carbon leakage.

6 Discussion and Conclusion

Unilateral climate actions aiming to reduce regional carbon emissions can result in carbon leakage occurring via energy-intensive and trade-exposed sectors. However, the environmental policy encourages these sectors to develop new carbon-saving technologies to reduce emissions abatement costs. Subsequently, the new technologies can spillover to unregulated regions and reduce the risk of carbon leakage. Steel is one of the world's most energy-intensive and trade-exposed commodities, and the sector is at substantial risk of carbon leakage.

On the grounds of the EU's ambitious climate goal to become climate neutral by 2050 and its plan to revise the EU ETS to include the heavy industry, this analysis investigated the risk of carbon leakage in the steel sector. In contrast to previous work, this study highlighted the role of technological change and technological spillover effects on carbon leakage within the sector. A simple analytical model was used to evaluate carbon leakage with and without accounting for induced technological change. A numerical illustration using an analytical model and steel sector-specific parameters resulted in a leakage rate of 27%. This result is supported by the estimated leakage rate in the steel sector found by Mathiesen & Mœstad (2004). In their study, the authors found the carbon leakage rate in the steel sector to be 26% when accounting for factor substitution within an existing production technology.

Further, this analysis provided a comprehensive assessment of the economic parameters determining the carbon leakage rate in the steel industry. The most influential parameter for the magnitude of carbon leakage was the price elasticity of the coal supply. Therefore, the coal market structure is a fundamental component impacting the effectiveness of the environmental policy. The result showed that the more responsive the carbon market is to changes in coal price, the lower the risk for carbon leakage. A value for the elasticity of coal supply close to 10 reduces the risk of carbon leakage to zero. This observation aligns with the results found in the study by Burniaux & Martins (2000). The authors also found that the elasticity of coal supply is the most crucial parameter determining the magnitude of the leakage rate. However, according to their study, a robust and low leakage rate was only obtained with a somewhat implausible value of 45 for the supply elasticity of coal.

The main result of this analysis revealed that accounting for induced technological change and spillover effects reduced the carbon leakage rate within the steel sector. The effect accelerated when allowing for higher rates of induced technological change. Assuming an initially low rate of induced technological change of $\gamma = 0.05$ reduced the leakage rate by 2%. Further, assuming that the technological transition continues and the rate of technological change increases to $\gamma = 0.5$, the risk of carbon leakage decreases to 15%. Allowing for higher substitutability of carbon energy in production due to technological change, $\gamma = 0.8$, reduced the carbon leakage rate substantially to 5%. The results support the current debate that estimates of carbon leakage might be overestimated if technological change and spillover effects are disregarded in modeling. However, in comparison to previous literature, the effect of innovation on the steel industry's carbon leakage found in this analysis was much less pronounced. In the study by Gerlagh & Kuik (2014), the authors tested the analytical model against real data using a multi-region and multi-sector CGE model. They found that $\gamma = 0.05$ decreased the carbon leakage rate to 2.6% and that carbon leakage becomes negative for relatively low rates of induced technological change.

Technological progress in the steel sector can make technological spillovers increasingly significant in the upcoming decades. In order to achieve a substantial emissions reduction, the sector requires a switch to carbon-free technologies. Several steel producers around the world have initiated green steel projects. For example, electrolysis technologies based on renewable energy sources allow fossil-free hydrogen to be used in the steelmaking process instead of coal. Hydrogen can be used for the reduction of iron ore, and the only byproduct occurring from the chemical process is water (LeadIT, 2022). The new technologies transform the steel production from a carbon-based process into an electricity-based process (Komendantova et al., 2019). The steel sector has the potential to make use of large-scale renewable electricity. However, the acceleration of technological change and the international uptake of new technologies may depend on various factors. For example, it has been shown that the capacity to absorb innovation varies across region and tend to flow from developed countries to developing countries (Gerlagh & Kuik, 2014). Furthermore, power supply, hydrogen-supply security, and extraction of raw materials may impact the technology transition.

The analytical model used in this analysis is based upon selective assumption and is very simple. Reality is more complex than the analytical model. Varying the assumption about the production function and technology development may lead to different results. A simplified model may also leave out essential mechanisms that influence the magnitude of carbon leakage. For instance, assessing the steel industry in isolation may omit significant interaction effects across markets. Environmental policy impact all kinds of EITE industries which are all connected via the market for carbon energy. Burniaux & Martins (2000) discuss that the supply response of other carbon-intensive fuels can be affected by the carbon price and interact whit coal supply. Overlooking these interaction effects may lead to misleading conclusions.

Carbon leakage has been detected to occur via more than one channel. Although the energy channel has been proven to be the most critical, carbon leakage can arise via reallocation of production sights or changes in investment flows to regions with laxer climate policies. Not considering all the possible channels could underestimate the magnitude of carbon leakage. Furthermore, the results depend on empirical parameter values estimated using different modeling simulations and assumptions. Therefore, the results in this analysis are highly dependent on the reliability of previous findings. Especially, there is no direct evidence for the substitutability between carbon energy and other production factors in steel production. Instead, this analysis relies on the more general relationships between energy and non-energy inputs based on estimates on an aggregate level.

This study has shown that technological change and spillover effects can reduce the risk of carbon leakage in the steel industry. The effect of technological change should, therefore, not be ignored when assessing the effectiveness of unilateral climate policy. However, the exact numbers found in this analysis should be interpreted with caution. The possibility exists that carbon leakage in the steel sector arising due to the stringency of the EU ETS could be compensated by an accelerating technology transition. The findings in this analysis provide support for decision-makers to design environmental policies that restrict emissions and facilitate technological development. Facilitating the expansion of new technologies has the potential to maintain the competitiveness of EU steel producers and reduce carbon leakage and decrease.

The analysis leaves room for further extensions. For example, an area for future research would be to estimate the expansion and speed of technological change and the dimensions of spillover effects in the steel industry. In addition, one crucial aspect to consider is that the demand for fossil-free steel increases in manufacturing industries, and environmental awareness rises. These effects can modify the incentives of steel producers to establish new technologies to produce green steel. Therefore, it would be meaningful to investigate the impact of further drivers of technological change in the steel industry. Lastly, testing the analytical model against real steel data and for multiple regions could give an interesting insight into the impact of unilateral climate policy and technological change in the steel sector.

Appendix

Appendix A - Solution to the Basic Carbon Leakage Model

The carbon leakage rate (LR) is defined as as the absolute increase in emissions in region B divided by the decrease in absolute decrease in emission in region A:

$$LR = -\frac{(1-\theta)}{\theta}\frac{E_B}{E_A} \tag{C1}$$

Using Eq. (2) - (7) from the analytical model in section 3 gives following expressions of carbon energy demand E_A and E_B:

$$E_A = (p+\tau)(\mu(\alpha-1)-\varepsilon\alpha) \tag{C2}$$

$$E_B = p(\mu(\alpha-1)-\varepsilon\alpha) \tag{C3}$$

Inserting Eq. (C1) and (C2) in Eq. (C1) gives a transformed expression for the LR directly depending on the emission tax τ:

$$LR = -\frac{(1-\theta)}{\theta}\frac{p(\mu(\alpha-1)-\varepsilon\alpha)}{(p+\tau)(\mu(\alpha-1)-\varepsilon\alpha)}$$

$$\Leftrightarrow \qquad LR = -\frac{(1-\theta)}{\theta}\frac{p}{p+\tau}$$

Using Eq. (1) from the model and transforming this expression gives:

$$\theta E_A + (1-\theta)E_B = \psi p$$

$$\Leftrightarrow \qquad 1 + \frac{(1-\theta)E_B}{\theta E_A} = \frac{\psi p}{\theta E_A}$$

$$\Leftrightarrow \qquad 1 - \frac{\psi p}{\theta E_A} = \underbrace{-\frac{(1-\theta)E_B}{\theta E_A}}_{LR}$$

$$\Leftrightarrow \qquad LR = 1 - \frac{\psi p}{\theta E_A} \tag{C4}$$

Inserting the same expression for E_A in Eq. (C1) into Eq. (C4) gives:

$$LR = 1 - \frac{\psi p}{\theta(p+\tau)(\mu(\alpha-1)-\varepsilon\alpha)}$$

Extending with $(1-\theta)$ gives:

$$LR = 1 \underbrace{-\Big(\frac{1-\theta}{\theta}\Big)\Big(\frac{p}{p+\tau}\Big)}_{LR}\frac{\psi}{(1-\theta)(\mu(\alpha-1)-\varepsilon\alpha)}$$

$$\Leftrightarrow \qquad 1 = LR\Big[1 + \underbrace{\frac{\psi}{(1-\theta)(\mu(\alpha-1)-\varepsilon\alpha)}}_{:=B}\Big]$$

$$\Leftrightarrow \qquad 1 = LR\Big[1 + \frac{\psi}{B}\Big] \qquad \Leftrightarrow \qquad \frac{1}{LR} = 1 + \frac{\psi}{B} \qquad \Leftrightarrow \qquad LR = \frac{1}{1 + \frac{\psi}{B}}$$

$$\Leftrightarrow \qquad LR = 1 - \frac{\frac{\psi}{B}}{1 + \frac{\psi}{B}} \qquad \Leftrightarrow \qquad LR = 1 - \frac{\frac{\psi}{B}}{\frac{\psi}{\psi} + \frac{\psi}{B}} \qquad \Leftrightarrow \qquad LR = 1 - \frac{\psi}{\psi + B}$$

Inserting the original expression for B into the last step gives the final carbon leakage rate Eq. (9) which only depends on the economic variables:

$$LR = 1 - \frac{\psi}{[\psi + (1-\theta)(\varepsilon\alpha + \mu(1-\alpha))]}$$

For simplicity $b = \varepsilon\alpha + \mu(1-\alpha)$ will be used in upcoming calculation.

Appendix B - Solution to the Extended Carbon Leakage Model

The new carbon leakage rate capture technological spillover effects via the technology parameter. The log-linear version of the technology parameter is stated in Eq. (19) and defined as:

$$H_i = \gamma\,(Y_i - E_i)$$

The model assumes that the technological spillover is symmetric so that the global technology, H, is defined by the weighted average of both region A's and region B's changes in carbon-energy demand. This is stated in Eq. (22) in the extended model.

$$H = \gamma\,\Big[\theta(Y_A - E_A) + (1-\theta)(Y_B - E_B)\Big]$$

The technology parameter enters the model in Eq. (20) and (21) for carbon-energy demand.

$$E_A = Y_A - H_A + \mu(q_A - p - \tau)$$

$$E_B = Y_B - H_B + \mu(q_B - p - \tau)$$

To derive the new carbon leakage rate we fist need an expression for the technology parameter. Inserting E_A and E_B into H we obtain:

$$H = \gamma \left[\theta(H_A - \mu\ (q_A - p - \tau) + (1-\theta)(H_B - \mu(q_B - p)\right]$$

By assuming symmetric technology H for both regions and using the expressions in Eq.(6) and (7) for the prices in the basic carbon leakage model we obtain:

$$H = \gamma \left[\theta(H - \mu\ \underbrace{\alpha(p-\tau)}_{q_A} + \mu(p-\tau) + (1-\theta)(H - \mu\ \underbrace{\alpha p}_{q_B} - \mu p)\right]$$

Simplifying gives:

$$H = \gamma \left[\theta(H + \mu(1-\alpha)(p-\tau) + (1-\theta)(H + \mu(1-\alpha)p\right]$$

Rearranging gives an expression for H depending only on economic variables:

$$H = \underbrace{\left(\frac{\gamma}{1-\gamma}\right)\mu(1-\alpha)}_{c}\left[\theta(p+\tau) + (1-\theta)p\right]$$

Substituting the above expression for H_A back into E_A using Eq. (6) for the price and Eq. (4) for quantity result in:

$$E_A = Y_A - \underbrace{c\left[\theta(p+\tau) + (1-\theta)p\right]}_{H} + \mu(q_A - p - \tau)$$

$$\Leftrightarrow \qquad E_A = \underbrace{-\varepsilon\alpha(p-\tau)}_{Y_A=-\varepsilon q_A} - c\left[\theta(p+\tau) + (1-\theta)p\right] + \mu\Big(\underbrace{\alpha(p+\tau)}_{q_A} - p - \tau\Big)$$

$$\Leftrightarrow \qquad E_A = -(p+\tau)\underbrace{(\varepsilon\alpha + \mu(1-\alpha))}_{b} - c\left[\theta(p+\tau) + (1-\theta)p\right]$$

$$\Leftrightarrow \qquad E_A = -b\,(p+\tau)\; - c\left[\theta(p+\tau) + (1-\theta)p\right] \tag{D1}$$

Following the same structure substituting H for H_B into E_B using Eq. (7) for the price and Eq. (5) for quantity result in:

$$E_B = Y_B - \underbrace{c\left[\theta(p+\tau) + (1-\theta)p\right]}_{H} + \mu(q_B - p)$$

$$\Leftrightarrow \qquad E_B = \underbrace{-\varepsilon\alpha p}_{Y_B=-\varepsilon q_B} - c\left[\theta(p+\tau) + (1-\theta)p\right] + \mu\,(\underbrace{\alpha p}_{q_A} - p)$$

$$\Leftrightarrow \qquad E_B = -(p)\underbrace{(\varepsilon\alpha + \mu(1-\alpha))}_{b} - c\left[\theta(p+\tau) + (1-\theta)p\right]$$

$$\Leftrightarrow \qquad E_B = -b\,p\; - c\left[\theta(p+\tau) - (1-\theta)p\right] \tag{D2}$$

Substituting Eq. (D1) and Eq. (D2) into Eq. (1) gives:

$$\theta D1 + (1-\theta)D2 = \psi p$$

$$\Leftrightarrow \qquad \theta\Big[-b\ (p{+}\tau)\ -c\ \theta(p{+}\tau){+}(1{-}\theta)cp\Big]{+}(1{-}\theta)\Big[-b\ p\ -c\ \theta(p{+}\tau){-}(1{-}\theta)cp\Big]{-}\psi p = 0$$

$$\Leftrightarrow \qquad (p+\tau)\Big(\theta b+\theta^2 c+(1-\theta)\theta c\Big)+(1-\theta)\Big(\theta cp+bp+(1-\theta)cp\Big)+\psi p = 0$$

$$\Leftrightarrow \qquad \theta(p+\tau)(b+c)+(1-\theta)(b+c)p+\psi p$$

$$\Leftrightarrow \qquad \frac{p+\tau}{p} = \underbrace{-\Big(\frac{1-\theta}{\theta}\Big)-\frac{\psi}{\theta(b+c)}}_{:=G} \tag{D3}$$

Substituting Eq. (D1) and (D2) into the definition of carbon leakage in Eq. (C1) and dividing by $(-p)$ gives:

$$LR = -\Big(\frac{1-\theta}{\theta}\Big)\frac{\theta c(\frac{(p+\tau)}{p})+b+(1-\theta)c}{(b+\theta c)(\frac{p+\tau}{p})+(1-\theta)c}$$

$$\Leftrightarrow \qquad = \ -\frac{\theta(1-\theta)c(\frac{p-\tau}{p})+(1-\theta)b+(1-\theta)^2 c}{\theta(b+\theta c)(\frac{p-\tau}{p})+\theta(1-\theta)c}$$

$$\Leftrightarrow \qquad = 1\ -(b+c)\ \frac{\theta(\frac{p-\tau}{p})+(1-\theta)}{\theta(b+\theta c)(\frac{p+\tau}{p})+\theta(1-\theta)c}$$

Inserting expression G for $(\frac{p-\tau}{p})$ from Eq. (D3) in the previous step and rearranging result in:

$$LR = 1 \; - \; \frac{(1-\theta)(b+c)+\psi-(1-\theta)(b+c)}{(1-\theta)(b+\theta c)+\psi(\frac{b+\theta c}{b+c})-\theta(1-\theta)c}$$

Simplifying the last expression gives the final leakage rate in Eq. (24) from the extended carbon leakage model. Comparable to the basic carbon leakage rate the new expression for carbon leakage depend on the econometric parameters of the model as well as the induced technological change. As shown in section 3.2 the parameter for induced technological change enter the leakage rate via the expression for c.

$$LR = 1 - \frac{\psi}{[\psi\;(\frac{b+\theta c}{b+c}) + b\;(1-\theta)]}$$

$$c = \frac{1-\alpha}{1-\gamma}\;\mu\gamma$$

Appendix C - Interpretation of the Carbon Leakage Rate

Differentiating the carbon leakage rate in Eq. (9) with respect to each economic parameter gives the following results:

Fig 1. The leakage rate is decreasing in EU's share of global steel production:

$$\frac{\partial LR}{\partial \theta} = -\frac{\psi((1-\alpha)\mu+\varepsilon\alpha)}{[\psi+(1-\theta)((1-\alpha)\mu+\varepsilon\alpha)]^2}$$

$$\frac{\partial LR}{\partial \theta} < 0$$

Fig 2. The leakage rate is decreasing in the elasticity of coal supply:

$$\frac{\partial LR}{\partial \psi} = -\frac{(\theta - 1)((\alpha - 1)\mu - \varepsilon\alpha)}{[\psi + (\theta - 1)((\alpha - 1)\mu - \varepsilon\alpha)]^2}$$

$$\frac{\partial LR}{\partial \psi} < 0$$

Fig 3. The leakage rate is increasing in the elasticity of crude steel demand:

$$\frac{\partial LR}{\partial \varepsilon} = \frac{\psi\alpha(1 - \theta)}{[\psi + (1 - \theta)(\alpha\varepsilon + (1 - \alpha)\mu)]^2}$$

$$\frac{\partial LR}{\partial \varepsilon} > 0$$

Fig 4. The leakage rate is increasing in the elasticity of factor substitution:

$$\frac{\partial LR}{\partial \mu} = \frac{\psi\alpha(1 - \theta)}{[\psi + (1 - \theta)((1 - \alpha)\mu + \varepsilon\alpha)]^2}$$

$$\frac{\partial LR}{\partial \mu} > 0$$

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