

A Work Project, presented as part of the requirements for the Award of a Master's degree in
Impact Entrepreneurship & Innovation from the Nova School of Business and Economics

Carbon Economics and Emission Reduction
in the Metal Sector:
The AI Advantage

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ABSTRACT

Due to the EU's commitment to achieve net-zero emissions by 2050, climate regulations, including carbon pricing, compel companies to develop effective emission reduction strategies. Artificial intelligence, through methods like Product Carbon Footprinting and Demand Forecasting, plays a crucial role. Despite the increasing impact of carbon costs, counteracting trends like the shift to renewables and low-emission steel production offer potential mitigations. Especially the carbon-intensive metal sector can benefit, as carbon costs could significantly decrease margins. Notably, reducing emissions early helps companies proactively manage additional costs. These insights provide a foundational understanding of informed and sustainable business practices amid evolving regulatory dynamics.

Keywords: Climate Change; CO₂ Emissions; Carbon Pricing; Artificial Intelligence; Emissions Reduction; Product Carbon Footprint; Demand Forecasting

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1 INTRODUCTION

1.1 Relevance

Since the Industrial Revolution, the Earth has been steadily warming, primarily due to greenhouse gas (GHG) emissions. To address global warming, numerous countries, committed to the Paris Agreement's goal of achieving net-zero emissions by 2050, have implemented policies targeting carbon dioxide (CO₂) and other GHG emissions. As the energy sector and industries contribute significantly to the generation of emissions (European Parliament 2018), achieving climate targets necessitates rigorous efforts from businesses. In response, political mechanisms, such as emission trading systems (ETS), have been introduced to incentivize companies to reduce emissions by assigning a financial value to the carbon they emit (European Commission 2016). Thus, “CO₂ emissions are becoming a measurable cost” (Bock and Böhler 2023). In order to effectively reduce emissions and therefore costs, companies must identify the sources of their emissions and implement targeted reduction strategies. Given the urgency of climate concerns and the growing complexity of political requirements, transparency regarding existing regulations, associated costs for businesses, and effective countermeasures is crucial. Understanding all these aspects is essential for proactive decision-making. This study aims to shed light on carbon economics and emission reduction strategies, emphasizing the importance of knowledge for meaningful change.

1.2 Scope and Limitations

In light of these considerations, the study aims to investigate the current and future landscape of costs associated with product emissions and potential saving opportunities. By using the methods of Product Carbon Footprinting (PCF) and Demand Forecasting in conjunction with Artificial Intelligence (AI), the aim is to identify ways in which companies can gain

transparency over these emissions and to identify opportunities for reducing both emissions and the resulting costs. To achieve this, the following questions are addressed in this study:

1. What prevailing regulations are in place concerning the pricing of emissions?
2. How can PCF, Demand Forecasting, and AI contribute to reduction of emissions?
3. What costs may arise from product emissions, and how are they influenced by changes in economic trends, regulations, and emission reduction efforts?

1.3 Structure of the work project

This paper comprises five chapters. Following the introduction, the second chapter establishes the theoretical foundation for the subsequent analysis. Chapter 2.2 defines PCF and Demand Forecasting, serving as foundational principles for the subsequent analysis of AI's impact on related methods and emission reduction potentials in the supply chain (see Chapter 3.1 and 3.2). In the fourth chapter, a case study analyzes the carbon costs of a product in the metal industry based on the previously established foundations and insights. This involves explaining the case (see Chapter 4.1), detailing assumptions and calculations (see Chapter 4.2), presenting results (see Chapter 4.3), and discussing findings (see Chapter 4.4). The fifth chapter provides a comprehensive summary of the key findings.

2 THEORETICAL FOUNDATION

2.1 Regulatory state of affairs and current policies

In 2015, under the Paris Agreement, the United Nations Convention of Climate Change established a global temperature increase limit of well below 2°C above pre-industrial levels, with efforts to limit it to 1.5°C to significantly reduce climate change risks (UNFCCC 2015). Acknowledging the adverse effects of GHG emissions on climate change, the European Parliament underscores the imperative to reduce emissions across all sectors. To achieve climate neutrality by 2050, the European Union (EU) introduced the comprehensive "Green Deal", which

encompasses various initiatives, including "Fit for 55" to align EU legislation with climate goals, aiming for a minimum 55% reduction in GHG emissions by 2030 compared to 1990. The Green Deal also includes diverse measures such as a Circular Economy Action Plan, climate adaptation strategies, and more. All these goals are legally binding under the EU Climate Law, which led to the "Fit for 55" legislative proposals of the EU Commission. The upcoming discussion delves into specific laws and legislative proposals to illustrate their impact on businesses in the market, with a specific emphasis on the carbon pricing mechanisms they are exposed to (European Commission 2023c; European Council 2023; European Parliament 2021).

A key tool for cost-effectively lowering GHG emissions, is the EU Emissions Trading System (EU ETS). It operates since 2005, placing a price on carbon emissions in the sectors electricity and heat generation, energy-intensive industry and aviation. The EU ETS operates under the cap- and trade principle, meaning that an emission cap is set as the highest amount entities are allowed to emit. The annual cap reduction is currently at 2.2%, but it will increase to 4.3% in 2024 and further to 4.4% in 2028 to meet the ambitious 62% reduction goal by 2030, in the sectors covered (European Union 2022). Within this cap, "companies receive or buy emission allowances which they can trade" (European Commission 2016, 2) as allowances granting the holder the right to emit one ton of CO₂. These EU allowances (EUAs) possess inherent value and are tradable because their limited supply makes them scarce and, consequently, valuable. If an emitting entity lacks sufficient EUAs to cover its emissions, significant fines are imposed (European Commission 2022). Thus, the cap-and-trade principle encourages emission reductions where most cost-effective, while generating revenue for climate initiatives. Different methods exist for allocating allowances, with auctioning being the primary approach. In this method, businesses purchase allowances through an auction, which makes their climate-related costs transparent and ensures that polluters bear the cost (European Commission 2022; European Commission 2023d). Regarding the auction price dynamics of EUAs, challenges emerged

during the second trading period (2008-2012), marked by surpluses that led to a significant drop in prices. In 2012, auction prices for Germany averaged 7.34€/tCO₂; however, by 2013 and 2014, prices fell to an average of 4.35€/tCO₂ and 5.91€/tCO₂, respectively (see App., Fig. 2). Consequently, measures like Backloading (withholding allowances) and the Market Stability Reserve, which regulate allowances surpluses and shortages, were introduced. These measures play a decisive role in stabilizing prices for emission allowances and eliminating market imbalances. The significant and consistent increase in German auction prices since 2018 demonstrates the effectiveness of these measures. By 2023, the price has reached 86.19€/tCO₂, representing a price increase of over 1000% compared to 2012 (DEHSt 2023a; EEX 2022).

In addition to auctions, a significant number of allowances are also distributed for free to address the risk of carbon leakage. Carbon leakage refers to the possibility of ETS-regulated activities relocating to non-EU countries with less ambitious climate policies, potentially leading to higher overall GHG emissions. Sectors particularly vulnerable to carbon leakage are allocated allowances for free to maintain their competitiveness. The allocation of free allowances to less exposed sectors is intended to phase out by 2034 (see App., Fig. 3) (European Commission 2022; European Commission 2023d). This is the rationale behind the gradual implementation of the “Carbon Border Adjustment Mechanism” (CBAM) which is expected to cover “100% of embedded emissions of the CBAM goods” (European Commission 2023b, 19) from 2034. It “ensures that importers of goods from non-EU countries bear similar carbon costs for the ‘embedded emissions’ of the imported goods” (European Commission 2023b, 18) for particular industries covered by the EU ETS and facing the highest risk of carbon leakage. Those importing CBAM-regulated products into the EU will need to provide CBAM certificates, the cost of which will be calculated based on the weekly auction price of EUAs. EU importers must annually report the volume of goods and their associated emissions imported into the EU in the previous year. Simultaneously, importers must submit CBAM certificates equivalent to the

emissions within the products. Importers may provide evidence, if carbon pricing has already been applied during the production of imports (European Commission 2023a).

In addition to the existing European system, Germany introduced a national emissions trading system (nETS) in 2021 to reduce the emissions generated in the heating and transport sectors by the use. These are not yet covered by the EU ETS, as only emissions from fuel generation are relevant there (see App., Fig. 4). The nETS includes emissions from fuel use in agriculture, fisheries, forestry, rail transport, as well as sectors in energy and industry not covered by the existing EU ETS (Wissenschaftliche Dienste des Deutschen Bundestages 2023). Unlike the EU ETS the nETS follows an upstream approach, where costs are not placed on the direct emitters but on entities responsible for introducing emissions into the market, such as gas and coal suppliers. This approach is chosen because these sectors involve a much larger number of participants, including private individuals. To simplify the process, it is managed through the Federal Emissions Trading Act by responsible parties, who then pass on the additional costs to end consumers. In contrast to the EU ETS, prices in the nETS are initially fixed. Currently, in 2023, this price stands at 30€/tCO₂ and will increase to 45€/tCO₂ by 2025. Starting in 2026, the auction phase will commence, where CO₂ will cost a minimum of 55€/tCO₂ and a maximum of 65€/tCO₂, depending on market demand (see App., Fig. 5) (DEHSt 2023b).

Since the nETS covers sectors that the EU ETS doesn't, even though these sectors are major sources of CO₂ emissions, there have been efforts in the “Fit for 55” package to review emissions trading in Europe (DEHSt 2023b). This includes, among other things, the extension of the existing EU ETS (EU ETS I) to include maritime transport from 2024 and the introduction of a second EU ETS (EU ETS II) for road transport, buildings and industrial activities not covered by the EU ETS I. Starting in 2025, “regulated entities should be required to hold a greenhouse gas emissions permit and to report their emissions for the years 2024 to 2026. The issuance of allowances and compliance obligations for those entities should be applicable as from 2027”

(Publications Office of the European Union 2023, 17). Similar to Germany's nETS, the EU ETS II will adopt an upstream approach, where those introducing emissions into the market bear the costs. In countries with their own ETS for the sectors involved in EU ETS II, like Germany, fuel suppliers may be exempted until 2030 if they face a national carbon tax at least as high as the ETS II auction price (icap 2023, 51–52; Publications Office of the European Union 2023, 18–21). In the EU ETS II it is planned to distribute all allowances via auctions, with some mechanisms in place that ensure that prices do not exceed 45€/tCO₂ in the initial years to ensure stability. The design of how to deal with overlapping systems, such as the EU ETS II and the nETS is currently still under discussion. For instance, questions such as whether the nETS, which covers more sectors than the EU ETS II, can be transferred to the EU ETS II need to be clarified (German Environment Agency 2021).

2.2 Product Carbon Footprinting

As previously discussed, the implementation of the CBAM necessitates the disclosure of product emissions to determine the corresponding levies on imported goods. Similarly, the Ecodesign Directive, an integral part of the EU Green Deal, mandates the disclosure of product emissions, aligning with its goal to introduce a Digital Product Passport, which aims to provide information on environmental sustainability (European Commission 2023e). The method known as Product Carbon Footprinting not only describes the accounting and reporting of product emissions but also aids in identifying high-emission lifecycle stages for targeted reduction efforts (Greenhouse Gas Protocol 2011).

According to ISO 14067:2018 (ISO 2019, 16), a Product Carbon Footprint (PCF) is defined as “sum of GHG emissions (...) and GHG removals (...) in a product system (...), expressed as CO₂ equivalents (...) and based on a life cycle assessment (...) using the single impact category (...) of climate change”. This means that the PCF solely addresses the climate change impact within

the product's lifecycle and does not encompass the product's overall environmental performance, such as resource scarcity or negative impacts on ecosystems (ISO 2019, 72).

There is no single universally accepted definition or approach for conducting a PCF assessment. Various standards exist, with the most well-known being ISO 14067, the GHG Protocol Product Standard, and PAS 2050, all of which are rooted in the principles of Life Cycle Assessment (LCA) and, consequently, ISO 14040 and 14044 standards. Despite sharing the same foundation, adherence to these individual standards can yield different results (Wang, Wang and Yang 2018, 2). Therefore, the following paragraph outlines a general approach to PCF assessment based on ISO 14067 (ISO 2019):

As PCF accounting is grounded in LCA principles, the assessment must adhere to the four LCA phases: Goal and Scope Definition, Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA), and Life Cycle Interpretation.

Defining the Goal and Scope of a PCF study involves setting clear objectives and determining the product, life cycle stages, and data validity period for representative results. Considerations include specifying the product, choosing life cycle stages (e.g. cradle-to-grave or cradle-to-customer), and defining the data's validity period for representative PCF results.

LCI analysis as a second step involves gathering and quantifying inputs and outputs for a product's entire lifecycle. Data must be collected, validated for quality, and the essential data for the PCF study determined. Proper allocation of materials and energy to specific products is essential, and specific rules apply for handling different GHG quantities, such as fossil and biogenic carbon, electricity, or land use. To ensure high-quality and accurate PCF assessments, proper data utilization is crucial. The emphasis is on the collection of location-specific data for individual processes, including direct emission measurements, activity data, or emission factors. If no location-specific data is available, non-location specific primary data must be used as a priority which not necessarily needs to derive from the product system under study but can

pertain to a different yet comparable product system. Secondary data and emission factors must be used if no primary data is available.

The LCIA as a third step involves calculating the potential climate impacts of each emitted and sequestered GHG quantity by multiplying it by a specific factor known as Global Warming potential (GWP). Notably, GWP100, representing the impact over a 100-year period, is considered the most relevant factor. This approach allows for the expression of these impacts in a standardized unit, CO₂ equivalents (CO₂e) per kilogram, facilitating the assessment of the contributions of various gases to climate change.

Finally, during the life cycle interpretation of a PCF, several critical steps need to be examined. These include an analysis of the results concerning significant parameters, an assessment of the study's completeness and consistency, including a sensitivity analysis, and the formulation of conclusions, limitations, and recommendations. These outcomes should encompass an assessment of uncertainty and a comprehensive report on the PCF study (ISO 2019).

As evident from the preceding explanation, the complexity of a PCF study lies not in the actual computation of the PCF but in the accompanying efforts related to data collection, scope determination, documentation, and more. An overview of the steps of a PCF calculation can be found in the Appendix, Fig. 6. In accordance with these or similar standards, companies use various applications to calculate their PCF. In principle, the calculation of a PCF can be carried out manually or with the assistance of software like Microsoft Excel. However, PCF calculations can become highly complex when dealing with extensive datasets that require compilation and computation, coupled with the necessity for choosing the correct emission factors. Hence, dedicated software tools are increasingly being used for these calculations (Hottenroth, Joa and Schmidt, 18). A survey by the German government's "Scope3 Transparent" project revealed that most companies commonly utilize tools like Excel, Umberto, GaBi, SigmaPro, or in-house software for data collection and calculations (Umwelttechnik BW GmbH 2023).

In conclusion, PCF serves as a valuable tool for quantifying the environmental impact of products. Furthermore, it empowers companies to enhance sustainability throughout their supply chains by identifying and addressing specific areas for emission reduction. This enables strategic decision-making, including potential adjustments to materials, production locations, and distribution methods. Additionally, PCF offers insights into the pricing dynamics associated with emissions, highlighting the potential effects on product pricing (Bock and Böhler 2023).

2.3 Demand Forecasting

As the regulations and also consumer interests show, there is a growing importance of environmental considerations in global trade. But the integration of sustainability principles into business practices often raises concerns about potential harm to profitability (Whelan and Fink 2016). In addition to enhancing sustainability in supply chains through PCF, there is another strategic method that enables companies to act sustainably and environmentally responsibly while also benefiting their business by reducing costs, known as demand forecasting. Demand forecasting is a fundamental process integral to supply chain management, encompassing various managerial decisions such as demand planning, order fulfillment, production planning, and inventory control. This essential task involves predicting future demand for a product or service, forming the foundation for informed planning and decision-making. Given the substantial risks associated with demand volatility, precise forecasting becomes paramount. However, achieving accuracy is challenging due to underlying volatility and uncertainties arising from factors like promotions, weather, market trends, and seasonality. This volatility poses a significant risk to the supply chain, affecting costs related to stock-outs, inventory, and capacity utilization (Abolghasemi et al. 2020).

Various best practices and standards have been established for Demand Forecasting. The choice of which forecasting method to use depends heavily on the industry the organization is operating in, the type of forecast needed and the data available. The forecasting methods can be cate-

gorized into qualitative and quantitative approaches. Qualitative methods come into play when relevant data is scarce. They are subjective and rely on human judgment, although some well-structured approaches can overcome inherent limitations and yield accurate forecasts. Some common qualitative techniques include the Delphi method, forecasting by analogy, scenario forecasting, new product forecasting, and judgmental adjustments. Quantitative forecasting methods either use time series data or cross-sectional data (Hyndman, 2018). Common methods are statistical techniques such as moving averages, regression models or exponential smoothing, bayesian methods or heuristics-based models. Newer techniques use AI and Machine Learning (ML), as well as artificial or evolutionary neural networks and many more (Swaminathan and Venkitasubramony 2023). Further information on how companies can decide for the right forecasting method can be found in the Appendix, Fig. 7.

In essence, Demand Forecasting not only enhances decision-making processes and mitigates volatility-related risks but also yields positive impacts on both business and the environment. The subsequent chapter delves into its active contribution to emission reduction.

3 EMISSION REDUCTION POTENTIALS THROUGH AI

3.1 Enhancing PCF and Demand Forecasting methods with AI

After exploring the definitions and best practices of PCF and Demand Forecasting, the following chapter sheds light on the significant challenges in these areas. Unpacking the complexities of PCF and Demand Forecasting reveals various hurdles, underscoring the crucial role that AI plays in overcoming these challenges and promoting sustainability in the business environment. Despite the existence of best practices and standards, users encounter significant challenges in achieving accurate results in both PCF calculation and Demand Forecasting. The reasons behind these challenges are multifaceted. For PCF, the primary content-related challenges in GHG emissions accounting are the complexity of the supply chain, collaboration with suppliers, as well as a wide range of products, component breakdown, standardizing GHG reporting for

suppliers, consistent data collection, dealing with data gaps, emission factor availability, and more. In addition to content-related challenges, there are often barriers to even accounting GHG emissions due to a lack of method knowledge, personnel, time, or the high cost involved (Umwelttechnik BW GmbH 2023).

In contrast to the PCF, Demand Forecasting has a longer history, and as a result, the current focus of the issues is less on the initial challenges and more on adapting to today's problems. Experts, in a study examining future forecasting practices, anticipate that Demand Forecasting will encounter complexities such as product diversification, shorter lead times, and disruptions, which are key concerns in the modern business landscape. They highlight a shift towards greater automation using AI and the utilization of big data and quantum computing for forecasting models (Petropoulos et al. 2022).

AI can help to solve many of the beforementioned challenges. This is why an increasing number of AI-powered tools are entering the market. They not only aid in lowering emissions across different stages of the value chain but also improve transparency by highlighting factors contributing to elevated emissions (Delanoë, Tchunte and Colin 2023).

3.2 Emission reduction within the supply chain

AI not only enhances the functionality of these methods but also holds significant potential for emission reduction in the supply chain. The upcoming chapter highlights how AI can be used to elevate PCF and Demand Forecasting for broad market adoption and support emission reduction strategies.

A wide array of methods, tools, and practices have been employed and recommended to address climate change, and among these, AI stands out. AI is a crucial component for predicting and optimizing strategies aimed at reducing emissions, offering innovative solutions that align with the goals set in the Paris Agreement. It has the potential to revolutionize the existing approach to climate change mitigation by providing new tools and insights, ultimately assisting in the

realization of a more sustainable future (Chen et al. 2023; Delanoë, Tchuente and Colin 2023). The following discussion addresses how AI can contribute to reducing emissions from products and within a product's supply chain with the help of two tools: a PCF Tool, providing transparency on product emissions, and a Demand Forecasting Tool, which enhances forecast accuracy, impacting various aspects of the supply chain. In addition to solving some of the aforementioned problems currently faced by users, AI impacts emission reduction on two levels (see App., Fig. 8 for a visualization of emission reduction on the different levels). Firstly, at the tool level: AI aids the PCF Tool for example by automating the matching of emission factors through AI and Deep Learning algorithms, streamlining data acquisition, and facilitating communication with suppliers. This ensures a faster and easier calculation of PCFs, enhancing transparency regarding product emissions. Furthermore, AI can identify emission hotspots within the product's supply chain, allowing for targeted and facilitated emission reduction efforts within the products supply chain for instance by sourcing from suppliers with lower emissions levels (Greenhouse Gas Protocol 2011; Rolnick et al. 2022; TfS 2022, 7, 37). At the tool level of Demand Forecasting, AI primarily leads to greater forecasting accuracy, which in turn has a direct impact on emissions by improving inventory management and preventing overproduction. With appropriate adjustments to the forecast, both improvements contribute to emission reductions (dena 2019, 27; Kemmner 2022a; Rolnick et al. 2022, 27).

Furthermore, AI can take emission reduction to another level. When the information obtained through the tools on the first level is utilized, such as the emission hotspot presentation by the PCF tool or a precise demand forecast, it is possible to optimize the entire product supply chain and reduce emissions, also with the assistance of AI. A study conducted by Rathore (2019, 32–33) highlights the considerable potential of AI to revolutionize the supply chain, with favorable environmental implications throughout the entire supply chain process. This transformative impact extends from the sourcing of raw materials to supplier evaluation, manufacturing,

distribution, and disposal. AI contributes to these advancements through functions such as real-time monitoring, compliance validation using AI-powered document analysis, predictive analytics for anticipating supply chain disruptions, transparency enhancement via blockchain tracking, waste management by identifying inefficiencies, and supporting sustainable decision-making through analysis of complex supply chain data. Therefore, the subsequent section delves into a thorough analysis of various steps within the supply chain to explore how optimizing each step can impact product emissions (see App., Fig. 9 for a visualization of the supply chain steps described below). At the beginning of the supply chain, AI and ML play crucial roles in enhancing sustainability standards and mitigating emissions. They achieve this by influencing product design and raw material sourcing. AI and ML contribute to designing products that are resource-efficient and rely less on carbon-intensive materials, such as cement and steel (Rolnick et al. 2022, 27–28). Furthermore, AI fosters a more sustainable design process conducive to a circular economy (Boll et al. 2022, 26). Looking ahead, ML is set to assist in the development of new eco-friendly materials. Moreover, it can enhance material efficiency, which measures the ratio of finished products to the materials procured and processed. This improvement reduces both material costs and product emissions. By incorporating generative design, ML facilitates the creation of structural products that require fewer raw materials. Moreover, emissions can increase when material requirements do not align with the demand forecast. Prolonged material storage, in some cases, can render them unusable, resulting in scrap and waste, and consequently, contributing to emissions (Kemmer 2022b; Rolnick et al. 2022, 27–28).

As part of efforts to improve sustainability within the supply chain, the next crucial phase that AI can influence is supplier management. In this phase, AI plays a valuable role in evaluating supplier data that includes environmentally friendly practices, labor standards and material quality. The data obtained enables informed decisions to be made when selecting suppliers. For instance, it is helpful in comparing the PCF of deliveries from different suppliers and also serves

as a useful tool for verifying certifications that demonstrate suppliers' compliance with sustainability standards. This validation process ensures that the company's sustainability policies are adhered to without introducing subjective bias (Rathore 2019, 32–33).

After material selection and the delivery of different product parts by suppliers, the production process begins. Here, AI offers several options for emission reduction. Production often requires substantial energy. AI can optimize factories to electrify industrial processes using low-carbon energy while enhancing energy efficiency, thus mitigating emissions resulting from energy consumption. Additionally, as previously mentioned, a more accurate demand forecast can reduce overproduction. This is particularly advantageous for products with short lifespans, as avoiding unnecessary disposal can lead to significant emission reductions. ML indirectly contributes to this by enabling predictive maintenance in the production process. By identifying machines on the verge of failure before producing damaged products, production waste can be minimized (Chen et al. 2023; Rolnick et al. 2022). Furthermore, processes can be optimized and automated with the help of AI, enhancing efficiency potential, precision, system efficiency and reducing scrap rates (dena 2019). A study by Delanoë, Tchuente et al. (2023, 3) also confirms this for the iron and steel industry. With the help of extreme learning machines, a ML algorithm, they found that production capacity and energy efficiency are essential drivers of carbon emission reduction.

Following the production process, AI's influence extends into logistics. It allows for the optimization of transportation routes by considering various factors such as traffic patterns, road conditions, and weather. This optimization can result in shorter travel times, enhanced fuel efficiency, and consequently, a reduction in emissions. Additionally, AI facilitates more efficient management of vehicle fleets. Utilizing predictive maintenance, AI can forecast maintenance needs and refueling requirements, ultimately reducing downtime and fuel consumption (Chen et al. 2023, 2538). When electric vehicles are involved, AI plays a central role in minimizing

energy consumption by selecting cost-effective route profiles and Bayesian regression techniques can predict necessary energy consumption (Delanoë, Tchente and Colin 2023, 3).

Besides transportation, storage of products and materials within the supply chain is a significant driver of emissions. The more products are stored and unutilized due to lower demand or over-production, the greater the emissions bound within these warehouses. These emissions stem from various factors, including product handling and the energy required for warehouse operations. Therefore, reducing the quantity of unused products could lead to not only cost savings but also reductions in energy consumption, material usage, and, consequently, emissions (Harvard Business Review 2011). Kemmer (2022a) states that each percentage point reduction in inventory could potentially reduce the carbon footprint by 5-9.9%. Thus, an accurate demand forecast, as emphasized, holds substantial and sustainable potential for emissions reduction.

The preceding discussion underscores the substantial potential of AI in reducing emissions within product supply chains. However, the research reveals a noticeable gap: while the literature qualitatively emphasizes emission reduction possibilities throughout various supply chain steps, there is a distinct absence of robust quantitative data on this potential.

4 CASE STUDY OF CARBON COSTS IN THE METAL SECTOR

4.1 Description of the case

The forthcoming case study focuses on a detailed examination of a product from the metal industry, analyzing emissions generated from cradle to customer and outlining the associated costs imposed on the producer due to existing regulations. The main objective is to answer the question of what the carbon costs of a product from the metals sector are under current regulations today and in the future, and how these will change if emissions can be reduced at certain stages of the supply chain. The data foundation for the case study is derived from an automotive supplier that has calculated the PCFs for its product range. The product under consideration is a purchased component in the automotive industry, essential for every car and therefore

produced in significant quantities. The product weighs around 4 kg and consists mainly of steel components, lubricating oil and small plastic parts. The PCF of the product totals 19.64 kgCO₂e. A breakdown of emission shares by different scopes is provided in the Appendix, Fig. 10.

This case was chosen due to its representativeness of a hard-to-abate industry, where product material composition and production processes notably contribute to carbon costs. Automotive components often have substantial proportions of steel, and the production involves electricity and gas, all of which are regulated and priced under current regulations. Additionally, the majority of the supply chain steps occur in Europe, emphasizing a regional focus in this case study. In the examined study, ~70% of the products emissions fall under the EU ETS.

4.2 Assumptions and calculation procedure

To manage the complexity of this case study specific assumptions have been strategically chosen to ensure a focused and feasible analysis of carbon costs and emission reductions.

For the analysis, influential regulations are examined, with a focus on emissions pricing in the EU ETS and CBAM. The price is determined by EUA costs, averaging 86.19€/tCO₂ in 2023 (EEX 2022). Considering current regulations, the study assumes only EU ETS and CBAM levies, excluding national laws like nETS. Furthermore, no free allowances within the EU ETS are considered, aligning with the expected phase-out and emphasizing the theoretical costs companies would bear, both presently and projected for 2030 (EEX 2022; European Commission 2022; European Commission 2023a).

The study further assumes total cost-pass-through across the supply chain, indicating that all suppliers, including electricity and lubricating oil producers, transfer the CO₂ levies they pay for their products (e.g., steel, electricity, lubricating oil) directly to the final product producer, resulting in additional carbon costs for the product producer. The focus of the case study is solely on the pure carbon costs, excluding offsetting from process redesigns or cost savings from supply chain optimizations that intend to reduce emissions.

With a focus on calculation assumptions, the following outlines assumptions for the three regulated components in the PCF study. Emissions across the entire supply chain are considered, but the calculation of carbon costs specifically involves components subject to current EU ETS and CBAM regulations, including materials like steel and lubricating oil, along with energy generated for production. Other materials are excluded due to their minimal impact on costs (see App., Fig. 11 for emission data at relevant supply chain steps).

For steel components, the study derives costs by examining each part of the final product made of steel and summing up emissions from their production. Additionally, it considers material loss in steel component production, assuming that scrap generated during production can be repurposed for other products, redistributing emissions from scrap to other items.

For electricity, the regulations govern the energy requirements for the production of subcomponents and final assembly. However, they target emissions from electricity generation, not emissions from electricity use. Therefore, the calculation utilizes relevant emission factors from the Ecoinvent database, as electricity generation was not included in the original PCF study, since these don't count as product emissions, but are still crucial for the study, as a cost pass-through is assumed (Bourgault, Minas and Müller 2022; Meili 2022).

For lubricating oil production, the study estimates emissions as the PCF study does not provide a detailed breakdown of emissions along the supply chain. Consequently, the calculation is based on the total emission value specified by the supplier.

Overall, the study adopts a conservative approach, not considering future ETS developments such as the expansion of the EU ETS II to other sectors such as transportation or national systems, potentially leading to increased emissions in product pricing in the future (German Environment Agency 2021).

A final assumption was made regarding the examined emission reduction in the calculation. Due to the absence of quantitative data in the literature review on the extent to which AI can

reduce emissions, the assumed emission reductions in the analysis are hypothetical. Assuming businesses can cut emissions using AI in supply chain steps, the analysis explores reductions from 0-30%, without specifying these numbers for particular use cases.

4.3 Results presentation

Following an overview of the case, assumptions, and calculations, the focus turns to carbon costs. Initially, the current carbon costs for the product are presented, considering the likely cost trajectory for 2030 and emphasizing the role of EUA prices. Under specified assumptions, and a current EUA price of 86.19€/tCO₂ carbon costs result in 1.25€ per unit for the analyzed product. These carbon costs per product encompass charges for various components, with material fees constituting ~60% of the costs at 0.75€. Within material fees, ~93% represent charges for steel materials and ~7% for lubricating oil. Component production contributes ~23% to the overall carbon costs, and product manufacturing is accounting for ~17%. Figure 1 shows an illustration of these costs. These costs have a significant economic viability impact for the manufacturer as typical EBIT margins of automotive suppliers are at ~5% and yearly production volumes are high (Placek 2023; Sarvankar and Yewale 2019). For instance, with an annual production of 1 mn units, additional costs in 2023 due to emission charges would amount to ~1.25 mn€.

Before examining the likely development of carbon costs in 2030, the factors influencing future costs are outlined. Key factors include the anticipated increase in the EUA price and the evolution of the electricity mix. A study sponsored by the German Federal Ministry of Education and Research, conducted in November 2022 as part of the "Kopernikus Project," surveyed organizations on EUA price forecasts. Five of six models estimated prices between 120€/tCO₂ and 160€/tCO₂, averaging ~140€/tCO₂ for 2030 (Pahle et al. 2022).

The shift to a greater proportion of renewable energy in the electricity mix is beneficial for reducing carbon costs by lowering emissions linked to electricity production. To meet the "Fit

for 55" target of a 55% emissions cut by 2030, the EU Commission aims for renewable energy to constitute 42.5-45% of the EU's energy consumption. The associated emission intensity of electricity requires faster decarbonization, aiming for an emission factor of 118gCO₂e/kWh by 2030 (European Environment Agency 2023). To calculate the emissions generated by electricity in 2030, forecasts of the emission factors of the electricity generation were used for the individual countries that produce electricity for the production of the product (IEA 2021, 43; IRENA and the European Commission, 69; SHURA Energy Transition Center 2020, 11). This shift in the electricity mix results in a 50% reduction in emissions from electricity production by 2030. Despite progress, the average emission factor in the example remains at 270gCO₂e/kWh in the EU by 2030, indicating that further emission reductions are possible with the fulfillment of political targets for expanding renewable energies.

Assuming an average EUA price of 140€/tCO₂ and a higher share of renewable energy in the electricity mix by 2030 (based on the emission factor of 270gCO₂e/kWh), the carbon costs in 2030 amount to 1.62€ per product. The composition of carbon costs shifts due to changes in the electricity mix, with a larger share attributable to material charges, as fewer levies are paid for electricity during production. Consequently, the ratio becomes 75% for material fees, 20% for supplier production costs, and 5% for the final product's production. Compared to 2023, costs per product are expected to increase by ~37 cents by 2030, with EUA prices increasing by ~54 €/tCO₂ and electricity generation costs decreasing due to changes in the energy mix.



Figure 1: Carbon costs for the analyzed product in years 2023 and 2030

The following section demonstrates the impact of supply chain emission reduction on the carbon costs of the studied product. On the one hand, the effects of hypothetical emission reductions in the supply chain are examined, as explained in the assumptions. On the other hand, the influence of alternative steel production methods on emissions and costs is illustrated.

The assumed emission reductions range from 0-30% in relevant supply chain steps, achieved through measures like improving energy efficiency, selecting low-emission suppliers, or other options described in Chapter 3. Results show that emission reduction and cost reduction are directly proportional: A 5% reduction in emissions leads to a corresponding 5% reduction in costs. Savings per product range from 6-37 cents in 2023 to 8-48 cents in 2030 for a 5-30% emission reduction, highlighting the growing impact of reductions with rising EUA prices.

The following section further investigates the impact of emission reductions, specifically in the material production step, focusing on steel as the most significant contributor to carbon costs. Traditional steel production, utilizing coal in blast furnaces, yields substantial emissions, while alternative methods like natural gas (NG DR) or hydrogen-based production (H₂ DR) show potential reductions. Using hydrogen from fossil fuels (blue hydrogen) cuts emissions by 95%, while green hydrogen from renewable sources achieves nearly 99% reduction (LBST 2022). Applied to the analyzed product in 2030, with an EUA price of 140€/tCO₂, it results in cost reductions of 42%, 67%, and 69% for NG DR, H₂ DR (blue), and H₂ DR (green), respectively, leading to cost savings of up to 1.12€ (See App., Fig. 12). Table 1 presents a comparison of costs for the years 2023 and 2030 and all emission reduction scenarios described above.

		Emission reduction in %							
		No emission reduction	Hypothetical reduction values in the supply chain (e.g. through AI)				Reduction through alternative steel production processes		
			5%	15%	30%	NG DR	H ₂ DR (blue)	H ₂ DR (green)	
Year	EU ETS Price	0%	5%	15%	30%	~42%	~67%	~69%	
2023	86.19 €	1.25 €	1.19 €	1.06 €	0.88 €	0.72 €	0.42 €	0.39 €	
2030	140.00 €	1.62 €	1.54 €	1.38 €	1.14 €	0.94 €	0.54 €	0.50 €	

Table 1: Carbon costs of the analyzed product with variable EU ETS price and level of emission reduction in the supply chain

4.4 Discussion of the results

Analyzing the results reveals that product material composition and production, the evolution of EUA prices and changes in the electricity mix are key determinants for companies' future carbon costs. The growing potential for emission reductions is also evident. Subsequent sections detail the impact of these factors to provide a comprehensive presentation of the results. For a product of the automotive industry, often predominantly composed of steel, the majority of carbon costs emanate from material expenses, particularly steel-based materials. Producing CO₂-free steel in the near future could therefore result in a significant reduction in carbon costs for products heavily reliant on steel, with a potential reduction of 69% in the examined case. Concerning the trends in the EUA price and electricity mix composition, a contrasting dynamic unfolds. Despite the anticipated rise in EUA prices, the costs do not increase as sharply due to a higher proportion of renewable energy in the electricity mix, resulting in reduced charges for energy production and, consequently, lower overall costs compared to the current electricity mix. Table 2 illustrates how costs in 2030, factoring in the 2030 electricity mix, would be approximately ~20% lower per product than under the current electricity mix.

Table 2: Carbon costs of the analyzed product with variable EU ETS price, level of emission reduction in the supply chain and electricity mix

	EU ETS Price ↓ Year of electricity generation →	Emission reduction in %											
		0%		5%		10%		20%		30%		40%	
		2023	2030	2023	2030	2023	2030	2023	2030	2023	2030	2023	2030
2023	86.19 €	1.25 €	1.00 €	1.19 €	0.95 €	1.13 €	0.90 €	1.00 €	0.80 €	0.88 €	0.70 €	0.75 €	0.60 €
2030	140.00 €	2.03 €	1.62 €	1.93 €	1.54 €	1.83 €	1.46 €	1.63 €	1.30 €	1.42 €	1.14 €	1.22 €	0.97 €

Examining EUA price development reveals a proportional rise in costs with increasing EUA prices. For every 1€ increase in the EUA price, carbon costs for this product under the current mix increase by ~1.5 cents. This impact lessens with a higher share of renewable energies in the electricity mix. With the future mix, costs only rise by 1.2 cents for each euro increase in the EUA price. This trend suggests that as the share of renewables increases, the effect of EUA

price hikes will be less pronounced (See App., Fig. 13).

The results can be used to draw conclusions about the emission reductions as well. The potential of (AI-driven) emission reduction directly reflects in costs. If companies successfully reduce emissions in the regulated steps of their product supply chain, proportional cost savings accompany the reduction in emissions. Achieving a 5% reduction in emissions within the relevant supply chain steps results in a direct 5% reduction in carbon costs for the company. This observation also applies for other products with diverse compositions, provided that carbon cost calculation is exclusively based on a uniform price for all incurred emissions, such as EU ETS and CBAM. However, a correlation with the EUA prices emerges. A higher EUA price amplifies the impact of the same percentage of emission reductions on cost savings. While at the current EUA price of 86.19€/tCO₂ and a 5% reduction in emissions, 30 cents per product can be saved, the savings increase to 49 cents at a price of 140€/tCO₂ and to 56 cents at 160€/tCO₂.

All these findings reaffirm the underlying concept of carbon-pricing systems like the EU ETS: Emitting becomes costlier, prompting companies to strategize emission reduction for sustained competitiveness.

5 CONCLUSION

The study aimed to uncover costs incurred by the metal sector due to product-related emissions and explored how AI can target these costs for reduction. Examining current climate regulations, with a focus on carbon pricing mechanisms like the EU ETS system, unveiled their broadening influence, reaching national (e.g., nETS) and international levels (CBAM) as well as additional areas of impact (EU ETS II). Phasing out free allowances and rising prices due to a shortage also indicate an increasing influence of carbon costs on businesses.

To mitigate financial penalties, companies must reduce emissions, and AI-assisted tools like PCF and Demand Forecasting prove effective. These methods serve as preparations for further

emission reductions in the supply chain. While qualitative literature extensively discusses AI's potential, quantitative data on the magnitude of these reductions remains scarce.

The results of the case study confirms the theoretical findings from the regulatory analysis: as soon as regulations take full effect and EUA prices rise, carbon costs will have a significant impact on businesses. However, counteracting trends, such as the evolving electricity mix driven by political goals for increased renewable energy shares, a shift toward eco-friendly steel production, along with the potential for AI-assisted emission reductions, offer potential mitigations. The study emphasizes that proactively initiating emission reduction measures in the supply chain already now, can strategically position companies to mitigate additional costs in future, given the increasing cost-effectiveness of achieving equivalent emission reductions with rising EUA prices.

Although the results of the case study are specific to the product examined, they can be applied to other products with a similar material composition and supply chain, taking into account the assumptions made. Therefore, in conclusion, the findings of this study should provide a wide spectrum of decision makers with a guide to understanding the dynamics of regulatory developments regarding carbon economics. It should additionally underscore the importance of adept navigation for sustained competitiveness, serving as a foundation for informed decisions on sustainable business practices and as an incentive for action.

Further studies are essential to enhance transparency and gain a comprehensive understanding of the emissions and costs associated with diverse products. This should include products from various sectors with different structures and supply chains. Research should also emphasize the explored AI methods, uncovering their quantitative potentials. This approach will empower businesses to identify and implement the most effective strategies for reducing both emissions and costs.

REFERENCES

- Abolghasemi, Mahdi, Eric Beh, Garth Tarr, and Richard Gerlach. “Demand Forecasting in Supply Chain: The Impact of Demand Volatility in the Presence of Promotion.” *Computers & Industrial Engineering* 142 (2020): 106380. doi:10.1016/j.cie.2020.106380. <https://www.sciencedirect.com/science/article/pii/S0360835220301145>.
- Armstrong, J. S., and K. Green. “Methodology Tree of Forecasting Methods by Knowledge Source.” 2014.
- Bock, Carsten, and Christian Böhler. “How to Calculate the Carbon Footprint of Your Products.” Updated November 28, 2023. Accessed November 28, 2023. <https://www.roland-berger.com/en/Insights/Publications/How-to-calculate-the-carbon-footprint-of-your-products.html>.
- Boll, Susanne, Markus Schnell, Michael Dowling, Wolfgang Faisst, Olga Mordvinova, Alexander Pflaum, and Martin Rabe et al. “Mit Künstlicher Intelligenz Zu Nachhaltigen Geschäftsmodellen – Nachhaltigkeit Von, Durch Und Mit KI.” *Whitepaper aus der Plattform Lernende Systeme*, 2022. Accessed September 1, 2023. https://www.plattform-lernende-systeme.de/files/Downloads/Publikationen/AG4_WP_KI_und_Nachhaltigkeit.pdf.
- Bourgault, G., N. Minas, and J. Müller. “Documentation of Scope 2 and 3 Separation of Electricity GHG Emissions in Ecoinvent V3.9.1.” *Ecoinvent*, 2022.
- Chen, Lin, Zhonghao Chen, Yubing Zhang, Yunfei Liu, Ahmed I. Osman, Mohamed Farghali, and Jianmin Hua et al. “Artificial Intelligence-Based Solutions for Climate Change: A Review.” *Environmental Chemistry Letters* 21, no. 5 (2023): 2525–57. doi:10.1007/s10311-023-01617-y. <https://link.springer.com/article/10.1007/s10311-023-01617-y>.
- Commission to the European Parliament and the Council, ed. *REPORT from the COMMISSION to the EUROPEAN PARLIAMENT and the COUNCIL on the Functioning of the European Carbon Market in 2021 Pursuant to Articles 10(5) And 21(2) Of Directive 2003/87/EC (As*

- Amended by Directive 2009/29/EC and Directive (EU) 2018/410*., 2022. Accessed August 29, 2023. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0516>.
- DEHSt. “Factsheet: Auktionsierung Im EU-ETS.” 2023a. Accessed September 11, 2023. https://www.dehst.de/SharedDocs/downloads/DE/publikationen/factsheets/factsheet_Auktionierung.pdf?__blob=publicationFile&v=5.
- DEHSt. “National Emissions Trading.” Updated September 5, 2023b. Accessed September 5, 2023. https://www.dehst.de/EN/national-emissions-trading/understanding-national-emissions-trading/understanding-nehs_node.html.
- Delanoë, Paul, Dieudonné Tchente, and Guillaume Colin. “Method and Evaluations of the Effective Gain of Artificial Intelligence Models for Reducing CO2 Emissions.” *Journal of Environmental Management* 331 (2023): 117261. doi:10.1016/j.jenvman.2023.117261. <https://www.sciencedirect.com/science/article/pii/S030147972300049X>.
- Deutsche Energie-Agentur. “Künstliche Intelligenz Für Die Integrierte Energiewende: Einordnung Des Technologischen Status Quo Sowie Strukturierung Von Anwendungsfeldern in Der Energiewirtschaft.” *Deutsche Energie-Agentur*, 2019. Accessed October 23, 2023. https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/dena-ANALYSE_Kuenstliche_Intelligenz_fuer_die_integrierte_Energiewende.pdf.
- European Commission. “The EU Emissions Trading System (EU ETS).” 2016. Accessed August 30, 2023. https://climate.ec.europa.eu/system/files/2016-12/factsheet_ets_en.pdf.
- European Commission. “Carbon Border Adjustment Mechanism Factsheet.” 2023a. Accessed September 11, 2023. <https://taxation-customs.ec.europa.eu/system/files/2023-05/20230510%20CBAM%20factsheet.pdf>.
- European Commission. “Guidance Document on CBAM Implementation for Installation Operators Outside the EU.” 2023b. Accessed September 11, 2023.

customs.ec.europa.eu/system/files/2023-08/CBAM%20Guidance_non-EU%20installations.pdf.

European Commission. “Delivering the European Green Deal.” Updated August 29, 2023c. Accessed August 29, 2023. https://climate.ec.europa.eu/eu-action/european-green-deal/delivering-european-green-deal_en.

European Commission. “Revision for Phase 4 (2021-2030).” Updated August 31, 2023d. Accessed August 31, 2023. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/revision-phase-4-2021-2030_en.

European Commission. “Ecodesign for Sustainable Products.” Updated November 17, 2023e. Accessed November 17, 2023. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en.

European Council. “European Green Deal.” Updated November 17, 2023. Accessed November 17, 2023. <https://www.consilium.europa.eu/en/policies/green-deal/>.

European Energy Exchange AG. “EEX EUA Primary Auction Spot - Download.” Updated September 11, 2023. Accessed September 11, 2023. <https://www.eex.com/en/market-data/environmental-markets/eua-primary-auction-spot-download>.

European Environment Agency. “Greenhouse Gas Emission Intensity of Electricity Generation in Europe.” Updated November 16, 2023. Accessed November 16, 2023. <https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1?activeAccordion=ecdb3bcf-bbe9-4978-b5cf-0b136399d9f8>.

European Parliament. “Die Antworten der EU auf den Klimawandel.” Accessed November 22, 2023. https://www.europarl.europa.eu/news/de/headlines/society/20180703STO07129/die-antworten-der-eu-auf-den-klimawandel?&at_campaign=20234-

Green&at_medium=Google_Ads&at_platform=Search&at_crea-
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ca-
tion=DE&gclid=Cj0KCQiA6vaqBhCbARIsACF9M6lgMzc6F3YaGC7yMU2gLMxGaLY
gX3RxeC6owbcCBPXoPqn7-B6-ZXYaAi71EALw_wcB.

European Parliament. “Klimaschutz: Einigung über ehrgeizigeren EU-Emissionshandel (ETS).” News release. December 19, 2022. Accessed November 20, 2023. <https://www.europarl.europa.eu/news/de/press-room/20221212IPR64527/klimaschutz-einigung-uber-ehrgeizigeren-eu-emissionshandel-ets>.

European Union. “Fit for 55: Reform of the EU Emissions Trading System.” Updated September 13, 2023. Accessed September 13, 2023. <https://www.consilium.europa.eu/en/infographics/fit-for-55-eu-emissions-trading-system/>.

German Environment Agency. “Introduction of an Emissions Trading System for Buildings and Road Transport in the EU.” 2021. Accessed September 19, 2023. https://www.umweltbundesamt.de/sites/default/files/medien/479/dokumente/2022_02_08_factsheet_ets_2_final_engl_bf.pdf.

Greenhouse Gas Protocol. “Product Life Cycle Accounting and Reporting Standard.” 2011. Accessed September 26, 2023. https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard-EReader_041613_0.pdf.

Harvard Business Review. “Excess Inventory Wastes Carbon and Energy, Not Just Money.” Updated July 23, 2014. Accessed November 5, 2023. <https://hbr.org/2011/08/excess-inventory-wastes-carbon>.

Hottenroth, Heidi, Bettina Joa, and Mario Schmidt. “Carbon Footprints Für Produkte: Handbuch Für Die Betriebliche Praxis Kleiner Und Mittlerer Unternehmen.” Accessed October 11, 2023. <https://businesspf.hs->

pforzheim.de/fileadmin/user_upload/uploads_redakteur/Forschung/INEC/Dokumente/Hottenroth_et_al_Carbon_Footprints_fuer_Produkte_web.pdf.

International Carbon Action Partnership. “Emissions Trading Worldwide 2023 Status Report.” 2023. Accessed July 24, 2023. https://icapcarbonaction.com/system/files/document/ICAP%20Emissions%20Trading%20Worldwide%202023%20Status%20Report_0.pdf.

International Energy Agency. “The Role of China's ETS in Power Sector Decarbonisation.” 2021. Accessed November 19, 2023. https://iea.blob.core.windows.net/assets/61d5f58d-4702-42bd-a6b6-59be3008ecc9/The_Role_of_China_ETS_in_Power_Sector_Decarbonisation.pdf.

International Organization for Standardization. *DIN EN ISO 14067: Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification (ISO 14067:2018)*. 2019.

IRENA and the European Commission. “Renewable Energy Prospects for the European Union: Preview for Policy Makers.” Accessed November 19, 2023. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Feb/IRENA_REmap_EU_2018.pdf.

Kemmner, Andreas. “Reduction in Inventory Brings CO2 Reduction.” *Abels & Kemmner*, August 1, 2022a. Accessed November 1, 2023. <https://ak-online.de/en/2022/08/reduction-in-inventory-brings-co2-reduction/>.

Kemmner, Andreas. “Improvement of Material Efficiency Also Reduces the Carbon Footprint.” *Abels & Kemmner*, August 8, 2022b. Accessed November 5, 2023. <https://ak-online.de/en/2022/08/material-efficiency-reduces-carbon-footprint/>.

Ludwig-Bölkow-Systemtechnik. “Emissionsfreie Stahlerzeugung: Metastudie Zu Den Technischen, Technologischen Und Wirtschaftlichen Parametern Für Die Umstellung Der Deutschen Stahlindustrie Auf Eine Emissionsarme Stahlproduktion Auf Basis Von Grünem

- Wasserstoff.” 2022. Accessed November 26, 2023. https://lbst.de/wp-content/uploads/2022/04/2022-03-30-HySteel-LBST_Emissionsfreie_Stahlerzeugung.pdf.
- Meili, C. “Life Cycle Inventories of Crude Oil and Natural Gas Extraction.” *Ecoinvent*, 2022.
- Pahle, Sitarz, Osorio, and Ecologic. “The EU-ETS Price Through 2030 and Beyond: A Closer Look at Drivers, Models and Assumptions: Input Material and Takeaways from a Workshop in Brussels.” 2022. Accessed November 15, 2023. https://ariadneprojekt.de/media/2023/01/Ariadne-Documentation_ETSWorkshopBruessel_December2022.pdf.
- Petropoulos, Fotios, Daniele Apiletti, Vassilios Assimakopoulos, Mohamed Zied Babai, Devon K. Barrow, Souhaib Ben Taieb, and Christoph Bergmeir et al. “Forecasting: Theory and Practice.” *International Journal of Forecasting* 38, no. 3 (2022): 705–871. doi:10.1016/j.ijforecast.2021.11.001. <https://www.sciencedirect.com/science/article/pii/S0169207021001758>.
- Placek, Martin. “Global Auto Supplier Industry's EBIT Margin 2014-2021.” Updated November 24, 2023. Accessed November 24, 2023. <https://www.statista.com/statistics/1032448/global-auto-supplier-industry-ebit-margin/>.
- Publications Office of the European Union. “DIRECTIVE (EU) 2023/959.” *Official Journal of the European Union*, 10.05.2023. Accessed September 19, 2023. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023L0959>.
- Rathore, Bharati. “Artificial Intelligence in Sustainable Fashion Marketing: Transforming the Supply Chain Landscape.” *Eduzone: International Peer Reviewed/Refereed Multidisciplinary Journal* 8, no. 2 (2019): 25–38. <https://eduzonejournal.com/index.php/eiprmj/article/view/363>.
- Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’). European Climate Law.

- European Parliament. July 9, 2021. Accessed August 29, 2023. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119>.
- Rolnick, David, Priya L. Donti, Lynn H. Kaack, Kelly Kochanski, Alexandre Lacoste, Kris Sankaran, and Andrew Slavin Ross et al. “Tackling Climate Change with Machine Learning.” *ACM Computing Surveys* 55, no. 2 (2022): 1–96. doi:10.1145/3485128.
- Sarvankar, Shruti Ganesh, and Sanket Nandaram Yewale. “Additive Manufacturing in Automobile Industry.” 2019. Accessed November 24, 2023. https://www.academia.edu/38718198/Additive_Manufacturing_in_Automobile_Industry.
- SHURA Energy Transition Center. “Optimum Electricity Generation Capacity Mix for Turkey Towards 2030.” 2020. Accessed November 19, 2023. <https://shura.org.tr/wp-content/uploads/2020/07/SHURA-2020-07-Optimum-Electricity-Generation-Capacity-Mix-for-Turkey-Towards-2030.pdf>.
- Swaminathan, Kritika, and Rakesh Venkitasubramony. “Demand Forecasting for Fashion Products: A Systematic Review.” *International Journal of Forecasting*, 2023. doi:10.1016/j.ijforecast.2023.02.005. <https://www.sciencedirect.com/science/article/pii/S0169207023000134>.
- Together for Sustainability. “The Product Carbon Footprint Guideline for the Chemical Industry.” 2022. Accessed November 2, 2023. https://www.tfs-initiative.com/app/uploads/2023/04/TfS_PCF_guidelines_2022_English.pdf.
- Umwelttechnik BW GmbH. “Treibhausgas-Bilanzierung: Ergebnisse Der Online-Umfrage / Zeitraum Februar Bis November 2022.” 2023. Accessed October 11, 2023. https://www.scope3transparent.de/wp-content/uploads/2023/04/S3T_Umfrageergebnisse_barrierefrei-optimiert_UA.pdf.
- UNFCCC. “Adoption of the Paris Agreement - Paris Agreement Text English.” 2015. Accessed August 29, 2023. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

- Wang, Shanshan, Weifeng Wang, and Hongqiang Yang. "Comparison of Product Carbon Footprint Protocols: Case Study on Medium-Density Fiberboard in China." *International journal of environmental research and public health* 15, no. 10 (2018). doi:10.3390/ijerph15102060.
- WBCSD. "Pathfinder Framework Guidance for the Accounting and Exchange of Product Life Cycle Emissions." 2023. Accessed September 25, 2023. https://www.carbon-transparency.com/media/b13h4b25/pathfinder-framework_report_final.pdf.
- Whelan, Tensie, and Carly Fink. "The Comprehensive Business Case for Sustainability." *Harvard Business Review*, 2016. Accessed October 3, 2023. <https://everestenergy.nl/new/wp-content/uploads/HBR-Article-The-comprehensive-business-case-for-sustainability.pdf>.
- Wissenschaftliche Dienste des Deutschen Bundestages. "Neuer EU-Emissionshandel Für Gebäude Und Straßenverkehr." 2023. Accessed September 12, 2023. <https://www.bundestag.de/resource/blob/935752/11ab46422ea31a5a3195319d5fa05f4d/WD-8-001-23-pdf-data.pdf>.

APPENDICES

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1 ABBREVIATIONS

AI	Artificial Intelligence
CBAM	Carbon Border Adjustment Mechanism
CO ₂	Carbon dioxide
CO ₂ e	CO ₂ equivalent
ETS	Emissions Trading System
EU	European Union
EU ETS	EU Emissions Trading
EUA	European Allowance
GHG	Greenhouse Gases
GWP	Global Warming Potential
H ₂ DR	Hydrogen Direct Reduction
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ML	Machine Learning
nETS	National Emissions Trading System
NG DR	Natural Gas Direct Reduction
PCF	Product Carbon Footprint

2 Figures - Theoretical Foundation

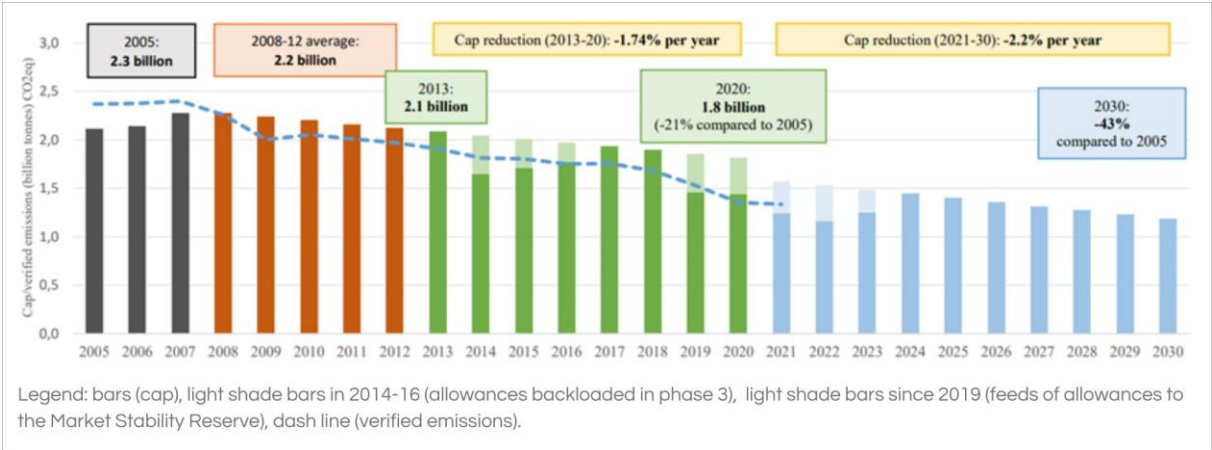


Figure 2: Emissions cap in the EU ETS, compared with verified emissions (European Commission 2022, 8)



Figure 3: Development of the gradual phase out of free EU Allowances (European Parliament 2022)

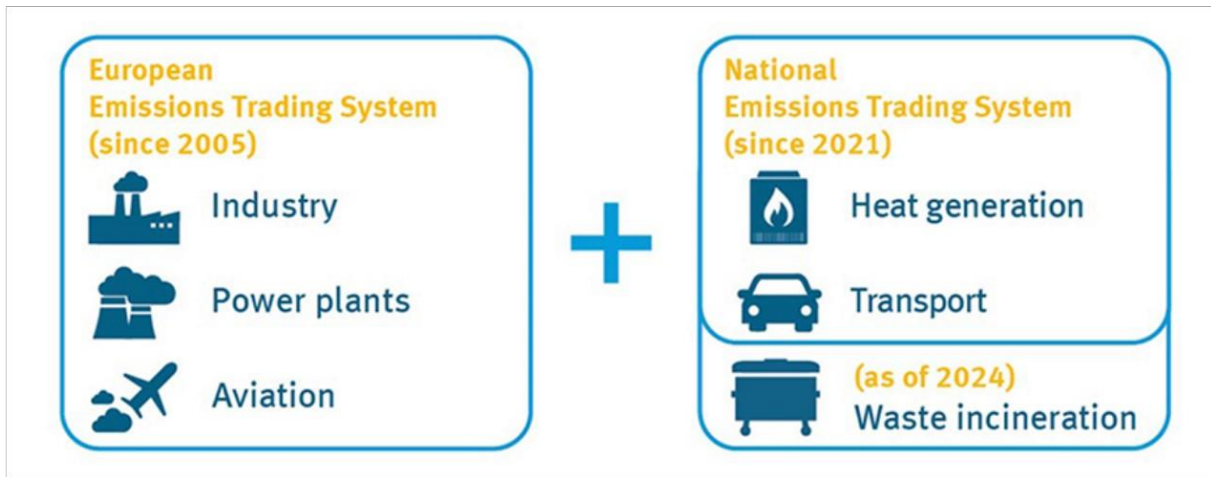


Figure 4: Comparison of EU ETS and German nETS sector coverage (DEHSt 2023b)



Figure 5: Price trend of the nETS from 2021 to 2026 (DEHSt 2023b)

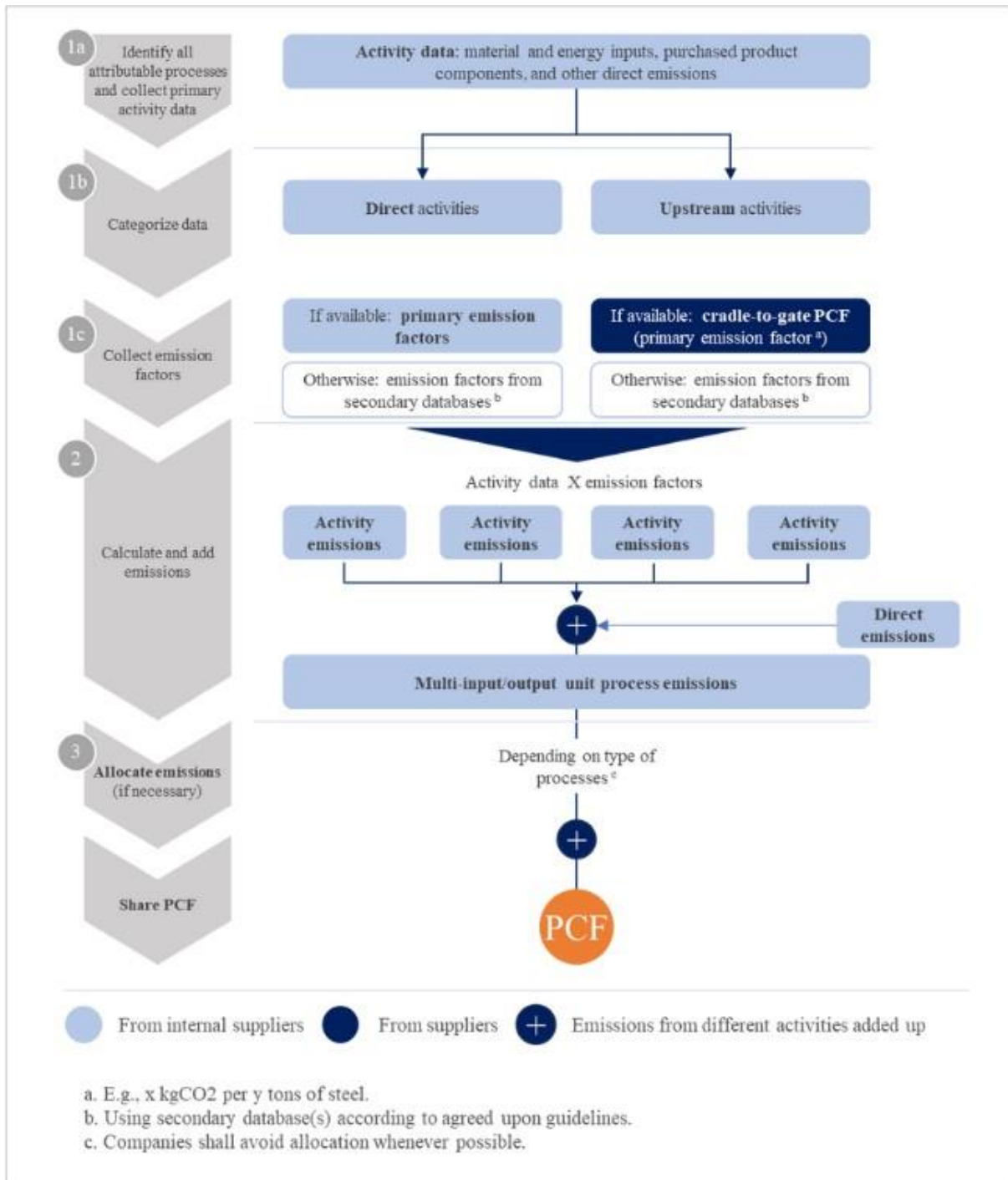


Figure 6: Overview of steps for PCF calculation (own illustration according to (WBCSD 2023, 22))

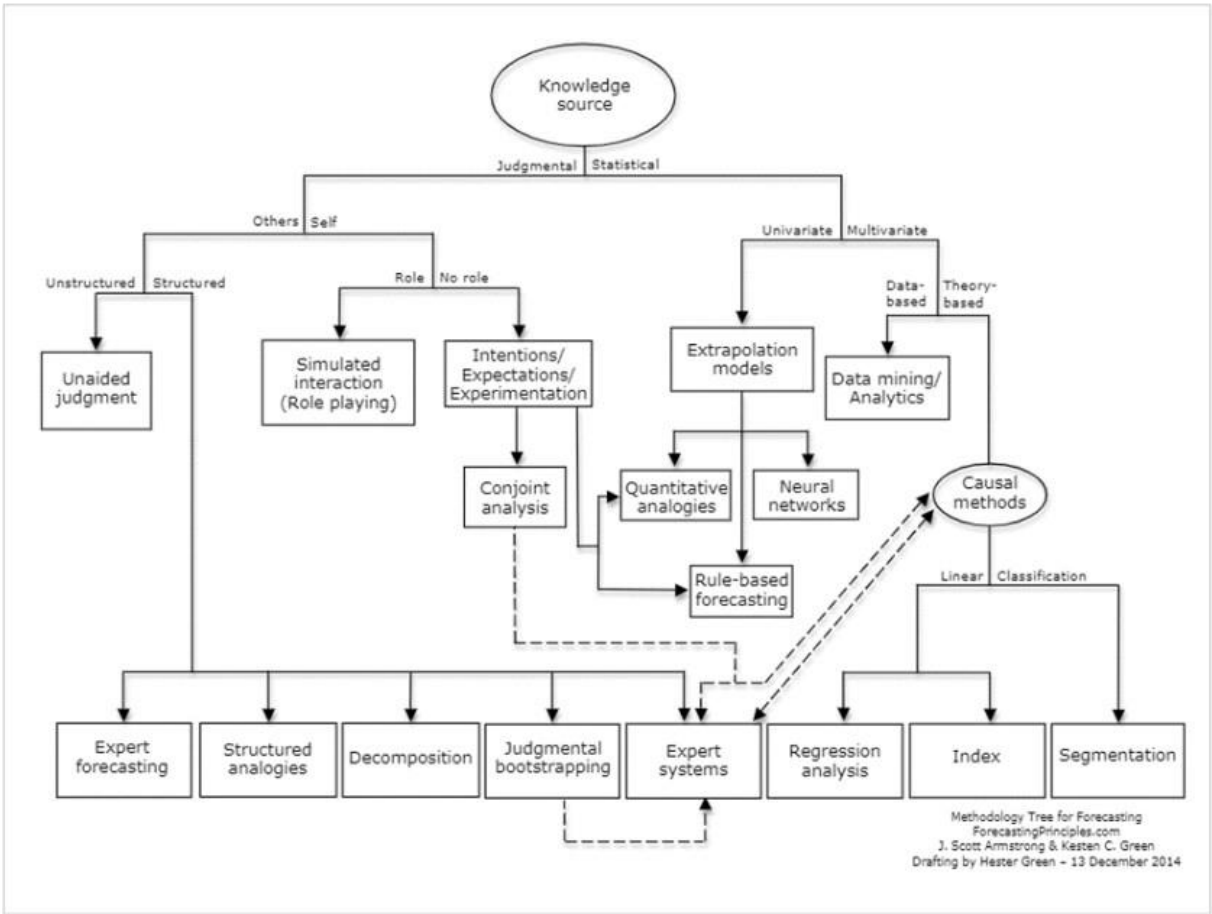


Figure 7: Methodology Tree for Forecasting (Armstrong and Green 2014)

3 FIGURES - EMISSION REDUCTION POTENTIALS THROUGH AI

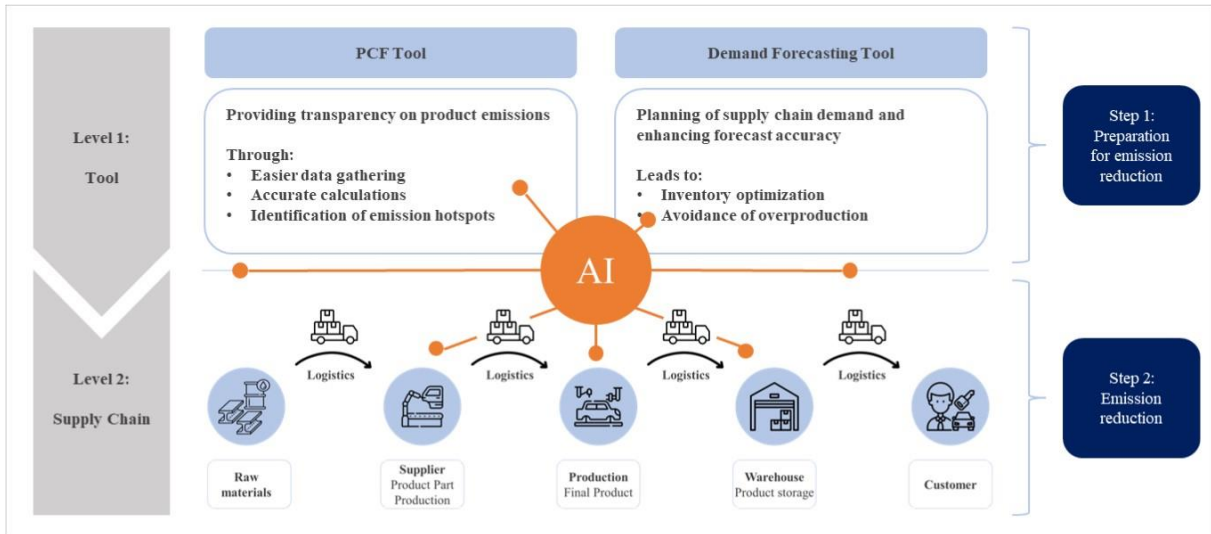


Figure 8: Levels of emission reduction (own illustration)

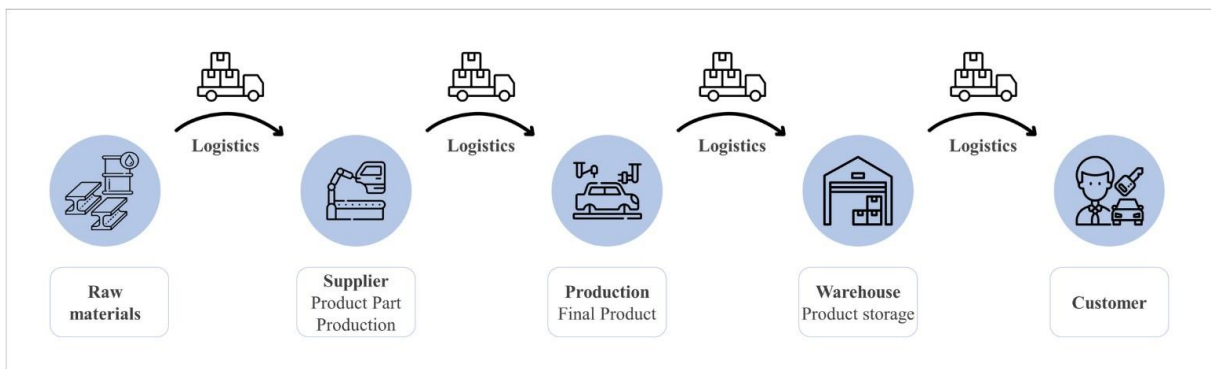


Figure 9: Steps of a supply chain (own illustration)

4 FIGURES - CASE STUDY OF CARBON COSTS IN THE METAL SECTOR

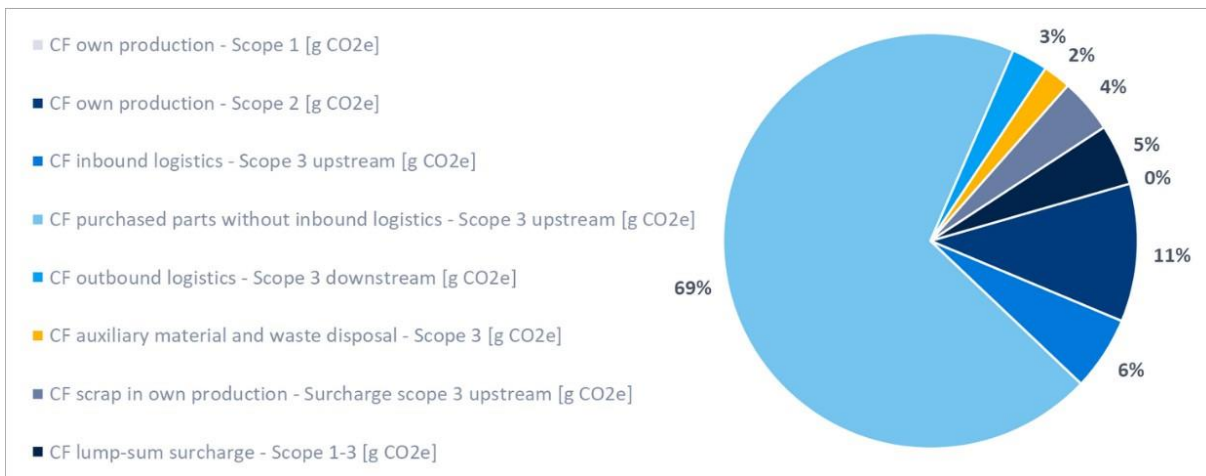


Figure 10: Breakdown of emission shares by different scope (own illustration based on company data)

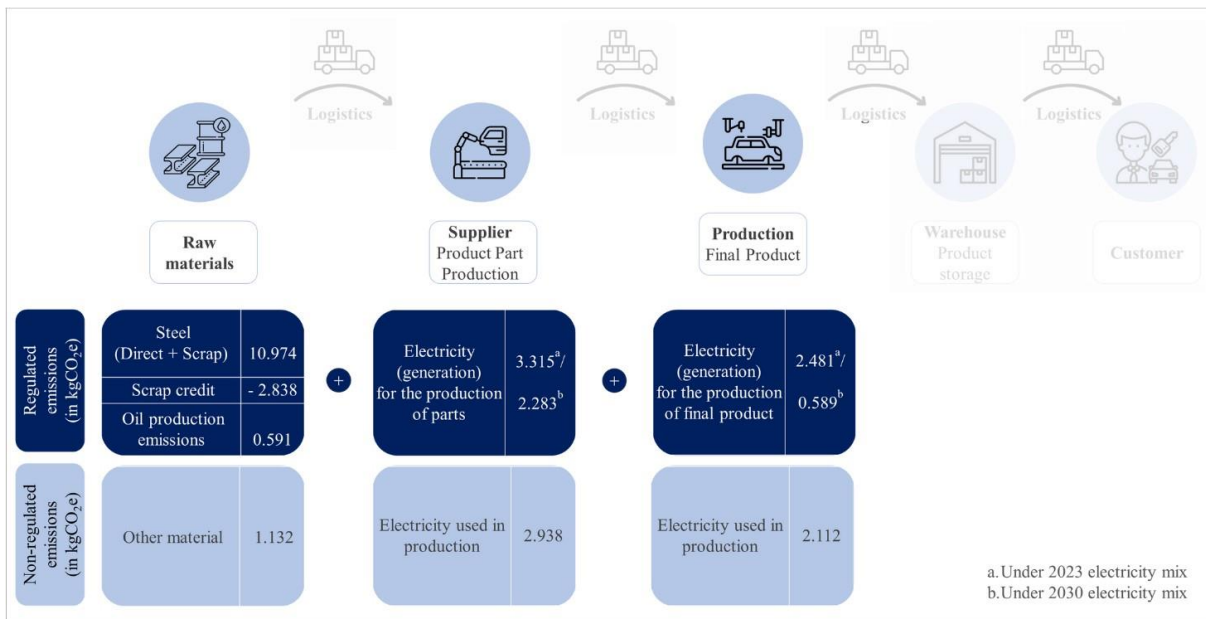


Figure 11: Emissions at relevant supply chain steps (own illustration based on company data and calculation results)

Production technology	Energy source	Reduction potential of emissions from steel production	Emissions of steel production	Carbon Costs in 2030, EUA price: 140€/tCO ₂
1 Conventional blast furnace route	Coal (fossil)	-	8.136 kgCO ₂ e	1.62€/tCO ₂
2 Natural Gas Direct reduction	Natural Gas (fossil)	Up to 60%	3.254 kgCO ₂ e	0.94€/tCO ₂ -42%
3 Hydrogen Direct reduction	Hydrogen (blue- fossil)	Up to 95%	0.407 kgCO ₂ e	0.54€/tCO ₂ -67%
	Hydrogen (green- renewable)	Up to 98%	0.130 kgCO ₂ e	0.50€/tCO ₂ -69%

-x% Cost reduction compared to conventional steel production technology

Figure 12: Impact of different steel production technologies on carbon costs (own illustration based on (LBST 2022) and calculation results)

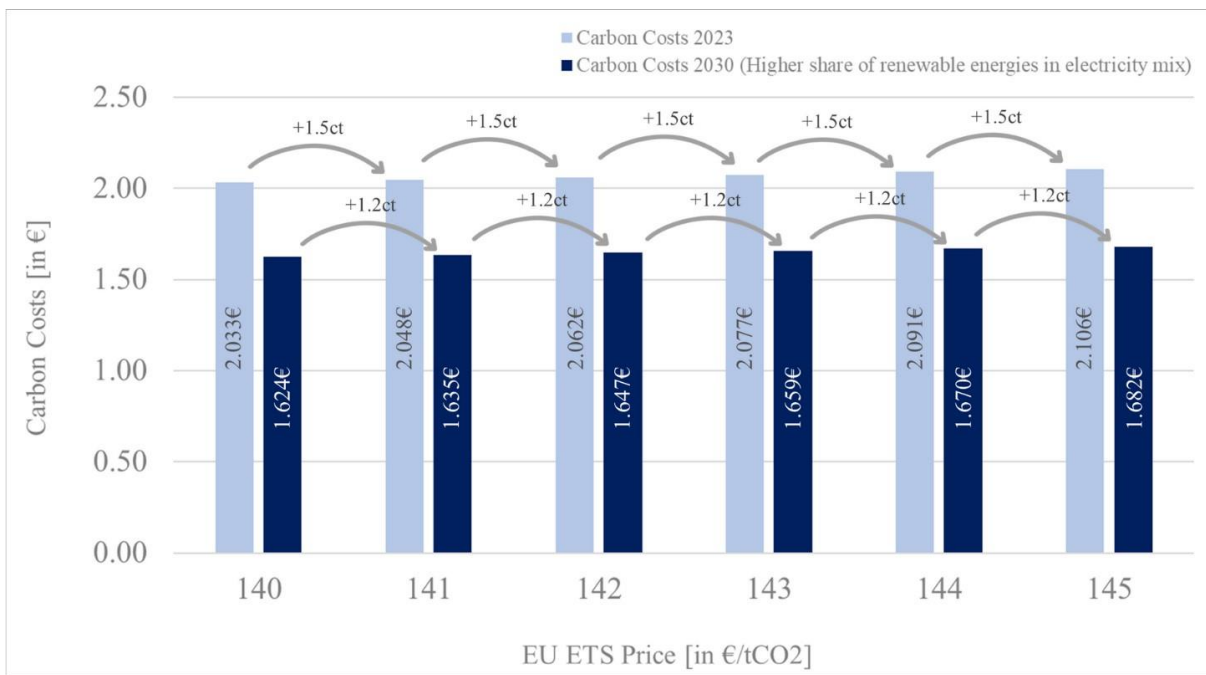


Figure 13: Mitigation of EU ETS price impact with increase of renewable energies in the electricity mix (own illustration based on company data and calculation results)