The impact of the CBAM

Exploring the impact of the CBAM on promoting sustainable adjustments in the production process of semiconductor machines: A Malaysian case study in the semiconductor industry

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Exploring the impact of the CBAM on promoting sustainable adjustments in the production process of semiconductor machines: A Malaysian case study in the semiconductor industry

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EXECUTIVE SUMMARY

This thesis aimed to investigate the potential of the EU's carbon border adjustment mechanism (CBAM) to promote sustainable adjustments in the production process of semiconductor machines, considering uncertainties in carbon accounting. The research combines a review of existing literature, a case study analysis of a selected semiconductor company, and a policy analysis of the EU's CBAM to provide insights into the ability of the CBAM to promote the use of sustainable materials in the semiconductor industry.

The literature review highlighted the significance of life cycle assessment (LCA) as a carbon accounting tool and its potential to assess the relevant embedded emissions for the CBAM. The review showed indeed that LCA could be useful to assess the first phases of the production of the raw materials. Additionally, the review showed that it is less useful as a decision-making tool due to the fact that decision-making regarding the CBAM requires the consideration of other parameters as well, not only the environmental ones. Additionally, the review revealed the novelty of the EU's CBAM regarding the carbon accounting tools and the CBAM's design. At the same time, it highlighted the relevance of this research project.

The statistical sensitivity analysis (SSA) conducted as an element of the case study showed that there exists a significant variation in the total embedded emissions of the semiconductor machine depending on the kind of steel and aluminium used. This highlighted the opportunity for improvements in the embedded emissions caused by the semiconductor machines. The SSA is also used to evaluate the cost-benefit analysis (CBA) of the implementation of green steel and aluminium in semiconductor machines. The CBA showed that a high reduction in embedded emissions is required to achieve a break-even level with the costs of sustainable steel and aluminium. However, this reduction also depends on the design and implementation of the CBAM. The stakeholder analysis highlighted the actors, transactions, frictions, and games caused by the implementation of the CBAM. A concluding policy analysis was conducted to present possible implementations of the CBAM. The analysis showed that under the current circumstances for the CBAM to be successful in promoting sustainable changes in the semiconductor machine, while considering the uncertainty in the carbon reporting process, an unrealistically high carbon price is needed to break even. The analysis, however, indicated a bright spot; if global electricity production becomes less carbon-intensive, the CBAM may work very well in promoting sustainable materials.

Thus, this thesis concludes that for this case study the EU's CBAM is not effective in promoting sustainable adjustments in semiconductor machines. However, this conclusion is obtained for this specific case with its specific extreme policy scenarios. Therefore, further research could be conducted

in assessing other policy scenarios or carbon accounting tools and test how they evaluate the CBAM on its potential to promote the use of sustainable materials in other industries as well.

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ACRONYMS

NOMENCLATURE

Prefix

G	Giga
k	Kilo
M	Mega
T	Tera

Symbols

$^{\circ}C$	Degrees Celsius
EUR	Euro
g	Gram
in	Inch
J	Joule
K	Kelvin
m	Meter
MEUR	Million euro
mol	Mole
s	Second
t	Tonne
W	Watt
Wh	Watt-hour
yr	Year

1 INTRODUCTION

1.1 PROBLEM STATEMENT

Europe announced its plans to implement the CBAM on imported goods in 2026. The CBAM is a carbon border tax that EU importers need to pay over the embedded emissions of their products. The 'tax' is paid by obtaining a number of carbon allowances depending on the embedded emissions and the number of products imported. These allowances are sold against the carbon price of the EU emission trading system (EU ETS) that is imposed on producers in the EU. If EU importers, however, can prove that they already paid a price for the carbon emitted during the production of their goods in foreign countries, they will be excepted partly or fully from the carbon border tax depending on the cost they already paid.

As stated in European Commission (2021), this policy is built to serve two main objectives. The first objective is to create a level playing field for both domestic and international producers Mehling et al. (2019). The second objective is to apply pressure on foreign countries to follow the climate action pathway of the EU and, hence, enhance climate actions around the world Mehling et al. (2019). During the transitional period from 2023-2025, the policy will apply to goods with high pollution and monitoring risk, such as steel, aluminum, hydrogen, and electricity European Commission (2021). If the transitional period happens to be successful, the Commission may apply the CBAM to more products and processes European Commission (2021).

Therefore, it becomes important for manufacturing companies and the EU to know how much energy and consequently CO2 emissions are related to imported goods. With the upcoming policy, manufacturers all over the world would use a generic and understandable tool to have an overview of the life cycle energy in their products.

LCA are used across various industries to find the cradle-to-grave energy and corresponding emissions Toniolo et al. (2021). During this assessment, the direct and indirect emissions are taken into account. Thus, both emissions caused by the manufacturer of products and the producers of raw materials up the value chain are considered. This makes LCA very suitable for an assessment of the embedded emissions. Firstly, when importing a product into the EU, a carbon report will be required which takes into account the total embedded emissions of the products, so both direct and indirect emissions European Commission (2021). Only with an overview of the total embedded emissions, it is feasible to create fair and competitive trade flows in terms of production costs, financial flows, and fossil fuels. If not taken into account, producers with higher indirect emissions and for instance, cheaper electricity for production will still have an advantage over the ones with lower indirect emissions and perhaps a higher price of electricity. Moreover, this effect is strengthened for complex products up the value stream which need multiple suppliers and materials to manufacture their products. In these cases, LCA could be a very useful tool to include all these different materials and components and at the same time have a clear overview of the origin and emissions of these complex products. It should be mentioned that LCA is not the only carbon accounting tool that can be used to assess the emissions of traded goods Hinman (2023). Thus, other carbon accounting tools could also be used to assess the impact of the emissions caused by various manufacturing industries.

However, there is also little known about the level of variation of the claimed statements in life cycle assessments, due to the large amounts of measured and modeled data Toniolo et al. (2021). Especially, the assumptions and estimates used to calculate material characteristics or energy flows can result in large variations regarding the embedded energy and emissions. Variations in LCA data due to the large amounts of measured and simulated data could affect the outcomes and conclusions in terms of sustainability or costs Toniolo et al. (2021). Therefore, conclusions about the life cycle energy or emissions of a product or process could differ depending on the data or methodology used. In this thesis, the translation of this variation on embedded emissions into variation on tax levels and decisions made by companies covered under the CBAM is explored. The CBAM is relatively new, thus, little information is available on how variations in LCA data could influence tax levels, hence, decision-making.

This analysis is conducted on a case study of a multinational in the semiconductor industry, BE Semiconductor Industry (BESI). BESI has its production and manufacturing faculty in Malaysia from which they export their machines throughout the world. In 2016, BESI was already working together with the Lucerne University of Applied Sciences and Arts in Switzerland to create an LCA model of various semiconductor machines. This research aimed to create an insight into the embedded emissions in various parts of the machine's life cycle. In this way, BESI knew in what part of the life cycle of the machine, it would be most effective to have more sustainable processes or products. BESI, as a big player in the semiconductor industry, could be affected by the CBAM, if the EU determines that it will be applied to other products and processes as well. For this research project, this is considered a reasonable assumption due to the fact that the inclusion of raw steel and aluminium producers will not be sufficient to achieve the desired impact of the CBAM. A logical consequence is the inclusion of industries down the value stream as well. Otherwise, manufacturers down the value stream will relocate their procurement and manufacturing to countries outside the European Union (EU) and buy cheap steel and aluminium outside the EU and at the same time not be subject to the CBAM and consequently, have a more competitive price than their competitors in the EU.

1.2 RESEARCH OBJECTIVE

The objective of this research is to assess the feasibility and effectivity of the CBAM through a case study conducted for BESI Malaysia. Hence, the main research question is constructed as follows:

- *Does the EU's CBAM promote sustainable adjustments in the upstream production process of semiconductor machines, considering uncertainties in carbon accounting?*

For this case study, a statistical framework is designed to analyse the level of variations of the LCA data used to calculate the embedded emissions of the semiconductor machines. It must be mentioned that the LCA study conducted by BESI will be used Besi (2022) and no new LCA will be performed. To assess the influence of this variations on the embedded emission constructively, a statistical framework will be implemented to display the variation of the embedded emissions and its influence on the total embedded emissions. This statistical framework can also be used to assess the variation in other carbon accounting tools as well. With this statistical framework, a sensitivity and cost-benefit analysis are conducted to analyse the influence of the variations in LCA data and to give a comparison of the costs associated with the use of sustainable materials and the price of the carbon border tax associated with the CBAM. The results of these analyses are interpreted for three different policy scenarios to analyse the feasibility and effectivity of the CBAM while considering the variation in carbon reporting. Depending on how the EU determines to implement the CBAM, different results will be obtained with regard to the level of effectiveness of the implementation of the CBAM.

1.3 RESEARCH SCOPE

The implementation of the CBAM will affect various major manufacturing industries European Commission (2021). Through the case study of this research project, the influence of this policy will be assessed. During this study, the assumption is made that the CBAM has completed a successful transitional period and therefore is ready to be implemented to goods down the value stream. With the results of this study, one can assess the future consequences of expanding this policy to other sectors. Since strategic decisions regarding the implementation of sustainable materials are of interest for the import of products to the EU, the scope will be narrowed down to the so-called, cradle-to-gate LCA as illustrated in Fig.1.1. The cradle-to-gate LCA only considers the first two phases of LCA consisting of raw materials extraction and production. Thus, an analysis will be conducted on the raw materials content

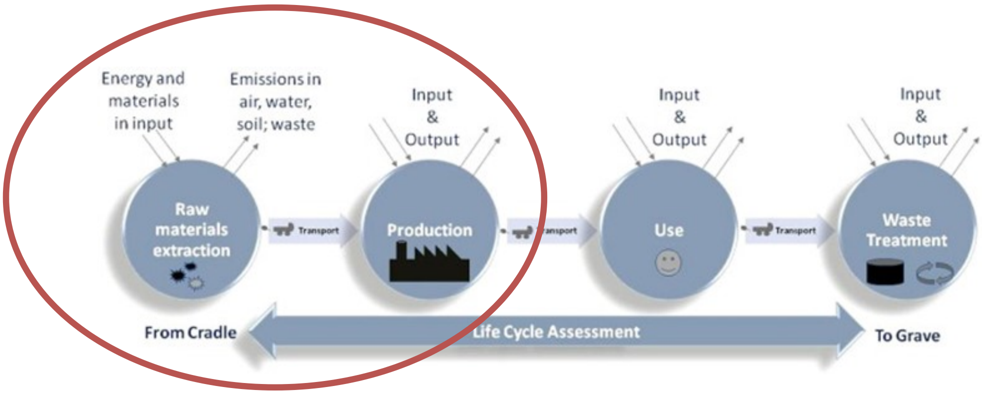


Figure 1.1: Candle-to-Grave scheme of the life cycle thinking framework as described by Toniolo et al. (2021).

Since these emissions occur during the production processes of suppliers, they are categorised as scope 3 emissions Toniolo et al. (2021). Fig.1.2 shows the different proposals, approaches, and reports of each entity of the EU with various variables. As shown under the variable 'scope', one of the three EU entities will be expanding its scope to level 3 emissions. However, after the transitional period in 2025 or 2026, the commissions and council could decide to expand the scope to level 3 emissions, if the CBAM is successfully implemented during this period European Commission (2021). Recently, the council of the EU and the European Parliament reached an agreement regarding the CBAM Council of the EU (2023). Under the aforementioned agreement, the CBAM will set off in October 2023 and will include the following materials: iron and steel, aluminium, cement, fertilisers, electricity, and hydrogen. Also a not specified but limited number of downstream products will be included. The specified co-existence with the EU ETS is still under examination and will be communicated in a later stadium. This case study can be used as a reference to decide whether the inclusion of this scope is valuable or not. Also, since BESI exports goods to the EU, the assumption is made that the EU will only implement the CBAM on the import of products, not the export. This is firstly more relevant for BESI since they export their products to the EU. Also, the CBAM will have less influence if implemented on export products also since these products will already be subject to the EU-ETS and therefore by definition be excluded from the CBAM European Commission (2021). To assess the influence of improvements in purchasing sustainable materials for the semiconductor assembly machines, it is chosen to analyse the improvements in steel, aluminium, and electricity since these materials will be subject to the CBAM European Commission (2021).

Topic	European Commission's Proposal	Council's General Approach	European Parliament's Report
Scope	▪ Aluminium, cement, electricity, fertilisers, and iron and steel	▪ Expand the scope to aluminous cement, other articles of iron and steel (CN 7326), and a number of additional aluminium products such as aluminium structures, reservoirs and cans (CN 7610, 7611 00 00, 7612, 7613 00 00, 7614, 7616)	▪ Expand the scope to aluminous cement and additional sectors: organic chemicals, hydrogen, anhydrous ammonia, ammonia in aqueous solution and polymers, including plastics and articles thereof ▪ By 1 January 2030 CBAM shall apply to all EU ETS sectors
	▪ Direct emissions ▪ Commission's report by 2025 on potential extension of the scope to indirect emissions	▪ Direct emissions ▪ Commission's report by 2025 on potential extension of the scope to indirect emissions	▪ Direct and indirect emissions
Transitional period	▪ 2023 - 2025	▪ 2023 - 2025	▪ 2023 - 2026
CBAM authority	▪ Member State competent authorities	▪ Member State competent authorities	▪ Single EU-wide CBAM authority
Co-existence with the EU ETS	Commission's proposal on the revised EU ETS: ▪ Gradual phase-out of free emission allowances for CBAM sectors between 2026-2035, by 10 % each year	Council's General Approach on the revised EU ETS: ▪ Gradual phase-out of free emission allowances for CBAM sectors between 2026 and 2035: 95% in 2026, 90% in 2027, 85% in 2028, 77.5% in 2029, 70% in 2030, 60% in 2031, 50% in 2032, 35% in 2033, 20% in 2034, and 0% In 2035	▪ Gradual phase-out of free emission allowances for CBAM sectors between 2026 and 2032: 100% in 2026, 93% in 2027, 84% in 2028, 69% in 2029, 50% in 2030, 25% in 2031, and 0% in 2032
Export adjustment	▪ n/a	▪ Commission's report by 2025 on the impact of the CBAM on carbon leakage, including in relation to exports	▪ Commission report by 2025 on WTO-compatibility ▪ Free emission allowances for CBAM products destined for export to third countries without carbon pricing mechanisms similar to the EU ETS
Penalties	▪ EUR 100 per missing CBAM certificate ▪ Member States *may* impose administrative and criminal penalties	▪ EUR 100 per missing CBAM certificate ▪ More severe penalties for importing without authorisation: 3 to 5 times the regular penalty ▪ Revocation of authorisation in case of serious or repeated infringement	▪ 3 times the average price of a CBAM certificate in the previous year per missing certificate ▪ Member States *shall* impose administrative or criminal penalties ▪ Suspension of CBAM account in case of repeated offences

Figure 1.2: Illustration of various CBAM proposals by European Union entities as described in KPMG (2021)

1.4 CONTRIBUTION AND OUTLINE OF RESEARCH

This research project will start with a literature review on the state-of-the-art applications and methodologies of the LCA approach and CBAM. This chapter will give the reader background information on the two main aspects of this thesis and discuss the relevance of this subject. For LCA, it will become evident why an analysis of the variation in the input data of a carbon accounting tool such as the LCA is of utmost importance and how this variation affects the uncertainty of the carbon reporting process of the CBAM and its feasibility and effectivity. With this information, the knowledge gap will be identified and outlined, so that the reader has a clear understanding of the aspects that are being studied in this thesis. In the following chapter, the research approach is discussed with corresponding sub-questions, deliverables, and objectives. Consequently, an elaboration is given on the scope and goal of this research project by connecting the CBAM with the LCA study and highlighting the relevance of this study.

With these components, a conceptual framework is created in which the interconnection of all components is visualised. An illustration is shown in Fig.1.3. The research project starts with an analysis of the case study conducted by BeSI. This analysis composes of an analysis of the data and modeling techniques used by BESI to conduct their LCA study. This analysis also identifies the materials of the semiconductor machines that can be adjusted by BESI to lower the embedded emissions and, hence, create more Eco-friendly semiconductor machines and lower the carbon border tax costs that need to be paid because of the CBAM. In the next chapter, this knowledge is used to model the effect of the sustainable changes in the semiconductor machines on the total embedded emissions considering the variation related to this data. This statistical framework will provide the reader with a better understanding of the influence of these uncertainties on the total embedded emissions for different environmental cases; from the use of conventional materials to the use of 100% sustainable materials. After all, assessing the feasibility and effectivity of the CBAM constructively requires consideration of the uncertainties associated with the data of a carbon accounting tool such as the LCA. This will give the reader also a better understanding of the range of possible embedded emissions and how this will influence the carbon border tax that will be paid due to the CBAM. To analyse the feasibility and effectivity of the CBAM, a cost-benefit analysis is conducted considering both the carbon border tax costs and the realisation costs of the sustainable materials identified before. During this analysis, it is determined whether BESI will choose to become more sustainable or pay the carbon border tax while ensuring financial profitability. The results of the aforementioned analyses will be interpreted for different policy scenarios and, consequently, be used to reflect on the feasibility and effectivity of the CBAM for this case study. Overall, this research project will assess the transformation of the current LCA model by adjusting foreground processes data, analyse how these adjustments will influence decision-making by BESI regarding the CBAM, and how these decisions will influence the effectivity and feasibility of the CBAM. Therefore, it will give a contribution in the form of a policy analysis that will be used to assess the effectivity and feasibility of the CBAM in reaching its objectives while considering the uncertainty associated with carbon reporting by importers subjected to the CBAM and at the same a strategic analysis for BeSI on handling the CBAM.

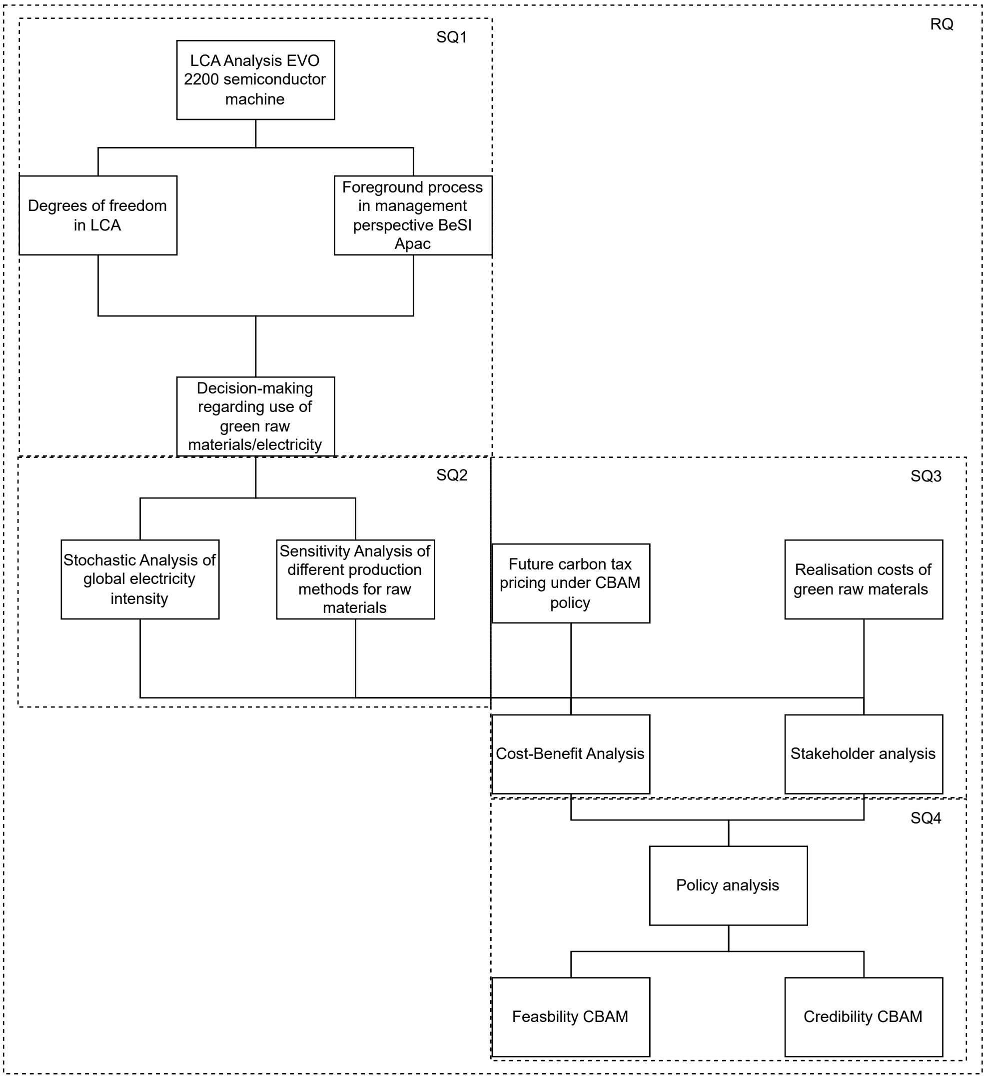


Figure 1.3: Conceptual framework visualising the interconnections of each sub-question with its components

1.5 LINK TO COSEM PROGRAMME

As described by the main research question in Sec.1.2, the main objective of this research project is to explore the ability of the CBAM in promoting the use of sustainable materials in the semiconductor industry through a case study in Malaysia. This exploration consists of various components design and analysis components. Statistical analysis is used as a tool to assess the impact of the implementation of sustainable steel and aluminium in semiconductor machines considering the variation in LCA data. This typical CoSEM tool is used to creatively assess this impact. Also, this research project considers both public and business values; on one side, the statistical analysis is used to assess how BESI will apply financially effective management strategies, and on the other side, the CBAM is assessed on its ability to promote the EU's ambition on climate action which affects the public as a whole. The latter is addressed by designing three possible policy scenarios and using them to conduct a policy analysis that explores the ability of the

CBAM to promote sustainable improvements in the semiconductor industry from three scenarios of the CBAM while considering the stakeholders and the uncertainty in the carbon reporting process. Thus, both public and business assessments address both technical challenges on one side but also the management of stakeholders with different objectives and interests.

2 LITERATURE REVIEW

2.1 REVIEW OF STATE-OF-THE-ART

In this section, both state-of-the-art of the LCA and its integration with the CBAM will be studied. In both Sec.2.1.2 and 2.1.1, the strengths and limitations of both will be discussed. With this discussion, the knowledge gap will be identified and elaborated on in Sec.2.2.

2.1.1 CBAM Framework

Policy Outline

The EU is at the pole position of international efforts to fight climate change. The Green Deal sets out a path towards becoming a "climate-neutral continent" by 2050 European Commission (2021).

To achieve their goals, as described in the Green Deal, the EU is intensively working on climate policies, such as the Emissions Trading System. However, only implementing these policies in the EU will trigger companies to move their carbon-intensive production to countries outside the EU, i.e. give rise to carbon leakage. In this way, they would avoid paying taxes or buying carbon permits European Commission (2021). Eventually, this could lead to a loss of competitiveness in global trade for the EU. Currently, this issue is solved by the free allocation of emission allowances to companies in the EU that are at risk of carbon leakage Nordhaus (2015). However, there is a lot of critique on that approach since it does not create enough incentive to do abatement. Therefore, the EU will work on gradually phasing these free emission allowances for CBAM sectors to create an effective implementation of the CBAM and replace it with a carbon border tax to ensure a level playing field between producers in and outside the EU. Otherwise, a situation will occur in which companies in the EU have a clear advantage due to their free allowances while a competitor outside the EU has to pay for these allowances in the form of a carbon border tax.

The carbon border tax, paid in the form of purchasing carbon allowances, will be applied to heavy-polluting products imported into the EU European Commission (2021). As shown in Fig.2.1, the CBAM will be implemented as an addition to existing energy policies such as the EU ETS. These policies will exist together since the price of the tax paid for the CBAM will be based on the "weekly average auction price" of carbon permits traded in the EU ETS European Commission (2021). Therefore, producers will be paying the same carbon costs as if they were producing in the EU. This will not only influence the producers but could also trigger other countries to consider implementing such a carbon tax because they would be exempted from the CBAM as illustrated in Fig.2.1. After all, Fig.2.1 shows that the CBAM will only be applied to non-EU companies, which are not already compliant with EU climate standards. So if importers did already pay a carbon price during a part of the production of the imported good, the requested amount of tax under the CBAM will be decreased accordingly. In this way, companies that are already buying allowances on a foreign carbon pricing market, will not be paying double for their allowances and this system can therefore function alongside existing carbon pricing markets. Furthermore, importers will not be able to sell their CBAM allowances to other players or third parties. However, they can get a refund on one-third of unused allowances from the previous year European Commission (2021).

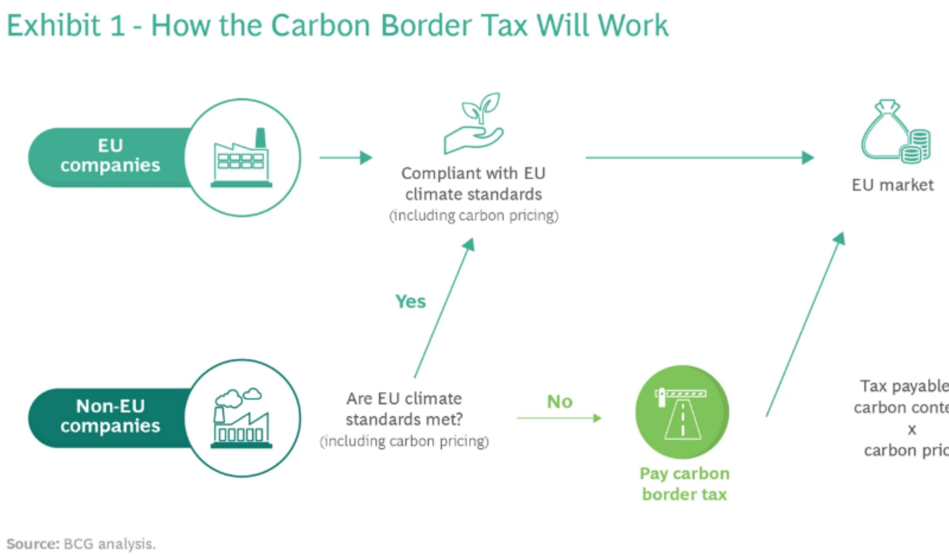


Figure 2.1: Overview of implementation of the carbon border tax as distinguished by Figures et al. (2021).

Since embedded carbon accounting will be important for both producers and the EU, a reporting system must be implemented to have a clear image of the system. Therefore, the European Commission is working on a CBAM system, in which national governments will be responsible for handling and verifying the reports European Commission (2021). Nevertheless, there is still an ongoing discussion on how to assess the embedded emissions of products. However, due to the variations in embedded emissions, a framework is missing which takes these variations into account. These variations could have a great influence on the resulting carbon emissions and paid tax. Therefore, new irregularities could arise when implementing the CBAM since there is no general framework that asses the certainty of the claimed CO2 emissions. When taking into account the different goals and objectives of the players, this could lead to tension in the relationships between importers and the EU.

The European Commission is planning on introducing this policy gradually. They will start with "a transitional phase" in 2023, in which only the report-

ing of embedded carbon emissions will be implemented; so, no tax must be paid yet. If the evaluation happens to be successful, the Commission will start implementing the CBAM in more products and processes European Commission (2021).
Nevertheless, entities inside the European Union are still negotiating the details of the outline European Commission (2021). Fig.1.2 shows how each entity inside the EU proposes various components in implementing the CBAM. As illustrated by Fig.1.2, this concerns minor differences in implementation. However, these differences could affect the eventual outline of the CBAM.

Objectives of the CBAM

As described above, the CBAM is seen as an effective policy to reduce carbon leakage. Carbon leakage is a phenomenon that occurs when companies move their emissions from an area with carbon pricing policies to an area without. Due to this movement, the aggregated reduction of emissions and the success of collaborative climate action is sabotaged Nordhaus (2015). As will be described further, this leakage occurs through three different routes. To successfully abate this leakage, the CBAM has two main functions.

The first objective is to create fair and competitive trade flows for both the EU and international markets Mehling et al. (2019). If producers of product X in the domestic market are facing a regulatory burden in the form of carbon taxes or an emission trading system, they lose their competitiveness to international producers of product X which produce this product in countries without these policies. Also, due to the higher prices, the producers of product X in the domestic market will lose competitiveness in their exports to other countries. Also, a change in the capital flows will incline investors to move their money to parts of the world with less stringent climate policies and therefore more return on capital. In this way, product X will also enjoy fewer investments than product Y, which will eventually lead to a higher production level for the heavier polluting product Y. In addition, climate policies will put pressure on the price of fossil fuels and consequently lead to higher energy prices. Therefore, companies, especially in the manufacturing industry, will move their business elsewhere to avoid high energy prices and eventually high production costs in comparison with their competitors. However, with the CBAM, the producers of product X in the domestic and international markets will pay the same carbon costs.

The second objective is to apply political pressure on other countries which are slow with their actions against climate change Mehling et al. (2019). Studies have shown that when managing global issues, free-riding on the endeavors of others is a serious risk Nordhaus (2015). With the implementation of global policies, which affect the entire trade flow, 'free riders' will have to make new strategic calculations regarding their cost of products and competitiveness and therefore be more inclined to implement their regulations against climate change.

Carbon border costs

LI et al. (2022) distinguishes various factors that influence the auction price of carbon allowances. Fig.2.2 visualizes the interaction of the influencing entities. On one hand, governments come up with policies to support, lead, and influence enterprises, consumers, and the carbon market. Also, consumers have changing product demands which influence the production of enterprises. The enterprises, in their turn, buy and sell carbon allowances in the carbon market which influences the carbon price due to changing demand and supply. On the other hand, price adjustments in energy and stock markets also have an influence on the demand and supply of carbon allowances by enterprises. These price adjustments are influenced by geopolitical, economical, and environmental issues around the world. This makes the determination of future carbon prices very complex Lovcha et al. (2022). Bruninx & Ovaere (2022) argues that the major driver of carbon prices is the perception of a future scarcity of allowances or in other words the emission reduction ambition or the usage of carbon-intensive fuels. During the Ukrainian war, for instance, the demand in the coal market increased due to the shortage of gas from Russia. Since coal emits more carbon dioxide into the atmosphere than natural gas, this resulted in an increase in the demand for carbon allowances and consequently in an increase of the carbon price. This makes the carbon price a relatively volatile parameter.

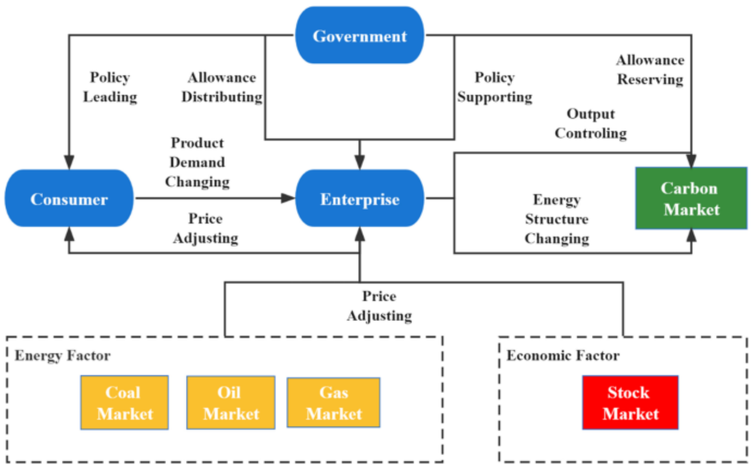


Figure 2.2: Influencing factors of carbon market as distinguished by LI et al. (2022)

However, studies have also made predictions on the range of future carbon prices. A range is more useful to be implemented in this analysis, because of the high level of complexity and volatility of the carbon market. In Pahle et al. (2022), research is conducted by modeling groups of different consultancy firms to create an overview of EUA price predictions. Each of the groups based its results on different scenarios and price drivers. This workshop resulted in differences for short-term predictions but showed a convergence at the end of the 2020s Pahle et al. (2022) as illustrated by Fig.2.3.

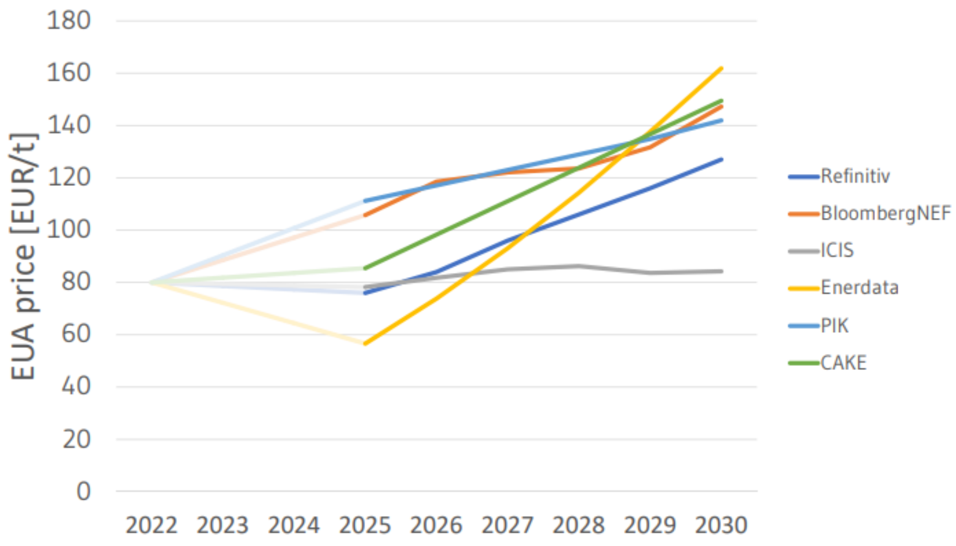


Figure 2.3: EUA price predictions made by different modeling groups. Source: Pahle et al. (2022)

Resistance to the CBAM

Furthermore, the CBAM will put pressure on the business relationship of the EU with the rest of the world. As described by Overland & Sabyrbekov (2022), various countries are likely to oppose the CBAM. Each country has its reasons to oppose this policy varying from high exports to the EU to high carbon intensity to innovation capacity. In the case of BESI, Malaysia has an index of 58 ranging from 0 to 100 with 100 being the country with the highest opposition Overland & Sabyrbekov (2022). Furthermore, several solutions are proposed by Overland & Sabyrbekov (2022); for less innovative countries, the EU could help with innovation to lower the carbon intensity of the products. On the other hand, countries with large economies, along with high carbon intensity and low levels of innovation could pressure the EU to take their interest into account. In this case, it becomes relevant for BESI to include this framework to assess the extra costs induced by this policy.

2.1.2 LCA Framework

During the 21st century, LCA is proven to be a useful tool for environmental management Toniolo et al. (2021). Due to its quantitative nature, data-backed statements could be made regarding the energy and materials used for production, waste produced, and possible environmental improvements at various parts in the life cycle processes Bjørn et al. (2020). As shown in Fig.2.4, LCA is based on the concept of life cycle thinking. This means that if there is a need to access the environmental impacts of a product, the entire life cycle is considered, starting from the extraction and processing of raw materials, through production, transport, and distribution, to the use, operation, recycling, and scrapping Toniolo et al. (2021). Therefore, one could say that LCA is a method to evaluate the environmental impacts of goods and processes 'from cradle-to-grave' based on data. The input and output data of each cycle are obtained through measurements and the impacts are calculated using quantitative models based on scientific resources Bjørn et al. (2020).

On the other hand, Tillman (2000) states that system boundaries could be set depending on the purpose of the study. Two main categories are distinguished; retrospective or accounting perspective and prospective perspective Tillman (2000). For the retrospective or accounting case, the study's goal is described as assessing the system's environmental performance, while not thinking about adjustments or changes in the system. In this case, the system as a whole needs to be taken into account to create a complete picture. Therefore, averaged emission or energy data could be used to have a general impression of the life cycle. From the prospective perspective, however, it is allowed to use only parts of the life cycle since a change or adjustment in the material will only affect a part of the system. By analysing this part, a reflection can be made on how the use of sustainable materials will influence the eventual outcome of the life cycle Tillman (2000). Therefore, the choice of data is described as marginal since only a part of the system is changed. In this case, the system is also subdivided into the foreground and background processes and data which will be discussed in more detail in Sec.2.1.2.

The standards ISO 14040 ISO (2006a) and ISO 14044 ISO (2006b) set the LCA methodology of a process or a product. Also, the goal, scope, and data collection methods are set by the aforementioned standards. For instance, these standards describe how an LCA assessment can be divided into the following four phases, as indicated by Fig.2.4. During Phase 1 the goal and scope of the research project are described. During this phase, the system boundaries and the limits to the analysis are determined to identify where the life cycle study starts and where it ends and to indicate which processes will be assessed. Phase 2 is indicated in Fig.2.4 as the Inventory Analysis. In this phase, the data concerning the materials and energy flows within the technical system is collected. Phase 3 describes the Impact assessment. The environmental impacts resulting from the included inputs and outputs are assessed in this phase. Finally, Phase 4 is performed parallel along all three phases to include evaluating all the results obtained to conclude, as illustrated by Fig.2.4.

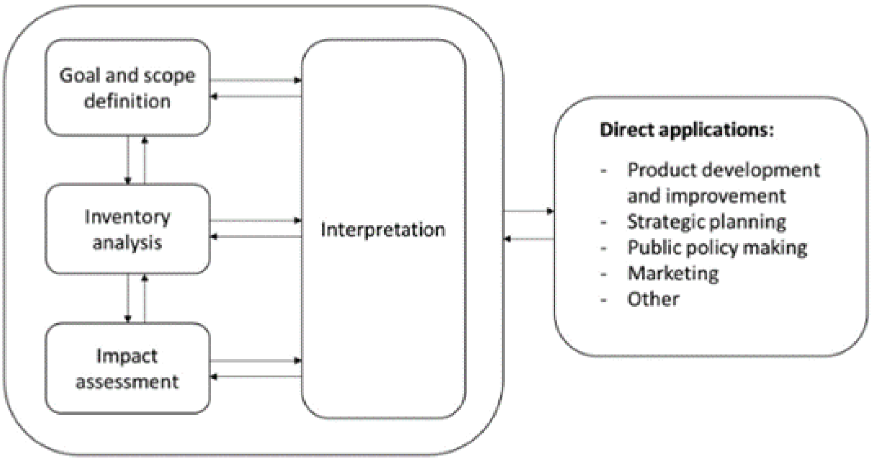


Figure 2.4: Life cycle framework as described in ISO (2006a)

Various studies, however, have shown that during the Inventory Analysis data concerning the materials and energy flows could be missing or measured inaccurately Huijbregts et al. (2001). Furthermore, differences in the production processes and the lack of measured production data lead to significant variations in embedded CO2 levels of raw materials or electricity. These results can affect the conclusions and resulting decision-making significantly E. Wang & Shen (2013).

Foreground and background processes

To be a useful environmental management and decision-making tool, large amounts of data from companies need to be analysed. These large amounts of LCA data can be divided into two categories namely: foreground data and background data. Foreground processes require foreground data, which is only available to the producer or on which only the producer has significant influence Bicalho et al. (2017). This includes measured real-time data, which is specifically assigned to this product or system. On the other hand, generic or secondary data is used for the background process. Databases, such as EcoInvent, contain generic data which can be used to assign values to less specific processes of the life cycle of the product Centre et al. (2011). However, their availability is essential for the existence of LCA studies since they provide a less costly and time-intensive approach to executing an LCA study. This is sometimes needed to have a general overview of the life cycle of a process or product and could also be used in some parts of the foreground processes, in which the producer has less decision-making power or information available.

For this case study, the focus will be on the management perspective. More specifically, on the variables, which a company can change internally to improve its sustainability and decrease its total life cycle emissions. These changes will be searched for in the first two phases of the LCA because adjustments in these phases influence the carbon costs associated with the CBAM. Hence, the focus of the analysis will be on adjusting the procurement of the raw materials for the semiconductor machines. This analysis will be assessed using background data available in online libraries, so a foreground process will be analysed using background data.

2.1.3 LCA as a decision-making tool

As described by Pryshlakivsky & Searcy (2021), current literature on LCA still lacks the connection with management literature in regards to decision-making. As LCA has the potential to be used as a decision-support tool, it is relevant to consider the connection with management literature Sandin et al. (2015). Also, Pryshlakivsky & Searcy (2021) suggest examining decision-making in LCA from the perspective of managerial theory. Currently, however, different decision support approaches are being used to help decision-makers, depending on the specific field of application Dong et al. (2018). One of the established approaches is risk-based decision-making. This approach is applicable when exposed to disadvantageous events such as natural disasters e.g. floods or pandemics Pasman et al. (2022). In addition, the CBA is used to analyse decisions based on the lowest cost Dehnhardt et al. (2022). Also, the multi-criteria analysis (MCA) is seen as one of the widely used decision-making approaches Sahabuddin & Khan (2021). MCA also makes use of various criteria to support decision-makers depending on the goal. In addition, Seidl et al. (2022) states that a sensitivity analysis (SA) gives an overview of the significance of various variables on the output. Therefore, SA is seen as an impact assessment method that supports decision-makers with their work.

Furthermore, Pryshlakivsky & Searcy (2021) state that the aforementioned approaches do not take life cycle perspectives into account. This resulted in issues when applying these to real cases. In the context of this thesis, if companies want to know which raw materials to implement in their products and only take CBA into account, this will lead to having way more costs if a carbon border tax is introduced. Pryshlakivsky & Searcy (2021) argue that this is mainly caused by a lack of integration of life cycle methods into decision-making approaches.

In addition, Elbanna & Child (2007) state three entities influence decision-making outcomes. To these structures belong the composition of the organization involved(i.e., how the organization is formed and the work environment), the framing of the problem(i.e., the origin of the problem, methods to define the problem and the solution options), and factors and external factors(i.e., policies or economies). With the aforementioned structures, Pryshlakivsky & Searcy (2021) argue that these three structures inform decision-making in LCA. Therefore, Pryshlakivsky & Searcy (2021) suggests combining these entities with LCA. In this way, LCA is implemented through a managerial lens. An overview of this interconnection is shown in Fig.2.5.

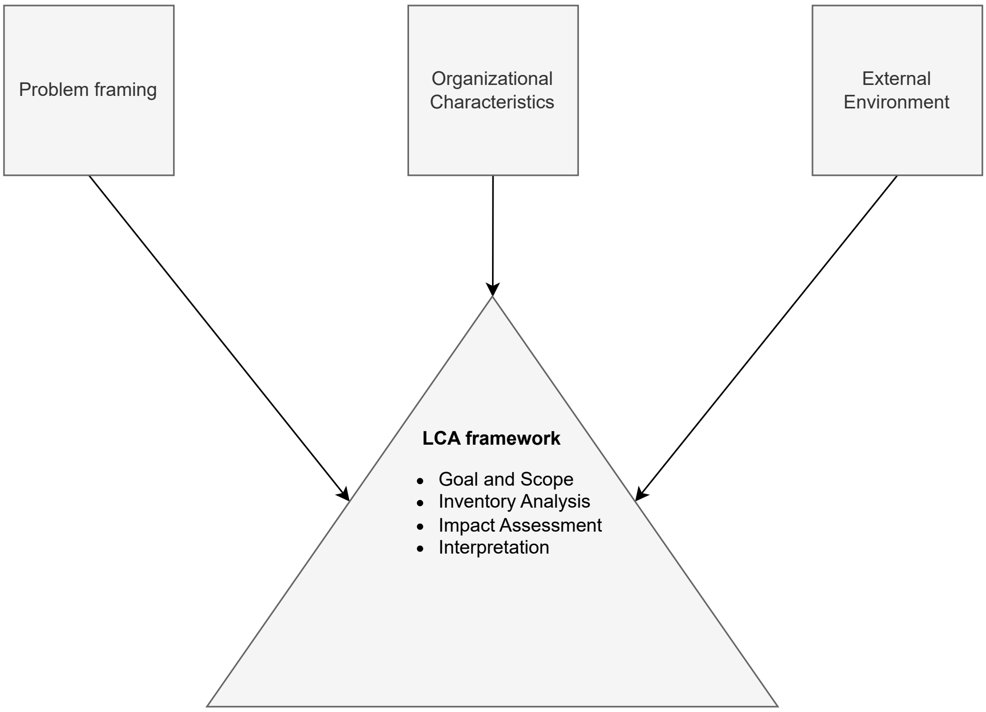


Figure 2.5: Overview of three entities that inform decision-making in LCA as distinguished by Pryshlakivsky & Searcy (2021).

2.2 KNOWLEDGE GAP

With the implementation of the CBAM in 2026, new challenges arise for importers from non-European countries with less stringent or no climate policies. On one hand, due to the relatively new nature of the CBAM, little in-depth analysis is conducted into carbon accounting tools such as LCA acting as a decision-support tool. The LCA is needed to evaluate the carbon intensity of imported products that are subject to the CBAM. The variations associated with the background data used for LCA will have an influence on the decisions made by enterprises under the CBAM. These variations need to be studied so that the usefulness of carbon accounting tools such as LCA is enhanced. In this way, both enterprises, subjected to the CBAM, and the EU has a better understanding of the level of the variations associated with carbon accounting tools. This study will, consequently, also reflect on the effectivity and feasibility of the CBAM considering the uncertainties in carbon reporting caused by these variations. After all, the variations in background data used in carbon accounting tools such as LCA can lead to different embedded emissions and consequently a variable carbon border tax. For the EU to achieve its objectives and implement an effective and feasible climate policy, these uncertainties need to be analysed and reflected on so that this policy is indeed as effective as desired by the EU.

To assess the variation in the background data of carbon accounting tools such as the LCA and its interaction with the CBAM, a case study is conducted in cooperation with BESI. During this case study, the background data of the current LCA model is adjusted in the raw materials extraction and production phases by the implementation of sustainable materials. Through a statistical framework, the influence of these adjustments on the total embedded emissions of the semiconductor machines is analysed. At the same time, analyses are conducted on the costs of these adjustments alongside the benefits associated with lower carbon costs. Together with an analysis of the stakeholders involved, a policy analysis is conducted of the CBAM under three different carbon reporting designs. The case study is eventually closed with a reflection on the effectivity and feasibility of the CBAM in achieving its desired objectives.

In this way, both the variations in background data of carbon accounting tools and their interaction with the CBAM are analysed and used to reflect on the effectivity and feasibility of the CBAM for this case study.

3 RESEARCH APPROACH

In Ch.2, the knowledge gap was identified and discussed. The knowledge gap shows there is little research focused on the use of background data for foreground processes in LCA assessments and how the use of this data will influence decision-making regarding the CBAM by importers from Malaysia and consequently influence the effectivity and feasibility of the CBAM. Therefore, this research project will assess the transformation of the current LCA model by adjusting foreground processes data, analyse how these adjustments will influence decision-making by BESI regarding the CBAM, and how these decisions will influence the effectivity and feasibility of the CBAM.

3.1 RESEARCH SCOPE

In this section, the scope of this research project is described more extensively. The research scope indicates the boundaries and focus of both the LCA and the CBAM.

As described in Sec.2.2, the main objective of this research project is to assess the influence of adjustments in data of foreground processes on decision-making by importers regarding the CBAM through a case study conducted for BESI Malaysia. With this assessment, conclusions regarding the effectivity and feasibility of the CBAM are made. The adjustments in data will be made in the first three phases of the LCA; the so-called cradle-to-gate phase. This part is chosen since producers are able to make decisions regarding transformations in these phases. Firstly, they can choose to use more sustainable materials. This will lower their total embedded emissions and create a new interplay between BESI and the EU. In this new playfield, BESI has more options regarding its decision-making process for the CBAM. They can choose to use more sustainable materials or to pay the carbon border tax if being economically more attractive. Furthermore, it is chosen to exclude the other phases of the life cycle model since these parts will not be taken into account by the CBAM. This is caused by the fact that the other phases, namely the operation and recycling phase, originate inside Europe, so they will not be part of the carbon border tax.

Fig.3.1 illustrates the results of the current life cycle model of BESI. As shown in the figure, the first three phases will be of interest for the CBAM. However, the transportation and packaging phase will not be considered for two reasons. Firstly, it's not part of the foreground process because BESI does not have first-hand power in lowering the emissions of their transport service or changing the way they conduct their business. They could, however, apply pressure so that the transport service is inclined to make a sustainable change. This is already happening with their current transport service provider DHL DHL Global (2022). They are switching to sustainable fuels to reduce their CO_2 emissions in different freight including air, ocean, road, and rail, and consequently, reduce the embedded CO_2 emissions of their clients' products.

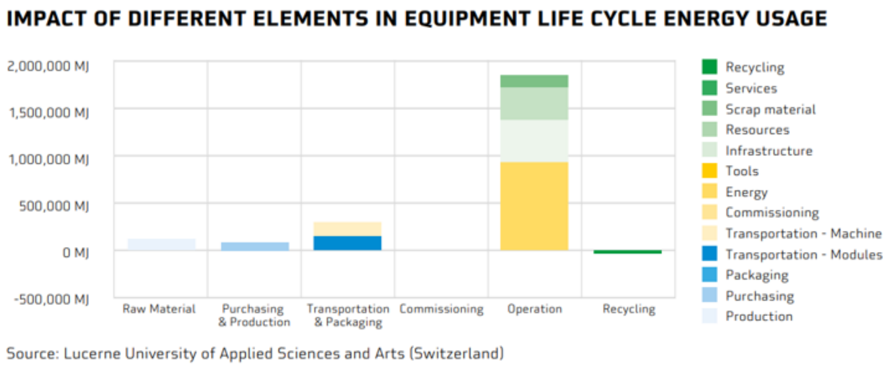


Figure 3.1: Life Cycle Usage semiconductor machine BeSI

3.2 RESEARCH OBJECTIVE

As described by the knowledge gap, the objective of this research project is to assess the influence of adjusting foreground processes data on the decision-making by BESI regarding the CBAM and how this will affect the effectivity and feasibility of the CBAM. As described in Sec.1.3, the following main research question was derived:

- **Does the EU's CBAM promote sustainable adjustments in the upstream production process of semiconductor machines, considering uncertainties in carbon accounting?**

This case study has as its goal to assess the interaction between the uncertainty in LCA data and the effectivity and feasibility of the CBAM by designing a statistical framework of the embedded emissions of the semiconductor machines. The total embedded emissions will, in contrast to the current life cycle model of BESI shown in Fig.3.1, be characterised by a probability distribution to evaluate the sensitivity of different raw materials and carbon intensities of electricity on the embedded emissions of the semiconductor machines. The different raw materials used in the production process of these machines will be elaborated on further in Sec.4. Hence, the embedded emissions will also be characterised by a probability distribution instead of a deterministic value. This distribution will then be translated to the height of the carbon border tax that hypothetically needs to be paid by BESI. With these results and the expected costs of using sustainable materials in the raw materials or production phase, a strategic business recommendation will be created, i.e. an advice on how to deal with the CBAM in a financially favourable manner, backed by statistical analysis. Together with this recommendation and a stakeholder analysis, a policy analysis will be conducted so that conclusions could be drawn regarding the effectivity and feasibility of the CBAM.

3.3 SUB-QUESTIONS AND METHODOLOGIES

To answer the main research question as described in Sec.3.2, it is divided into four sub-questions. In this section, each sub-question and its corresponding research methodology are discussed.

What sustainable changes in purchasing of materials can be made to lower the embedded emissions of semiconductor machines?

For this sub-question, firstly interviews with experts will be conducted to understand how the data is retrieved and processed. For this research-project, experts of both BESI and TU Delft are interviewed to understand how LCA data is used for carbon accounting. On one side, BESI experts will help with explaining how the LCA is conducted and which online libraries are used for data gathering and which sources are used to make the life cycle calculations. On the other side, TU Delft experts will be consulted on the use of LCA in the industry and which sustainable changes and online libraries could be incorporated in the use of materials. With this information, a case study will be conducted to explore which materials can be exchanged with more sustainable ones, a so-called inventory analysis. To identify these adjustments, the life cycle assessment of the Datacon 2200 EVO^{Advanced} will be analysed. The Datacon 2200 EVO^{Advanced} is chosen because, for this semiconductor machine, the highest number of data was available to conduct a successful analysis. Also, this machine is the one that is currently being sold the most by BESI and hence, analysing this semiconductor machine will have the highest impact regarding the interaction with the CBAM. Afterwards, a literature study is conducted to understand the production process of raw materials. Also, sustainable production processes are researched and analysed to create an overview of possible adjustments that result in lowering embedded emissions of LCA.

Can the effect of the implementation of green raw materials on the embedded emissions in semiconductor machines accurately be demonstrated or is the effect insignificantly due to uncertainty?

To assess the effect of these changes on the output on the LCA, the variations of these changes is analysed. At first, the data of the sustainable changes found under Sec.3.3 is retrieved from online data libraries. Afterwards, this data is modeled in the LCA of the case study for BeSI. To find the influence of these changes on the total embedded emissions(i.e the output of LCA), a statistical model is implemented to find the sensitivity of these changes on the output. Depending on the amount of data found in the online data libraries, it is chosen to apply a sensitivity or statistical analysis. With this in-depth analysis of the influence of sustainable changes in materials or production processes, it is assessed whether this change with its corresponding uncertainty has a significant influence on the embedded emissions.

What trade-offs need to be considered by BeSI to make economically and environmentally favourable choices in terms of costs of sustainable improvement and carbon costs considering the variations in LCA data?

A CBA will be conducted to analyse whether sustainable changes are cost-effective in comparison to paying the carbon border tax. To have a realistic image of these carbon costs, studies are used to create an image on how the carbon price will possibly develop in the future. Also, the costs of sustainable raw materials will be evaluated using various online libraries and studies. Together with a qualitative analysis of the stakeholders influenced by the CBAM and the aforementioned quantitative SA and CBA, economical trade-offs will be evaluated that influence decision-making regarding the CBAM. These trade-offs include the assessment of switching to sustainable raw materials or choosing to pay the carbon border tax depending on the benefits gained with the implementation of sustainable materials against their costs. For this assessment, the SSA will be used as the base of this analysis.

What is the influence of the results of the impact assessment under different policy scenarios on the feasibility and effectivity of the CBAM considering uncertainty in carbon reporting?

To interpret the impact assessment under Sec.3.3, the results are evaluated with regards to the feasibility and effectivity of the CBAM in reaching its objectives and the usefulness of the implementation of LCA as a decision-support tool. In this way, the meaning of the results obtained under Sec.3.3 is constructed. A policy analysis is conducted using the SSA to evaluate the effectivity and feasibility of the CBAM. This qualitative analysis is conducted under two different implementations of the CBAM. The difference in implementation depends on how the EU decides to assess the embedded emissions of imported products. They can choose to implement a benchmark which is set at the average embedded emissions in the EU or give enterprises complete freedom in deciding how to report their emissions. For each of these scenarios, conclusions will be drawn regarding their effectiveness in promoting the use of sustainable materials and consequently, use these conclusions to evaluate the feasibility and effectivity of the CBAM. A summary of each sub-question with the corresponding data collection method and the deliverable is shown in Fig.3.1.

Table 3.1: Overview of each sub-question with data collection method and corresponding deliverable.

Sub-question	Data collection method	Deliverable(s)
1. Adjustments in LCA data caused by purchase of sustainable materials	Literature study Case study Expert interviews	Overview of possible adjustments in choice of raw materials resulting in lowering embedded emissions of the machines
2. Assessment of effect of adjustments considering uncertainties	Online data libraries Case study Modelling	Statistical Sensitivity Analysis of sustainable adjustments on the total embedded emissions of the machines
3. Trade-offs	Online data libraries Case study Modelling	Cost-benefit analysis of costs associated caused by the use of sustainable materials against the benefits of reduced carbon costs
4. Feasibility and credibility of CBAM	Interpretation of results Modelling	Policy analysis of CBAM under different implementations with the goal of evaluating the CBAM on its credibility and feasibility

3.4 RESEARCH METHODOLOGY

To achieve the objective, described in 3.2, a case study-modeling approach is chosen. This approach will on one side consist of adding a statistical framework to the BESI LCA model. During this stage, the data of foreground processes will be adjusted to have a more sustainable design for BESI equipment. With this new model, a case study will be conducted to analyse the new carbon tax which BESI needs to pay under the CBAM. This case study will give answers on whether the use of more sustainable materials will result in different decisions by BESI regarding the CBAM. Furthermore, the focus is on whether it is economically and technically feasible to make changes in the design or to pay the carbon tax of the CBAM with the current design. Eventually, with these results, a reflection regarding the effectivity and feasibility of the CBAM is given.

The research methodology can be summarized as follows:

- Literature review on state-of-the-art use of LCA as a carbon accounting tool for decision-making purposes.
- Literature review on implementation of CBAM with corresponding actors, objectives, strengths and limitations.
- Assessment of possible adjustments in the procurement of raw materials for BESI semiconductor machines and their influence on the embedded emissions shown in the life cycle model.
- Analysis of the sensitivity and cost-benefit of this problematically distributed sustainable improvements in material choices on the total embedded emissions of the semiconductor machines.
- Interpretation of the results of the analyses conducted under 3.4 by modeling two policy scenarios and consequently analysing the CBAM on its effectivity and feasibility.

3.5 CASE STUDY

For this case study, the analysed semiconductor assembly machines are part of the back-end process for manufacturing semiconductors and electronics. High-tech semiconductor applications are one of the fastest-growing sectors of any technology. This is caused by the fact that many electronic applications contain a chip or microchip consisting of various layers of integrated circuits *Integrated circuit* (2023). At the background process of the production of these electronic devices, BE Semiconductor Industries (BeSI) supplies die attach systems based on state-of-the-art technology BeSI (2023). Die attach is known as the process of accurately picking and placing the die onto the substrate or PCB. Due to the high level of accuracy (up to micrometers), high reliability, and productivity, high-quality die attach equipment is needed. Due to the specificity and high demand for these machines, new machines are being developed every one or two years with a high level of weight for raw materials and energy. Therefore, this research project will analyse how to reduce these embedded emissions by changing the material and energy sourcing policy. The Datacon 2200 EVO^{Advanced}, as shown in Fig.3.2, is the die attach machine that will be analysed for this case study. In addition, an uncertainty analysis of the proposed improvement to give realistic advice for BeSI. This is not only relevant for the BeSI because of environmental changes, but also because of new policies proposed by the EU. The CBAM can significantly influence their trade flow and competitive position.

Figure 3.2: The Datacon 2200 EVO^{Advanced} machine

4 INVENTORY ANALYSIS

In this chapter, the life cycle model of the datacon EVO 2200*Advanced* semiconductor assembly machine, as modeled by BESI in cooperation with Lucerne University of Applied Sciences and Arts (Switzerland), is discussed. Moreover, the adjustments of the procurement of raw materials and their corresponding data are discussed. In this section, an analysis is given of how green materials could lower the embedded emissions of the EVO 2200 semiconductor machines. Eventually, the degrees of freedom of the raw materials of the semiconductor machines are identified and elaborated on. This information will be used to conduct the SSA in Sec.5.

4.1 LIFE CYCLE MODEL EVO 2200

The datacon EVO 2200*Advanced* machine consists of various parts. Firstly, the machine consists of a frame, which takes about 58% of the total weight. This frame holds the following modules Besi (2022):

- Front panel, hood, and covers
- Component supply (WT, WC, WL, WG, EJ, Flipp unit, Dipping, Base socket)
- Substrate handling (TS, without I/O System)
- Pick and Place incl. Bond head
- Dispenser incl. Dispenser holder
- Supply (control cabinet, pneumatics, cable set)
- Control (PC, controller (ETEL))

Furthermore, different tools are attached to the machine, depending on the wishes of the clients. These tools, however, account for a significantly smaller portion of the total mass of the machine. For the sake of simplicity, these tools will not be taken into account in this research project. Moreover, Fig.4.1 shows that a cradle-to-grave assessment approach is implemented. Therefore, all life cycle phases, from processing raw material to recycling of parts, are included. An overview of the steps of the calculation of the life cycle model of BESI with its data is shown in Fig.4.1. In each phase of the LCA, various metrics are used to calculate the energy needed for the process. These metrics consist on one hand of background data retrieved from online libraries Bey (2000) and on the other hand foreground data measured during the production and operation phase. For the raw materials phase, the energy required to produce steel is retrieved from an environmental evaluation in material and process selection study Bey (2000). In this step, the total energy required for the production of various materials, extracted from Bey (2000), are averaged out and implemented as fixed values. This estimation will influence the overall energy required for these materials since production processes do have a significant influence on the embedded emissions of materials. For steel, for instance, new production processes, for which less polluting energy sources such as hydrogen or gas are being implemented, the embedded emissions will be significantly lower than the average estimation. Also, each material requires different combinations of fuels and consequently, will require different energy values for production. In addition, these energy values, expressed in MJ, are converted to electricity, expressed in kWh. For this conversion, the model used the global overall efficiency of electricity production. These efficiencies also depend on the country of production. In the EU, the average overall efficiency production is estimated at 30% Bey (2000). This is also the value that is taken for the LCA model by BESI. This is also a rough assumption because the production process of raw materials such as steel and aluminium requires different fuel types. To make the assumption that all the energy required for the production process is converted to electricity, will result inaccurate calculations and hence, lead to inaccuracy in the calculations of the total embedded emissions. After all, the carbon intensity of electricity differs from that of gas and other fuels. In the last step, these energy values are converted to CO_2 values using the global average carbon intensity for electricity. Again, the carbon intensity of electricity varies across countries all over the world depending on which energy sources are used to produce electricity.

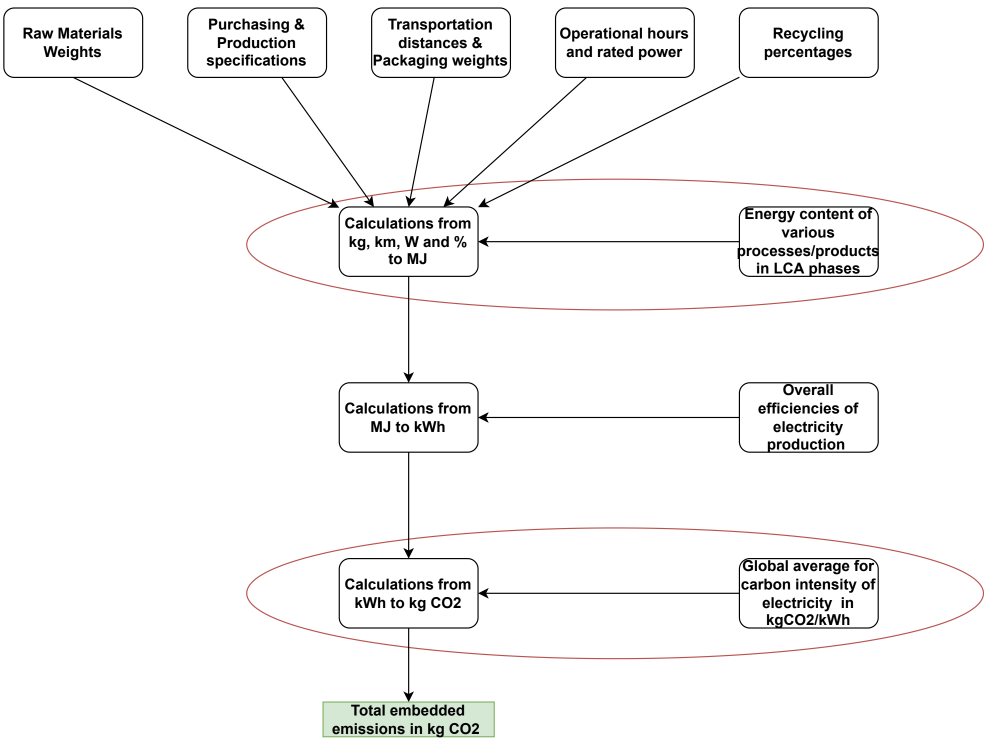


Figure 4.1: Overview of the calculations of the life cycle model values

The resulting life cycle energy model (LCEM) is shown in Fig.3.1. In this figure, some observations can be made. Firstly, the operation phase accounts for 82.5% of the total life cycle energy. This is caused by various factors. In the first place, the whole product lifetime is considered in the energy phase. In this phase, the assumption is made that the machine is operating for 24 hours for 10 years in three modes, namely process, idle, and rest. In each mode, the power consumption is set equal to the rated capacity. Secondly, the resources phase describes the energy embedded in the resources needed to operate the machine namely, vacuum for the substrate handling, clean dry air to avoid dust entering the assembled parts, and nitrogen for fabrication, assembly, and component soldering. Thirdly, the embedded energy of the tools is included in the operation phase since these tools are needed to operate the machine. Fourthly, the infrastructure consists of the energy required to operate the air conditioning of the room where the machine is placed. Furthermore, the scrapping phase which consists of recycling, burning, or landfill requires a portion of the energy. Eventually, the services phase which is needed for the maintenance of the machine is also included. All these factors together cause the operation phase to have the highest level of energy usage in comparison to the other phases. For the operation phase, BeSI did come up with new solutions to lower the energy usage in these phases by for instance using sleep mode or standby mode for various devices.

4.1.1 Degrees of freedom in raw materials

To create an understanding of the degrees of freedom of BESI in the life cycle of the datacon EVO $2200^{Advanced}$, the key parameters of the life cycle model that are affected by the CBAM have to be determined. As described in Sec.3.1, the emissions associated with steel, aluminium and electricity are variables that are subject to the CBAM. Thus, the steel, aluminium and electricity used in the production of the datacon EVO $2200^{Advanced}$ will be analysed.

As described above, the raw materials, purchasing and production, and packaging are of interest to the CBAM. However, when analysing the model thoroughly, it can be concluded that the in-house purchasing and production, and packaging account for less than 5% of the life cycle energy of the raw materials. Therefore, adjustments in these phases will lead to an insignificant improvement in comparison to adjustments in the raw materials. Knowing this, an overview of the structure of the raw materials is created, as shown in Fig.4.2: Fig.4.2 shows that steel and aluminium account for 82.5% of the total weight of the machine. Thus, adjustments in these materials will lead to the highest improvement in the output while at the same time not changing a lot of the business strategy and consequently keeping the costs of adjustment as low as possible.

In conclusion, for both the life cycle model and CBAM three main degrees of freedom with the highest influence have been identified. As described above, for both cases, purchasing more sustainable steel or aluminium as a base for the machine structure will lead to the highest improvements on the output side. Furthermore, when importing the whole machine, these are the key parameters that will be assessed by the CBAM and therefore also have a high influence on the carbon border tax which eventually needs to be paid.

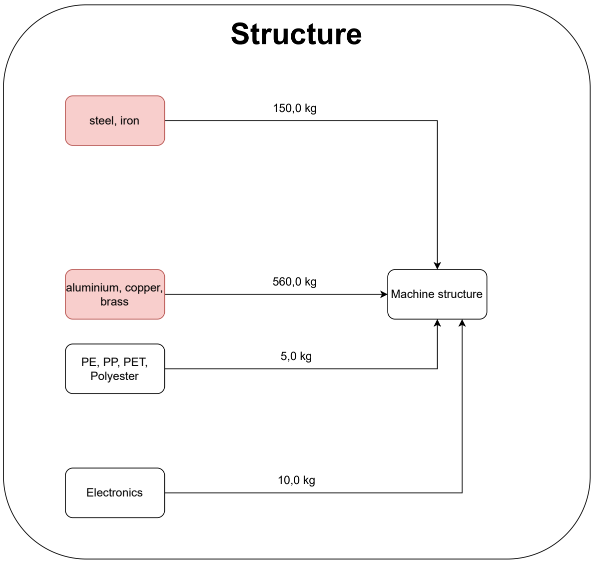


Figure 4.2: Raw material decomposition of the datacon EVO $2200^{Advanced}$.

4.2 CARBON INTENSITY OF ELECTRICITY

As shown in the last step of Fig.4.1, the global average for the carbon intensity of electricity is used to calculate the resulting embedded emissions in the various phases of the LCA. In this research project, however, the carbon intensities of all countries will be considered as a proxy to get a reasonable distribution of embedded emissions in electricity. An overview of these carbon intensities is shown in App.A.1.1. The carbon intensity of electricity will not be used in accordance with BESI's method described in Sec.4.1. Instead, the energy needed to produce steel and aluminium will be broken down into different categories (electricity, coal, gas, h2) and their respective carbon intensities will be used. App.A.1.1 shows that the data on the carbon intensity of electricity varies significantly Ritchie et al. (2020).

$$TCE = E_{Prod} \cdot CIE_i \quad \text{with i the corresponding country} \tag{4.1}$$

As shown by Eq.(4.1), the total carbon emissions (TCE) are straightforwardly calculated by multiplying the electricity required for the production process E_{prod} with the CI_E. Countries X with a low CIE will have a lower TCE than country Y with a high CIE for the same product. By integrating all the CIE of all countries a clear overview of the difference in TCE is given.

4.3 PRODUCTION PROCESSES OF STEEL

To have an overview of the range of the energy required for the production of steel and aluminium, the production processes of both raw materials will be assessed. As shown in Fig.4.1, the BESI LCA model uses an average value to calculate the embedded emissions of steel, which corresponds to the emissions produced during the conventional production process of steel. As distinguished by *Material Economics* (2019), new production processes are of significant importance to achieve an industrial transformation to net-zero emissions. They not only play a huge role in the pathway that will lead to sustainable processes but are also necessary for a circular economy. Therefore, this section will give an elaboration on the new processes for steel production.

During the transition to sustainable steel production, three main steps can be identified R. Wang et al. (2021):

- The present-day production route: the Blast Furnace - Basic Oxygen Furnace (BF-BOF)
- First emissions reduction step: Direct reduction with natural gas and electric arc furnaces (EAF's)
- Second emissions reduction step: Direct reduction with hydrogen and EAF's

For this research project, it is chosen to analyse the three main production routes; the classic one with the highest CO2 intensity, namely the Blast Furnace - Basic Oxygen Furnace (BF-BOF), one in between the transition to fossil-free steel production, namely the direct reduction with natural gas and electricity and one of the lowest CO2-intensity, namely the Hydrogen Direct Reduction (H-DRI) R. Wang et al. (2021). In each production route, the fuel types are modeled either as a constant or as a probability distribution as illustrated in Fig.4.3. This approach will be discussed more thoroughly in Sec.5.1. These production routes are chosen because firstly, the BF-BOF route is currently used in 60% of the current steel production *Material Economics* (2019), and secondly, the H-DRI route is seen as one of the most promising carbon-neutral steelmaking technologies R. Wang et al. (2021) and therefore, these routes are together with the transition route useful to serve as the range of the sensitivity analysis of the embedded CO2 in steel. As shown in Fig.B.1, there are various other production processes between both extremes *Material Economics* (2019). The specifics of the aforementioned production routes are given in App.B.1 and B.2.

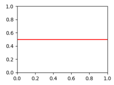
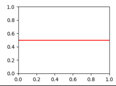
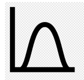
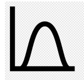
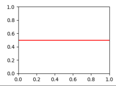
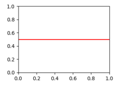
	Coal	Natural gas	Electricity	Hydrogen
BF-OF				
NG-DRI				
Yellow H-DRI				
Green H-DRI				

Figure 4.3: Breakdown of each production route with its corresponding fuel type and modeling approach

4.4 PRODUCTION PROCESS OF ALUMINIUM

The production process of aluminium is seen as one of the most energy-intensive production process in the industry. Due to the strong chemical bonding between aluminium and oxygen, the production of aluminium requires significantly more energy than steel Farjana et al. (2019). In this process four main stages are identified Cushman-Roisin & Cremonini (2021): bauxite extraction, alumina purifying, aluminium melting, aluminium ingot casting. A visualization of the production process is shown in Fig.B.4.

Each stage requires a different amount of energy. An overview of the energy consumption per production stage is shown in Tab.4.1. The energy consumption per stage is broken down into fractions with specified energy types for each stage. Since the mining stage occurs outside the factory and is a small fraction of the total energy consumption, this production stage will be left out of the analysis. Also, the 'other' energy type takes up to 54% of the energy consumption in this stage. However, the energy mix of this energy type is not specified and can therefore not be analysed accurately. Thus, during the analysis, the refining, smelting, and casting production stage will be used to implement sustainable improvements in the electricity and gas used in the process. A further elaboration on this process and its specifics are given in App.B.4.

Table 4.1: Overview of energy consumption per production stage as described by Cushman-Roisin & Cremonini (2021)

	Energy consumption		**Energy type**		
	MJ/kg	Fraction	Electricity	Gas	Other
Refining	44.5	17.1%	12%	80%	7.5%
Smelting	193.6	68.6%	85%	3%	12%
Casting	38.6	13.7%	38%	51%	11%
Total	279.0	100%			

In this research project, the focus will be on sustainable aluminium that is produced with electricity with a lower carbon intensity and on the elimination of the emissions caused by the gas used in the process. This elimination will be caused by the use of carbon capture technologies that capture the emitted CO_2 caused during the combustion of the gas. In both production routes, the fuel types are modeled either as a constant or as a probability distribution as illustrated in Fig.4.4. This approach will be discussed more thoroughly in Sec.5.1.

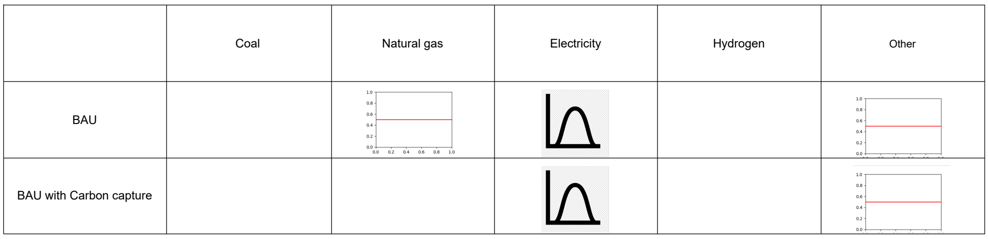


Figure 4.4: Breakdown of each production route with its corresponding modeling approach

5 IMPACT ASSESSMENT

The integration of sustainable steel or aluminium also depends on economic aspects. For BESI, it is of utmost importance what the price of this steel is in comparison to the use of conventional steel. Aluminium is considered an expensive raw material in comparison to steel for instance. Therefore, as described for the case of steel, a cost-benefit analysis will be conducted to analyse the economical feasibility of this recommendation depending on key parameters which influence the price for both the costs and savings. Also, the carbon price has a significant influence on the attractiveness of this option. If the reduction in carbon border tax due to the use of green materials is not significantly higher than the extra costs associated with green steel, it will make this transition less attractive. To assess these considerations, a cost-benefit analysis will be conducted in Sec.5.2.

After assessing the impact of both steel and aluminium in the production process of the Datacon EVO 2200^{Advanced}, both components will be aggregated to have a total impact assessment of the aforementioned improvements on the resulting embedded emissions. For this assessment, it is chosen to implement four comparison scenarios as described in Tab.5.1. The first two scenarios represent the most frequently used routes for the production of aluminium and steel. The distinction between both cases is made in the production route for steel. Here two options are assessed, namely the use of coal in the BF-OF route and the use of NG in the direct reduction route. These routes will be used to compare the benefits associated with the implementation of two so-called 'green' cases. For the green cases, the differentiation is also made in the production route for steel. Here also two options are assessed, namely the implementation of steel produced by green and yellow hydrogen through the direct reduction route. It is chosen to make two distinctions for steel because the production of steel more sustainably is at a more developed phase than the production of aluminium and therefore offers more space to apply various scenario comparisons.

Table 5.1: Breakdown of the different cases for the production of steel and aluminium and its use in the Datacon EVO 2200^{Advanced}.

	Production route	
	Aluminium	Steel
BAU option with coal	E, NG and other	BF-OF
BAU option with NG	E, NG and other	DRI-NG
Green case 1	E, CC and other	DRI-yellow hydrogen
Green case 2	E, CC and other	DRI-green hydrogen

5.1 STATISTICAL ANALYSIS

To analyse the influence of the use of more sustainable steel and aluminium, two approaches are proposed to model the energy required for the production process depending on the availability of data. The carbon intensity of electricity which has a significantly high number of data points and a high level of variety is modeled with a probability distribution that is fitted and sampled as will be described in Sec.5.1.1. The carbon intensity of burning gas or other fuels that have a lower number of data points, that do not have a high variety of information, there is no need for a probability distribution as the variety is not significantly high and hence, these variables are modeled discretely using their average values. An overview of the modelling approach for each energy type is shown in Tab.5.2. Next to the information on the modelling approach, each energy type used to model the energy required for the production of the raw material is indicated.

Table 5.2: Overview of the modelling approach for each energy type and its use in the raw material production process.

	Model		**Material**	
Energy type	Probabilistic	Discrete	Steel	Aluminium
Electricity	×		×	×
Hydrogen		×	×	
Coal		×	×	
Gas		×	×	×
Other		×		×

A Monte-Carlo simulation procedure is a statistical methodology whereby variables that are described by probability distributions are repeatedly randomly sampled to create an overall image of the specified variable Wu & Buyya (2015). Thus, depending on the probability distribution of the random variable, a value is given iteratively. To have meaningful outcomes simulations are conducted up to 1,000,000 times. Furthermore, it is proven to be useful to perform an analysis of the influence of the variety of the input and investigate the propagation of these varieties to the output of the system Dunn & Shultis (2023).

For the discrete parameters indicated in Tab.5.2, a straightforward implementation will be conducted in which average values of the carbon intensity of the energy types which are retrieved from the literature study and online libraries will be used to analyse the influence of these energy types on the total embedded emissions of the raw materials and consequently on the embedded emissions of the semiconductor machines. These values will not be sampled since they are not described by a probabilistic distribution. In this way, a one-on-one analysis will be conducted to analyse the influence of the use of sustainably produced steel or aluminium on the total embedded emissions of the machines.

To implement both analyses, Python is used as the programming language.

The energy types are modeled as a probability function or static function as indicated in Tab.5.2 and aggregated to form the total embedded emissions. In this way, the discrete parameters will be added as an offset to the range of the probabilistic values determined for the carbon intensity of electricity.

5.1.1 Monte-Carlo simulation procedure

To start sampling and the statistical analysis, data on the carbon intensity of electricity in various countries around the world have to be collected. Afterwards, a distribution has to be fitted on the data to create a distribution that can be analysed as an input for the resulting output of the LCA. When fitted, the inputs will result in a range of occurrences for each value found in the data set. In addition, to find the right distribution, the mean, standard deviation, minimum, maximum, and various confidence intervals of the population are calculated (i.e. the carbon intensity of electricity around the world) according to Eq.(5.1), (5.2). With this information, the best distribution for this variable is selected. Afterwards, a Monte-Carlo simulation is conducted for which the iterations can be chosen manually or automatically. After some trials, 500,000 iterations were chosen because this resulted in a sufficient level of accuracy while not taking much time to run.

$$\mu = \frac{\sum_{i=1}^{N} X_i}{N} \tag{5.1}$$

$$s = \sqrt{\frac{\sum_{i=1}^{N} (X_i - \mu)^2}{N}} \tag{5.2}$$

The total embedded emissions are constructed of a sampled probability function of the carbon intensity of electricity together with the offsets caused by the implementation of the discrete values of the energy types indicated in Tab.5.2. Consequently, this will result in a range of possible total embedded emissions, depending on the occurrence of each value. With this analysis, a conclusion could be made regarding the range of total embedded emissions of the system. A visualization of the described methodology is shown in Fig.5.1.

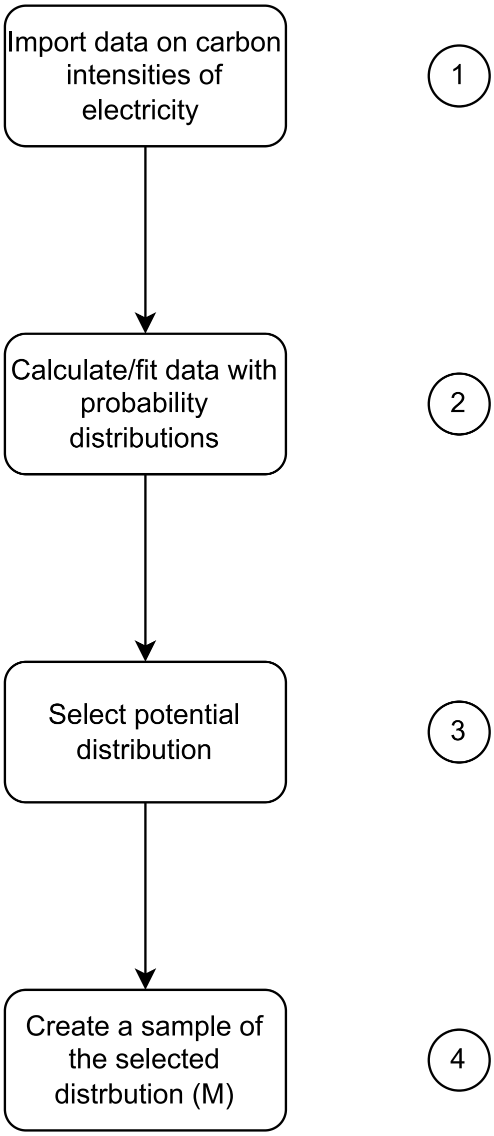


Figure 5.1: Methodological framework for the Monte-Carlo simulation procedure

In step 4 of the framework, shown in Fig.5.1, for the sake of simplicity, the choice is made to select a normal distribution. The author, however, acknowledges the fact that other distributions such as a uniform distribution could be used as well.

5.1.2 Carbon intensity of electricity model

To assess the variability and uncertainty of the carbon intensity of electricity in countries around the world, the Monte-Carlo simulation procedure, as described in Sec.5.1.1, will be implemented. Firstly, the data on carbon intensities of countries all around the world are collected. The 'In Our World' database powered by Oxford University Ritchie et al. (2020) is used to find the average carbon intensity of electricity in countries all around the world. It is chosen to use the average values of electricity generation instead of the marginal ones since the average values give a realistic representation of the carbon intensity of the generation of electricity in countries. The marginal values will put more emphasis on fossil fuels such as gas and coal, hence a negative image will be sketched which does not take all the energy sources into account. Also, the data for 2020 is used due to the lack of data availability for 2021 and 2022. To have a clear picture of the various options around the world, it is chosen to use less recent data with higher availability. Furthermore, the data used is shown in App.A.1.1. With this data, steps 2 to 5 of Fig.5.1 are conducted. The results are shown in Fig.5.2.

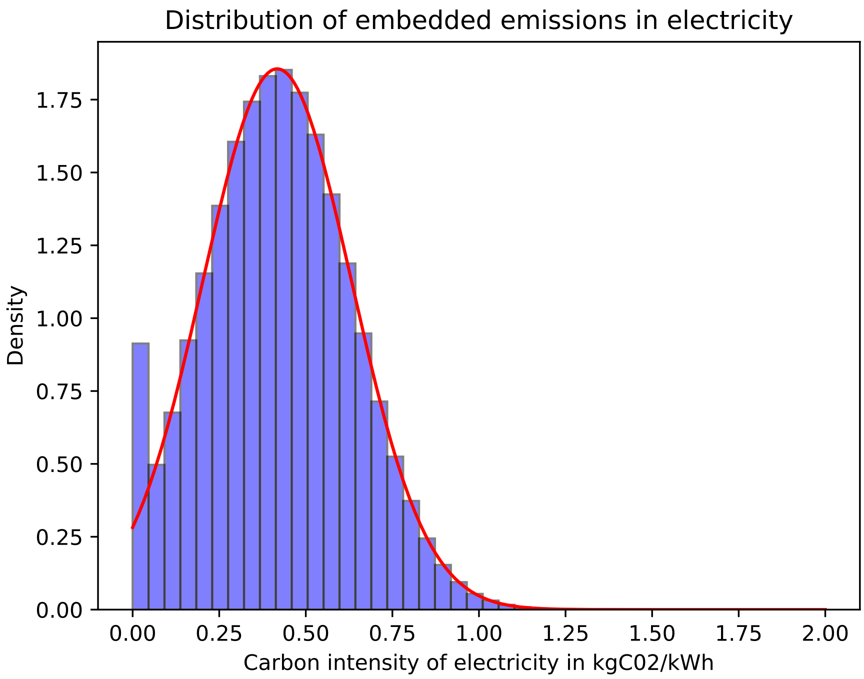


Figure 5.2: Probability distribution of the carbon intensity of electricity in kg CO_2/kWh

Fig.5.2 shows that it is chosen to have a sampled normal distribution for the carbon intensity of electricity. In Fig.5.2, it can also be identified that the normal distribution is cut off at zero carbon intensity of electricity because it is not realistic to have a negative carbon intensity of electricity. However, when sampling the carbon intensity of electricity with the identified mean and standard deviation, negative values appear and therefore it was chosen to not delete these values but add them to the bin located at zero carbon intensity of electricity. In this way, no data is deleted and at the same time, a realistic distribution is created and used for the model.

5.1.3 Raw materials model

As described in Sec.5.1, for energy types with deterministic data points with little variation a straightforward sensitivity analysis is conducted. Firstly, the influence of the use of 'green' steel on the embedded emissions of the semiconductor machine is analysed by incorporating the data from case studies and online libraries together with the model of the carbon intensity of electricity as illustrated in Fig.5.2. Secondly, the influence of the carbon intensity of electricity on the embedded emissions of aluminium is analysed by incorporating the results obtained in Sec.5.1.2 in the production process of aluminium. Also, new technologies such as carbon capture mechanisms will be Incorporated in the model to analyse the influence of these technologies on the embedded emissions.

Steel

As described in Sec.4.3, three possible production processes of steel will be assessed in during this research project. The embedded emissions of these production processes are shown in Tab.5.3. With these results, a sensitivity analysis is conducted to evaluate the influence of the use of steel produced in various processes on the embedded emissions of the semiconductor machine as shown in Fig.5.3. Other production processes are also included, however, this is done for the purpose of giving an illustration of other cases as well and will not be further discussed in this research project.

Table 5.3: Results of CO_2 emissions of various steel production processes as found by *Material Economics* (2019)

Unit	Case 1 BF-OF	Case 2 Natural gas DRI	Case 3 H-DRI
tonne CO_2/tonne steel	1.9	1.1	0.025

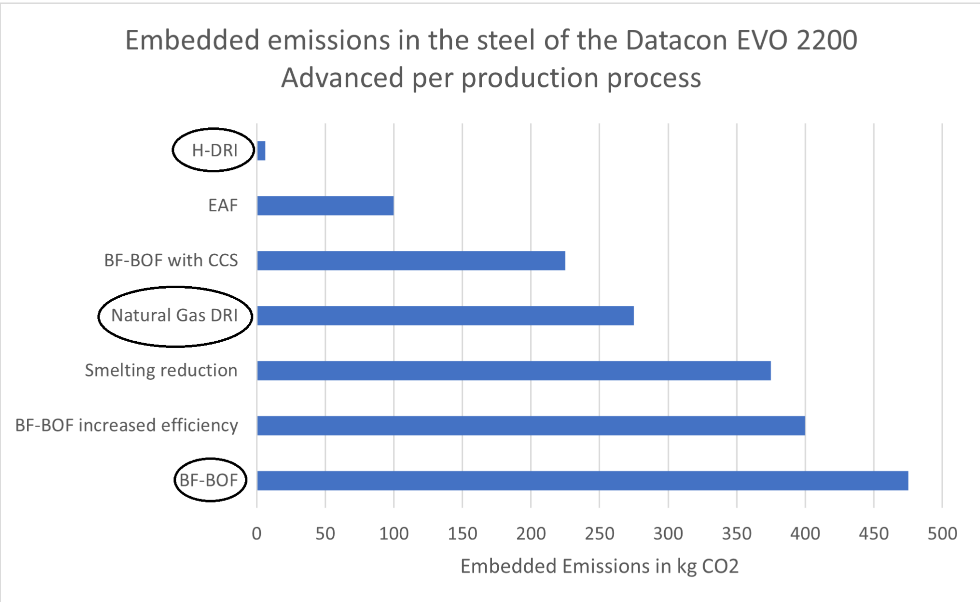


Figure 5.3: Embedded emissions in steel of Datacon EVO $2200^{Advanced}$ per production process

In Fig.5.3, an overview of the embedded emissions of steel in the Datacon EVO $2200^{Advanced}$ for each production process is shown. The cases that will be used in this research project are encircled. As discussed in Sec.4.3, Fig.5.3 shows indeed that steel production through Hydrogen Direct Reduction will lower the embedded emissions of steel in the Datacon EVO $2200^{Advanced}$ with

99.99% if the primary source of the electricity used in the production process of hydrogen is 100% renewable, also known as 'green' hydrogen. A grid-connected hydrogen plant, however, will result in the carbon intensity of electricity which is higher than zero and therefore the emissions in the steel production will also be higher than the values described in Fig.5.3. To have an accurate view of the use of grid-connected hydrogen for the production of steel, the yellow hydrogen route is modeled as the sum of the embedded emissions of the H-DRI route and the normal distribution determined for the carbon intensity of electricity, as described by Eq.(5.3). CI_E represents the probabilistic distribution of the carbon intensity of electricity and E_D represents the electricity demand required for the production of the steel of the Datacon EVO 2200^{Advanced}.

$$CO2_{yellow} = CI_E \cdot E_D + CO2_{green_{Off}} \text{ with } CO2_{green_{Off}} = CI_{green_{Off}} \cdot M_{steel} \quad (5.3)$$

The embedded emissions of the H-DRI are seen as an offset added to the normal distribution of the carbon intensity of electricity indicated as $CO2_{green_{Off}}$ in (5.3). The offset is calculated by multiplying the carbon intensity of the production of one kilogram of steel produced by the green hydrogen route with the mass of this green steel. This carbon intensity of the production of this type of steel is illustrated in Tab.5.3. In this way, the embedded emissions of both the green hydrogen process and electricity generation are taken into account to have a more accurate image of the embedded emissions for the yellow hydrogen production route. Fig.5.4 shows the results of the model and its range of embedded emission for the steel in the datacon EVO 2200^{Advanced} if the steel used in the machine is produced through the yellow hydrogen-route. Fig.5.4 shows indeed that the embedded emissions of the steel produced with the yellow-hydrogen route reflect the variability of the carbon intensity of the electricity used in the hydrogen production process.

As described in Tab.5.3, direct reduction with natural gas does reduce the embedded emissions of steel significantly and since the use of natural gas is seen as a pathway to a net-zero emissions industry, it is also included in the impact analysis. To model the embedded emissions associated with this route, a similar approach is implemented as described in Eq.(5.3). Since electricity is still needed for the electric furnaces used in this route, the carbon intensity of electricity is included alongside an offset created by the use of natural gas during the direct reduction stage. This approach is described in Eq.(5.4). The fractions, shown in Eq.(5.4), are obtained by analysing the ratios illustrated in Fig.5.3. Since the electricity used in the natural gas DRI-route is caused by the electric arc furnaces used in the production process, the ratio between the embedded emissions of the EAF and the natural gas DRI-route is used to find the ratios 0.3636 and 0.6364.

$$CO2_{NG} = 0.3636 \cdot CI_E \cdot E_D + 0.6364 \cdot CI_{NG_{Avg}} \cdot NG_D \quad (5.4)$$

Fig.5.4 visualizes the distribution of this route together with the yellow-hydrogen route. When comparing both distributions, a few observations can be made. Firstly, both distributions are indeed identical with different offsets caused by two different offsets namely $CI2_{NG_{Avg}}$ and $CO2_{green_{Off}}$. For the carbon intensity of natural gas, it is chosen to use the average value instead of an additional probabilistic distribution of the carbon intensity (CI) of natural gas because of its small level of variability. Secondly, there is a significant difference in the range of the embedded emission of both routes. Thus, it can be concluded that despite the fact that the NG-route is seen as the right step towards net-zero emissions from heavy industry, the implementation of yellow hydrogen will eventually have an even higher impact on lowering the embedded emissions of the Datacon EVO 2200^{Advanced}.

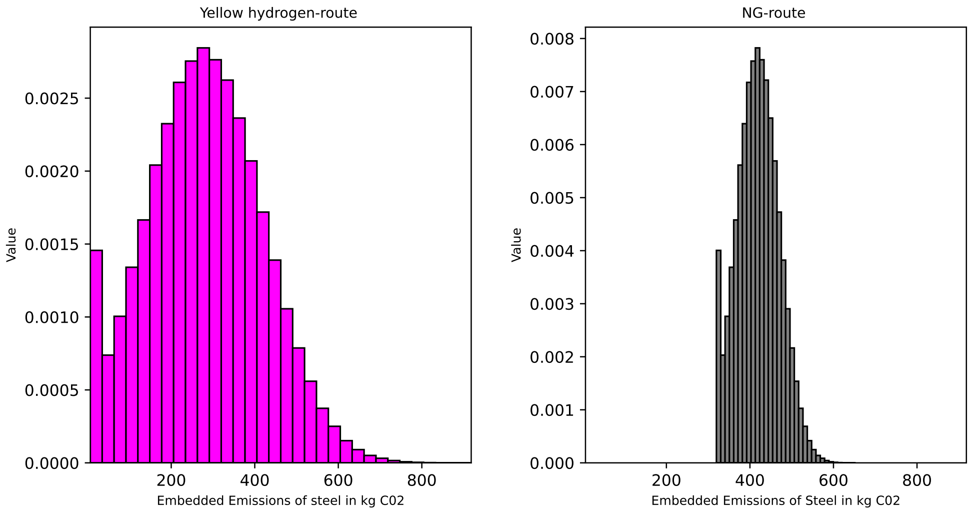


Figure 5.4: Distribution of the embedded emissions in kg CO_2 caused by the steel in Datacon EVO 2200^{Advanced} for two different production routes of the steel.

Aluminium

To lower the embedded emissions in the production process of aluminium, two possible solutions are considered in this analysis. Firstly, the use of electricity with a lower carbon intensity will reduce the embedded emissions of aluminium as depicted by Fig.5.2. This includes the use of cleaner grid-connected electricity or the implementation of renewable energy sources which are directly connected to the aluminium production site. Secondly, the implementation of carbon capture technology to store the carbon dioxide emissions caused by the combustion of natural gas. In this way, the embedded emissions caused by the use of natural gas will also be reduced and consequently, both fuels responsible for the highest fraction of the required energy in the production process will have a lower impact on the total embedded emissions of aluminium.

To have a consistent research approach and assess the carbon dioxide content of the natural gas used in the three production stages of aluminium, the average carbon intensity of burning one MJ of natural gas, indicated as $CI2_{NG_{Avg}}$, is used as described for steel case. In addition, for the energy type labeled as 'other', the average global carbon intensity of energy is used to calculate the remaining carbon dioxide emissions. This method is chosen since, due to its complexity, little information could be found on the remaining energy type and its energy mix. Therefore, it is assumed that the average global carbon intensity is sufficient to cover this part of the analysis.

Now that both the carbon intensity of electricity, the carbon intensity of natural gas, and the carbon intensity of the 'other' energy type are modeled, the distributions are aggregated according to the following equations:

$$CO2_{BAU} = CI_E \cdot E_D \cdot 0.65568 + CI_{NG_{Avg}} \cdot NG_D \cdot 0.22725 + CI_{E_{Avg}} \cdot E_D \cdot 0.11707 \tag{5.5}$$

$$CO2_{CC} = CO2_{BAU} - CI_{NG_{Avg}} \cdot NG_D \cdot 0.22725 \tag{5.6}$$

The numerical values in both Eq.(5.5) and (5.6) correspond to the fractions of the total energy consumption which are consumed by each energy type as illustrated in Tab.4.1. The results of both models implemented for the Datacon EVO 2200^{Advanced} are shown in Fig.5.5. As described in Sec.4.1.1, the mass of aluminium corresponds to 78.9% of the total weight of the semiconductor machine, hence the high level of embedded emissions of aluminium in comparison with the embedded emissions of steel as shown in Fig.5.4. Furthermore, it can be distinguished that for the BAU-route shown in Fig.5.5 the range of embedded emissions relatively high is due to the fact that electricity is used as the main energy carrier in the production process of aluminium. Thus, as shown by Farjana et al. (2019), the use of electricity generated by a renewable energy source results indeed in a significant decrease of the CO_2 emissions. This can also be observed when comparing both the BAU-route and CC-route: the difference in the range of embedded emissions is not very significant. However, the CC-route indeed results in a lower mean and higher standard deviation and therefore still has a positive effect on the total embedded emissions of the semiconductor machines.

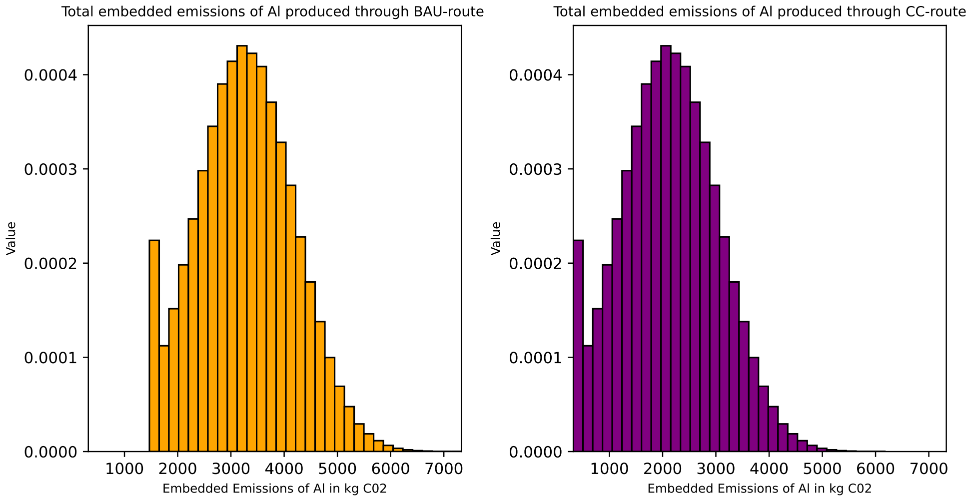


Figure 5.5: Distribution of the embedded emissions in kg CO_2 caused by the aluminium in Datacon EVO 2200^{Advanced} for two different production routes of the aluminium.

5.1.4 Aggregated output

The results of the cases described in Tab.5.1 are shown in Fig.5.6. A few observations can be made from this figure. Firstly, it shows that the use of coal or natural gas together with the BAU-route does have a significant effect on lowering the embedded emissions of the Datacon EVO 2200^{Advanced}. Secondly, it can be seen that the best reduction in embedded emissions is achieved when transitioning from the use of conventional steel and aluminium to the use of green steel and CC technologies. This will reduce the embedded emissions of Datacon EVO 2200^{Advanced} for almost 2000 kg CO2 per produced machine during its entire lifetime. Also, the integration of raw materials produced by green case 2 will cause a reduction of 1500 kg CO2 of embedded emissions in the steel and aluminium per produced machine, which is a significant value as compared to the expected value of 4187.047 kg CO2 of embedded emissions in the steel and aluminum per produced machine. An overview of the expected embedded emissions in steel and aluminium for each production route is shown in Tab.5.4. With these results, the cost-benefit analysis will be continued in Sec.5.2, in which the costs of these green cases will be assessed against the aforementioned benefits.

Table 5.4: Overview of expected values for each of the cases illustrated in Fig.5.6

Production route	Expected value (kg CO_2 per semiconductor machine)
BAU option with BF-OF	4918.65
BAU option with NG	4863.18
Green case 1	3576.85
Green case 2	3302.38

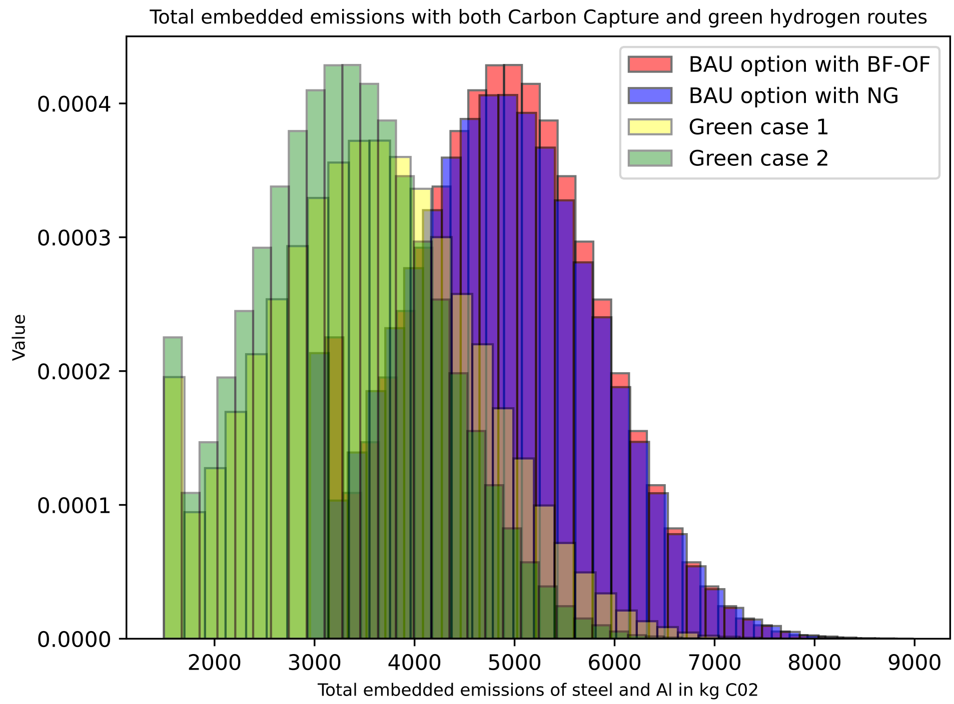


Figure 5.6: Distributions of the total embedded emissions of the steel and aluminium in the Datacon EVO 2200^{Advanced} for the four production routes of steel and aluminium described in Tab.5.1

5.2 COST-BENEFIT ANALYSIS

Now that the environmental impact of the implementation of green steel and aluminium is analysed, a financial cost-benefit analysis will be conducted. During a cost-benefit analysis, the extra costs associated with the use of green steel and aluminium will be weighed up against the reduction of the embedded emissions caused by the implementation of green steel and aluminium. The reduction of the embedded emissions will consequently lead to a reduction in the carbon border tax. In this section, this reduction in carbon costs will be compared with the extra costs of green steel and aluminium, so that a financial analysis will be constructed for the specific BESI case study.

5.2.1 EU Emissions Trading System carbon price

As described in Sec.2.1.1, the price of the carbon border tax is determined by the weekly auction price of carbon allowances traded in the EU ETS. Since the CBAM will be implemented first for basic products, the results towards the end of 2020s are therefore the most useful in providing a range of possible carbon prices as illustrated in Fig.2.3. The relevance of the predictions shown in Fig.2.3 is that they provide a range that can be used for the future cost-benefit analysis in this case study.

As described in Sec.1.3, however, the CBAM will be implemented gradually and thus companies will only be obliged to pay a border tax on a certain fraction of their embedded emissions. Therefore, it is decided to start the cost-benefit analysis from 80 euros to 180 euros per allowance to have a complete and realistic picture of what the cost associated with the border tax will be.

5.2.2 Costs improvements

To finalise the cost-benefit analysis, an overview of the costs associated with the transition to green steel and aluminium has to be analysed. Studies have shown that the costs of green materials are dependent on various aspects. Firstly, electricity prices play a huge role in the costs of both green steel and aluminium since both materials require electricity as their primary energy source for the production process. If the electricity price increases, the production costs for green steel and aluminium will also increase, and consequently the price for one tonne of green steel or aluminium will also increase. Furthermore, the future development of carbon prices will also put pressure on the transition to green materials.

Steel

As described in Sec.B.1, high quantities of coal are needed for the BF-OF production process. Therefore, producers in the EU need carbon allowances to be able to use coal and emit carbon dioxide into the atmosphere. Since coal is a heavily polluting fuel, more carbon allowances are needed than for less heavily polluting fuels. However, if the price of the carbon allowances is too high, producers will be more inclined to use less polluting fuels or to implement a more sustainable production process. Fig.5.7 gives an illustration of the relation of the aforementioned variables and the cost-competitive of the H-DRI, the Smelting Reduction with Carbon Capture and Storage, and the BF-BOF production process. *Material Economics* (2019) distinguishes for each variable a threshold: for the electricity price a value of 40 EUR/MWh and for the auctioned carbon price a value of 50 EUR/tCO_2. To have a profitable production scenario for the H-DRI process the CO_2 price has to be above 50 EUR/tCO_2. This requirement is already fulfilled as described in Sec.5.2.1. Also, the expectation is that this price will not be lower than 50 EUR/tCO_2 in the near future.

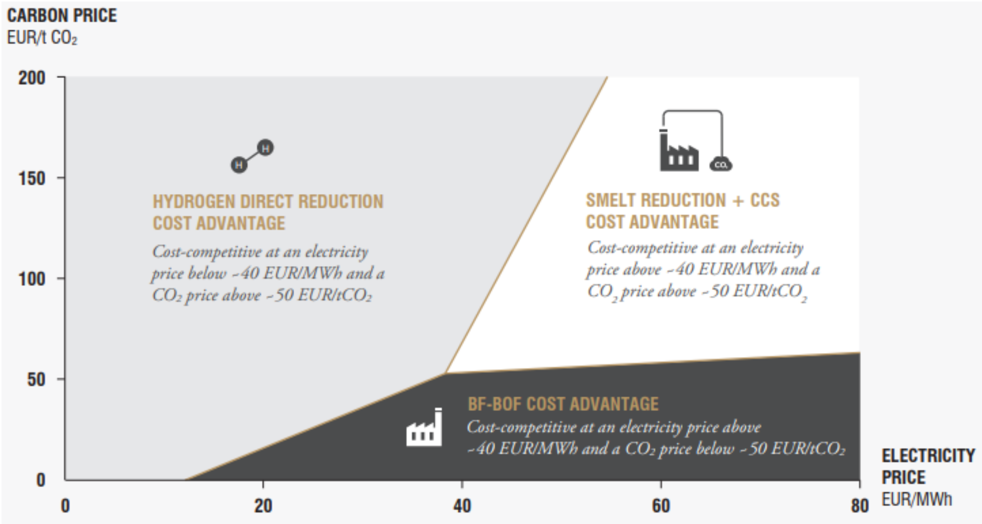


Figure 5.7: Visualization of the profitability thresholds for three steel production processes.
Source: *Material Economics* (2019)

Moreover, the capital expenditures (CAPEX) for low CO_2 production routes will be higher than the conventional routes since more sophisticated technology is needed in comparison to the BF-BOF production process. Especially, during the first years of implementation, the costs per tonne of steel will be much higher due to high investment costs and relatively low level of familiarisation *Material Economics* (2019). This is illustrated in App.B.3.

Fig.5.8 visualizes the cost breakdown of the aforementioned production routes. It confirms that the H-DRI route is highly sensitive to the price of electricity; an increase of 50% in electricity price causes a 46.53% increase in production costs in EUR/tonne steel. Also, Fig.5.8 shows that the CAPEX for H-DRI is significantly higher than the BF-OF and EAF and even higher than the smelting reduction with Carbon Capture and Storage route, while this route still needs to overcome lots of challenges such as scale-up and public acceptance Laguna et al. (2022).

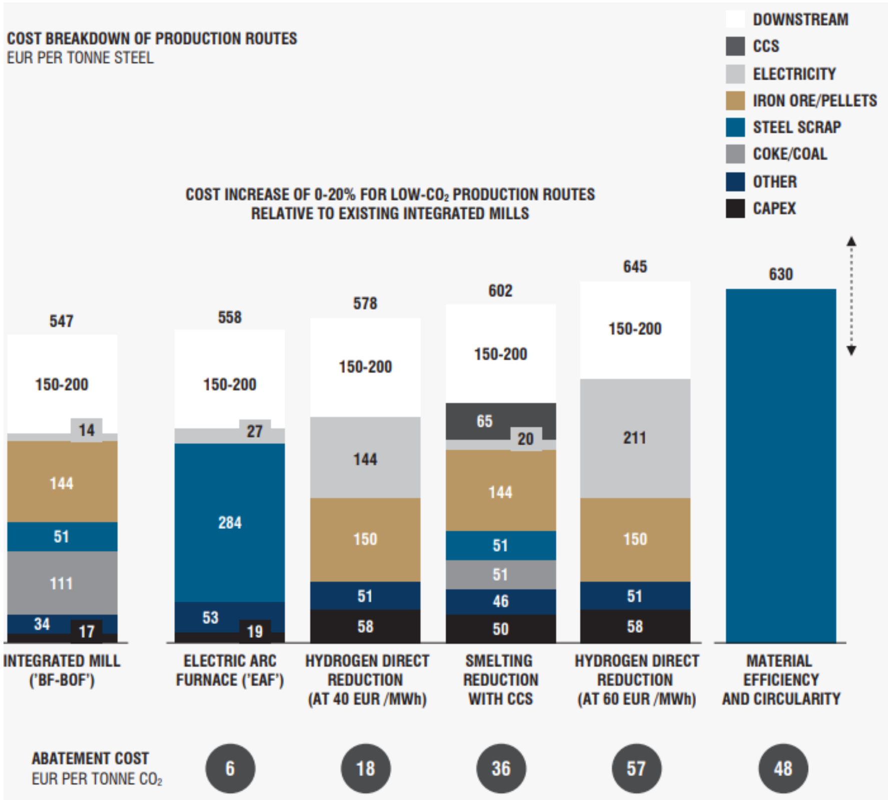


Figure 5.8: Predicted costs of various production routes.
Source: *Material Economics* (2019)

Eventually, it is decided that for the cost-benefit analysis of this research project, the assumption will be made that the electricity price is around a higher average of 60 EUR/MWh. The author, however, acknowledges the fact that this electricity price is too low for the current situation. On the other side, the CBAM is expected to be operational towards the end of the 2020s. Since the current electricity prices are due to temporary geopolitical issues in Europe, the predictions are that this price will be lower in the future. Also, before the crisis in Ukraine, at the beginning of the 2020s, the average electricity price in Europe was around 40 EU/MWh. Considering the fact that the price will not return entirely to the point before the war, 60 EUR/MWh is seen as a sufficient estimator for the foreseen future. Also, often a power purchase agreement (PPA) is performed between the electricity producer and the producer of steel in which a fixed electricity price is agreed upon. This strengthens the usability of a fixed nominal electricity price for this cost-benefit analysis. The carbon price, however, will be variable during the cost-benefit assessment as described in Sec.5.2.1.

In addition, the additional costs associated with the use of green steel are calculated by using the values described in Fig.5.8. For this analysis, the BF-BOF and yellow hydrogen direct reduction at an electricity price of 60 EUR/MWh are used as comparisons. By taking the difference between both routes and multiplying this with the mass of the steel in the Datacon EVO 2200^{Advanced}, the additional costs resulted in **24.5 EUR** per Datacon EVO

2200^{Advanced}. It must be noted that the value of 24.5 EUR only stands under the assumption that the electricity price is fixed at 60 EUR/MWh.

Aluminium

Since the transition to green aluminium is relatively new, there are not lots of studies conducted on the cost associated with this transition. According to Farjana et al. (2019), this is caused due to the lack of information on this transition. Nevertheless, Attwood (2021) conducted a recent study on the competitiveness of net-zero primary aluminium. During this study, the focus was on using clean energy during the smelting stage of the production process of aluminium. Fig.5.9 shows the results of this study based on the levelized costs of aluminium in $/ton.

The term 'clean energy' is not specified in the article and therefore statements regarding the costs of this material are hard to make. However, as different values of the CI_E are used in the model shown in Fig.5.5, clean energy is already considered in the model of this research project. Furthermore, the implementation of carbon offsets to neutralize the effect of carbon emissions differs significantly in quality and experiences a shortage in supply Attwood (2021). Therefore, this option is also not taken into consideration during the cost-benefit analysis. Furthermore, the CC-route, as described in Sec.5.1.3, does have a significant influence on the embedded carbon emissions of aluminium and shows a significant difference in production costs as shown in Fig.5.9. Thus, this option is compared with the BAU-route during the cost-benefit analysis. A similar approach is used as the aforementioned one for steel. This resulted in an overall extra production cost of **819 EU** per Datacon EVO 2200^{Advanced}. Both the extra costs associated with the implementation of green steel and aluminium are processed in Sec.5.2.3 to analyse the tipping points at which it is financially favourable for BeSI to invest in these technologies.

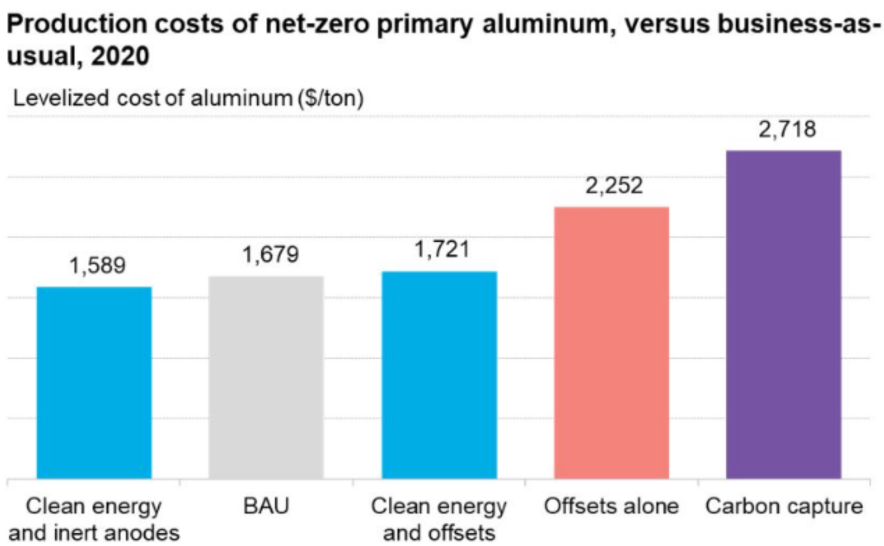


Figure 5.9: Levelized costs for various aluminium production routes. Source: Attwood (2021)

5.2.3 Tipping points

Now that both the costs and benefits of the implementation of greener steel and aluminium are analysed, the tipping points corresponding to a financially viable implementation are assessed. The conclusions of this CBA will later be connected with the achievable emissions reductions as indicated by the statistical analysis shown in Fig.5.6. For the CBA, it is decided to include three variables that influence this decision. Firstly, the carbon price in EUR/tonne CO2, which is modeled with a range of predicted values. This variable is included because the carbon price eventually determines the benefit gained by implementing greener materials. As described for both aluminium and steel cases, this gain is calculated by assessing the embedded emissions of the 'before' case and 'after' case: in Fig.5.6 visualized as the BAU-route and Green case. These two variables determine the saved expenses associated with the Carbon Border Tax. To have a financially favourable implementation, these savings have to be at least equal to the extra costs associated with the use of greener raw materials. If the savings are higher than the extra costs of these materials, then this transition would be financially attractive for BeSI. If not, there will be money lost, however, environmental progress will still be achieved. This relation is illustrated in (5.7). The supply chain data of BeSI showed that around 2000 Datacon EVO $2200^{Advanced}$ are being exported per year indicated as $\mathbf{U}_{total}$ in Eq.(5.7).

$$C_{improvements} = EUA_{price} \cdot |CO2_{BAU} - CO2_{green}| \cdot U_{total} \quad (5.7)$$

As described before, the extra costs for greener steel and aluminium are **844.27 EUR** per Datacon EVO $2200^{Advanced}$. This results in a total extra cost of 1,688,542 EUR/year associated with the use of sustainable steel and aluminium. This is shown in Eq.(5.8).

$$1,688,542 = EUA_{price} \cdot |CO2_{BAU} - CO2_{green}| \cdot U_{total} \quad (5.8)$$

This result together with the aforementioned variables is visualized in Fig.5.10. The blue line represents Eq.(5.7). The orange line represents the total extra costs of 1,688,542 EUR/year.

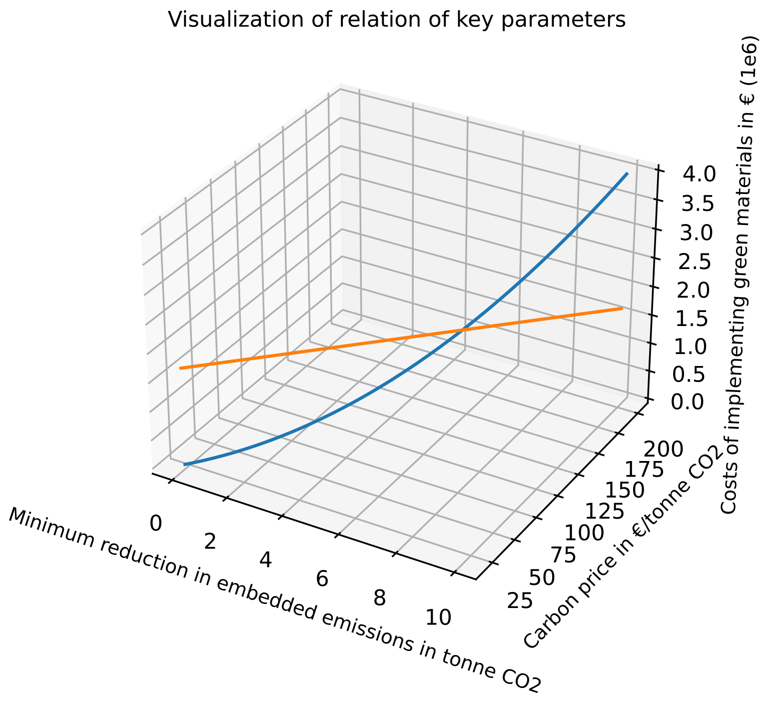


Figure 5.10: 3-D plot of the relation of the change in embedded emissions after improvements, carbon price and costs associated with these improvements.

The result of Eq.(5.8) with corresponding tipping points for each carbon price are shown in Fig.5.11.

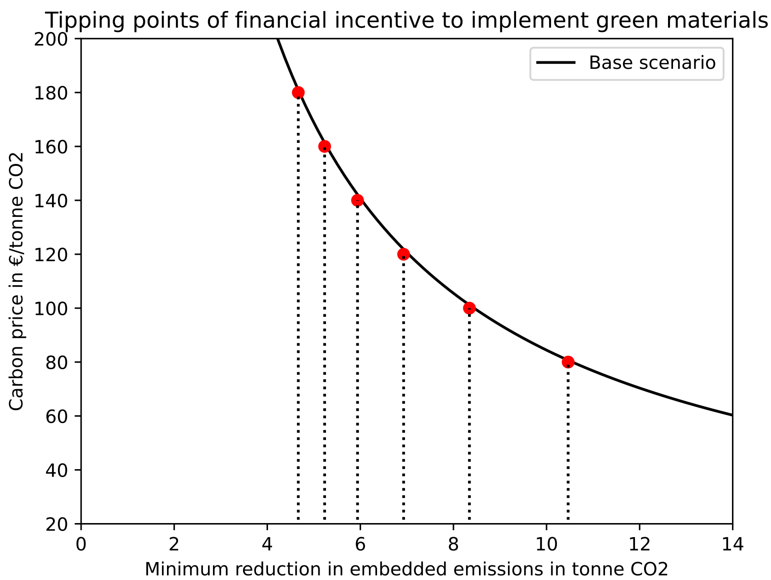


Figure 5.11: Visualization of intersection of each carbon price with Eq.(5.8)

This analysis resulted in the tipping points shown in Tab.5.5. These tipping points represent the minimal improvement in embedded emissions needed to reach a financially favourable situation. Tab.5.5 shows that the higher the carbon price, the higher the benefit caused by the sustainable improvements and the lower the range between the BAU and Green case must be to achieve a financially favourable situation. At this phase, the probability distributions such as Fig.5.6, are used to identify whether the required minimum reduction is achievable so that a financially viable implementation is achieved. Fig.5.6 shows that the probability of an improvement of 10 tonnes is close to zero, hence it can be concluded that for a carbon price of 80 EUR/MWh it is very unlikely that the use of greener raw materials will result in a financial benefit for BeSI. In addition, for a carbon price of 100 and 120 EUR/MWh, it is unlikely that a financial benefit will be reached from the recommended improvements. From 140 EUR/MWh onwards, it is more likely to achieve a financial benefit and thus not only implement greener materials for environmental, but also for financial purposes.

Table 5.5: Results of tipping point analysis for variable carbon prices

Carbon price (€/tonne CO2)	Minimum reduction tipping point (tonne CO2)
180	4.60
160	5.21
140	5.94
120	7.03
100	8.36
80	10.55

Moreover, an analysis is conducted into the sensitivity of the costs of improvements. For this analysis two additional cases are implemented: one with an increase of costs of 25% and one with a decrease of 25%. The dependence of the remaining variables is kept the same as described by Eq.(5.7). This analysis is conducted to research the influence of an increase or decrease of variables such as the price of electricity, the capital Expenditures (CapEx), or other variables on the minimum reduction needed to achieve a financially favourable situation. After all, these variables have a direct influence on the costs associated with the use of sustainable materials as illustrated in Fig.5.8. The results of this analysis are shown in Fig.5.12: the red dotted lines correspond to the intersections of the red graph with the different carbon prices and likewise for the other colors.

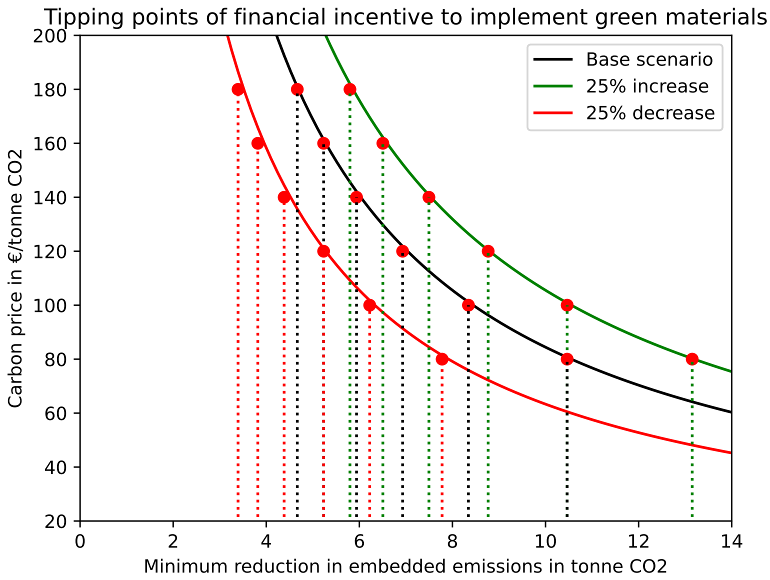


Figure 5.12: Visualization of the intersection of each carbon price with two additional scenarios according to Eq.(5.7)

In Fig.5.12, it can be seen that the higher the carbon price, the lower the minimum reduction difference is between the base scenario and the 25% increase scenario and the 25% decrease scenario. For a carbon price of 80 EUR/tonne CO2, the difference between the intersections of the graphs is the highest, while for a carbon price of 180 EUR/tonne CO2, the difference between the intersections of the graphs is the lowest. This means that for carbon prices above 120 EUR/tonne CO2, the sensitivity of the costs of improvements on the minimum reduction required is lower than under this price. Thus, the effect of a change in the costs of improvements will be higher for carbon prices lower than 120 EUR/tonne CO2 than for higher carbon prices.

To make conclusions regarding the results of the impact assessment, the results have to be interpreted first. There is no connection established between the results of the SA and the CBA. More specifically, there is no direct relation between the distributions shown in Sec.5.1 and the cost-benefit graph shown in Fig.5.11. This is done by purpose since this relation depends on the implementation of the CBAM: in particular, how the carbon reporting system will be designed. If the EU, for instance, determines that companies can determine independently their level of embedded emissions without restrictions, how would BESI deal with this situation given the analyses shown in Sec.5. The way the EU chooses to implement this system will therefore affect how BESI assesses the tipping points illustrated in Fig.5.11 and use it to determine whether it is financially viable to use sustainable steel or aluminium in their semiconductor machines. Therefore, the connection between the results of the SA and the CBA and the design options of the CBAM will be established and discussed further in Sec.6.

5.3 STAKEHOLDER ANALYSIS

Now that the impact assessment of the sustainable improvements is analysed quantitatively, it is also of utmost importance to understand the effect of these results on the border tax and which factors could play a role in this implementation. Before starting this interpretation, a stakeholder analysis will be conducted to understand the role and objectives of the actors involved in the CBAM. Furthermore, the decision-making arena will be highlighted with possible corresponding frictions which could arise due to differences in objectives and goals. In this way, a better understanding will be created to have a better understanding on how the results of Sec.5.2 can be interpreted in the real world.

5.3.1 Actors

To start the stakeholder analysis, the actors and their objectives will be highlighted first. The involved actors follow sources that explain how the CBAM will be implemented and what the division of tasks is. European Commission (2021) distinguishes various actors who are involved in the implementation of the CBAM. Firstly, the EU is the entity that is responsible for the design of this policy and therefore carries the responsibility of instructing the member states on how to implement and apply this policy on heavily polluting companies in their country. Furthermore, the EU assigns the responsibility of selling the EUAs to the competent national authority of the member states. Also, the national authority of the member state is licensed to repurchase up to 1/3 of the unused allowances of companies. In addition, BeSI has an obligation to the national authority in the EU to register and submit their CBAM report on the number of carbon emissions embedded in their products. With this report, they will be able to buy the required EUAs European Commission (2021). Also, they need to bring proof in case they already paid a carbon tax in foreign countries. In this way, they are protected from paying this tax twice. Moreover, BeSI can hire consultants which will inform them of the embedded emissions of their products using data from online libraries and/or measured data from BESI G.Korevaar (2022). On the other hand, BeSI can execute this LCA for various reasons other reasons depending on the goals of this assessment. LCA could be used for other purposes as well. From the interviews conducted, it became clear that the goal of this LCA was mainly the see in which part of the life cycle of the machine, adjustments can be made to increase sustainability. For this research project, it is used as a carbon accounting tool instead of an insight tool.

Also, the WTO reviews the CBAM and other trade policies and can come up with sanctions or adjustments if trade flows are affected by this policy. In the case of BESI, for instance, the National Authority of Malaysia could challenge the CBAM in the WTO with legal action Overland & Sabyrbekov (2022). In addition, the WTO can act as a forum for negotiations for the National Authority of Malaysia and help solve their issues regarding the CBAM together with the EU. In this way, each actor involved eventually has its own responsibilities and influence during the implementation of the CBAM. In Tab.5.6, a simplified overview is given of the key actors and their corresponding objectives. This overview presents a simplified version of the actors involved in and affected by the CBAM. Since the stakeholder analysis is not a central part of this research project, it was decided to only mention and include the key actors. For instance, the three entities of the EU, namely the European Commission, the Council and the European Parliament, which are involved in the implementation process are simplified to one entity named EU.

Table 5.6: Overview of relevant actors and their corresponding objectives

Actors	Objectives
1.Consultant	Objectively analyse the cradle-to-gate LCA of BESI products.
2.BESI	Report the most financially favourable amount of embedded emissions in their products.
3.National Authority EU	Ensure cooperation of importers of goods in their country.
4.EU	Demand a realistic tax on imported products into the EU.
5.WTO	Ensure trade is used as means to enhance living standards, make jobs and improve people's lives.
6.National Authority Malaysia	Ensure fair, stable and profitable trade flows in Malaysia.

5.3.2 Transactions

In Fig.5.13, a simplified overview of the key actors with their corresponding transactions is given. As can be distinguished in this figure, each actor described under Sec.5.3.1 is in some way connected and therefore dependent on each other. Therefore, it is of utmost importance to have a reliable, resilient, and trustworthy carbon accounting methodology to assess the embedded emissions of the products rightfully. The statistical analysis conducted in this research project showed that carbon reporting on imported products can have a high level of variety and hence, the discussion on how to implement and assess the CBAM will follow in Ch.6.

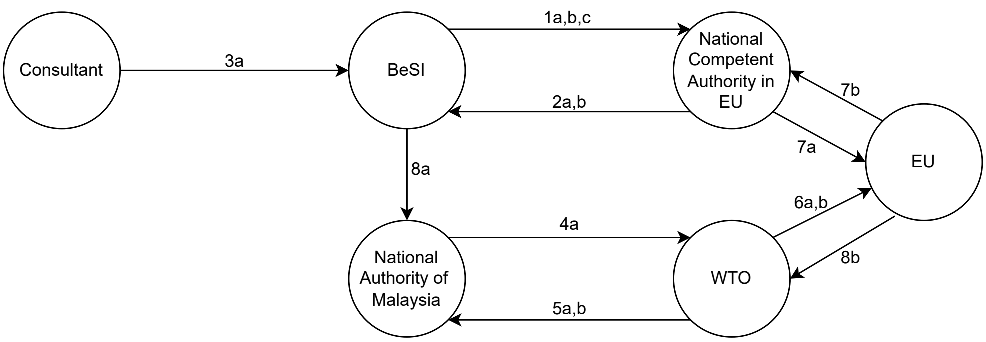


Figure 5.13: Overview of playfield with relevant actors

Tab.5.7 gives a description of the transactions corresponding to the relations described in Fig.5.13.

Table 5.7: Overview of relevant relations and their corresponding transactions

Indicator	Transaction
1a	Register with National Authority to buy CBAM allowances to compensate for emissions.
1b	Submit a CBAM report on the amount of carbon emissions embedded and CBAM allowances needed to cover this.
1c	If applicable prove that a carbon price is already paid in a foreign country, so that they could be excluded from buying CBAM allowances.
2a	Sells CBAM allowances to BESI.
2b	Repurchase up to 1/3 of un-used allowances from BESI.
3a	Objectively analyses and reports embedded emissions of BESI products.
4a	Challenge CBAM in world trade organisation (WTO) with legal action.
5a	Acting as a forum for negotiations.
5b	Building trade capacity for BESI.
6a	Reviewing CBAM.
6b	Come up with sanctions or adjustments regarding the trade flows affected by CBAM.
7a	Report back on progress of the implementation of the CBAM
7b	Instruct member states on execution of CBAM.
8a	Apply pressure to be exempted from paying carbon taxes.
8b	Report the policy outline of the CBAM that is inline with the WTO rules.

In this part of the analysis, a number of 'games' can be identified between the actors shown in Fig.5.13. A game arises when the actors anticipate the effect their actions will have on the behaviour of other actors in their playfield Romp (1997). From BESI's perspective, a number of games can be identified. Firstly, they can start applying pressure on the national authority of Malaysia to design their own carbon taxing system or to challenge the CBAM in WTO, knowing that the EU will implement the CBAM. This can consequently give rise to new discussions and challenges regarding the implementation of the CBAM and hence, delay the implementation of the CBAM to products down the value stream. In the case in which the EU does not have an effective method to analyse the certainty of the claimed emissions caused by the imported products, BESI can be inclined to show opportunistic behavior and report less embedded emissions to avoid paying the total amount of taxes caused by their products.

On the other hand, the EU can also anticipate certain actions from the actors involved in the implementation of the CBAM and act on them. Firstly, knowing that BESI of goods will challenge the CBAM in the WTO, the EU can work extensively on a fair and robust implementation of the CBAM with no violations of world trade rights. This will put them a step ahead when being tested since they already have considered certain legal aspects of the CBAM. Secondly, anticipating the fact that BESI can be inclined to show opportunistic behavior regarding the uncertainty in carbon reporting, the EU can be encouraged to design the carbon reporting process in such a way that the uncertainty is accounted for, so that BESI is less inclined to show this opportunistic behavior. In this case, the design of the CBAM has to be tested against the uncertainty in carbon reporting. This part of the game will be further analysed in the policy analysis conducted in Ch.6.

5.3.3 Frictions

Now that an overview of the relevant actors and transactions are shown in Fig.5.13 and described in Tab.5.13, a power-interest grid will be constructed to identify the different power levels of the stakeholders with corresponding interest levels Olander (2007). With these distinctions, potential allies and opponents of the outcome can be determined. In this way, potential frictions between stakeholders are identified and will be used in Sec.6 to review whether the objectives of the CBAM could be achieved taking into account these frictions.

The main outcome analysed for this part is the implementation of the CBAM for this case study considering the uncertainty in the cradle-to-grate data. As shown in Fig.5.14, the key actors described in Tab.5.7 do have different levels of interests regarding the implementation of the CBAM. For instance, BESI and the national authority of Malaysia do not have a high interest in the implementation of such a policy since this will affect their position in the world trade negatively. BESI, however, can have a higher interest than the national authority of Malaysia since the CBAM has the potential to make their products Eco-friendly and therefore give them a stronger trade position in comparison to their competitors, especially now with the growing demand for Eco-friendly products. Furthermore, they are also located at the upper half of the power axis due to the fact that BESI has to report the embedded emissions in their products and consequently giving them the power to choose to reduce these emissions or pay the carbon border tax. Also, the WTO is placed in the middle since this they are considered to be neutral in this case. After all, the WTO does not have any financial or legal interest in the implementation of the CBAM as long as it is done according to the WTO rules. However, the reader should keep in mind that this could change depending on the implementation of the CBAM as will be discussed in Sec.6.

On the other side of the y-axis, both the EU and the corresponding member states are located. Depending on which EU member state the semiconductor machines are exported to, this member state will have the power to ask for a report of the embedded emissions. However, the EU designs the climate laws that have to be executed by the member states. Therefore, their level of power is higher than that of the member state. Also, their position creates a tension field between both sides of the y-axis and consequently could lead to friction. Therefore, the WTO is placed between both to act as a negotiator and preserve world trade flows. Eventually, the consultant is added to the crowd since the consultant informs on the embedded emissions of the imported goods, hence he or she can have an interest in the CBAM because it brings them work but he or she does not have any power since they do not have any influence regarding the decision-making of both the semiconductor machines or the CBAM.

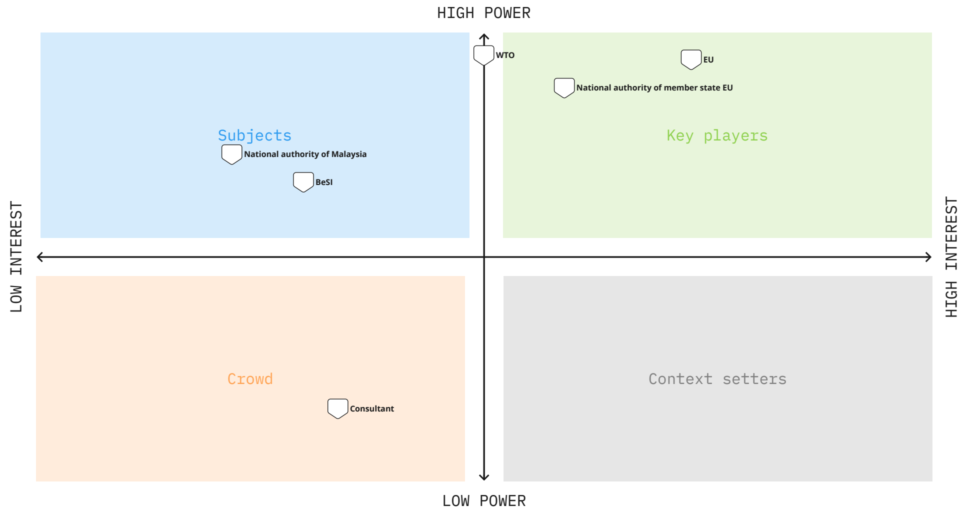


Figure 5.14: Overview of PI-grid with key actors as described in Tab.5.6.

6 INTERPRETATION

As discussed at the end of Sec.5.2, this chapter will outline three extreme policy scenarios regarding the implementation of the CBAM, and based on these policies, scenarios will give three interpretations of the results shown in the impact assessment. It must be noted to the reader that these scenarios are implemented as a thought experiment and are considered extreme. This makes them, however, useful to analyse whether uncertainty influences the carbon reporting process and consequently the ability of the CBAM to promote the use of sustainable steel and aluminium in semiconductor machines. In the first scenario, the EU gives BESI the freedom to report their embedded emissions as they see fit. In this case, the EU does not consider the uncertainty in the carbon reporting process and makes the assumption that BESI will be entirely truthful. In the second scenario, the EU does take the uncertainty into account and hence, decides to implement a benchmark at the average of the CI_E distribution. For the third scenario, the EU considers the uncertainty in carbon reporting extremely and assumes that BESI will not be entirely truthful and hence, implements a benchmark at the top five percent of the CI_E distribution. For all three policy scenarios, the CI_E distribution is analysed because the CI_E is the only parameter that is modeled probabilistically as shown in Tab.5.2. An illustration of the described policy scenarios is shown in Fig.6.1. Therefore, BESI can, for instance, can report that they bought the steel embedded in their machines from a country or producer that uses electricity with a low CI_E for the production process of their steel or aluminium. This encapsulates the uncertainty that could possibly occur during the carbon reporting process for the CBAM.

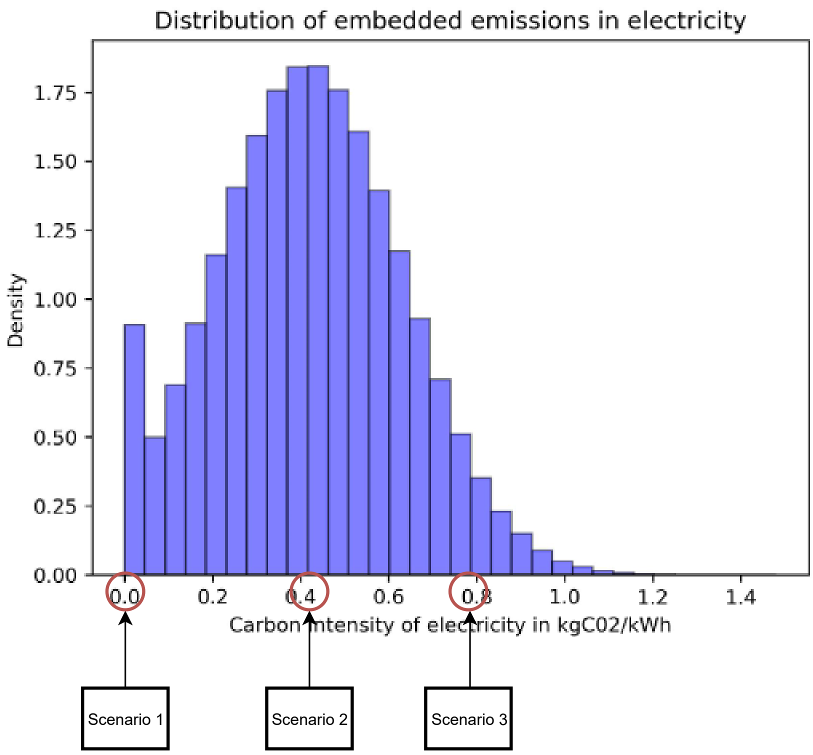


Figure 6.1: Schematic overview of the described policy scenarios illustrated in the probabilistic distribution of CI_E.

The final objective of the composition of these policy scenarios will be to assess how each policy scenario will trigger BESI to choose emissions points on the x-as of Fig.5.6 and consequently how these choices translate to carbon border tax according to Eq.(5.8). The results of this assessment are shown in Tab.6.1. The results show that independent of the policy scenario, an unrealistic carbon price is needed to give BESI a financial incentive to implement sustainable steel and aluminium in their semiconductor machines. Thus, under the current circumstances, BESI will be inclined to pay the carbon tax instead of implementing sustainable materials. Based on these insights, a conclusion will be given in which these results will be used to assess the feasibility and effectivity of the CBAM.

Table 6.1: Overview of the reduction in embedded emissions per semiconductor machine per policy scenario and its corresponding carbon price

Policy scenario	Resulting reduction per machine (tonne CO_2)	Minimum required carbon price (EUR/tonne CO_2)
Scenario 1	1.637	515.74
Scenario 2	1.358	621.70
Scenario 3	1.127	748.80

6.1 POLICY SCENARIO 1

During the transitional phase, as described in European Commission (2021), importers will have to report the embedded emissions of their products. During this phase, however, they will not be obliged to pay the carbon tax since this phase is seen as a testing phase of the CBAM. Therefore, the EU will ask the corresponding member state to collect this information at the company of interest. Thus, it is assumed that companies can have the freedom to report their emissions as they see fit.

To set out a possible outcome for this policy scenario, a few assumptions will be made beforehand. Firstly, it is assumed that the costs of green steel and aluminium are kept constant as illustrated in Fig.5.8. In this wat, the cost-benefit analysis conducted in Eq.(5.8) will be leading in assessing the possible outcome for each policy scenario. The costs shown in Eq.(5.8) are calculated by considering the costs of yellow hydrogen and carbon capture technologies. Hence, both cases are used for all policy scenarios as indicated in Fig.6.2. The points that will be used to calculate the reduction in embedded emissions for this policy scenario are indicated with the red circle and arrows.

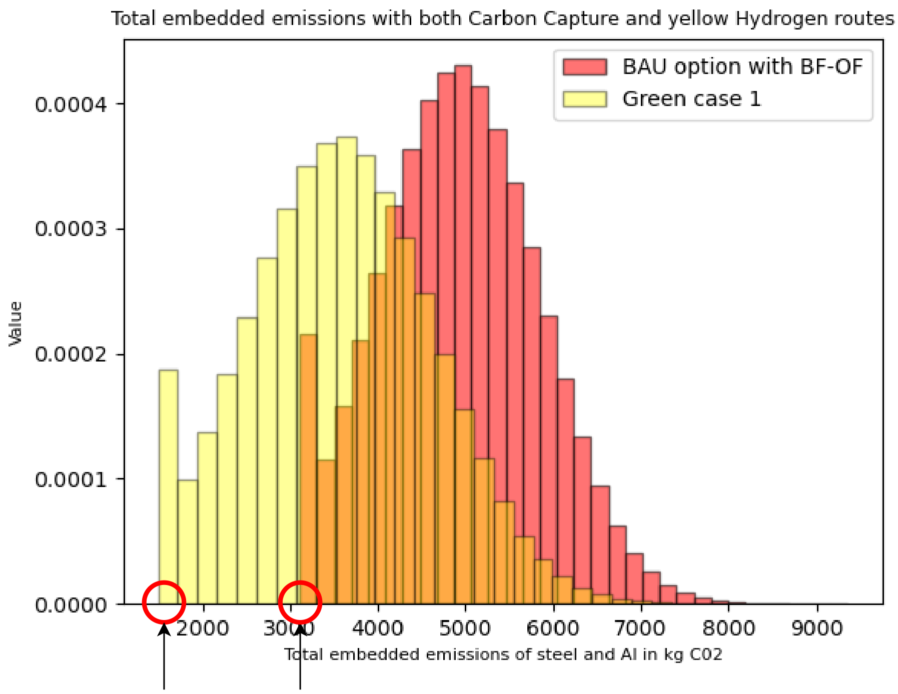


Figure 6.2: Distributions of the total embedded emissions of steel and aluminium in the Datacon EVO 2200^{Advanced} for two different production routes. A description of both routes in given in Tab.5.1.

Secondly, it will be assumed that BeSI chooses to make the most financially attractive decision in each scenario. Thus, for this policy scenario, BeSI will be inclined to report the lowest amount of embedded emissions because this will lead to the lowest carbon border tax and therefore is seen as the most attractive solution. Thus, for the BAU case, they will report that they use steel and aluminium produced with a zero carbon intensity of electricity; vice versa for green case 1. After all, this is the point with the lowest embedded emissions and consequently the lowest carbon border tax in both cases. Furthermore, it must be recalled that for each Monte Carlo simulation, random samples are created and simulated to design the probability distributions. Thus, each simulation will lead to a different point on the x-axis, hence it was chosen to run the simulation ten times and to take the average of these simulations. Summarised, the following approach is constructed for this policy scenario:

- Find the total embedded emissions for a zero carbon intensity of electricity on the x-axis (total embedded emissions) for both distributions shown in Fig.6.2. Both points are indicated by the red circles in Fig.6.2.
- Run ten simulations and store the zero values of both distributions after each simulation. Results are shown in App.A.4.
- Take the average of the difference of the zero point of both distributions.
- Use this difference to find the carbon price needed to break even according to Eq.(5.8).

This approach resulted in an average reduction of 1.637 tonne CO_2 of embedded emissions per semiconductor machine when transitioning from steel and aluminium produced via the BAU route with BF-OF to the green case 1 route. According to Eq.(5.8), this will result in a minimum required carbon price of **515.74** EUR/tonne CO_2 to break even with the costs associated with the sustainable improvements. Thus, for this policy scenario, a minimum carbon price of **515.74** EUR/tonne CO_2 will give BeSI an incentive to invest in the use of sustainable materials. The various models that predicted the carbon price for the upcoming 10 years which are shown in Fig.2.3 concluded that a price of 180 EUR/tonne CO_2 is to be expected in the future Pahle et al. (2022). Thus, it can be concluded that it is unlikely that under these circumstances a carbon price of **515.74** EUR/tonne CO_2 will be reached.

Moreover, this result also shows that the lower the standard deviation in the distributions shown in Fig.6.2, the lower the minimum carbon price to give BeSI incentive to invest in the integration of sustainable materials in the datacon EVO 2200^{Advanced}. A lower standard deviation in the distribution of the carbon intensity of electricity means that the carbon intensity around the world is located more around the average carbon intensity of electricity and is less spread out. Therefore, for the same average carbon intensity of electricity, the point of zero carbon intensity in the BAU route with BF-OF will increase faster than the increase in the point of zero carbon intensity in the green case 1 route. This statement is also tested by adjusting the standard deviation of the carbon intensity of electricity and analysing the difference between both zero points indicated in Fig.6.2. Therefore, we can conclude that higher penetration of renewables into the electricity grid will lower the minimum carbon price needed to give BESI incentive to invest in green steel and aluminium in their semiconductor machines. This observation will be discussed more extensively in Sec.6.4.

Furthermore, Eq.(5.8) has shown that, for this policy scenario, a higher difference between the CO_2 values of the BAU and the green case will lead to a lower minimum carbon price and hence make it more likely for BeSI to choose the adaptation of sustainable materials in their semiconductor machines. This can, for instance, be achieved by the use of green hydrogen instead of yellow. As shown in Fig.5.6, green case 2 will shift the distribution to the left, which locates the leftmost point more to the left and hence makes the gap between the zero-point of both distributions larger and consequently a lower minimum carbon price will be needed to create a financially viable implementation for BESI and hence, promote the use of sustainable materials across this industry.

In conclusion, the results of this policy scenario show that for the distributions shown in Fig.6.2 an unrealistic carbon price is needed to reach a financially favourable situation for BeSI. Therefore, for this policy scenario, it can be concluded that BeSI will be more inclined to pay the carbon border tax than to invest in the use of sustainable materials under the current circumstances and hence, the CBAM under this design will not promote the implementation of sustainable materials across the semiconductor industry. However, as noted before, depending on the evolution of the carbon intensity of electricity around the world and the costs associated with green steel and aluminium, this conclusion may be influenced.

6.2 POLICY SCENARIO 2

To prevent carbon leakage and level the production costs of products across all countries, the EU could choose to implement a benchmark against the average CI_E Titievskaia et al. (2022). With this benchmark, the average CI_E is seen as the reference point. In this way, importers will have an incentive to invest in sustainable materials to be as close as possible to this reference value to avoid any extra costs in the form of a carbon border tax. A similar approach was implemented during the implementation of the EU ETS Kuneman et al. (2022). To decrease the risk of carbon leakage under the EU ETS, the so-called free allowance allocation was implemented for producers that could have the incentive to move their production to countries with less strict climate policies Kuneman et al. (2022). However, with the implementation of the CBAM the risk of carbon leakage will be weakened due to the leveling of products in and outside the EU, and the free allowances will hence be gradually phased out.

As described for the aforementioned policy scenario in Sec.6.1, a few assumptions have to be made regarding the implementation of a benchmark against the average carbon intensity of the EU. Firstly, the assumptions described in Sec.6.1 will also apply to this policy scenario. Secondly, it will be assumed that the benchmark implemented is a product-based benchmark (PPB), so that it considers the datacon EVO $2200^{Advanced}$ as a whole. Moreover, to find the average carbon intensity of steel and aluminium of the datacon EVO $2200^{Advanced}$, Fig.6.2 is analysed. To find this value on the distribution, the average CI_E is found by taking the calculating the mean of the distribution shown in Fig.6.1. This resulted in 0.41733 tonne CO2/kWh. To find the corresponding embedded emissions and break-even carbon price for the cases shown in Fig.6.2, the following approach was applied:

- Find the corresponding total embedded emissions for the average CI_E around the world of 0.41733 tonne CO_2/kWh in the distributions shown in Fig6.2. With a function in Python, described in App.C, the corresponding bin with its exact x-and y-value is retrieved. This command is executed simultaneously for both distributions.
- Run ten simulations and store the corresponding x- and y-values of both distributions. Results are shown in App.A.4.
- Take the average of the difference of the x-values of both distributions.
- Use this difference to find the carbon price needed to break even according to Eq.(5.8).

This approach resulted in an average reduction of 1.358 tonne CO_2 of embedded emissions per semiconductor machine when transitioning from steel and aluminium produced via the BAU route with BF-OF to the green case 1 route. According to Eq.(5.8), this will results in a carbon price of **621.70** EUR/tonne CO_2 to break even with the costs associated with the sustainable improvements. Thus, for this policy scenario, a minimum carbon price of **621.70** EUR/tonne CO_2 will give BeSI an incentive to invest in the use of sustainable materials. The various models that predicted the carbon price for the upcoming 10 years which are shown in Fig.2.3 concluded that a price of 180 EUR/tonne CO_2 is to be expected in the future Pahle et al. (2022). Thus, it can be concluded that it is unlikely that under these circumstances a carbon price of **621.70** EUR/tonne CO_2 will be reached. Furthermore, this scenario showed that the difference between both points on the distributions became smaller which consequently leads to a higher carbon price, as illustrated by Eq.(5.8).

In conclusion, this analysis showed that for a relatively simple policy scenario, a higher carbon price is needed to create incentives for BeSI in order to invest in sustainable materials. Also, this policy scenario shows that BeSI will be more inclined to pay the carbon border tax than to invest in the use of sustainable materials.

6.3 POLICY SCENARIO 3

As described in the introduction of this section, the third and last policy scenario will consider the case in which the EU uses an extreme implementation of the CBAM. In this scenario, the EU implements the benchmark at the top five percent of CI_E as shown in Fig.6.1. In this case, one could say beforehand that BESI will not be inclined to use sustainable steel or aluminium because they will be paying a high carbon tax either way. On the other side, the EU will eliminate the uncertainty in carbon reporting caused by heavy polluters because everyone is obliged to pay the carbon border tax equal to the top ten percent whether the imported products cause these emissions or not.

To find the corresponding x-value that returns the lower bound of the 95 percentile of the distribution of the CI_E shown in Fig.6.1, Python is used. This analysis resulted in an x-value of 0.771. This value is also visualised in the distribution in Fig.6.1 above the block 'scenario 3'. To find the corresponding total embedded emissions, the same procedure is applied as described in Sec.6.2.

The aforementioned approach resulted in an average reduction of 1.127 tonne CO_2 of embedded emissions per semiconductor machine when transitioning from steel and aluminium produced via the BAU route with BF-OF to the green case 1 route. According to (5.8), a carbon price of **748.80** EUR/tonne CO_2 is needed so that BESI will be financially inclined to adopt the use of sustainable steel and aluminium in their semiconductor machines. From this analysis, it can be concluded that this design choice for the CBAM will not only charge importers a high carbon border tax but also limit the ability of the CBAM in promoting the use of sustainable materials in their products.

6.4 REFLECTION ON POLICY SCENARIOS

Both scenarios described in Sec.6.1 and Sec.6.2 needed an unrealistically high carbon price to result in a financially favourable situation when implementing sustainable materials in the datacon EVO $2200^{Advanced}$. Hence, the analysis showed that the implementation of the CBAM for high-tech products down the value stream with a relatively low mass such as semiconductor machines does not create a financially favourable incentive to make these machines greener with regards to raw materials. By analysing Fig.6.2, it became evident that the gap between the BAU with BF-OF and Green case 1 is not big enough to break even with the costs associated with the use of green materials. Even if the policy scenario is changed and hence different points on the probability distribution are chosen as reference points, it is impossible to come up with a carbon price that matches the predicted values shown in Fig.2.3.

As shortly described in Sec.6.1, there are options in which the difference between the BAU and green case can be made large enough to break even with the costs as described by Eq.(5.8):

- Firstly, the Monte-Carlo simulations showed that independently of the mass of the semiconductor machines and consequently the embedded emissions caused during the production process, the required carbon price to break even will not decline. The range becomes larger with increasing embedded emissions, however, the cost of the implementation of sustainable materials will also increase. After running five simulations, it became evident that the increase in costs of green steel and aluminium caused by a larger semiconductor machine eventually rise faster than the rise of the reduction of the embedded emissions when transitioning from steel and aluminium produced via the BAU route

BF-OF to the green case 1 route. Therefore, it was concluded that independent of the size of the semiconductor machine, the carbon price will still be too large to create a financial incentive for BESI to invest in green steel and aluminium.

- As mentioned shortly in Sec.6.1, Monte-Carlo simulations have shown that a lower standard deviation for the distribution of the carbon intensity of electricity will result in a larger range for both the BAU route and the green route. Consequently, this will lead to a relatively larger gap between both reference points of the BAU route and the green route. According to Eq.(5.8), this will result in a higher number for $|CO2_{BAU} - CO2_{green}|$. Because of that, the required carbon price will also decrease and BeSI will be more inclined to adopt these sustainable improvements.

  In other words, if the electricity is produced by renewable energy sources and consequently the carbon intensity of electricity is decreased and less spread around the world, the CBAM may create an incentive for BESI to use green steel and aluminium in their semiconductor machines. This means that for BESI the timing of the implementation of green steel and aluminium is a crucial aspect to gaining a financial benefit with regards to the CBAM. Thus, it is of utmost importance for BESI to monitor the transition to renewable energy sources, so that when the carbon intensity of electricity around the world is decreased and more centered around the average, the transition to green steel and aluminium is made to be and stay financially beneficial.

  For the EU, this observation shows that the CBAM may be successful in promoting the use of sustainable steel and aluminium in semiconductor machines if the carbon intensity of electricity around the world is decreased and more centered around the average carbon intensity of electricity. It could be argued that the EU anticipated this development and designed the CBAM using a long-term vision. In a future world, it is not unlikely that electricity around the world will be mainly produced by renewable energy sources, hence one may conclude that in the future the CBAM could be effective in promoting the use of green steel and aluminum.

- Lastly, another option is the decrease of costs of green raw materials around the world. By lowering the left side of Eq.(5.7), the required EUA_{price} will also decrease. Logically, this follows from the fact that with lower costs a break-even point will be reached faster.

With the aforementioned reflections, a review will be conducted in the next sections on the effectiveness and feasibility of the CBAM based on the results of this case study. The results of this review will also be able to make conclusions regarding the effectiveness and feasibility of the CBAM on products in general.

6.5 EFFECTIVITY CBAM

With the results of the impact assessment and interpretation conducted in Sec.5.2, 6.1 and 6.2, an analysis can be made regarding the effectivity of the CBAM for this case study in reaching its objectives as described in Sec.2.1.1. It is significant to analyse the level of effectivity of the CBAM. This analysis is useful for both the importers and the EU. Importers will have a better understanding of why they are paying a carbon border tax and the EU will have an insight into how effective the current CBAM design is in achieving its objectives. The first objective is to create a fair and competitive trade for both domestic and international producers by making the production costs, financial flows, and fossil fuels consumption even Mehling et al. (2019). The second objective is to support the climate action pathway of the EU by creating an incentive for importers to lower the emissions caused by their products European Commission (2021).

6.5.1 Objective 1

The results of the case study showed indeed that BeSI Apac, which imports a fraction of its products to Europe may be subject to the CBAM and therefore is obliged to pay the carbon tax associated with this policy. It becomes evident that the CBAM could have a leveling effect on the production costs of the semiconductor machines depending on the policy scenario. If policy scenario 1 is implemented, the effect will be very low because BESI can report lower embedded emissions for their machines than they really may cause. However, if policy scenario 2 or 3 are implemented, the potential for leveling the production costs will be much higher. In comparison to the situation before the CBAM: BESI would have a financial advantage over manufacturers in the EU due to the lower production costs.

In addition, if BESI chooses to make the transition to green raw materials, more capital will flow to producers of these materials. Because of the novelty of these materials, most of these producers are located in the EU: consequently more capital will flow back to the producers in the EU Vogl.V et al. (2021). This will indeed level the capital flows associated with the manufacturing of semiconductor machines. However, as the results of the policy analysis showed, with the current carbon prices the first policy scenarios will not give any financial incentive for BESI to make a transition to the use of green materials. However, it will result in a lower carbon border tax than scenarios 2 and 3 and hence, will lower the financial flows created in the form of the carbon border taxes. Scenarios 2 and 3, however, will increase the financial flows associated with the carbon border taxes because BESI has to pay a higher tax by the benchmarks applied in scenario 2 and 3.

The same applies to fossil fuel consumption. As the implementation of sustainable steel and aluminium in the EU is not enhanced in the aforementioned policy scenarios, BESI will financially be inclined to buy steel and aluminium with the lowest production costs and due to the EU ETS they will choose to buy these materials in countries outside the EU that have lower costs for steel and aluminium due to the less stringent climate policies in these countries. This also shows that the CBAM will not be effective in bringing more production to the EU.

6.5.2 Objective 2

The policy analysis conducted in Sec.6.1 and Sec.6.2 showed that to break even with the current costs of improvement an unrealistic high carbon price is needed as illustrated by Eq.(5.8). With the carbon price prediction shown in Fig.2.3, it is concluded that it is very unlikely that carbon prices of 500 EUR/tonne CO_2 will be reached. Thus, this case study showed that a company such as BeSI would be inclined to pay the carbon tax instead of implementing sustainable materials in their products under the current circumstances. However, the policy analysis also showed that a decrease in the carbon intensity of electricity will make it more likely for BESI to make the transition to the use of green steel and aluminium. Under the assumption that there will be an increase in the electricity produced by renewable energy sources, the CBAM may be successful in promoting the use of green steel and aluminium in semiconductor machines in the future.

Furthermore, the aforementioned disadvantages indicate that effective implementation of the CBAM depends on various variables such as the costs of green materials, electricity, and fossil fuels and the development of carbon prices. Therefore, it is very complex to give conclusions on the level of success of the implementation of the CBAM in general. However, this case study resulted in useful insights for the implementation of CBAM in this industry at this moment in time.

6.6 FEASIBILITY CBAM

The feasibility of the CBAM is also a factor that will be assessed in this research project. After all, the feasibility of the CBAM is aside from the effectivity an important factor to asses because it firstly influences the successful implementation of the CBAM and will give insights into the significance and suitability of the objectives with the actual implementation of the CBAM. As described for the effectivity in Sec.6.5.1, the feasibility of both objectives will be explored through the results of the impact assessment and interpretation shown in Ch.5 and 6.

6.6.1 Objective 1

Various strengths can be identified for the feasibility of the CBAM in this case study. Firstly, it should be mentioned that the results of the policy scenarios described in Sec.6.1, Sec.6.2, and Sec.6.4 showed that a less complex carbon reporting method of the CBAM will result in a higher required carbon price to give BESI incentive to invest in green steel and aluminium. One

could argue that, under the described assumptions and circumstances, a less complex implementation of the CBAM will make it more feasible to promote the use of green steel and aluminium in semiconductor machines.
Secondly, the results showed that in terms of the feasibility of leveling the production costs, the CBAM is supporting the industry in making the first steps towards a leveled playing field for producers in and outside the EU. The policy scenarios showed that BESI is indeed obliged to pay a carbon tax in all scenarios and hence, the carbon costs for producers and importers will be leveled. However, in most cases, the production costs of products in South-East Asia are relatively lower than the ones in the EU due to the lower wages. This could change in the future if production processes are automated on a larger scale in the EU. For the time being, however, the production costs will still remain lower in Asia even with the implementation of embedded emissions costs. This phenomenon will result in the same conclusion for capital flows.

Eventually, leveling of the use of fossil fuels will not be feasible since the EU is working on the transition to green energy, while parts of Asia are not at the same level regarding the energy transition and therefore will not be inclined to use less fossil fuel because of the CBAM. However, if the CBAM is successful in applying pressure on companies to take climate actions, Asian countries will be more inclined to use green energy and therefore the use of fossil fuels is slowly leveled. The author recognizes the fact that these statements are speculative and influenced by various outside factors and hence, new conclusions can be derived depending on the circumstances at that point in time.

6.6.2 Objective 2

The CBAM under the three policy scenarios described in Sec.6.1, 6.2 and 6.3 created no financial incentive for BESI to invest in sustainable steel and aluminium in their semiconductor machines. The assessment showed that under these extreme policy scenarios and the corresponding assumptions, it is not feasible to support the climate action pathway of the EU directly. Nevertheless, the policy analysis showed that a decrease in the carbon intensity of electricity caused by an increase in renewable energy sources will lower the required carbon price to make the transition to green steel and aluminium. Hence, it can be concluded that the CBAM may work very well in promoting the use of green steel and aluminium in a world with more renewable energy and hence, support the climate pathway of the EU.

The EUA predictions, as shown in Fig.2.3, are positive. Also, Fig.5.12 shows that a 25% decrease in the costs of green materials will decrease the required reduction by approximately 1 tonne CO2 for every datacon EVO 2200^{Advanced} to create a financial incentive for BeSI to invest in green materials. Together with the continuous increase in EUA prices, a best-case scenario could emerge in which it will be financially more attractive to invest in green materials than to pay the carbon border tax. However, the assumptions made for this scenario are far-fetched and are for the time being not realistic.

7 CONCLUSION AND RECOMMENDATIONS

In this chapter, a conclusion of this research project will be given by answering the main research question. To answer the main research question, the sub-questions will be answered first. Afterwards, the limitation of this research project will be enumerated and discussed. Eventually, this chapter will be closed with recommendations for future research.

7.1 CONCLUSION

The goal of this research project was to answer the following main research question:

Does the EU's CBAM promote sustainable adjustments in the production process of semiconductor machines, considering uncertainties in carbon accounting?

To answer this question, the sub-questions of this research will be answered first. Subsequently, the answer to the main research question will follow and a conclusion will be drawn.

SQ1: What sustainable choices in the procurement of materials can be made to lower the embedded emissions of semiconductor machines?

In Ch.4, an analysis was conducted on the LCA study performed by BeSI. From this analysis, it became evident that to assess the impact of the CBAM the production routes of the raw materials used in the semiconductor machines are relevant and consequently, an inventory analysis was performed in Ch.4 to find the materials that have the highest contribution to the embedded emissions in the datacon EVO 2200^{Advanced}. This analysis showed that the replacement of conventional steel and aluminium with greener versions of both materials will result in the highest decrease of the embedded emissions in the semiconductor machine. This analysis showed that BESI may change its materials sourcing policy so that it could deal with the CBAM strategically. On the other hand, the inventory analysis indicated that the CBAM may have an influence on the materials sourcing policy of BESI and other importers depending on the costs of the carbon tax and green materials.

SQ2: Can the effect of the implementation of green raw materials on the embedded emissions in semiconductor machines accurately be demonstrated or is the effect insignificantly due to uncertainty?

The statistical analysis conducted in Ch.5 showed that the effect of the use of green steel and aluminium on the embedded emissions of the datacon EVO 2200^{Advanced} is significant even with the consideration of the uncertainties. Fig.5.6 showed that the range of the total embedded emissions in the datacon EVO 2200^{Advanced} is shifted to the left of the graph with 1500 kg CO_2 per semiconductor machine. In other words, the mean value and 95% confidence interval are shifted 1500 kg CO_2 per semiconductor machine to left, resulting in a decrease of 1500 kg CO_2 per semiconductor machine. This is considered a significant difference since the discrete value for the total embedded emissions in the datacon EVO 2200^{Advanced}, as analysed by the model of BeSI shown in Fig.3.1, was 4187.047 kg CO_2 per semiconductor machine. This demonstration indicated that BESI analyse the range of the embedded emissions and hence, has a clear picture of how the embedded emissions will evolve if green steel and aluminium are embedded into the semiconductor machines. BESI can use this information to assess what impact green materials will have on the embedded emissions and how this relates to the costs of green materials. Assessing the possible environmental impact of CBAM on the specific semiconductor machine is relevant information for the EU to determine the effectiveness of CBAM in reducing the embedded emissions per machine.

SQ3: What trade-offs need to be considered by BeSI to make financially and environmentally favourable choices in terms of costs of improvement, carbon taxes, and policy context?

Ch.5 identified various variables that have to be taken into account that influence the costs of green steel and aluminium, the carbon price, and the policy scenario of the CBAM. This research project showed that the costs of these materials depend heavily on the costs of electricity. Due to its green characteristic, electricity is heavily used in the production process of both green steel and aluminium. The country in which steel and aluminium are produced is, therefore, of utmost importance. Countries with a higher level of renewable energy penetration will result in lower costs. On the other hand, the carbon price also has a significant influence because it gives producers and manufacturers a financial incentive to invest in greener materials. Independent of the policy scenario, the costs benefit analysis showed that depending on the carbon price, BESI needed different minimum reductions in embedded emissions to be financially favourable: for a carbon price of 180 EU/tonne CO_2, a minimum reduction of 4.60 tonne CO_2 was needed, while for a carbon price of 80 EUR/tonne CO_2 a minimum reduction of 10.55 tonne CO_2 was required. The different policy scenarios analysis also showed that depending on how the CBAM will be implemented, the required carbon price for BESI to be financially beneficial and make the transition to green materials will be astronomically high hence, under the current circumstances, BESI will not be inclined to make these changes and therefore would choose to pay the taxes. The analysis, however, showed a bright spot that indicated that the CBAM may be effective in a future electricity grid with a high penetration of renewable energy sources. In this case, the required carbon price decreased and hence, the threshold to make the change to green steel and aluminium decreased. One could argue that the EU implemented the CBAM with a long-term vision to accelerate the transition to sustainable energy and materials.

SQ4: What is the influence of the results of the impact assessment of this case study on the feasibility and effectivity of the CBAM?

During the evaluation of the effectivity and feasibility in Ch.6, it became evident that assessing both characteristics using the results of the impact assessment in Ch.5 is very complex. Therefore, the author was forced to make assumptions about factors that would influence the conclusions, for instance concluding that the CBAM is not effective in leveling the productions costs of domestic and international markets due to the fact that the production costs without taking the carbon costs into account are very different in Europe and Asia. However, the conclusion was made that it helped make this difference smaller. Furthermore, leveling the capital flows resulted in a similar conclusion; while the carbon border taxes helped in providing the EU with more capital flows, companies are still inclined to make new factories outside the EU because of the lower wages and consequently lower production costs. Moreover, the CBAM might have an influence on foreign countries concerning the implementation of climate policies. However, as shown by the stakeholder analysis, this depends very much on whether BESI would be inclined to put pressure on the national authority of Malaysia and whether the national authority will cooperate with the CBAM and/or file lawsuits at the WTO.

Now that the sub-questions are answered, an answer to the following main research question will be formulated:

Does the EU's CBAM promote sustainable adjustments in the production process of semiconductor machines, considering uncertainties in carbon accounting?

The tipping points obtained and discussed in Sec.5.2.3, Sec.6.1, and Sec.6.2 showed that the carbon price would have to be astronomically high to promote sustainable adjustments in the production of semiconductor machines. Thus, this case study showed that a company such as BESI would be inclined to pay the carbon tax instead of implementing sustainable materials in their products. On the other hand, the analysis indicated that the CBAM may be successful in promoting green materials in semiconductor machines as global electricity production becomes less carbon-intensive. In this case, the required carbon price to give BESI incentive to make the transition to green steel and aluminium will decrease and hence, the step to green materials will be easier made. Also, it must be mentioned that depending on the development of other factors such as the price of electricity, the price of coal and gas, and other variables, this conclusion might be influenced.

This research project showed that the use of a statistical framework will result in a better overview of how the variability in LCA data might lead to different conclusions and outcomes. This result is useful for both the EU and corresponding member states on one side and companies such as BESI and foreign countries such as Malaysia on the other side.

LCA can be seen as a decision support tool however, due to the uncertainties described in this thesis and the dependency of various variables on the outcome, it must be concluded that it can work as a support tool but decisions still have to be made depending on the situation of the current application of the CBAM. Therefore, it can help to give a clear understanding and image of how the range of these uncertainties and how they propagate to the output of the system. However, it remains a complex task to use LCA as a decision-making tool due to the high level of complexity of the products and the uncertainty of embedded emissions, the costs of materials, and a turbulent economy.

7.2 LIMITATIONS

During the research project, various limitations were identified. These limitations can be categorised into two main categories. Firstly, the limitations caused by the scarcity of the availability of data and secondly, the limitations caused by the approach or methodology applied in this research project.

7.2.1 Limited data

During the impact assessment, various analyses were conducted based on data from literature and online libraries, especially for the statistical analysis described in Secs.4.2, 5.1, and 5.2. After all, in these sections, the distributions and equations are constructed to model the embedded emissions of the datacon EVO 2200^{Advanced}. Also, this observation is strengthened by the fact that the impact assessment is built upon data used by BeSI to construct their life cycle assessment as illustrated in Fig.4.1 Besi (2022). Furthermore, the data from literature and online libraries are mostly obtained through research, hence this data will contain a deviation from real-life measurements. Therefore, the probability distributions which follow directly from this data will possess an error component. Also, the equations used to model the embedded emissions of various scenarios follow directly from this data. Therefore, the author acknowledges the fact that these distributions and equations do not represent actual real-life conditions. This is not only applicable to this case study but applies to most LCA studies conducted.

Moreover, during the cost-benefit analysis described in Sec.5.2, predictions of the carbon price and costs of greens steel and aluminium were used to implement a cost structure for the integration of these materials. Predictions also possess an error component caused by the fact that future outcomes of parameters are influenced by various variables. This makes the prediction of future outcomes very complex and uncertain. However, as described before, the aim of this part was to come up with a methodology to assess these influences, not necessarily to come up with the most accurate assessment. Therefore, a number of assumptions were made to partly cancel out these influences and have predictions that are useful for this case study.

Eventually, the results of the policy analysis showed that the spread and variability of the data influenced the conclusion regarding the use of sustainable materials strongly. As discussed in Sec.6.4, the standard deviation of the data impacted the minimum required carbon price to break even with the costs associated with green steel and aluminium. Thus, the data used during the statistical analysis is a crucial factor to determine the credibility of the conclusions.

7.2.2 Methodology

Furthermore, it must be pointed out that depending on the available data for the production processes of raw materials, the modeling approach can be different. In this case study, for the analysis of steel production, it was chosen to model each production process with the carbon intensity of electricity since for almost all processes except the BF-OF process, electricity is needed. In addition, the carbon intensity of gas is also implemented and used as a second layer on the carbon intensity of electricity to determine the embedded emissions of steel produced through the direct reduction with natural gas.

However, the literature does not specify how much fuel of each type is needed for the production process, so it is chosen to include the carbon intensity of electricity as a base for the production of steel and add to this base various other fuel offsets depending on the production process as illustrated in Fig.5.3.

As described in Sec.7.2.1, the credibility of this methodology depends on the accuracy of the data used to perform the statistical analysis. The author acknowledges this fact and hence, further research could be conducted to improve the methodology and decrease its influence on the data.

In conclusion, various assumptions were made that were necessary to conduct this research project but would indeed be categorised as limitations. The aforementioned limitations will be used to make overall recommendations so that future research can be built upon this research project.

7.3 FURTHER RESEARCH

From BESI's perspective, further research could focus on the influence of other variables on the tipping points found in Sec.6.1 and Sec.6.2. This research could focus on how the variability of the price of electricity, coal, and gas influences the outcome of the tipping points. Moreover, further research could be conducted into changing the design of the semiconductor machines instead of implementing sustainable materials. In this way, the total embedded emissions could also be lowered by using fewer materials or implementing them in a smarter way.

Furthermore, further research could also assess the ability of the CBAM to promote the use of sustainable steel and aluminium using other carbon accounting tools. In this way, it can be concluded whether the conclusions of this research project are specific for the case of LCA or also apply to carbon accounting tools in general. From the CBAM's perspective, other policy scenarios could be implemented to assess the ability of the CBAM to promote sustainable materials considering the uncertainty in carbon reporting. With the inclusion of additional scenarios, more concise conclusions could be made regarding the effectivity and feasibility of the CBAM because the assessment is not limited to the extreme scenarios but also other scenarios are considered.

Another interesting further research topic could be an analysis of the interactions and conflicts between countries in and outside the EU. This analysis can for instance include the economic, geopolitical, and social influence of the CBAM on the relations and interactions between non-member and member states of the EU.

BIBLIOGRAPHY

Attwood, J. (2021, jun 16). *Green Aluminum is Competitive Today. It's Time to Start Transforming.* Retrieved from https://about.bnef.com/blog/green-aluminum-is-competitive-today-its-time-to-start-transforming/ ([Online; accessed 2022-12-22])

Besi. (2022, March). *Eco design of machines: Potential estimation tool.*

BeSI. (2023). *Products and Technology.* https://www.besi.com/products-technology/productgroup/die-attach/. ([Online; accessed 2023-01-27])

Bey, N. (2000). The oil point method-a tool for indicative environmental evaluation in material and process selection. *Ph.D., Department of Manufacturing Engineering, Technical University of Denmark, Lynby, Denmark.*.

Bicalho, T., Sauer, I., Rambaud, A., & Altukhova, Y. (2017). Lca data quality: A management science perspective. *Journal of Cleaner Production*, *156*, 888-898. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652617306571 doi: https://doi.org/10.1016/j.jclepro.2017.03.229

Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., ... Ryberg, M. (2020, 08). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environmental Research Letters*, *15*. doi: 10.1088/1748-9326/ab89d7

Bruninx, K., & Ovaere, M. (2022, 03). Covid-19, green deal and recovery plan permanently change emissions and prices in eu ets phase iv. *Nature Communications*, *13*. doi: 10.1038/s41467-022-28398-2

Centre, J. R., for Environment, I., & Sustainability. (2011). *International reference life cycle data system (ilcd) handbook : general guide for life cycle assessment : detailed guidance*. Publications Office. doi: doi/10.2788/38479

Council of the EU. (2023, Dec 13). *Eu climate action: provisional agreement reached on carbon border adjustment mechanism (cbam).* (Press release 13/12/2023)

Cushman-Roisin, B., & Cremonini, B. T. (2021). Chapter 1 - materials. In B. Cushman-Roisin & B. T. Cremonini (Eds.), *Data, statistics, and useful numbers for environmental sustainability* (p. 1-16). Elsevier. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128229583000121 doi: https://doi.org/10.1016/B978-0-12-822958-3.00012-1

Dehnhardt, A., Grothmann, T., & Wagner, J. (2022). Cost-benefit analysis: What limits its use in policy making and how to make it more usable? a case study on climate change adaptation in germany. *Environmental Science and Policy*, *137*, 53-60. Retrieved from https://www.sciencedirect.com/

science/article/pii/S1462901122002465 doi: https://doi.org/10.1016/j.envsci.2022.08.005

DHL Global. (2022, Mar 21). *Dhl express announces two of the largest ever sustainable aviation fuel deals with bp and neste amounting to more than 800 million liters.* (Press Release: Bonn/Germany, March 21, 2022)

Dong, Y., Miraglia, S., Manzo, S., Georgiadis, S., Sørup, H. J. D., Boriani, E., ... Hauschild, M. Z. (2018). Environmental sustainable decision making– the need and obstacles for integration of lca into decision analysis. *Environmental Science and Policy*, *87*, 33-44. Retrieved from https://www.sciencedirect.com/science/article/pii/S1462901118302776 doi: https://doi.org/10.1016/j.envsci.2018.05.018

Dunn, W. L., & Shultis, J. K. (2023). Chapter 1 - introduction. In W. L. Dunn & J. K. Shultis (Eds.), *Exploring monte carlo methods (second edition)* (Second Edition ed., p. 1-24). Elsevier. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128197394000093 doi: https://doi.org/10.1016/B978-0-12-819739-4.00009-3

Elbanna, S., & Child, J. (2007). The influence of decision, environmental and firm characteristics on the rationality of strategic decision-making*. *Journal of Management Studies*, *44*(4), 561-591. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-6486.2006.00670.x doi: https://doi.org/10.1111/j.1467-6486.2006.00670.x

European Commission. (2021, jul 14). *Carbon border adjustment mechanism.* https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661. ([Online; accessed 2022-11-03])

Farjana, S. H., Huda, N., & Mahmud, M. P. (2019). Impacts of aluminum production: A cradle to gate investigation using life-cycle assessment. *Science of The Total Environment*, *663*, 958-970. Retrieved from https://www.sciencedirect.com/science/article/pii/S0048969719304474 doi: https://doi.org/10.1016/j.scitotenv.2019.01.400

Figures, T., Gilbert, M., McAdoo, M., & Voigt, N. (2021, October). *The eu's carbon border tax will redefine global value chains.*

G.Korevaar. (2022, Nov.). private communication.

Hinman, M. (2023, May). *Net zero trade policy.* (Carbon accounting for traded goods)

Huijbregts, M., Norris, G., Bretz, R., Ciroth, A., Maurice, B., Bahr, B., ... Beaufort, A. (2001, 05). Framework for modeling data uncertainty in life cycle inventories. *The International Journal of Life Cycle Assessment*, *6*, 127-132. doi: 10.1007/BF02978728

Hybrit. (2021, feb 13). Retrieved from https://www.hybritdevelopment.se/en/ ([Online; accessed 2022-12-02])

Integrated circuit. (2023, jan 26). https://en.wikipedia.org/wiki/Integrated_circuit. ([Online; accessed 2023-01-27])

ISO, I. (2006a). 14040. *Environmental management—life cycle assessment—principles and framework.*

ISO, I. (2006b). 14044. *Environmental management—life cycle assessment—principles and framework.*

KPMG. (2021, April). *Impact of the eu's carbon border adjustment mechanism.*

Kuneman, E., Kardish, C., Hall, M., & Acworth, W. (2022). Benchmark-based allocation in emissions trading systems: experiences to date and insights on design. *Berlin: ICAP*.

Kvande, H. (2011). 3 - production of primary aluminium. In R. Lumley (Ed.), *Fundamentals of aluminium metallurgy* (p. 49-69). Woodhead Publishing. Retrieved from https://www.sciencedirect.com/science/article/pii/B9781845696542500031 doi: https://doi.org/10.1533/9780857090256.1.49

Kvande, H., & drabløs, p. a. (2014, 05). The aluminum smelting process and innovative alternative technologies. *Journal of occupational and environmental medicine / American College of Occupational and Environmental Medicine*, *56 Suppl 5S*, S23-S32. doi: 10.1097/JOM.0000000000000062

Laguna, J. C., Duerinck, J., Meinke-Hubeny, F., & Valee, J. (2022, 03). Carbon-free steel production ;cost reduction options and usage of existing gas infrastructure,. *EU Panel for the Future of Science and Technology*. doi: doi: 10.2861/01969

LI, M.-F., HU, H., & ZHAO, L.-T. (2022, 04). Key factors affecting carbon prices from a time-varying perspective. *Environmental Science and Pollution Research*, *29*. doi: 10.1007/s11356-022-20376-x

Lovcha, Y., Perez-Laborda, A., & Sikora, I. (2022). The determinants of co2 prices in the eu emission trading system. *Applied Energy*, *305*, 117903. Retrieved from https://www.sciencedirect.com/science/article/pii/S0306261921012162 doi: https://doi.org/10.1016/j.apenergy.2021.117903

Material economics. (2019). Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry.

Mehling, M. A., van Asselt, H., Das, K., Droege, S., & Verkuijl, C. (2019). Designing border carbon adjustments for enhanced climate action. *American Journal of International Law*, *113*(3), 433–481. doi: 10.1017/ajil.2019.22

Nordhaus, W. (2015, April). Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, *105*(4), 1339-70. Retrieved from https://www.aeaweb.org/articles?id=10.1257/aer.15000001 doi: 10.1257/aer.15000001

Olander, S. (2007). Stakeholder impact analysis in construction project management. *Construction Management and Economics*, *25*(3), 277-287. Retrieved from https://doi.org/10.1080/01446190600879125 doi: 10.1080/01446190600879125

Overland, I., & Sabyrbekov, R. (2022). Know your opponent: Which countries might fight the european carbon border adjustment mechanism? *Energy Policy*, *169*, 113175. Retrieved from https://www.sciencedirect.com/science/article/pii/S0301421522003974 doi: https://doi.org/10.1016/j.enpol.2022.113175

Pahle, M., Sitarz, J., (PIK), S. O., & (Ecologic), B. G. (2022, November). *The eu-ets price through 2030 and beyond: A closer look at drivers, models and assumptions.* (Input material and take-aways from the Ariadne Workshop in Brussels)

Pasman, H. J., Rogers, W. J., & Behie, S. W. (2022). Selecting a method/tool for risk-based decision making in complex situations [Article]. *Journal of Loss Prevention in the Process Industries*, *74*. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85118494889&doi=10.1016%2fj.jlp.2021.104669&partnerID=40&md5=349b7e6b02f79d39415489154a3a17cf (Cited by: 4) doi: 10.1016/j.jlp.2021.104669

Pryshlakivsky, J., & Searcy, C. (2021, 05). Life cycle assessment as a decision-making tool: Practitioner and managerial considerations. *Journal of Cleaner Production*, *309*, 127344. doi: 10.1016/j.jclepro.2021.127344

Ritchie, H., Roser, M., & Rosado, P. (2020). Co2 and greenhouse gas emissions. *Our World in Data*. (https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions)

Romp, G. (1997). *Game theory: introduction and applications*. Oxford University Press on Demand.

Sahabuddin, M., & Khan, I. (2021). Multi-criteria decision analysis methods for energy sector's sustainability assessment: Robustness analysis through criteria weight change. *Sustainable Energy Technologies and Assessments*, *47*, 101380. Retrieved from https://www.sciencedirect.com/science/article/pii/S2213138821003908 doi: https://doi.org/10.1016/j.seta.2021.101380

Sandin, G., Peters, G. M., & Svanström, M. (2015). Using the planetary boundaries framework for setting impact-reduction targets in lca contexts [Article]. *International Journal of Life Cycle Assessment*, *20*(12), 1684 – 1700. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84947488707&doi=10.1007%2fs11367-015-0984-6&partnerID=40&md5=eb97432b99ace8ae10d0a4dd02274f56 (Cited by: 74) doi: 10.1007/s11367-015-0984-6

Seidl, D., Ružiak, I., Koštialová Jančíková, Z., & Koštial, P. (2022). Sensitivity analysis: A tool for tailoring environmentally friendly materials. *Expert Systems with Applications*, *208*, 118039. Retrieved from https://www.sciencedirect.com/science/article/pii/S0957417422012520 doi: https://doi.org/10.1016/j.eswa.2022.118039

Shiva Kumar, S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. *Energy Reports*, *8*, 13793-

13813. Retrieved from https://www.sciencedirect.com/science/article/pii/S2352484722020625 doi: https://doi.org/10.1016/j.egyr.2022.10.127

Steinparzer, T., Haider, M., Fleischanderl, A., Hampel, A., Enickl, G., & Zauner, F. (2012, 11). Heat exchangers and thermal energy storage concepts for the off-gas heat of steelmaking devices. *Journal of Physics Conference Series*, *395*, 2158-. doi: 10.1088/1742-6596/395/1/012158

Tillman, A.-M. (2000). Significance of decision-making for lca methodology. *Environmental Impact Assessment Review*, *20*(1), 113-123. Retrieved from https://www.sciencedirect.com/science/article/pii/S0195925599000359 doi: https://doi.org/10.1016/S0195-9255(99)00035-9

Titievskaia, J., Simões, H. M., & Dobreva, A. (2022, July). *Eu carbon border adjustment mechanism.* (Implications for climate and competitiveness)

Toniolo, S., Borsoi, L., & Camana, D. (2021). Chapter 7 - life cycle assessment: methods, limitations, and illustrations. , 105-118. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128239872000076 doi: https://doi.org/10.1016/B978-0-12-823987-2.00007-6

Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, *203*, 736-745. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652618326301 doi: https://doi.org/10.1016/j.jclepro.2018.08.279

Vogl.V, Sanchez.F, T, G., F, L., Bhaskar.A, Swalec.C, ... Rootzén.J (2021). Green steel tracker. *Leadit*. (https://www.industrytransition.org/green-steel-tracker/)

Wang, E., & Shen, Z. (2013). A hybrid data quality indicator and statistical method for improving uncertainty analysis in lca of complex system – application to the whole-building embodied energy analysis. *Journal of Cleaner Production*, *43*, 166-173. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652612006543 doi: https://doi.org/10.1016/j.jclepro.2012.12.010

Wang, R., Zhao, Y., Babich, A., Senk, D., & Fan, X. (2021). Hydrogen direct reduction (h-dr) in steel industry—an overview of challenges and opportunities. *Journal of Cleaner Production*, *329*, 129797. Retrieved from https://www.sciencedirect.com/science/article/pii/S095965262103972X doi: https://doi.org/10.1016/j.jclepro.2021.129797

Wu, C., & Buyya, R. (2015). Chapter 18 - real option theory and monte carlo simulation. In C. Wu & R. Buyya (Eds.), *Cloud data centers and cost modeling* (p. 707-772). Morgan Kaufmann. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128014134000180 doi: https://doi.org/10.1016/B978-0-12-801413-4.00018-0

Zhao, J., Zuo, H., Wang, Y., Wang, J., & Xue, Q. (2020). Review of green and low-carbon ironmaking technology. *Ironmaking & Steelmaking*, *47*(3), 296-306. Retrieved from https://doi.org/10.1080/03019233.2019.1639029 doi: 10.1080/03019233.2019.1639029

A DATA

A.1 CARBON INTENSITY OF ELECTRICITY GLOBAL

A.1.1 Graphs

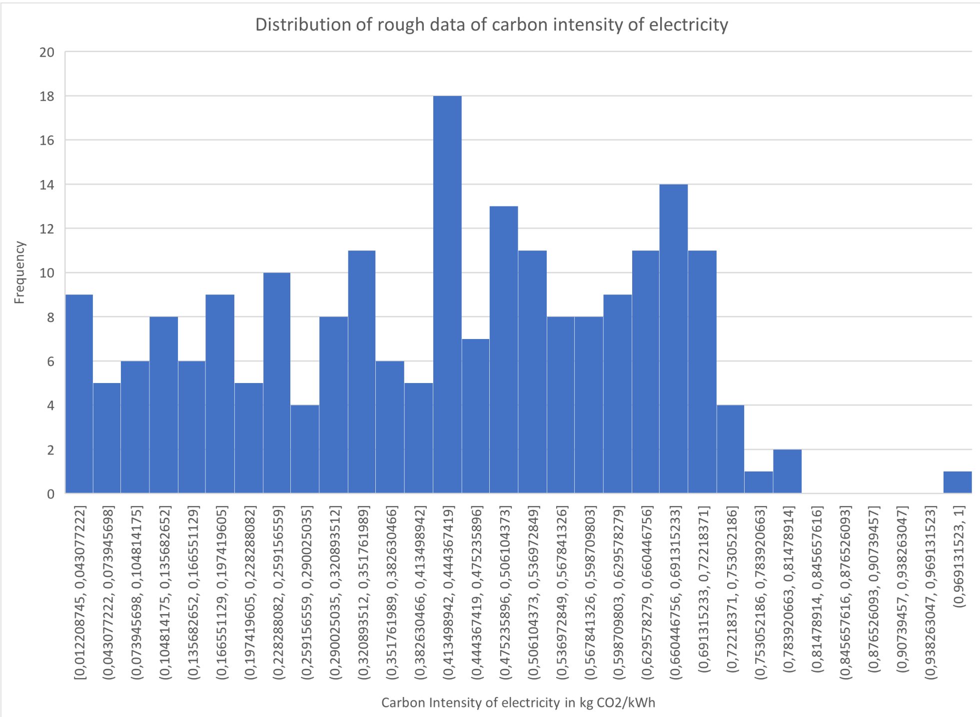


Figure A.1: Histogram of the rough data of the carbon intensities of electricity

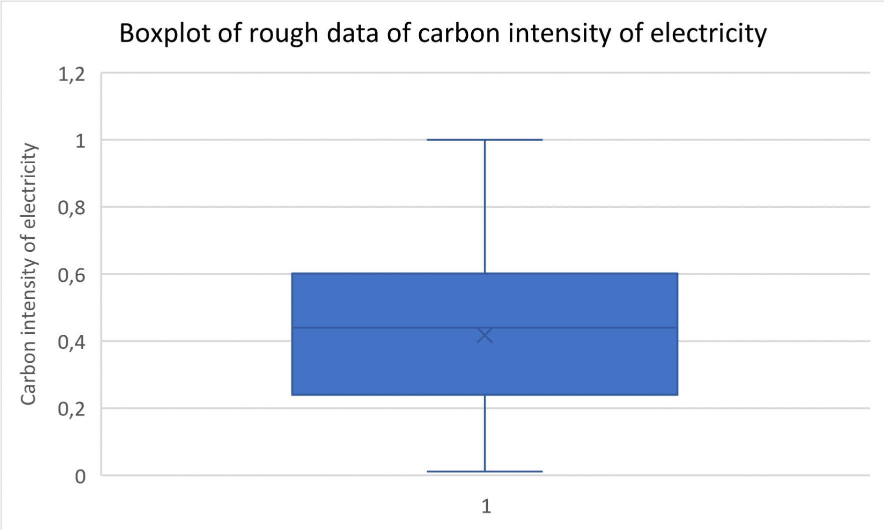


Figure A.2: Boxplot of the rough data of the carbon intensities of electricity

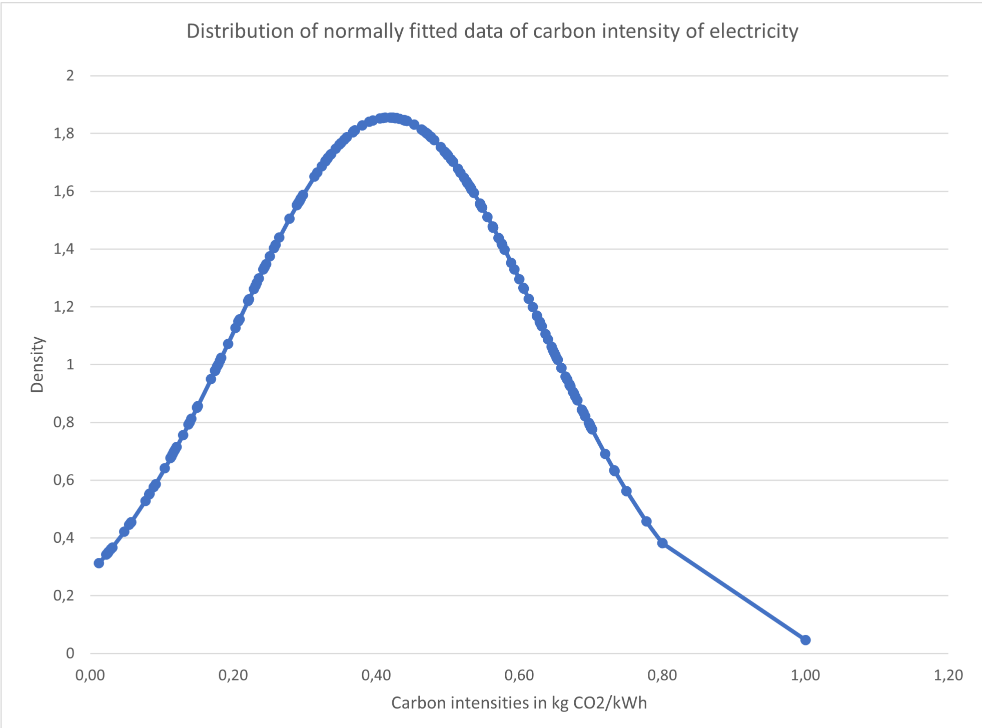


Figure A.3: Data of the carbon intensities of electricity fitted into normal distribution

A.1.2 Data

Entity	Code	Year	Carbon intensity of electricity (kgCO2/kWh)
Afghanistan	AFG	2020	0.11538463
Albania	ALB	2020	0.024482107
Algeria	DZA	2020	0.48901096
American Samoa	ASM	2020	0.7333333
Angola	AGO	2020	0.16886728
Antigua and Barbuda	ATG	2020	0.6875
Argentina	ARG	2020	0.35286432
Armenia	ARM	2020	0.20873123
Aruba	ABW	2020	0.5795454
Australia	AUS	2020	0.56038446
Austria	AUT	2020	0.08678045
Azerbaijan	AZE	2020	0.53467377
Bahamas	BHS	2020	0.69849243
Bahrain	BHR	2020	0.48995312
Bangladesh	BGD	2020	0.5621936
Barbados	BRB	2020	0.670103
Belarus	BLR	2020	0.47212207
Belgium	BEL	2020	0.18285715
Belize	BLZ	2020	0.47457626
Benin	BEN	2020	0.65217395
Bhutan	BTN	2020	0.023463686
Bolivia	BOL	2020	0.317757
Bosnia and Herzegovina	BIH	2020	0.5306604
Botswana	BWA	2020	0.8
Brazil	BRA	2020	0.11306892
British Virgin Islands	VGB	2020	0.6923078
Brunei	BRN	2020	0.6590909
Bulgaria	BGR	2020	0.3748126
Burkina Faso	BFA	2020	0.63125
Burundi	BDI	2020	0.25714288
Cambodia	KHM	2020	0.42352942
Cameroon	CMR	2020	0.2437071
Canada	CAN	2020	0.1205085
Cape Verde	CPV	2020	0.55555554
Cayman Islands	CYM	2020	0.6811594
Central African Republic	CAF	2020	0
Chad	TCD	2020	0.6785714
Chile	CHL	2020	0.38613617
China	CHN	2020	0.54953394
Colombia	COL	2020	0.21766563
Comoros	COM	2020	0.6923078
Congo	COG	2020	0.36414563
Cook Islands	COK	2020	0.5
Costa Rica	CRI	2020	0.03259005
Cote d'Ivoire	CIV	2020	0.42138367
Croatia	HRV	2020	0.1552795
Cuba	CUB	2020	0.5759049
Cyprus	CYP	2020	0.60483875
Czechia	CZE	2020	0.40690506

Democratic Republic of Congo	COD	2020	0.026002169
Denmark	DNK	2020	0.1039501
Djibouti	DJI	2020	0.8
Dominica	DMA	2020	0.5
Dominican Republic	DOM	2020	0.6057243
Ecuador	ECU	2020	0.14628072
Egypt	EGY	2020	0.46534152
El Salvador	SLV	2020	0.24585219
Equatorial Guinea	GNQ	2020	0.62831854
Eritrea	ERI	2020	0.6590909
Estonia	EST	2020	0.66006604
Eswatini	SWZ	2020	0.20312498
Ethiopia	ETH	2020	0.025441698
Faeroe Islands	FRO	2020	0.42857147
Falkland Islands	FLK	2020	0.5
Fiji	FJI	2020	0.29292926
Finland	FIN	2020	0.05884949
France	FRA	2020	0.056646526
French Guiana	GUF	2020	0.35051547
French Polynesia	PYF	2020	0.46969696
Gabon	GAB	2020	0.29491525
Gambia	GMB	2020	0.68965515
Georgia	GEO	2020	0.14157707
Germany	DEU	2020	0.31439398
Ghana	GHA	2020	0.35504724
Greece	GRC	2020	0.49103333
Greenland	GRL	2020	0.118644066
Grenada	GRD	2020	0.7
Guadeloupe	GLP	2020	0.5886076
Guam	GUM	2020	0.67058826
Guatemala	GTM	2020	0.3320158
Guinea	GIN	2020	0.175
Guinea-Bissau	GNB	2020	0.75
Guyana	GUY	2020	0.6363636
Haiti	HTI	2020	0.606383
Honduras	HND	2020	0.35864594
Hong Kong	HKG	2020	0.68498944
Hungary	HUN	2020	0.23474178
Iceland	ISL	2020	0.028750654
India	IND	2020	0.6255728
Indonesia	IDN	2020	0.66348816
Iran	IRN	2020	0.48799
Iraq	IRQ	2020	0.5168592
Ireland	IRL	2020	0.28763184
Israel	ISR	2020	0.5567718
Italy	ITA	2020	0.22324643
Jamaica	JAM	2020	0.5323383
Japan	JPN	2020	0.47647998
Jordan	JOR	2020	0.43220337
Kazakhstan	KAZ	2020	0.6553803

Kenya	KEN	2020	0.088888885
Kiribati	KIR	2020	0.6666667
Kosovo	OWID_KOS	2020	0.77761194
Kuwait	KWT	2020	0.4896191
Kyrgyzstan	KGZ	2020	0.09152752
Laos	LAO	2020	0.29763098
Latvia	LVA	2020	0.17331023
Lebanon	LBN	2020	0.54489166
Lesotho	LSO	2020	0.02
Liberia	LBR	2020	0.29213483
Libya	LBY	2020	0.49651044
Lithuania	LTU	2020	0.23752968
Luxembourg	LUX	2020	0
Macao	MAC	2020	0.48214288
Madagascar	MDG	2020	0.4528302
Malawi	MWI	2020	0.11320756
Malaysia	MYS	2020	0.5860496
Maldives	MDV	2020	0.7017544
Mali	MLI	2020	0.465625
Malta	MLT	2020	0.47169815
Martinique	MTQ	2020	0.6535948
Mauritania	MRT	2020	0.5227273
Mauritius	MUS	2020	0.6131387
Mexico	MEX	2020	0.4162847
Moldova	MDA	2020	0.6470588
Mongolia	MNG	2020	0.73264404
Montenegro	MNE	2020	0.42105264
Montserrat	MSR	2020	1
Morocco	MAR	2020	0.61939667
Mozambique	MOZ	2020	0.12977527
Myanmar	MMR	2020	0.31110156
Namibia	NAM	2020	0.056603775
Nauru	NRU	2020	0.75
Nepal	NPL	2020	0.022653723
Netherlands	NLD	2020	0.32591867
New Caledonia	NCL	2020	0.64
New Zealand	NZL	2020	0.13988571
Nicaragua	NIC	2020	0.34334766
Niger	NER	2020	0.67500006
Nigeria	NGA	2020	0.3952415
North Korea	PRK	2020	0.14955203
North Macedonia	MKD	2020	0.5340909
Norway	NOR	2020	0.031519575
Oceania		2020	0.49927948
Oman	OMN	2020	0.48991525
Pakistan	PAK	2020	0.34005298
Palestine	PSE	2020	0.6290322
Panama	PAN	2020	0.18339417
Papua New Guinea	PNG	2020	0.5636793
Paraguay	PRY	2020	0.023915686

Peru	PER	2020	0.22372685
Philippines	PHL	2020	0.572176
Poland	POL	2020	0.7231667
Portugal	PRT	2020	0.2117013
Puerto Rico	PRI	2020	0.6647727
Qatar	QAT	2020	0.48989215
Romania	ROU	2020	0.23210141
Russia	RUS	2020	0.34771478
Rwanda	RWA	2020	0.28915662
Saint Kitts and Nevis	KNA	2020	0.6666667
Saint Lucia	LCA	2020	0.6969697
Saint Pierre and Miquelon	SPM	2020	0.8
Saint Vincent and the Grenadines	VCT	2020	0.5333333
Samoa	WSM	2020	0.5
Sao Tome and Principe	STP	2020	0.6
Saudi Arabia	SAU	2020	0.5704731
Senegal	SEN	2020	0.53629034
Serbia	SRB	2020	0.59328357
Seychelles	SYC	2020	0.6981133
Sierra Leone	SLE	2020	0.04761905
Singapore	SGP	2020	0.488668
Slovakia	SVK	2020	0.127836365
Slovenia	SVN	2020	0.295683
Solomon Islands	SLB	2020	0.7
Somalia	SOM	2020	0.6486486
South Africa	ZAF	2020	0.72002313
South Korea	KOR	2020	0.44439807
South Sudan	SSD	2020	0.6981133
Spain	ESP	2020	0.1744076
Sri Lanka	LKA	2020	0.48586453
Sudan	SDN	2020	0.25931232
Suriname	SUR	2020	0.2987013
Sweden	SWE	2020	0.012180268
Switzerland	CHE	2020	0.05696861
Syria	SYR	2020	0.5452245
Taiwan	TWN	2020	0.5633813
Tajikistan	TJK	2020	0.08324382
Tanzania	TZA	2020	0.38022287
Thailand	THA	2020	0.50653683
Timor	TLS	2020	0.7
Togo	TGO	2020	0.57692316
Tonga	TON	2020	0.6666667
Trinidad and Tobago	TTO	2020	0.52195123
Tunisia	TUN	2020	0.470829
Turkey	TUR	2020	0.4123691
Turkmenistan	TKM	2020	0.5447316
Turks and Caicos Islands	TCA	2020	0.72000006
Uganda	UGA	2020	0.0770878
Ukraine	UKR	2020	0.27923917
United Arab Emirates	ARE	2020	0.4706024

United Kingdom	GBR	2020	0.24572304
United States	USA	2020	0.36957126
United States Virgin Islands	VIR	2020	0.6875
Uruguay	URY	2020	0.1124031
Uzbekistan	UZB	2020	0.48798618
Vanuatu	VUT	2020	0.5714286
Venezuela	VEN	2020	0.1660239
Vietnam	VNM	2020	0.5437848
Yemen	YEM	2020	0.53846155
Zambia	ZMB	2020	0.12077597
Zimbabwe	ZWE	2020	0.2790279

A.2 TOTAL EMBEDDED EMISSIONS RUNS FOR THE POLICY SCENARIO

benchmark: 0 kgC02/kWh	kg CO2 in machine										
bf-of	3029	2936	3084	2904	3212	3221	3269	2983	3071	2915	
yellow	1388	1286	1449	1251	1589	1599	1652	1338	1434	1263	
	1641	1650	1635	1653	1623	1622	1617	1645	1637	1652	1637,5
benchmark: 0.417 kg C02/kWh	kg CO2 in machine										
bf-of	4825	4814	4792	4775	4787	4903	4753	4737	4822	4885	
yellow	3469	3456	3431	3412	3425	3559	3386	3367	3466	3538	
	1356,00	1358,00	1361,00	1363,00	1362,00	1344,00	1367,00	1370,00	1356,00	1347,00	1358,40
benchmark: 0.771 kg C02/kWh	kg CO2 in machine										
bf-of	6365	6356	6316	6396	6285	6243	6331	6308	6402	6297	
yellow	5243	5233	5186	5278	5150	5102	5203	5178	5286	5165	
	1122	1123	1130	1118	1135	1141	1128	1130	1116	1132	1127,5

Figure A.4: Data of the total embedded emissions of the BAU case and green case 1 for three different policy scenarios.

B PRODUCTION ROUTES FOR STEEL AND ALUMINIUM

In this chapter, an additional elaboration on the various production routes for both steel and aluminium is given.

B.1 BLAST FURNACE – BASIC OXYGEN FURNACE (BF– BOF)

The BF-BOF is the most used process of producing steel. During this process, various phases can be identified. The first phase is known as the pelletising phase. In this phase, fine iron ore concentrate is dried and mixed with a binding substance to create small pellets, which are preheated, sintered, and cooled down. Sintering is the process of mixing the pellets with other fine minerals under high temperatures to create pellets that can be used in the blast furnace. This enhances the productivity of the blast furnace. During the heating process of iron ore concentrate, fossil fuels are used for the de-watering process R. Wang et al. (2021). In the second phase, the coal is converted to coke in a coke plant. During this process, more CO2 is being emitted than in the first phase. In the third phase, the iron ore pellets produced in phase 1 are mixed with coke produced by the coke plant in phase 2 with a blast furnace. In this stage, the iron ore reacts under high temperatures with the carbon of the coke to produce iron and carbon dioxide. The result is hot liquefied metal with a small percentage of carbon. During this phase 71.25% of the total emitted carbon dioxide is generated Vogl et al. (2018). In the last phase, the hot metal is mixed with oxygen gas and scrap to decrease the carbon capacity and create liquefied steel with the required quality. Moreover, experiments are conducted with various routes of steel production with the goal of reducing the CO2 emissions Zhao et al. (2020):

- BF-BOF with improved efficiencies
- Smelting reduction(i.e. the use of a Cyclone converter furnace for the smelting procedure) shown in Fig.B.1
- Direct reduced iron based on natural gas(i.e. replacement of coal in the production process with natural gas and an electric arc furnace) shown in Fig.B.1
- BF-BOF with Carbon Capture and Storage
- Electric Arc Furnace - applied for secondary steel route by using recycled steel

However, since these production processes are improvements of the existing Blast Furnace - Basic Oxygen Furnace (BF-BOF), it is decided to keep them out of the analysis. However, during the sensitivity analysis, these production processes will be taken into account to create a complete overview of how also other production processes will influence the embedded emissions of the datacon EVO $2200^{Advanced}$.

B.2 DIRECT REDUCTION WITH NATURAL GAS AND HYDROGEN

As shown in Fig.B.1, in each phase of production various improvements are implemented. To start, for the direct reduction route with either natural gas or hydrogen, sintering is not needed before the iron-making phase since natural gas or hydrogen is used as fuel in the furnace. Furthermore, direct reduction either through natural gas or hydrogen refers to the process in which the iron ore, shown in Fig.B.1 as pellets, are chemically changed by various carbons including hydrocarbon. Therefore, the iron oxides are already reduced in the shaft furnace and the last oxidization step can be skipped R. Wang et al. (2021). Since this process is conducted below the melting point of iron, electric arc furnaces are included in the last step to melt the steel together with scrap to cast the crude steel into the required forms. Thus, less energy is required in the raw material preparation as shown in Fig.B.1 Vogl et al. (2018). Also, natural gas and hydrogen are used as fuels for the shaft furnace, so emissions are also reduced in the shaft furnace. However, to call this process carbon neutral, step 2 has to be implemented with the use of solar and wind plants.

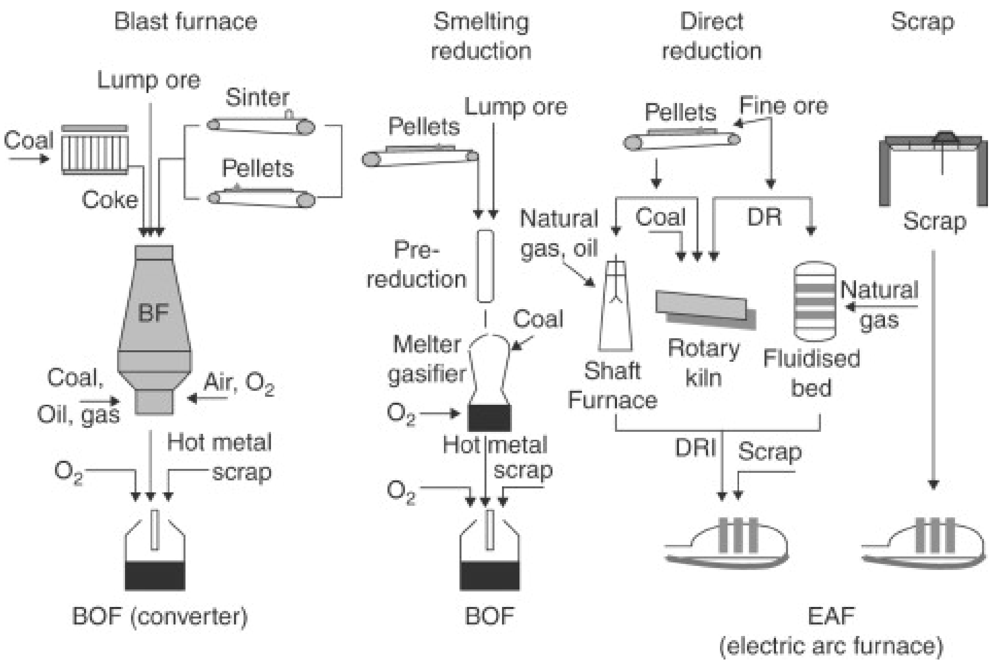


Figure B.1: Steps to reduce emissions for steel production as distinguished by Steinparzer et al. (2012).

In step 2, green hydrogen is produced through electrolysis with electricity generated in solar and wind plants. During the process of electrolysis, water is transformed with electricity into hydrogen and oxygen Shiva Kumar & Lim (2022). The chemical reaction for this process is shown in Eq.B.1.

$$1H_2O + Electricity + Heat \rightarrow H_2 + \frac{1}{2}O_2 \tag{B.1}$$

This hydrogen is used as input fuel for the production of green steel. In Fig.B.2 a Swedish implementation of green steel production, known as HYBRIT, is shown *Hybrit* (2021). HYBRIT is a joint venture of SSAB, LKAB, and Vattenfall which wants to decarbonise the steel and iron-making industry in Sweden and develop the first fossil-free steel. In Sweden, the carbon intensity of electricity is relatively low in comparison with the rest of the world A.1.1. Therefore, the electricity used in the process will not have a significant influence on the embedded emissions of this process. This makes Sweden a good fit for the production of steel through clean energy. However, if such projects will be implemented in other countries around the world, the embedded emissions of this steel will be higher than the one depicted in Fig.B.2. Thus, the electricity used for electrolysis determines the level of sustainability of the steel produced. In this research project, the focus will be on the implementation of steel produced by on-grid hydrogen production since this shift is more likely to happen because it requires fewer investment costs than 100% renewable energy and thus gives a more realistic view of the future of producing steel through hydrogen.

As shown in Fig.B.2, 75.49% of the total amount of required electricity is used for the electrolysis process. Therefore, for the assessment of this process, three variables should be considered to make this an environmentally and financially attractive solution *Material Economics* (2019):

- Price of electricity. Since a high amount of electricity is needed to generate hydrogen in the hydrogen plant, the price of electricity will have a significant influence on the implementation of steel-making through hydrogen plants.
- Price of coal. Since coal is needed to make steel through the integrated route, the attraction of the use of hydrogen will be affected by the price of coal. If the price of coal is low, the industry will not be inclined to make a shift to green steel-making.
- EU-ETS carbon price. Since steel-making companies in Europe are subject to the EU-ETS, they have to buy allowances to be able to produce steel. If the price of these allowances is very high, they will be more inclined to shift to green steel making and vice versa.

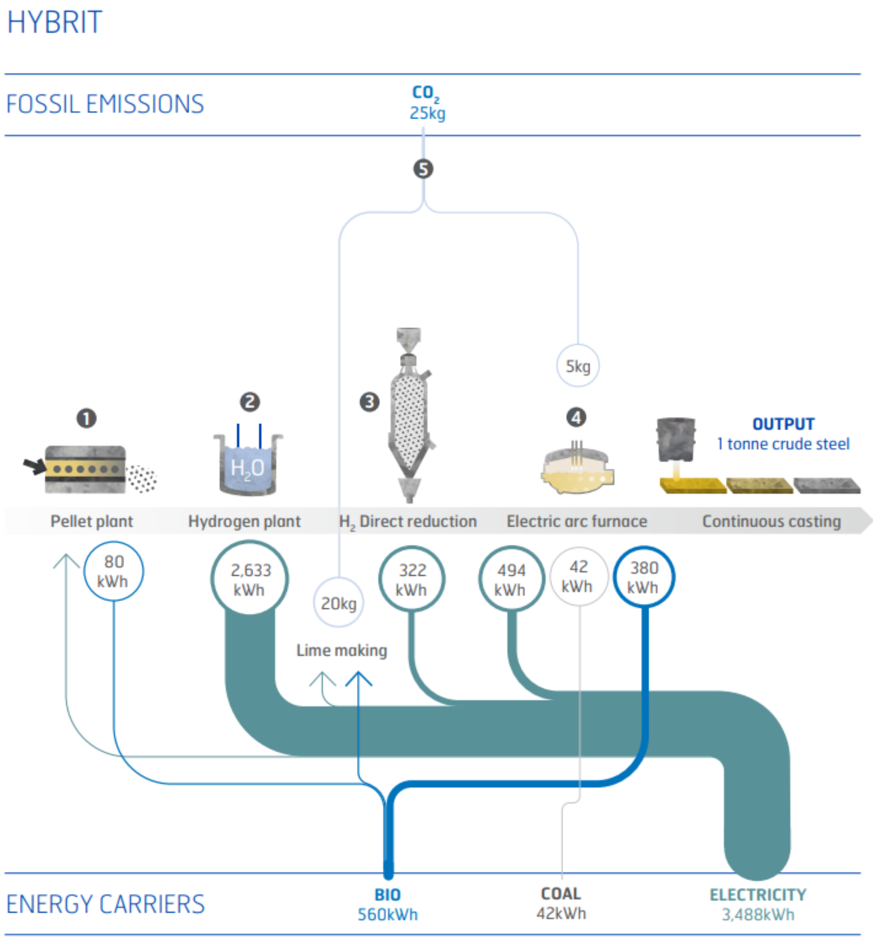


Figure B.2: Swedish implementation of green steel known as HYBRIT *Hybrit* (2021).

B.3 STEEL PRODUCTION COSTS

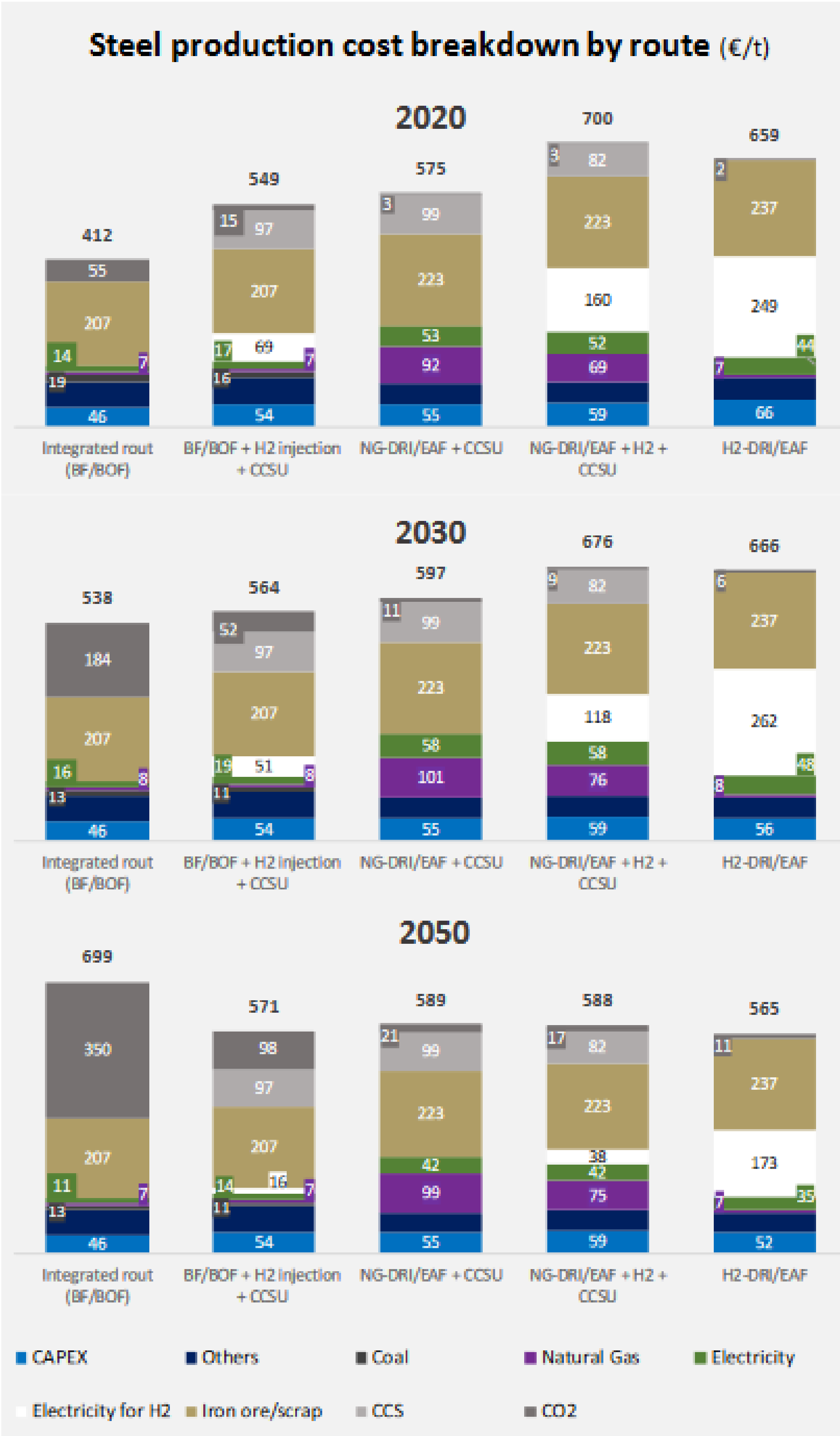


Figure B.3: Predicted costs of various production routes.
Source: *Material Economics* (2019)

B.4 ALUMINIUM PRODUCTION

Farjana et al. (2019) compares the emissions of the smelting process for four cases. In each case, the electricity used for the smelting process is generated by different power plants. Afterwards, each case is compared with the base scenario, which is represented by the electricity mix used in the alumina smelting process in the US consisting of coal, nuclear power, hydropower, and diesel. The results of this comparison are shown in Tab.B.1. The results of this research show indeed that a replacement of the energy source has a significant effect on the CO_2 emissions of the production process of aluminium. Therefore, for the production of aluminium, the replacement of the energy source used during the smelting will be investigated in this case study to see how the use of 'green' aluminium will affect the embedded emissions of the semiconductor assembly machines.

Table B.1: Results of CO_2 emissions of alumina smelting per scenario as found by Farjana et al. (2019)

Impact	Unit	Case 1 Base case	Case 2 Nuclear power plant	Case 3 Solar photovoltaic plant
Climate Change (CC)	kg CO_2 eq	10.91	5.26	6.1

Moreover, other critical components in the smelting process are the carbon anode and cathode shown in Fig.B.4. These components are needed to conduct the electrical power from the power plants and supply the carbon during the smelting process. During this chemical reaction, the alumina is reduced, the carbon anode is consumed and carbon dioxide is produced according to Eq.B.2.

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \tag{B.2}$$

Due to the breaking down the character of the carbon anode and cathode, these components require continued replacement and consequently increase the environmental impact of the smelting process. Nevertheless, new studies have shown that the use of an inert anode lowers this impact with 85% Kvande (2011). Inert anodes are formed from non-consumable oxides of Ni, Fe, and Al and possess sufficient conductivity for the smelting process of alumina. Also, they have sufficient mechanical stability to fulfill the function of the carbon anode without breaking down Kvande (2011). Therefore, together with the implementation of renewable energy and improved production processes, these technologies are seen as groundbreaking for the transition to green aluminium production.

As will be discussed in Sec.5.1.3, two production routes of aluminium will be analysed taking into account the three aforementioned production stages. Firstly, an analysis will be conducted on the business-as-usual case in which both gas and electricity are used for the production of aluminium. Secondly, the carbon capture route will be discussed to have a comparison of the influence of a cleaner route on the total embedded emissions of the datacon EVO $2200^{Advanced}$.

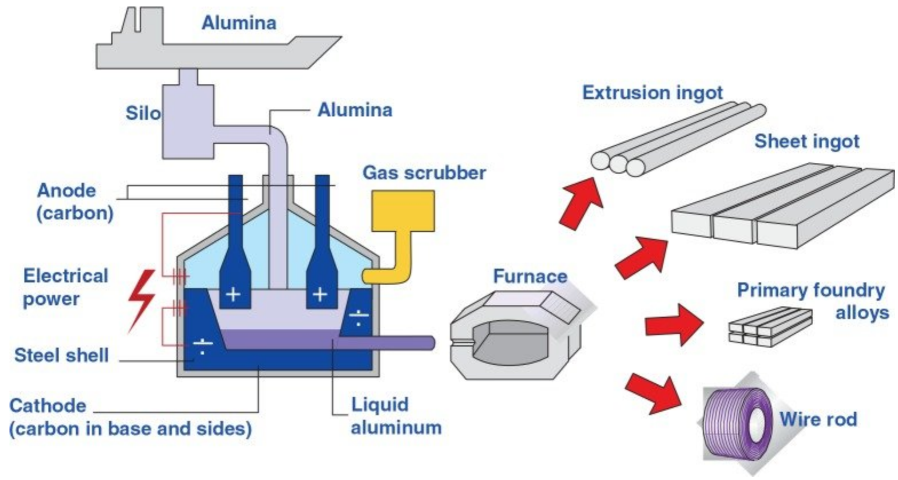


Figure B.4: Overview of aluminium production process
Source: Kvande & drabløs (2014)

C CODE

C.1 MONTE CARLO

```
# Setup
import numpy as np
import matplotlib.pyplot as plt
from scipy.spatial import distance as dist
import statistics
from scipy.stats import norm

# Vector version using numpy
# Number of simlations is specified with number of observations
obs = 500000
# generate the input vectors
from statistics import mean


################################################################
# Define the parameters of the normal distribution
mean = 0.41733 # midpoint of the desired range
std˙dev = 0.214989853 # determines the spread of the values

# Define the lower and upper bounds of the desired range
lower˙bound = 0
upper˙bound = 2

# Generate a large number of random samples from a normal distribution with the
    specified range
values = np.random.normal(mean, std˙dev, size=500000)
 carbon˙electricity = np.clip(values, lower˙bound, upper˙bound)

# Plot a histogram of the values
plt.hist( carbon˙electricity , bins=32, density=True, alpha=0.5, color='blue',
    edgecolor = 'black')
plt.close

# Plot the normal distribution curve
x = np.linspace(lower˙bound, upper˙bound, num=1000)
y = norm.pdf(x, mean, std˙dev)
#plt.plot(x, y, color='red')

# Set the axis labels and title
plt.xlabel('Carbon intensity of electricity in kgC02/kWh')
plt.ylabel('Density')
plt.title('Distribution of embedded emissions in electricity')
```

```
# Display the plot
#plt.show()
#plt.savefig ('emissiondistribution.pdf')
plt.savefig('emissiondistribution.jpg', dpi = 300, orientation = 'portrait',
    bbox_inches = 'tight')

####################################################################

carbon_gas = np.random.normal(0.064, 0.004898979, obs)
carbon_average = 0.41733
carbon_av_gas = 0.064
totalkWh = 10023.33333
totalkWhgreen = (10023.33333 - 654.16666667)
totalkwhsteel = 654.16666667
totalkWhAlu = 6575
totalMJAlu = 78900
totalMJsteel = 7850
k = 1

CO2_datacon = carbon_electricity * totalkWh
plt.hist(CO2_datacon, edgecolor='black', bins=32, color = 'cyan', density = True)
plt.xlabel("Total Embedded Emissions in kg C02", fontsize = 8)
plt.ylabel("Value", fontsize = 8)
plt.title("Total embedded emissions of electricity in kg C02 ", fontsize = 9)
#plt.show()
#plt.savefig('total_embedded_carbonin.pdf')
plt.close()

H_DRI = 6.25
NG_offset = 175
NG_steelprod = 275
Coal_steelprod = 475

CO2_steel_green = H_DRI

CO2_steel_yellow = carbon_electricity * totalkwhsteel + H_DRI
#plt.hist(CO2_steel_green, edgecolor='black', bins=32, color = 'blue')
plt.subplot(1,2,1)
plt.hist(CO2_steel_yellow, edgecolor='black', bins=32, color = 'magenta', density
    = True)
plt.xlabel("Embedded Emissions of steel in kg C02", fontsize = 8)
plt.ylabel("Value", fontsize = 8)
plt.xlim([-0.9,1000])
plt.title("Yellow hydrogen-route ", fontsize = 9)
#plt.show()
#plt.savefig(' yellow_steel.pdf')
value_yellow = (0.7709568394648139 * 654.166667 + H_DRI) * k
plt.close()

CO2_steel_NG= carbon_electricity * totalkwhsteel * 0.3636 + carbon_av_gas *
    totalMJsteel * (1-0.3636)
plt.subplot(1,2,2)
plt.hist(CO2_steel_NG, edgecolor='black', bins=32, color = 'grey', density =
    True)
```

```
plt.xlabel("Embedded Emissions of Steel in kg C02", fontsize = 8)
plt.ylabel("Value", fontsize = 8)

plt.title("NG-route ", fontsize = 9)
#plt.show()
#plt.savefig(' grey_steel .pdf')
#plt.subplots_adjust( left = 0.1,
#                     right=1.3)
#plt.show()
#plt.savefig('subplot.pdf', dpi = 300, orientation = 'portrait ', bbox_inches =
    'tight ')
plt.close()

CO2_alu_BAU = carbon_electricity * totalkWhAlu * 0.65568 + totalMJAlu *
    0.22725 * carbon_av_gas+ 0.11707 * carbon_average *totalkWhAlu
plt.subplot(1,2,1)
plt.hist(CO2_alu_BAU, edgecolor='black', bins=32, color = 'orange', density =
    True)
plt.xlabel("Embedded Emissions of Al in kg C02", fontsize = 8)
plt.ylabel("Value", fontsize = 8)
plt.title("Total embedded emissions of Al produced through BAU-route ",
    fontsize = 9)
#plt.show()
#plt.savefig('alu_BAU.pdf')
#plt.close()
value_CC = (0.7709568394648139 * totalkWhAlu * 0.65568+ 0.11707 *
    carbon_average *totalkWhAlu) * k
value_BAU = (0.7709568394648139 * totalkWhAlu * 0.65568+ + totalMJAlu *
    0.22725 * carbon_av_gas + 0.11707 * carbon_average *totalkWhAlu)*k

CO2_alu_CC = CO2_alu_BAU - totalMJAlu * 0.22725 * carbon_av_gas
plt.subplot(1,2,2)
plt.hist(CO2_alu_CC, edgecolor='black', bins=32, color = 'purple', density =
    True)
plt.xlabel("Embedded Emissions of Al in kg C02", fontsize = 8)
plt.ylabel("Value", fontsize = 8)
plt.title("Total embedded emissions of Al produced through CC-route", fontsize
    = 9)
#plt.subplots_adjust( left = 0.1,
#                     right=1.55)
#plt.show()
#plt.savefig('subplot2.pdf', dpi = 300, orientation = 'portrait ', bbox_inches =
    'tight ')
plt.close()


Totalbau1 = (CO2_alu_BAU + Coal_steelprod+ (totalkWh - 6575-totalkwhsteel) *
    carbon_average) * k
n, bins, patches = plt.hist(Totalbau1, edgecolor='black', bins=32, color = 'red',
    label ='BAU option with BF-OF', density = True, alpha = 0.55)
#first_bar_x = patches[1].get_x()
#plt.text( first_bar_x , patches[0].get_height(), str( first_bar_x ), color='black',
    fontsize=10)
#print( first_bar_x )
```

```
x˙value = 6433.513732279409
bin˙index = np.digitize([x˙value], bins)[0]

# Now that you have the bin index, you can find the corresponding bar
bar = patches[bin˙index-1]
print(bar)

#plt.xlabel("Total embedded emissions of steel and Al in kg C02", fontsize = 8)
#plt.title("Total embedded emissions BAU-route Al and steel through coal",
    fontsize = 9)
#plt.ylabel("Value", fontsize = 8)
#plt.show()
#plt.savefig('totalbau1.pdf')
plt.close()
total˙value = value˙BAU + Coal˙steelprod+ (totalkWh - 6575-totalkwhsteel) *
    carbon˙average
print(total˙value)

Totalbau2 = CO2˙alu˙BAU + CO2˙steel˙NG+ (totalkWh - 6575 - 654.166667) *
    carbon˙average
plt.hist(Totalbau2, edgecolor='black', bins=32, color = 'blue', label ='BAU
    option with NG', density = True, alpha = 0.55)
#plt.xlabel("Total embedded emissions of steel and Al in kg C02", fontsize = 8)
#plt.ylabel("Value", fontsize = 8)
#plt.title("Total embedded emissions BAU-route Al and steel through NG",
    fontsize = 9)
#plt.show()
#plt.savefig('totalbau2.pdf')
plt.close()

Totalyellow = (CO2˙alu˙CC + CO2˙steel˙yellow + (totalkWh - 6575 -
    totalkwhsteel) * carbon˙average) * k
n, bins, patches = plt.hist(Totalyellow, edgecolor='black', bins=32, color =
    'yellow', label ='Green case 1', density = True, alpha = 0.4)
#first˙bar˙x1 = patches[1].get˙x()
#print(first˙bar˙x1)
#plt.text(first˙bar˙x, patches[0].get˙height(), str(first˙bar˙x), color='black',
    fontsize=10)
x˙value = 5321.576398352961
bin˙index = np.digitize([x˙value], bins)[0]

# Now that you have the bin index, you can find the corresponding bar
bar = patches[bin˙index-1]
print(bar)

plt.xlabel("Total embedded emissions of steel and Al in kg C02", fontsize = 8)
plt.ylabel("Value", fontsize = 8)
plt.title("Total embedded emissions with both Carbon Capture and yellow
    Hydrogen routes", fontsize = 9)
#plt.show()
#plt.savefig('totalyellow.pdf')
plt.close()
value˙yellow = value˙CC + value˙yellow + (totalkWh - 6575 - totalkwhsteel) *
    carbon˙average
print(value˙yellow)
```

```
Totalgreen = CO2˙alu˙CC + CO2˙steel˙green + (totalkWhgreen - 6575) *
    carbon˙average
plt.hist(Totalgreen, edgecolor='black', bins=32, color = 'green', label = 'Green
    case 2', density = True, alpha = 0.4)
plt.xlabel("Total embedded emissions of steel and Al in kg C02", fontsize = 8)
plt.ylabel("Value")
plt.title("Total embedded emissions with both Carbon Capture and yellow
    Hydrogen routes", fontsize = 9)
plt.legend()
#plt.show()
#plt.savefig('totalgreen.jpg', dpi = 300, orientation = 'portrait', bbox˙inches
    = 'tight')
plt.tight˙layout()
#plt.savefig('totaleverything.pdf')
#plt.close()
```

C.2 COST

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from mpl˙toolkits.mplot3d import Axes3D

old˙case = 8.2 # in tonne * 10
green˙case = 2.5 # in tonne * 10
carbon˙price = 160
units = 2000
costs˙improvements = 1688542/1e6

carbon˙costs = carbon˙price * (old˙case - green˙case) * units


#carbon˙costs = z
#old˙case - green˙case = x
#carbon˙price = y

ax = plt.axes(projection ='3d')

x = np.linspace(0,10,100)
y = np.linspace(20,200,100)

z = (x * y * units)/1e6
g = costs˙improvements


ax.plot(x, y, z)
ax.plot(x,y,g)

#line˙pt = g.intersection(z)

ax.set˙xlabel("Change in embedded emissions in tonne CO2", fontsize = 9)
ax.set˙ylabel("Carbon price in EUR/tonne CO2", fontsize = 9)
ax.set˙zlabel("Costs of implementing green materials in EUR (1e6)", fontsize = 9)
ax.set˙title ("Visualization of relation of key parameters", fontsize = 10)
#plt.show()
#Axes3D.plot()
plt.savefig('3d-plot.pdf', dpi = 300, orientation = 'portrait', bbox˙inches =
    'tight')
```

C.3 TIPPING POINT

```
import numpy as np
import matplotlib.pyplot as plt

x = np.linspace(0,14,100)
y = 1688542/(2000*x)
v = 2110678/(2000*x)
w = 1266407/(2000*x)

limits = [180, 160, 140, 120, 100, 80]

plt.plot(x, y, color='k', label='Base scenario')
plt.plot(x, v, color='g', label='25% increase')
plt.plot(x, w, color='r', label='25% decrease')

for limit in limits:
    g = limit + x*0
    idx = np.argwhere(np.diff(np.sign(g - y))).flatten()
    plt.plot(x[idx], g[idx], 'ro')
    plt.vlines(x[idx], 0, limit, linestyles='dotted', colors='k')

    idx = np.argwhere(np.diff(np.sign(g - w))).flatten()
    plt.plot(x[idx], g[idx], 'ro')
    plt.vlines(x[idx], 0, limit, linestyles='dotted', colors='r')

    idx = np.argwhere(np.diff(np.sign(g - v))).flatten()
    plt.plot(x[idx], g[idx], 'ro')
    plt.vlines(x[idx], 0, limit, linestyles='dotted', colors='g')

plt.legend(loc='upper right')
plt.ylim([20,200])
plt.xlim([0,14])
plt.xlabel('Minimum reduction in embedded emissions in tonne CO2')
plt.ylabel('Carbon price in EUR/tonne CO2')
plt.title('Tipping points of financial incentive to implement green materials')
plt.show()
#plt.savefig('costs1.pdf', dpi = 300, orientation = 'portrait', bbox_inches =
    'tight')
```

COLOPHON