Utrecht University

TATA STEEL

# *Cost-effective ways to decarbonize Tata Steel IJmuiden*

## *A process analysis using an MILP framework*

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# Acknowledgments

This thesis marks one of the last steps in completing my study. During the thesis, I have been challenged to merge the knowledge from two worlds. On one side, I needed to gain in-depth knowledge about the steelmaking industry and its energy system. On the other side, I needed to learn to work with an MILP framework, the EHub tool, provided by the Utrecht University. Merging these two components was challenging, especially in the beginning, but it was satisfying to see the results in the end. I would like to thank the people who have contributed to this thesis. First of all, I would like to thank my supervisor Matteo Gazzani (Utrecht University) for having constructive discussions and always providing solutions where I never have thought of myself. I also would like to thank my other supervisor Lukas Weimann (Utrecht University) for always being available when I faced problems, both related to the EHub tool specific, and the rest of my thesis in general. Furthermore, I would like to thank Tom van der Velde (Tata Steel IJmuiden) who guided me in the complex world of Tata Steel. He was always there to answer my questions and introduced me to other people within Tata Steel. Lastly, I would like to thank Sanne Bours, Pam Engwirda, Stijn Maatman and Thijs Verboon for reading my concept thesis and providing me with constructive feedback to enhance it.

## Abstract

To protect the Netherlands for the effects of climate change, the Netherlands agreed to lower their $CO_2$ emissions by 49% in 2030 relative to 1990. Tata Steel IJmuiden (TSIJ) plays a crucial role in this reduction target since it emits 7% of the $CO_2$ emissions in the Netherlands. Deep decarbonization of TSIJ is therefore key to meet the $CO_2$ reduction goal. Using a Mixed Integer Linear Programming (MILP) based framework, this research quantifies the $CO_2$ reduction by changing the current energy system towards a minimal $CO_2$ emission design. The energy system is currently designed in a low-cost manner, which is not the most optimal regarding $CO_2$ emissions. The results showed that the potential of decarbonizing the energy system without process changes is limited. Therefore, the effects of three process changes, namely electrification of heat, utilization of an Electric Arc Furnace (EAF), and utilization of the Hisarna process, are investigated. The process changes were selected to represent the short-term and mid-term plans of TSIJ and are reflected in a change of demand and emission profiles. The results showed that the decarbonization potential of electrification of heat is limited, while the $CO_2$ reduction potential of utilization of the EAF and Hisarna is approximately 30% each. This is still not enough to reach the $CO_2$ reduction goal. To reach the $CO_2$ reduction goal, both the utilization of CCS and the implementation of renewable electricity are needed. The potential of renewables on the TSIJ is limited due to a lack of space. Hence the supply of lower carbon electricity relies on implementing more renewables for electricity generation on the national grid.

## Nomenclature

**Acronym**

| | |
|---|---|
| BAU | Business as Usual |
| BF-gas | Blast Furnace-gas |
| CCS | Carbon, Capture and Storage |
| CCU | Carbon, Capture and Utilization |
| CCUS | Carbon Capture, Utilization and Storage |
| CO-gas | Cokes oven gas |
| CHP | Combined Heat and Power |
| DRI | Direct Reduced Iron |
| EAF | Electric Arc Furnace |
| ERHT | Electrical Radiative Heating Tubes |
| GT | Gas Turbine |
| EHub-tool | Energy Hub tool |
| LHV | Lower Heating Value |
| MES | Multi Energy System |
| MILP | Mixed Integer Linear Programming |
| NG | Natural Gas |
| NDA | Non-Disclosure Agreement |
| OXY-gas | Oxygen steelmaking gas |
| PV | Photovoltaic |
| TSIJ | Tata Steel IJmuiden |
| TFX | Transverse Flux Inductor |
| UU | Utrecht University |
| WAG | Work Arising Gas |
| WHR | Waste Heat Recovery |
| Y | Year |

**Tata Steel IJmuiden plants**

| | |
|---|---|
| BF6 | Blast Furnace 6 |
| BF7 | Blast Furnace 7 |
| BOS | Basic Oxygen Steel-making plant |
| CEN 1-4 | Central 1-4 |
| CGP 1 | Coke and Gas Plant 1 |
| CGP 2 | Coke and Gas Plant 2 |
| CM | Cold Mill plant |
| CPR | Coated Products |
| HSM | Hot Strip Mill |
| IJm01 | IJmond 01 (CHP plant) |
| PEFA | Pellet Factory |
| SIFA | Sinter Factory |
| TSP | Tata Steel Packaging |
| VN24 | Velsen 24 (Steam turbine) |
| VN25 | Velsen 25 (Steam turbine) |
| WHR | Waste Heat Recovery |
| ZUFA | Linde air separation plant |

**Nomenclature for equations**

| | |
|---|---|
| $c$ | Hourly energy consumption |
| $e$ | Annual $CO_2$ emission $[\text{ton}_{CO_2}/y]$ |
| $\varepsilon$ | Specific emission coefficient $[\text{ton}_{CO_2}/y]$ |
| F | Input power [kW] |
| $i$ | Technology index |
| $j$ | Carrier index |
| $\mathcal{J}$ | Annual costs [€/y] |
| $\mathcal{J}_c$ | Capital costs [€/y] |
| $\mathcal{J}_m$ | Maintenance costs [€/y] |
| $\mathcal{J}_o$ | Operational costs [€/y] |
| L | User demand [kW] |
| $\lambda$ | Variable costs [€/y] |
| $m$ | Set of available technologies |
| $\mu$ | Fixed costs [€/y] |
| $n$ | Set of available carriers |
| P | Output power [kW] |
| $S$ | Technology size [kW] |
| $t$ | Time index [hr] |
| $T$ | Time horizon [hr/y] |
| $u$ | Import price [€/kWh] |
| $U$ | Import power [kW] |
| $v$ | Export price [€/kWh] |
| $V$ | Export power [kW] |
| $w$ | Binary variable |
| $\psi$ | Maintenance coefficient [-] |
| $\omega$ | Annuity factor [-] |

# Table of content

# 1. Introduction

The growth of the global population and economy are strongly related to the increasing primary energy demand. In 2012, 81% of the global primary energy demand was generated by fossil fuels, which emitted around 30.2 million tons of $CO_2$ (Otto et al., 2017). This emitted $CO_2$ leads to inevitable global warming (Kumar et al., 2011). The International Energy Agency calculated that the increase in temperature could be limited to 2 ºC if $CO_2$ emissions are reduced by 22 billion tons a year by 2035 (Otto et al., 2017). This means that global emissions must be reduced by 30% from 2012 to 2035 (Otto et al., 2017). Considering that the past years the global emissions are increased instead of deceased, the need for global $CO_2$ reduction enhances every year (Olivier & Peters, 2020). As one of the biggest emitters per capita in the world, the Netherlands has an extensive responsibility to meet these reductions (Jensen, 2015).

To take this responsibility, the Dutch government set up an energy agreement with 47 major stakeholders. In this energy agreement, the planned heading of the Dutch government towards a more sustainable energy generation has been captured (SER, 2013). One of the main targets of the energy agreement is to reduce $CO_2$ emissions by 49% in 2030 relative to 1990 (SER, 2013). To meet this 2030 climate target, a lot of attention and subsidies have been drawn to renewable electricity generation (SER, 2013). As a consequence, the cumulative renewable electricity generation in the Netherlands increased from 16 PJ in 2011 to 43 PJ in 2017 (CBS, 2018). This is mainly due to a high increase in wind- and solar power (CBS, 2018). However, industries that use other energy carriers than electricity, receive less attention. These industries account for 25% of the total $CO_2$ emissions, but less than half of the emissions that relate to these industries can be saved by renewable electricity- or heat generation (IPCC, 2014). Yet, these industries are vital in today's society. Examples are steel, cement and ammonia used for fertilizers. At the same time, due to the extensive share of $CO_2$ of these types of industries, the industry is key to reach the target of 2030 (CBS, 2019).

In the Netherlands, one of the biggest emitters of $CO_2$ is Tata Steel in IJmuiden (TSIJ) (Ekker, 2018).TSIJ accounts for 7% of the total $CO_2$ emissions in the Netherlands. At the same time, steel is one of the pillars of today's society, since it is incorporated in almost all industrial made products. Due to the extensive share in $CO_2$ emissions, reducing $CO_2$ at TSIJ is vital to reach the climate target. To lower the $CO_2$ emission of TSIJ, changes in the heavy processes of steel making are needed. Unfortunately, producing steel is a complex and $CO_2$ intensive process, and thus requires complex and intensive changes to decarbonize. Meanwhile, TSIJ faces difficult times due to decreasing demand in Europe, strong competitors in China, which can produce cheap steel, and tariffs from the USA, which makes the export of steel more expensive (Waard, de, 2019). It is therefore necessary that $CO_2$ reduction measures preserve the economical sustainability and quality of steel to remain competitive. Multiple decarbonization routes, both long term and short term are already investigated. Long term solutions have been for example provided by Tsai et al. (2013) whose research focusses on

Carbon Capture, Utilization and Storage (CCUS) and He & Wang (2017) who suggest implementing more energy-efficient technologies to reduce the energy demand by 20%. Examples of short term solutions have been given in the research of Porzio et al. (2013), which describes how to run energy-intensive applications more efficiently and the paper of Karlsson (2011), which describes how to implement simple energy efficiency measures. The presence of multiple routes creates the need for an in-depth analysis for TSIJ about what the most cost-effective way is to lower $CO_2$ emissions. This research will focus on this analysis using the perspective of a Multi Energy System.

## 1.1 Multi Energy System

The manufacturing process of TSIJ includes the entire steel production chain, which starts with raw materials like coal and iron ore and ends up in processed steel. This process requires a lot of different energy streams and energy carriers, which makes it a complex energy system. Also, the emergence of renewable electricity generators like photovoltaic (PV) and wind turbines, which increases the need for storage to balance the electricity generation, leads to an increase in the energy system complexity. Mancarella (2014) shows how the integration of energy at various levels can improve the energy system through technical, economic and environmental performances using a Multi Energy System (MES). Considering that TSIJ could benefit from this perspective, this work is carried out through the application of an MES. To handle the complexity of the TSIJ system, Mixed-Integer Linear Programming (MILP) is often used. This has been favored since MILP is flexible in reproducing complex systems while keeping computing time low (Gabrielli et al., 2018). The optimization of an MES can provide valuable insights to what extent $CO_2$ emissions will decrease for various decarbonization pathways while costs are minimized.

Previous research of Boldrini et al. (2019) already shows a preparation for an MILP optimization using an MES perspective. Boldrini et al. (2019) determined the current energy demand of all furnaces located at TSIJ. In addition, all energy carriers, energy conversion technologies and storage technologies are mapped. Also, the technology portfolio for new installations is identified which implies wind turbines, PV and solar thermal. Moreover, the research mapped the current energy network of TSIJ which is required for transporting energy carriers between plants and furnaces. Lastly, the research provided data of 2018 of energy consumption and production with an hourly resolution.

The model used in this research makes use of the abovementioned input data and uses the MILP-based framework developed by Gabrielli et al. (2018). Using this framework, several optimizations can be carried out to investigate the optimal technology selection, size, and operation. Moreover, the model is used to include three decarbonization routes. The decarbonization routes were selected to represent process changes for short-term and mid-term plans of TSIJ. By changing the demand and production profiles and including the current energy system of TSIJ, the effect of each decarbonization route can be explored. This allows this research to investigate the $CO_2$ reduction potential with the current energy system taken into account.

## 1.2 Research aim and research questions

Resulting from the preceding elaborations, the research aim is:

*''Explore three decarbonization routes for Tata Steel IJmuiden to obtain insights in decarbonizing the steelmaking process to reach the $CO_2$ emission reduction goal of at least 49% in 2030.''*

As mentioned earlier, this research makes use of an MILP framework. By varying the $CO_2$ limit when optimizing costs, multiple optimizations can be carried out. This way the potential for decarbonization of the current steel production process can be quantified when only the energy system is changed. Moreover, a reference is created to compare the decarbonization routes. Therefore, the first research question is:

1. *What is the potential of $CO_2$ reduction by changing the energy system?*

Next to changing the energy system, it is possible to reduce $CO_2$ emissions by changing the current steelmaking process at TSIJ by utilizing decarbonization routes. The second research question aims to obtain insights into how demand profiles change when three decarbonization routes are utilized. Therefore, the second research question is:

2. *How do the demand and emission profiles of furnaces change when the decarbonization routes are utilized?*

Thirdly, the $CO_2$ reduction potential of the three decarbonization routes, using the changed demand profiles as input data in the MILP framework, can be quantified. This is done by running the MILP framework and interpreting the results using the earlier mentioned reference. Therefore, the third research question is:

3. *What is the $CO_2$ reduction potential of each decarbonization route and what is the effect on the processes of Tata Steel IJmuiden?*

With an answer to all three research questions, this research aims to contribute to creating more insights in the decarbonization potential and a favorable technology selection for several decarbonization routes. With these insights, this research aims to stimulate the steel industry to implement these decarbonization routes which is needed to reduce $CO_2$ emissions.

## 1.3 Relevance of the research

The relevance of this research is threefold: to begin with, this research shows the potential of decarbonization by transforming the energy system without changing the steel making process. This quantifies the need for decarbonization routes to reach the $CO_2$ reduction goal. Moreover, both the $CO_2$ reduction potential of these decarbonization routes are analyzed as well as the $CO_2$ reduction potential of the decarbonization routes by changing the energy system design. The results of this analysis can be used for TSIJ to adjust their strategy to meet the $CO_2$ emission reduction targets of 2030. When these targets cannot be achieved by the decarbonization routes, this research quantifies the minimum share of CCUS to reach the $CO_2$ reduction target of 2030.

## 1.4 Structure

The remainder of this research reads as follows: first, a background of TSIJ is given which is an introduction to the steel making process. Furthermore, the energy system of TSIJ is introduced and the decarbonization routes which are currently taken into account are shown. Then the theory behind the MILP framework is discussed. This is followed by the methodology section, which explains for every research question how the research is carried out. The analysis shows the findings arising from this research. Then, the discussion is presented where limitations and implications are discussed. As the last chapter, the conclusion is displayed. Here an answer to the research questions is presented.

# 2 Background

To understand decarbonization at TSIJ, it is important to understand the basics of TSIJ first. In this chapter, the background of TSIJ is elaborated. To begin with, the geographical overview and the process of steelmaking are presented. Then, the energy system is discussed and lastly, the decarbonization routes, which are currently considered at TSIJ, are elaborated.

## 2.1 Overview site Tata Steel IJmuiden

Figure 1 shows an overview of the TSIJ site. From this figure, two parts within TSIJ can be distinguished: a north terrain, and a south terrain, separated by a road in the middle. At the south terrain, the heavy processes are carried out to produce crude steel from raw materials. At the north terrain, the crude steel is processed to 7.2 Mtonnes high-quality steel, customized for each customer.

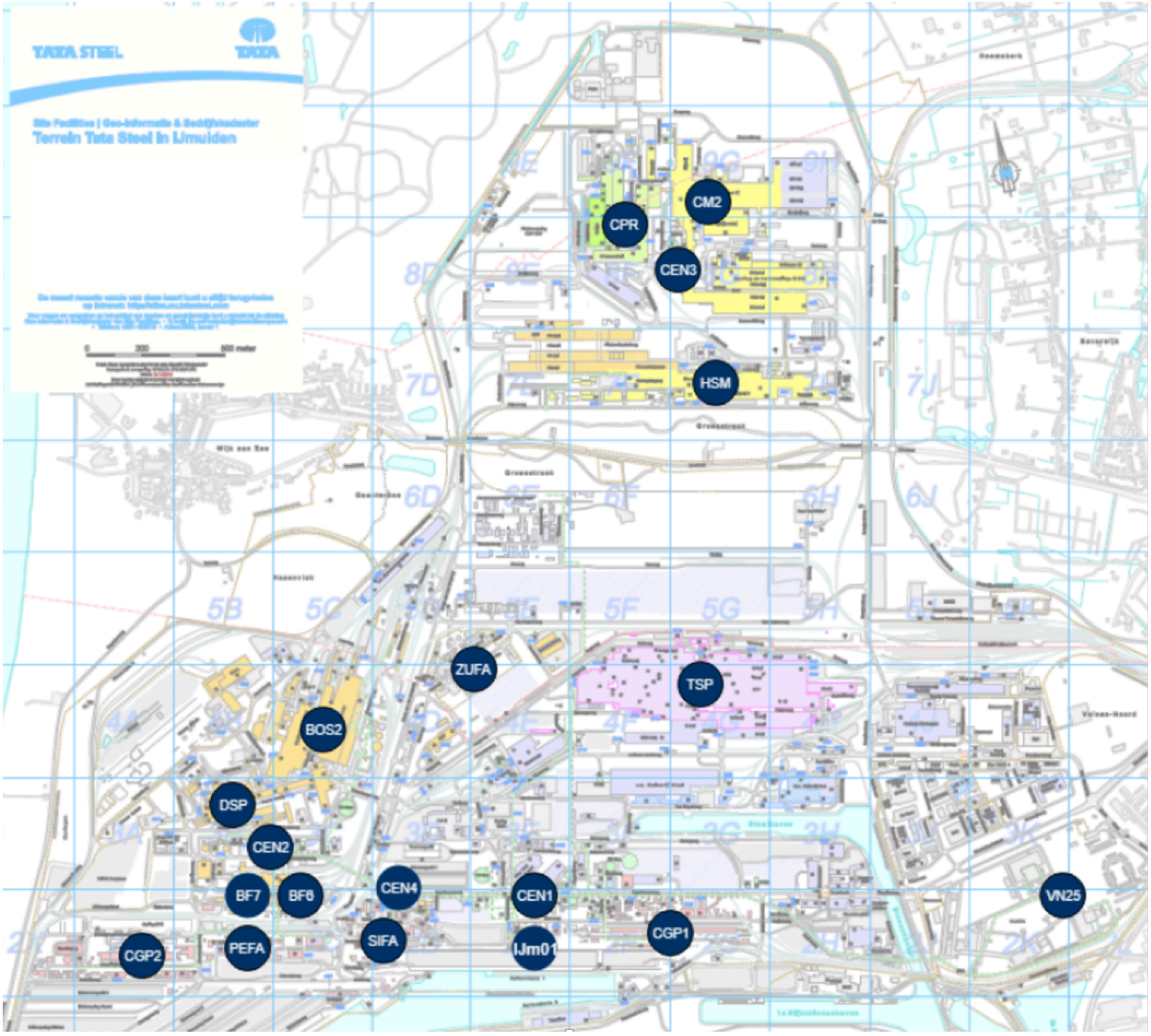

*Figure 1: An overview of the terrain of TSIJ, showing the main energy generation plants and furnaces.*

## 2.2 Manufacturing process Tata Steel IJmuiden

In Figure 2 the main processes of TSIJ are displayed. This Figure shows the process of raw materials to high quality steel.

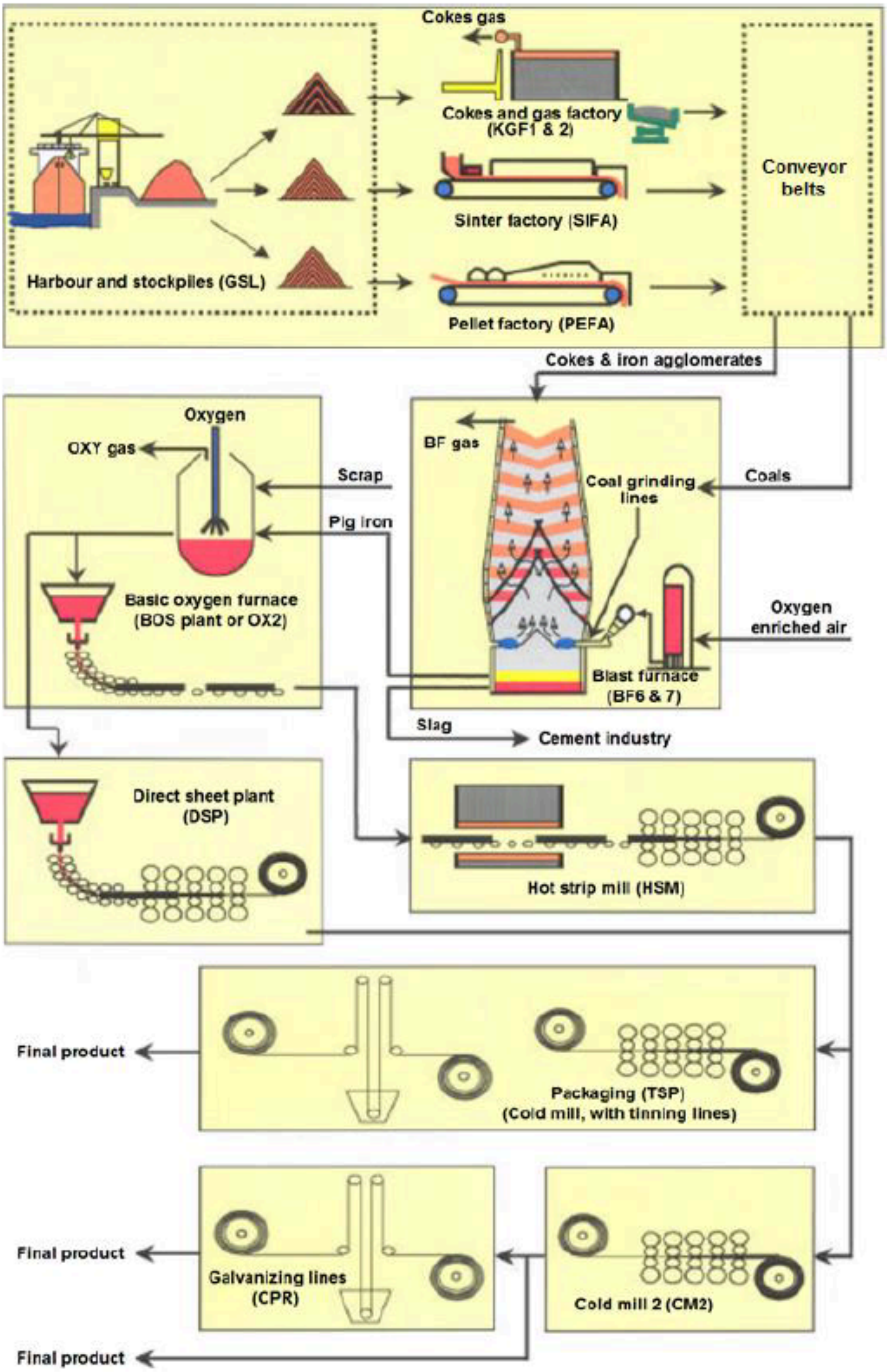


*Figure 2: Overview of the main processes carried out at TSIJ.*

As a first step, the coal enters the two Coke and Gas Plants (CGP1 and 2). Before coal going to the ovens, the coal is ground to prevent segregation in the piles and for size distribution. Then the coals are charged and heated to 1,100 $^{o}$C. The heating time determines the quality of the coal. The gas released is used as cokes oven gas (CO-gas), which is an imported input for the Blast Furnaces. When the cooking time is over and the impurities are forced out, the coke is pushed out. The red-hot coke is cooled in the quenching tower.

The iron ore is fed into the Sinter Factory (SIFA) and the Pellet Factory (PEFA). At SIFA various types of iron ore are mixed to reach a homogeneous chemistry. This is mixed with water and chemicals to form a kind of clay. This clay is baked at a temperature up to 1,600 $^{o}$C and then broken, this is called sinter. A similar process occurs at the PEFA. The finer iron ores are selected for the PEFA. These are mixed with water and chemicals and baked to form pellets. Pellets are smaller and circular shaped thus structurally stronger than sinter.

The products of SIFA, PEFA and the two CGPs, are fed into the two Blast Furnaces 6 and 7 (BF6 and 7). The first step in the BF is to charge the mixture. To achieve the desired charging, a charge-sequence is set up. This determines how much of each material enters the BF and where the specific products in the BF are charged. Then, with the help of CO-gas and Blast Furnace gas (BF-gas), the charged mixture is heated up to 1,100 $^{o}$C. A hot blast is injected at high speed from below the BF, which moves through the layers of coke and iron ore to the top of the BF. From the top of the BF, BF-gas is continuously produced, captured and cleaned, so it can be used as combustible gas. Pig iron and by-product slag come out of the bottom of the BF. This is transported in large torpedo wagons to the Basic Oxygen Steelmaking plant (BOS).

In the BOS, the pig iron is formed into steel by removing the carbon out to a value below 2.1%. At TSIJ, there is much more carbon removed to obtain a higher quality of steel. To remove the carbon, the hot metal from the BF enters the BOS and is desulfurized before the charging of the hot metal takes place. The charged hot metal is converted to liquid steel by blowing oxygen on the hot metal and oxidizing the carbon from the steel. This is cooled down by using scrap, pellets and slag. About 80% of the liquid steel undergoes continuous casting, where the liquid steel casts into slabs within the right dimensions and the demanded steel grade. The slabs are transported to the Hot Strip Mill (HSM) where the slabs are reheated, milled and coiled. The other 20% of the liquid steel goes directly to the Direct Sheet Plant (DSP). Here the processes of continuous casting and milling and coiling are combined. After these processes, the steel undergoes various processes like galvanizing, paint coating, etc. dependent on the need of the customers.

## 2.3 Energy system Tata Steel IJmuiden

In this research, five energy carriers are considered: electricity, Natural Gas (NG), Work Arising Gas (WAG), heat and waste heat. However, the largest energy input of TSIJ is from coal.

The coal is used as input for the CGP1 and 2 and the BF6 and 7. The energy output of the CGP plants is CO-gas and the energy output of the BF plants is BF-gas. In this research, these two gasses are combined as WAG. WAG is used as an energy carrier and fuel for various furnaces within the TSIJ energy system. The WAG is distributed through a wide network of pipelines within the TSIJ terrain. When WAG is not available, NG can be used as a replacement.

Heat is generated by four boilers: Central 1, 2, 3 and 4 (CEN 1-4). CEN1, CEN2 and CEN4 are located at the south terrain of TSIJ. These centrals supply the energy of the heavy processes at CGP 1 & 2, PEFA, SIFA, BF 6 & 7, BOS, DSP and TSP. Central 3 (CEN3) is located at the north terrain of TSIJ and is responsible for supplying the energy of the finishing processes of HSM, CM2 and CPR. All boilers of the CEN 1-4 run on NG and WAG, in this research referred to as boiler NG and boiler WAG respectively. Besides, heat can be generated by waste heat from Waste Heat Recovery (WHR). The waste heat is generated from the high temperatures which are needed in some furnaces in the steel making process. CEN 4 can utilize waste heat next to NG to reduce the $CO_2$ emission. In this research, this boiler is referred to as boiler WHR.

Electricity is produced by TSIJ owned electricity generation technologies and the national grid. The plants which are TSIJ owned are steam turbine located at Velsen 24 (VN24) and Velsen 25 (VN25). VN24 is more efficient and is primarily used, where VN25 is used as a backup. The input of both VN24 and 25 is WAG and the output is electricity. Furthermore, there is a CHP plant at IJmond 01 (IJm01) for both electricity and heat production. This CHP plant is fueled by NG.

The five energy carriers, which are defined in this research, have their unique distribution network at TSIJ. An overview of these networks is shown in Figure 3:

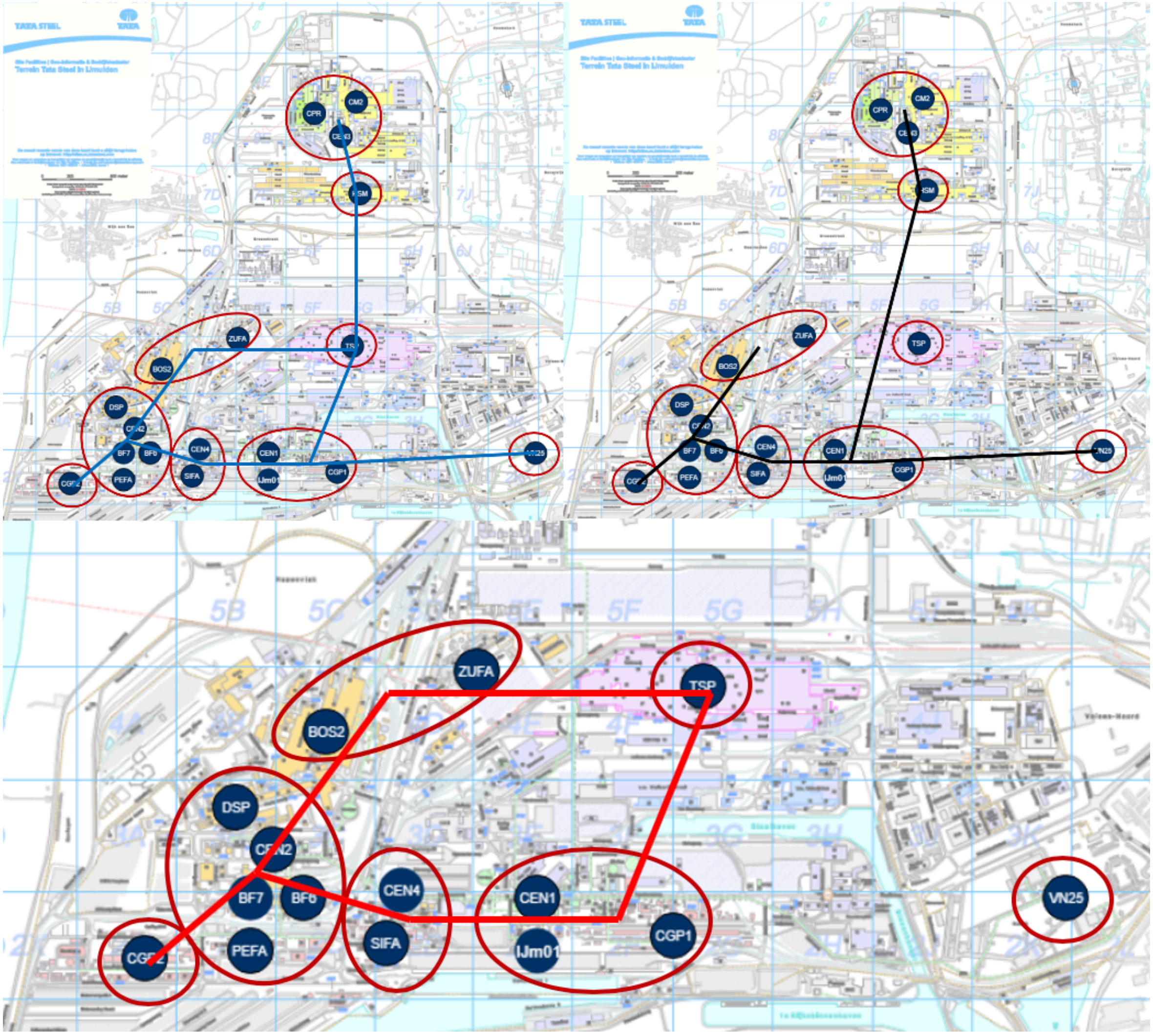


*Figure 3: The distribution network at TSIJ of electricity and NG (black, located left above, do not use the same network, but do have the same distribution), WAG (blue, located right above), and heat and waste heat (red, located beneath, making use of the same network).*

Figure 3 shows that electricity and NG have a network that is connected to all energy generation plants and furnaces. Although the networks of electricity and NG follow the same path, the networks are separated. WAG is connected to all energy generation plants and furnaces as well, except for TSP. This is a result of that TSP is not using WAG and is not located near a furnace that does use or produce WAG. Heat and waste heat have only a network at the south terrain, except for VN25. Since VN25 produces electricity and does not use or produce any heat or waste heat, a network at the north terrain is not needed. There is no heat network at the northern terrain, so heat cannot be distributed to furnaces located there. This means that when there is an overproduction of heat, this must be dissipated. Heat and waste heat do use the same network.

## 2.4 Ways to decarbonize Tata Steel IJmuiden

To lower the $CO_2$ emission of TSIJ, researches to changes in the manufacturing process of TSIJ have been carried out. Currently, four scenarios to reduce the $CO_2$ emission are researched by the Energy Efficiency Department of TSIJ. These are elaborated below.

The first scenario implies no major changes in the way of steel making. The two current BFs remain active, so the current energy mix and way of steel making remain roughly the same. To meet the climate goals, this scenario combines the BFs with Carbon Capture and Storage (CCS), Carbon Capture and Utilization (CCU) or both, CCUS, to reduce the $CO_2$ emission. This should be implemented in two phases, starting with BF7 and deciding later on BF6, as BF6 has a shorter lifetime. In the second scenario, liquid steel is produced by an Electric Arc Furnace (EAF) instead of the BFs. In an EAF, scrap iron is charged and melted allowing for high efficiencies. It should be taken into account is that an EAF uses high amounts of electricity to reach temperatures up to 3,500 $^oC$. The advantage of this route is that the EAF is a proven technology and the flexibility of the EAF is a lot higher than the flexibility of a BF. The third scenario utilizes a Hisarna furnace. Hisarna is a technology where fine raw materials are directly utilized to produce liquid iron. This means that one Hisarna plant substitutes the SIFA, PEFA, CGPs and a BF. The Hisarna plant uses less energy than the substituted plants combined. A disadvantage of this scenario is that Hisarna technology is not proven yet. Therefore, time and money still need to be invested before the Hisarna can run on full capacity. The fourth and last scenario describes the implementation of Direct Reduced Iron (DRI). DRI exists for 90% out of pure iron and is obtained by a direct reduction of iron oxide pellets. DRI and scrap iron combined could replace the current hot metal and scrap input in the BOS and therefore could replace all the furnaces needed before the BOS. (Eijk, 2018)

The one thing that all scenarios have in common is that they all use electricity (Eijk, 2018). This means that the installation of renewable electricity generation, like wind turbines and PV, is considered as a 'no regret action' (Eijk, 2018). More renewable electricity generation increases the attractiveness of furnace electrification (Boldrini et al., 2019). Considering that the electrification in combination with renewable electricity generation fits in every scenario, this is the first decarbonization route that is researched in this work.

The other decarbonization routes which are researched in this work, are the utilization of an EAF and a Hisarna plant. These are chosen because these scenarios allow TSIJ to produce the same amount of 7.2 Mtonnes steel while reducing $CO_2$ by implementing a different way of steel making. DRI is a different way of steel making as well, but the input of DRI should be imported. The 90% pure iron, which is the input of DRI, could still be produced when a lot of $CO_2$ is emitted. This is considered as greenwashing; although TSIJ does emit less $CO_2$, the route from raw material to steel emits is roughly the same. Therefore, this route is not considered in this research.

CCS is not taken as a decarbonization route, since it does not fit in the scope of the research. This comes from the fact that negative emissions are not implemented in the MILP framework used in this research. However, this research can still be valuable for insights relative to the potential of CCS. By exploring the alternative routes of steel making considered by TSIJ, any $CO_2$ gap towards the $CO_2$ reduction goal of 2030 is explored. This gap can be filled with CCS.

All decarbonization routes considered is this research, are elaborated below.

### 2.4.1 Electrification of heat

Within TSIJ, Vrijlandt et al. (2019) researched the possibilities to electrify the heat demand. According to this research, electrification for heat production can be reached in two ways: using Electrical Radiative Heating Tubes (ERHT) or using Transverse Flux Inductor (TFX). Heat generation at DSP can be partly electrified using the technology of ERHT, whilst the heat generation of HSM and TSP can be partly electrified using the technology of TFX.

The tubes, which are used in ERHT, are heated by running an electrical current through a resistance. The electrical energy is converted into heat through resistive losses in the material. This effect is called Joules Heating and is displayed in Equation [2.1]:

$$Q \propto I^2 * R \qquad [2.1]$$

Where Q is the heat that is generated is proportional to the product of its resistance R and the square of the current I. This means that a higher electrical current and a higher resistance, results in a higher heat generation. This heat generation is transferred with radiation. (Vrijlandt et al., 2019)

By passing an electrical current through a coil wound around a strip, an electromagnetic field is formed. With TFX induction, a field is generated perpendicular to the strip. By alternating the local flux densities, the heat generated by the TFX can be controlled. (Vrijlandt et al., 2019)

In this research, the electrification of heat is referred to as the electrification scenario.

### 2.4.2 Utilization of an Electric Arc Furnace

As an alternative of steelmaking with blast furnaces, liquid steel can be produced through an EAF. In an EAF, ferrous iron is the input as an alternative for coal. The $CO_2$ emission of the EAF, which allows more efficient recycling and increased circularity of steel products, is relatively low. (Keys et al., 2019; Remus et al., 2013)

The EAF process is graphically represented in Figure 4 and described as follows. The ferrous scrap is melted and refined using electrical energy. During the melting, oxidation of phosphorus, silicon and other materials occur. A slag, containing some of these oxidation products, forms on top of the molted steel. Oxygen is needed to decarburize the molten steel. The heat necessary for the melting process comes from an electric arc arising when graphite electrodes make contact with the charged metal. Due to this way of steelmaking, the EAF run on large amounts of electricity. However, since scrap material is used instead of molten iron, no WAG is associated with the steelmaking process using an EAF. (Cheremisinoff et al., 2008)

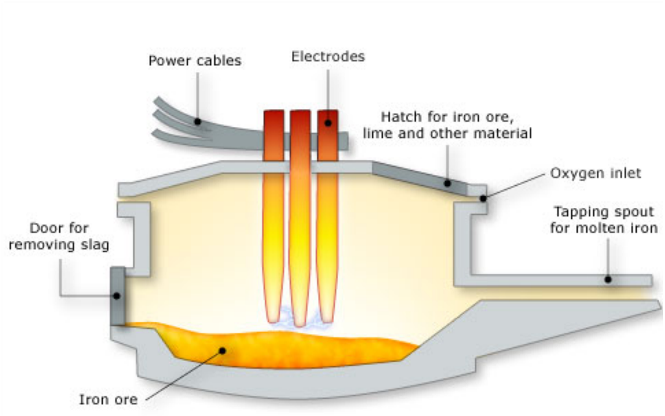

*Figure 4: Graphical representation of an EAF (Templeton, 2006).*

EAFs are available in varying sizes and capacities, which means that several furnaces are needed to replace one blast furnace. To reach the current steel production, other (alternative) ways of steelmaking are required. This is due to the limited availability of scrap, resulting in a limited capacity. Therefore, this research assumes that BF6 is replaced by an EAF. This means that 3Mtonnes of steel is needed to produce by an EAF. The other demand of 4.2 Mtonnes steel is fulfilled by BF7.

In this research, the utilization of an EAF, producing 3 Mtonnes steel, is referred to as the EAF scenario.

### 2.4.3 Utilization of a Hisarna plant

Another alternative of low carbon steelmaking is making use of a Hisarna reactor. Hisarna can utilize fine raw materials directly, where the input of the BFs need a lot of preparation before this can be utilized. Coal and liquid iron ore are needed as an input, similar to the BFs. Since all preparations of the input feedstock are not needed anymore, the PIFA, SIFA and the CGPs are not needed. This allows the Hisarna reactor for a more efficient design since the Hisarna uses less energy than all these plants combined do. (Qu et al., 2015)

The Hisarna process is graphically represented by Figure 5 and described as follows. Iron ore is injected at the top of the Hisarna reactor. This is liquefied in a high-temperature cyclone. Oxygen is injected, causing combustion to $CO_2$, which is the main heat source for the Hisarna process. The liquefied ore then drips to the bottom of the reactor. Here, powder coals are injected, causing the oxygen from the iron ores to bind with the carbon, forming pure liquid iron. Coals injection is not only responsible for mixing metal and slag, but also indirectly for heat transfer from gas to slag. The gas resulting from these processes contain high concentrations of $CO_2$, which is favourable for CCS. (Meijer et al., 2011)

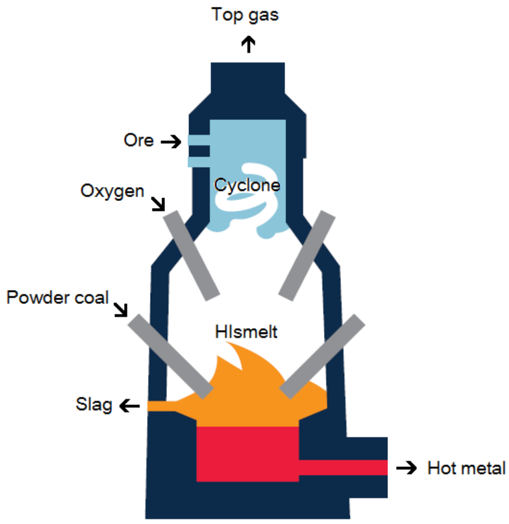


*Figure 5: Graphical representation of the Hisarna process (Meijer et al., 2011).*

A test plant of Hisarna is already built at TSIJ. When this is a success, it is planned to remove the BF6 and replace the capacity of the BF6 with Hisarna plant. Therefore, this research assumes that the BF6 is replaced by a Hisarna as well.

In this research, the utilization of a Hisarna plant, producing 3 Mtonnes steel, is referred to as the Hisarna scenario.

# 3 Theory

This research is conducted using an MILP framework. The theory, where this framework is based on, is elaborated below.

## 3.1 MILP

In this research, MILP has been favored as an optimization method for optimizing MES, since it catches the complexity of an integrated energy system while keeping computing complexity reasonable (Gabrielli et al., 2018). Gabrielli et al. (2018) recognized that the optimization problem lacks a significant simplification. Therefore, this research addresses the need for a different approach where weather and energy demand data are adopted on an hourly scale, and other data modeled based on typical design days. This is done by separating operation variables into two groups: (A) those related to binary variables and (B) those not related to binary variables. Group A includes the continuous variables of technologies which are characterized by a high number of binary variables like the GT. This group is coupled with typical design days, since these represent the main source of computational complexity. Group B represents all other decision variables like imported and exported electricity and energy generated by renewables. This group is defined for every hour in the year. The proposed method allows to precisely adopt weather data to compute renewable energy generation and storage whilst reducing computation time significantly. (Gabrielli et al., 2018)

## 3.2 Energy Hub approach

For MES to benefit from the synergy of different energy carriers, the concept of energy hub is developed. Within an energy hub, multiple energy carriers can be converted, conditioned and stored. As an input, energy hubs consume power connected to for example WAG and NG. As an output, energy hubs provide required energy services like electricity or heat. The energy hub consists of four major components which include input, conversion, storage and output. (Geidl et al., 2007; Mohammad et al., 2017)

## 3.3 EHub tool

To combine MILP and the concept of an energy hub, an MILP framework is used, in this research referred to as: Energy Hub tool (EHub tool). The primary target of the EHub tool is to match supply and demand on an hourly basis with the available resources, locally generated or bought from the national grid. The EHub tool can select the technology, size and operation time on an hourly basis. The input data of the EHub tool requires weather profiles, energy demand profiles, energy import prices and stock $CO_2$ emissions on an hourly basis. With these input details, the EHub tool reports the optimal technology selection, size and details on the operation with as little $CO_2$ emission as possible while optimized on costs for every hour of the year. (Gabrielli et al., 2018)

# 4 Methodology

This methodology chapter describes how the research is carried out aiming to answer the research questions to reach the research aim. The method consists of three steps linked to the three research questions. These steps are used as a basis for the research design.

## 4.1 Research design

The research design consists of three steps: a model analysis, a scenario analysis and scenario results. These steps are linked to the three research questions. So, each step describes how each research question is carried out. All steps of the research design are visually shown in Figure 6. After this figure, for each step is further elaborated.

In Figure 6, the research design used in this research is shown. In the first step, a model analysis is performed. This is done by carrying out multiple cost optimizations varying the $CO_2$ limit on the current situation of TSIJ using the EHub tool. This way the $CO_2$ reduction potential of TSIJ by changing the energy system can be quantified. Moreover, a reference for $CO_2$ emissions, annual energy costs, technology selection, size and details of operation is created to compare the decarbonization routes with. In this research, this reference is referred to as Business as Usual (BAU). The second step describes how energy demand profiles of the furnaces change when applying the different decarbonization routes. In other words, how does the input data change when the decarbonization routes are implemented. The last step consists of implementing these different profiles in the EHub tool. The changed $CO_2$ emissions, annual costs, technology selection and size are analyzed using the reference created in the first step. Based on this analysis the research aim can be explored.

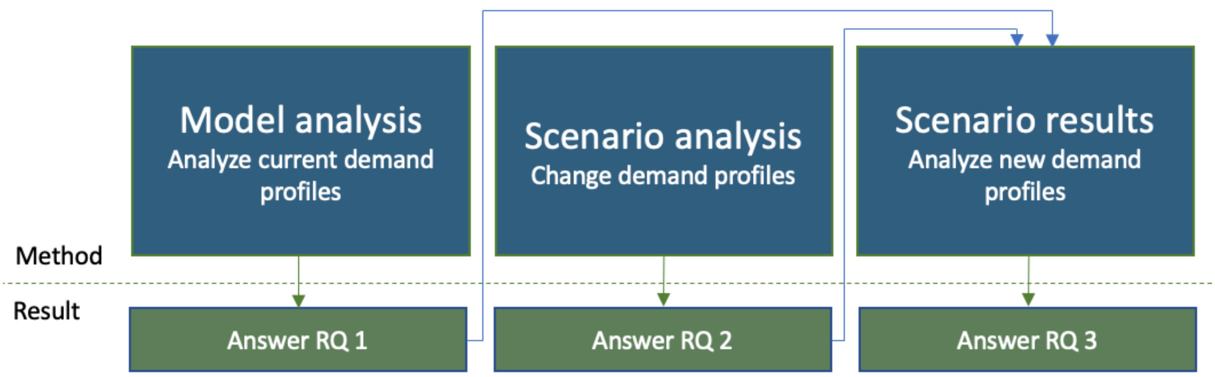


*Figure 6: Research design. The model analysis leads to the answer on research question 1. This is followed by the scenario analysis which leads to the answer on research question 2. The answers of the first two research questions, are used as input for the scenario results, which leads to the answer of research question 3.*

The EHub tool likely gives other results than the actual situation, because not all factors are taken into account due to the scope of this research and the limitations of using a computer model. To overcome this, a reference is created by mapping the current situation of TSIJ first using the EHub tool. By comparing the decarbonization routes with the reference of the EHub tool and not with the actual situation of TSIJ, the validity of the research is guaranteed.

## 4.2 Model analysis

The objective of the first research question is to perform a model analysis. This is done in three steps: first, the basic features of the EHub tool are elaborated. Then the input data required for the EHub tool to model the current TSIJ situation is discussed. As a last step, the type of optimizations and expected output of the EHub tool is elaborated upon.

### 4.2.1 Features EHub-tool

The EHub tool is used in this research to model the energy system of TSIJ. In the following section, the features of the EHub tool are explained.

The objective function of the optimization problem is defined as the total annual costs of the system $\mathcal{J}$. $\mathcal{J}$ is specified as the sum of three cost components, namely: the capital costs ($\mathcal{J}_c$), the operational costs ($\mathcal{J}_o$) and the maintenance costs ($\mathcal{J}_m$). See Equation [4.1]:

$$\mathcal{J} = \mathcal{J}_c + \mathcal{J}_o + \mathcal{J}_m \qquad [4.1]$$

The annual capital costs are defined as a combination of variable and fixed costs, see Equation [4.2]:

$$\mathcal{J}_c = \sum_{i \in m} (\lambda_i S_i + \mu_i)\omega_i \qquad [4.2]$$

where $\lambda_i$ represents the variable and $\mu_i$ represents the fixed costs for the i-th technology $m$; $S_i$ represents the size of the unit and $\omega_i$ is the annuity factor.

The annual operational costs are based on the amount of imported electricity and NG, see Equation [4.3]:

$$\mathcal{J}_o = \sum_{j \in n} \sum_{i \in m} \sum_{t=1}^{T} (u_{j,t} U_{j,i,t} - v_{j,i,t} V_{j,i,t}) \Delta t \qquad [4.3]$$

where the import price $u$ and export price $v$ and the imported- and exported power $U$ and $V$ depend on the energy carrier $n$, the technology $m$ and the time instant $t$.

The maintenance costs are defined as a fraction of $\mathcal{J}_c$, see Equation [4.4]:

$$\mathcal{J}_m = \sum_{i \in m} \psi_i \mathcal{J}_{c,i} \qquad [4.4]$$

where $\psi_i$ represents a fraction dependent on the technology $m$.

Next to the costs, the system is also evaluated on $CO_2$ emissions. Varying $CO_2$ limits are set to carry out multiple cost optimizations. The $CO_2$ emissions are calculated by all imported energy carriers and the $CO_2$ related to WAG. In this research, only NG and electricity can be imported from the national grid, so these are taken into account. Moreover, $CO_2$ emissions related to WAG are taken into account, see Equation [4.5]

$$e = \sum_{j \in n} \varepsilon_j \left( \sum_{i \in m} \sum_{t=1}^{T} U_{j,i,t} \Delta t \right) \quad [4.5]$$

where $\varepsilon_j$ is the specific $CO_2$ emission of energy carrier $n$.

There are two constraints in this optimization problem. Firstly, the unit size of each technology is determined. This can be defined as the power between the minimum and maximum capacity of the technology, see Equation [4.6]:

$$S_i^{min} w_i \leq S_i \leq S_i^{max} w_i \quad [4.6]$$

where $S_i$ represents the unit size and $w_i$ represents a binary value.

The second constraint is defined as an energy balance constraint, which assures that the imported and generated power is equal to the exported and consumed power, see Equation [4.7]:

$$\sum_{i \in m} \left( U_{j,i,t} + P_{j,i,t} - V_{j,i,t} - F_{j,i,t} \right) - L_{j,i,t} = 0 \quad [4.7]$$

where U is the installed energy, P is the generated energy, V is the exported energy, F the absorbed energy and L the energy required by the end-users.

### 4.2.2 Input data

Before the EHub can run, input data is required. First, the demand and supply of the five main carriers used in this research; electricity, WAG, NG, heat and waste heat are discussed. This input data is based on nodes: 'black boxes' where the in- and output of the five main carriers is defined. Boldrini et al. (2019) defined an hourly profile of the demand and supply of all furnaces over 2018 at TSIJ. Boldrini et al. (2019) processed this hourly profile in 19 nodes based on the 19 furnaces and production technologies that are available at TSIJ, see Figure 1 for an overview. However, because 19 nodes are a large set of in- and outputs for the EHub tool, this would imply a long computation time. Considering that many nodes have not defined an in- and output for each carrier, this research merged several nodes based on geographical location and different in- and outputs for a carrier. This way, the EHub tool decreases the computation time and, at the same time, keeps the results reliable. Figure 7 represents the new merged nodes by red circles. Moreover, this Figure represents the possible energy-generating technologies at TSIJ for each node, which are described in section 2.3.

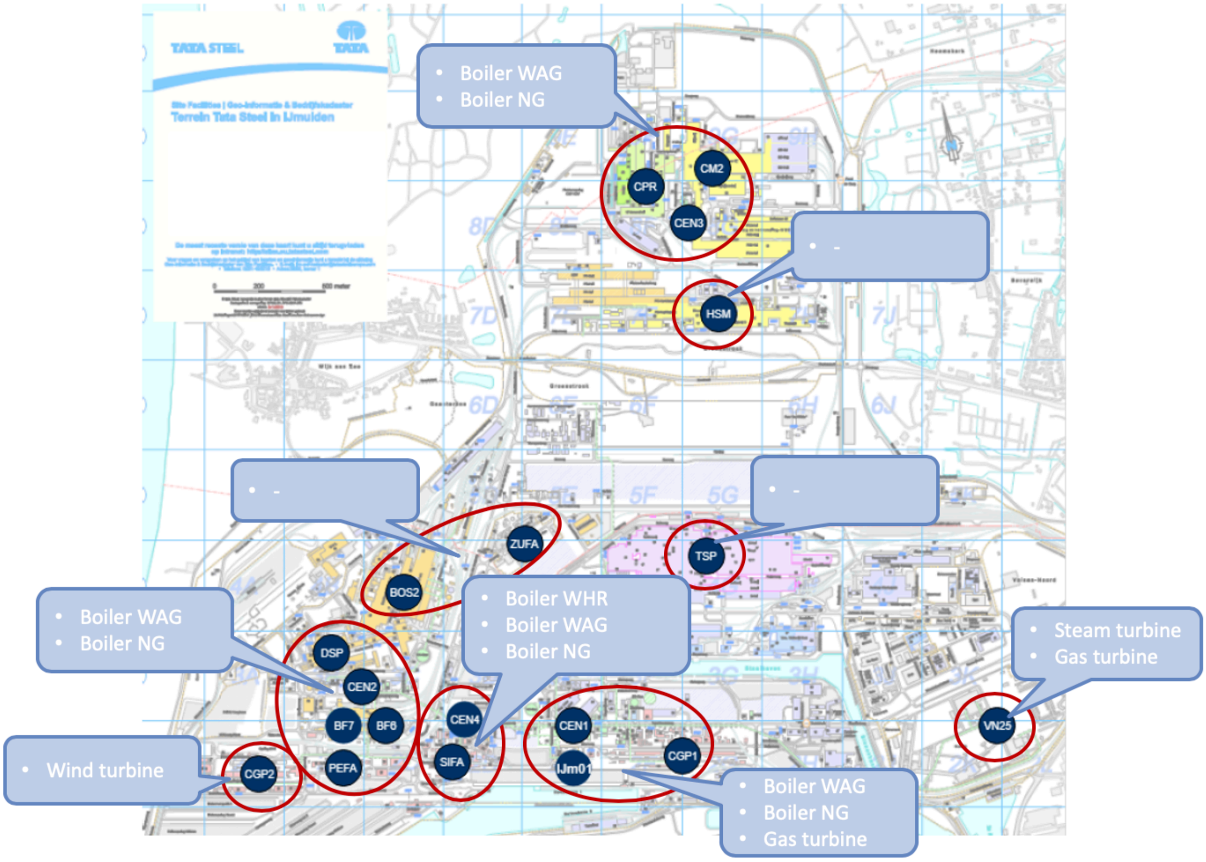


*Figure 7: The 9 nodes are clustered by a red circle. Node 1 is located above, and node 9 bottom left. The counting goes from top to bottom, from left to right. Moreover, the possible energy generating technologies, which can be installed at TSIJ, are shown at each node.*

Table 1 shows the technologies which are currently installed at TSIJ and thus can be selected by the EHub tool. These consist of two electricity generating-technologies, three heat-generating technologies and a CHP. Also, the in- and output, maximum capacity and average $CO_2$ emissions of these technologies are shown.

Note that the $CO_2$ emission resulting from WAG is taken into account in calculating the total emissions of all scenarios, despite that the EHub tool calculates with a $CO_2$ emission of 0 resulting from WAG. This method was chosen, since creating WAG is inevitable and cannot be adjusted when using BFs. WAG needs to be flared when it is not used in a steam turbine or boiler WAG. So, it is assumed that WAG results in the same $CO_2$ emission, independent whether it is used in WAG utilizing technologies or simply flared.

*Table 1: Heat and electricity generating technologies which can be installed at TSIJ. Note that the capacities and $CO_2$ emissions are a representation of the input of the EHub tool and not an exact image of the TSIJ situation.*

| ***Technology*** | **Input** | **Output** | **Capicity$_{max}$ [MW]** | **Average $CO_2$ emissions [gr/kWh]** |
|---|---|---|---|---|
| *Steam Turbine* | WAG | Electricity | 300 | - |
| *Wind Turbine* | Wind | Electricity | 9 | - |
| *GT* | NG | Electricity/Heat | 144 | 204 |
| *Boiler WAG* | WAG | Heat | 112 | - |
| *Boiler NG* | NG | Heat | 112 | 204 |
| *Boiler WHR* | Waste heat/NG | Heat | 112 | -/204 |

Next to the $CO_2$ emissions related to WAG, the $CO_2$ emissions are determined with imported electricity and NG from the national grid, which is displayed in Table 2. The price and $CO_2$ emission of the electricity are determined based on an hourly basis, based on the year 2018. Also, the price of the NG is based on an hourly profile based on the prices of 2018. To determine the output of the renewables, weather data of the year 2018 is used. Note that heat and waste heat are not taken into account in Table 2. This is a result of that both carriers cannot be imported but need to be produced at TSIJ. As a consequence, both energy carriers do not have a direct effect on $CO_2$ emissions.

*Table 2: All carriers which have a direct contribution to the $CO_2$ emissions. Next to the $CO_2$ emissions, there is displayed whether each energy carrier can be imported or exported.*

| ***Energy carrier*** | **Import possibility** | **Export possibility** | **Average $CO_2$ emissions [gr/kWh]** |
|---|---|---|---|
| *Electricity* | Yes | Yes | 505 |
| *NG* | Yes | No | 204 |
| *WAG* | No | No (flared) | 792 |

### 4.2.3 Perform optimizations in EHub tool

To display the results of the EHub tool, four optimizations are performed. First of all, a cost optimization is carried out to create a reference for the current $CO_2$ emissions at TSIJ. A cost optimization is chosen, as TSIJ makes decisions for their technology selection based on costs. To evaluate the $CO_2$ reduction by changing the energy system, also a $CO_2$ optimization is carried out. In this research, a $CO_2$ optimization refers to an optimization where both $CO_2$ and costs are minimized. Using the $CO_2$ optimization, the maximum potential of $CO_2$ savings with the current technologies and furnaces can be explored by changing the energy system. To explore what the trend from a cost to a $CO_2$ optimization is, two extra optimizations are carried out. This is done by carrying out two cost optimizations using two different $CO_2$ limits, which are oriented between the $CO_2$ limit of the $CO_2$ optimization and the $CO_2$ value of the cost optimization, see Equation [4.8]:

$$CO_2\ limt_i\ [Mtonnes] = \left(\frac{CO_{2\,costs\,opt}\,[Mtonnes] - CO_{2\ CO_2\,opt}\,[Mtonnes]}{3}\right) * i + CO_{2\,CO_2\,opt}[Mtonnes] \qquad [4.8]$$

Where i can be 1 or 2. $CO_{2\,costs\,opt}$ and $CO_{2\ CO_2\,opt}$ refer to the $CO_2$ value that results from the cost and $CO_2$ optimization respectively. In total four optimizations are carried out to create four designs, here ranked from lowest to highest $CO_2$ emissions: a design minimizing $CO_2$, emission design 1, emission design 2 and a design minimizing costs.

Figure 8 displays a graphical summary of the abovementioned input data that is required. It also provides a summary of the optimizations that are used in the EHub tool and the outcome of the EHub tool is added. With the four emission designs, the trends of the output of the EHub tool can be displayed. This way, a reference of technology selection, size and details of the operation, is created to compare the decarbonization routes with. Moreover, the $CO_2$ emissions and annual costs are used as output.

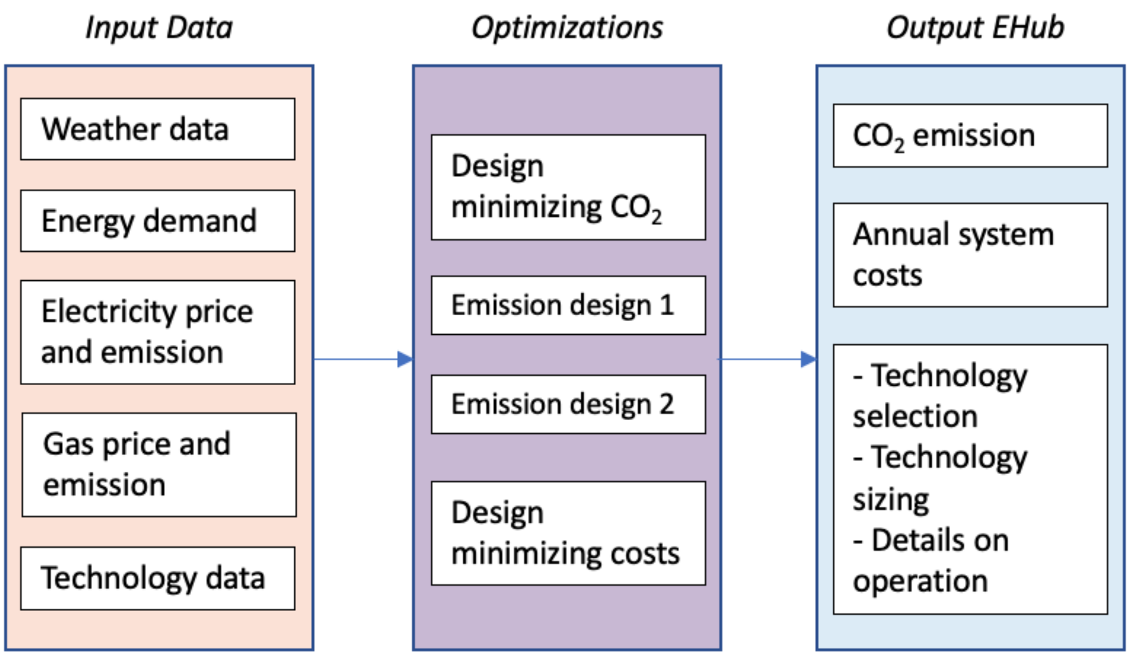


*Figure 8: Graphical representation of the in- and output of the EHub tool. The input data, optimizations and output of the EHub tool are displayed.*

## 4.3 Scenario analysis

The objective of the second research question is to perform a scenario analysis. The scenario analysis explains how different decarbonization affects the energy demand as input data. This section discusses how the demand profiles and thus the input data change when the three scenarios are utilized. Furthermore, it is shown how the nodes change.

### 4.3.1 Electrification scenario

This section explains how the heat generation of DSP, TSP and HSM can be electrified. First, the changed demand profiles are explained, followed by how this change affects the nodes.

#### *4.3.1.1 Changed demand profiles*

The electrification scenario is explained in section 2.4.1. A summary of the core values of TSP, DSP and HSM, the furnaces in which heat production could be electrified, can be found in Table 3. The core values are displayed as average input, average load and efficiency.

*Table 3: Summary of the core values of BAU (Vrijlandt et al., 2019).*

| ***Line*** | **$Q_{in}$ [GJ/h]** | **$Q_{load}$ [GJ/h]** | **Efficiency [%]** |
|---|---|---|---|
| *TSP* | 25.45 | 11.50 | 46.08 |
| *DSP* | 34.40 | 6.950 | 20.21 |
| *HSM* | 727.1 | 397.0 | 54.60 |

The values displayed in Table 3 can be used to recalculate the original demand. The NG, which is currently used to generate heat, can be replaced by extra electricity demand to generate the heat. This way, the input data of the electrification scenario is created. The core values of this electrification scenario can be found in
Table 4. Next to the core values, also a difference in the input is displayed relative to NG.

*Table 4: Summary of core values of the furnaces when electrification is implemented. The difference in the input is also shown as a percentage of the original input value (Vrijlandt et al., 2019).*

| ***Line*** | **$Q_{in}$ [GJ/h]** | **$\Delta Q_{in}$ [%]** | **$Q_{load}$ [GJ/h]** | **Efficiency [%]** |
|---|---|---|---|---|
| *TSP* | 14.07 | 44.72 | 11.50 | 81.71 |
| *DSP* | 16.36 | 52.44 | 6.950 | 42.50 |
| *HSM* | 669.0 | 7.99 | 397.0 | 59.34 |

The changed demand profiles are implemented as new input data in the EHub tool.

#### *4.3.1.2 Changed nodes*

When only electrification measures are taken into account, it is likely that the EHub tool imports more electricity and less NG, because there are no possibilities to install more electricity generation technologies at TSIJ. Therefore, this scenario gives the EHub tool the possibility to implement renewable electricity generation technologies. This is in line with the decarbonization plan of TSIJ, described in 0. PV and solar thermal can be installed on the roof and wind turbines can be installed on the land. Table 5 represents the possibilities to install renewables at TSIJ:

*Table 5: An overview of the roof- and land area which is available at TSIJ to install renewables.*

| ***Node*** | **Roof area [km$^2$]** | **Land Area [km$^2$]** |
|---|---|---|
| *CEN3* | 10.2 | 0 |
| *HSM* | 3.71 | 0 |
| *TSP* | 0.225 | 2.36 |
| *CGP 2* | 0 | 1.58 |
| *CEN 2* | 0 | 2.36 |
| *CEN 1* | 1.47 | 0 |

Note that PV and solar thermal compete for the same area on the roof. The EHub tool decides which of the technologies to install, dependent on which is the most favorable for the energy system. Figure 9 represents all possible energy generation technologies graphically in green boxes. Moreover, this figure shows the nodes which are affected by the changed input data. The electrification scenario changes the nodes 2, 4 and 6 which are displayed in orange.

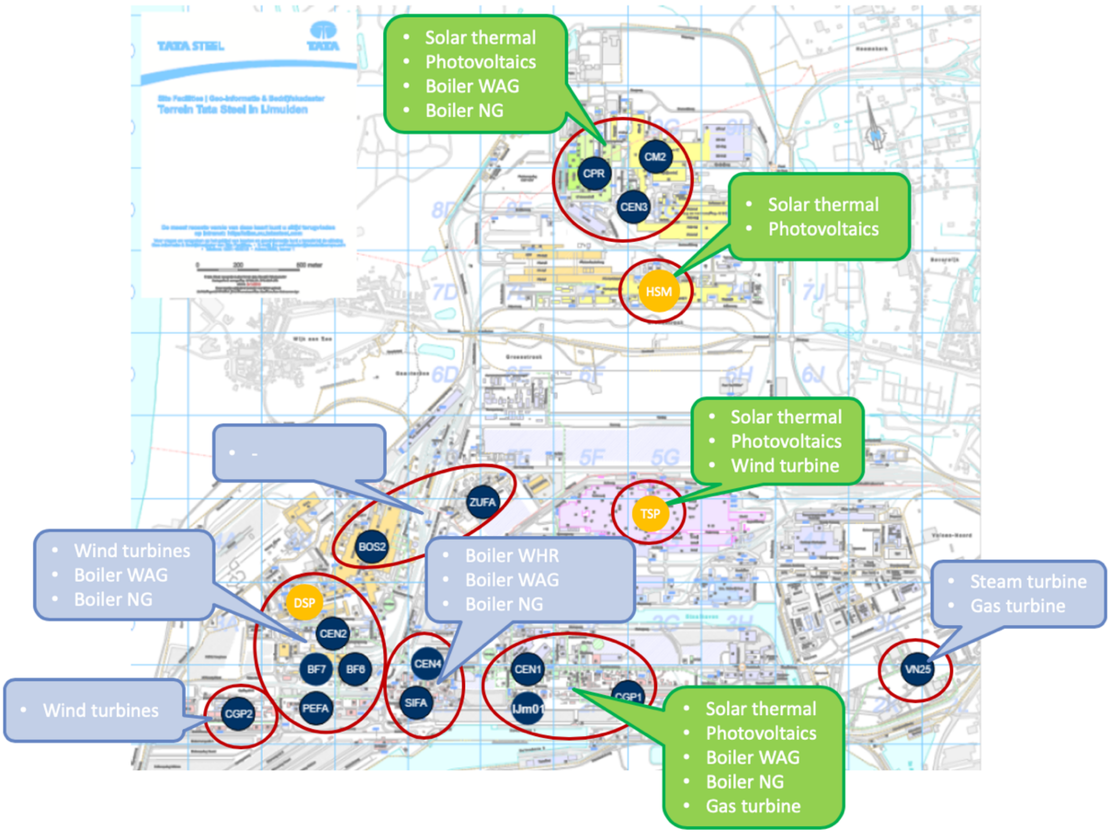


*Figure 9: Mix of furnaces and generation technologies which could be installed at TSIJ in the electrification scenario. The nodes where the boxes which are green, have the extra renewable possibility. The furnaces which are electrified are made orange.*

### 4.3.2 Electric Arc Furnace scenario

In this section, it is explained how the energy demand of TSIJ changes when an EAF producing 3Mtonnes of steel is implemented. First, it is explained how the profiles change. Then the changed nodes are elaborated.

#### *4.3.2.1 Changed demand profiles*

The EAF is explained in section 2.4.2. As explained in this section, major changes are needed to implement the EAF. BF6, CGP 2 need to be closed. Furthermore, SIFA, PEFA CGP 1, DSP and BOS are lowered in their capacity directly related to the closure of BF6 (Keys et al., 2019).

First of all, CGP1 needs to lower its capacity. The main task for the CGP plants is to produce CO gasses as an input for the BF to produce steel. Therefore, the CGP1 is lowered based on the lowering of demand CO gasses because BF6 closes. Equation [5.1] displays how this is done:

$$Lowering\ CGP1\ [\%] = \frac{Relative\ Net\ production\ CO\ CGP1\ [\%]}{Relative\ Consumption\ CO\ BF7\ [\%]} \quad [5.1]$$

Where the relative consumption CO of BF7 is determined by Equation [5.2]:

$$Relative\ Consumption\ CO\ BF7[\%] = \frac{Concumption\ CO\ BF7\ [kWh]}{Concumption\ CO\ BF7\ [kWh]\ + Concumption\ CO\ BF6\ [kWh]} \quad [5.2]$$

where the relative net production CO of CGP1 is determined by Equation [5.3]:

$$Relative\ Net\ production\ CO\ CGP1\ [\%] = \frac{Net\ CO\ production\ CGP1\ [kWh]}{Net\ CO\ production\ CGP1\ [kWh] +\ Net\ CO\ production\ CGP2\ [kWh]} \quad [5.3]$$

According to this method, CGP1 needs to be lowered by 7%.

Next, the other input of the BFs, SIFA and PEFA, are lowered in their capacity. On the contrary of CGP, SIFA and PEFA cannot be reduced by any percentage. Therefore, different methods are used. SIFA is reduced based on the three machines which produce the sinter. One of these machines is shut down in the case that BF6 is closed. There is chosen to shut down the third sinter machine, because closing this machine comes closest by the capacity of BF6 while keeping the capacity to fulfill the demand of BF7. As a consequence, the SIFA is lowered with 36%. (Tesselaar, 2011)

PEFA is lowered based on the difference between the minimum and maximum capacity it has produced pellets in the year 2018, see Equation [5.4]:

$$Lowering\ PEFA\ [\%] = \frac{Minimum\ pellet\ production\ \left[\frac{tonnes}{year}\right]}{Maximum\ pellet\ production\ \left[\frac{tonnes}{year}\right]} \quad [5.4]$$

Using this method, PEFA is reduced by 36% (Velde, 2020).

DSP and BOS are located after the production of the BFs. Therefore, the ratio of the typical production of pig iron is used to determine the new profiles, see Equation [5.5]:

$$Lowering\ DSP\ \&\ BOS\ [\%] = \frac{Production\ BF7\left[\frac{tonnes}{day}\right]}{Production\ BF6\left[\frac{tonnes}{day}\right] + Production\ BF7\left[\frac{tonnes}{day}\right]} \quad [5.5]$$

Using Equation [5.5], the profiles of DSP and BOS are lowered with 45%.

Naturally, using an EAF does not only lead to lower demand profiles, but also to more consumption. The EAF itself consumes NG and electricity as an input. Also, the EAF needs pure oxygen, which needs to be produced in ZUFA. These values need to be taken into account as extra input data. Table 6 shows the extra electricity and NG demand of the EAF and the changed electricity demand of ZUFA due to the new oxygen demand.

*Table 6: Overview of the electricity and NG demand of the EAF and the changed demand for ZUFA (Keys et al., 2019).*

| ***Line*** | **$Q_{BAU}$ [PJ]** | **$Q_{EAF}$ [PJ]** | **Change [%]** |
|---|---|---|---|
| *$ZUFA_{electricity}$* | 1.35 | 0.77 | -43 |
| *$EAF_{gas}$* | 0 | 2.31 | - |
| *$EAF_{electricity}$* | 0 | 1.98 | - |

Despite the extra pure oxygen demand of the EAF the electricity demand of ZUFA is 43% lower. This is because the demand of oxygen from ZUFA is circa 1% of the demand related to BF 6 & 7. The saving of oxygen demand related to BF6 is more significant than the extra demand of the EAF. Therefore, it cannot be seen in the change. Furthermore, the EAF uses a lot of electricity and NG to produce the 3 MTonnes steel.

#### 4.3.2.2 Changed nodes

Figure 10 provides an overview of the abovementioned changed nodes. In this figure, the closed nodes are represented by a red dot, the furnaces which are reduced are represented by orange and the newly installed EAF is represented by green. Moreover, the possible renewable capacity is represented by green boxes. The possible installations of these renewables can be found in Table 5.

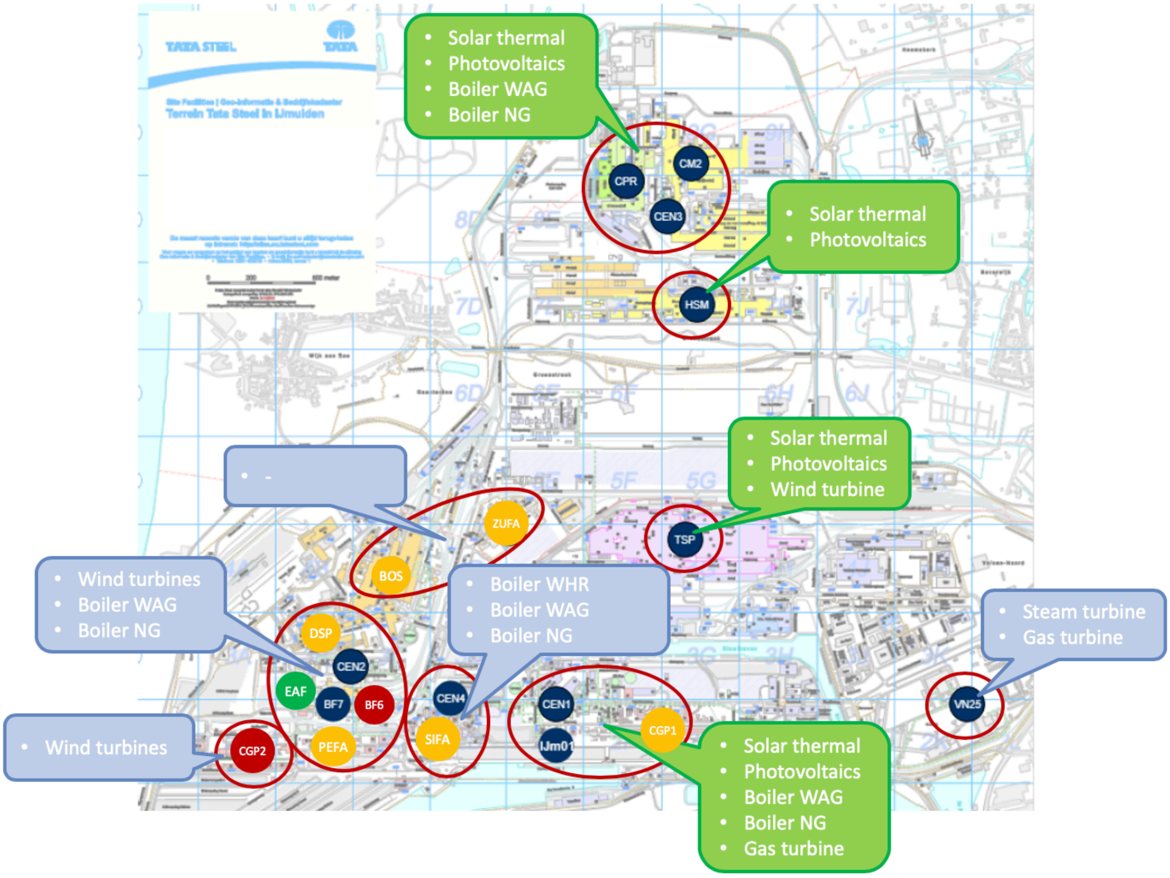


*Figure 10: Overview of TSIJ in an EAF scenario. The furnaces which are closed, are represented by a red dot. The furnaces which are reduced, are represented by an orange dot and the EAF is represented by a green dot. The green boxes are the nodes where renewables could be installed.*

### 4.3.3 Hisarna scenario

This section describes how the demand profiles changed of all furnaces when the capacity of BF6 is replaced by a Hisarna plant. First of all, this section explains how the profiles change. Then the changed nodes are elaborated.

#### 4.3.3.1 Changed demand profiles

The Hisarna scenario is explained in section 2.4.3. As explained in this section, major changes are needed to implement a Hisarna plant. BF6 closes and the Hisarna plant takes over the capacity. Considering that Hisarna does not need the capacity of PEFA, SIFA and CGP these reduce in the same manner as in the EAF scenario. Therefore Equation [5.1], [5.2], [5.3] and [5.4] are used to change the input data of the Hisarna scenario.

On the contrary of the EAF, the Hisarna plant is not able to produce crude steel. Instead, the product of Hisarna is pig iron comparable with the product of the BF. As a consequence, the BOS is needed to process the pig iron into crude steel. Therefore, the full capacity of BOS is needed, for both BF7 and the Hisarna to produce 7.2 Mtonnes steel.

Using the Hisarna plant lead to extra demand as well. The input consists of electricity and oxygen. The oxygen is provided at ZUFA, where electricity is required to provide the required oxygen. Table 7 shows the electricity demand of the Hisarna plant and the changed electricity demand of ZUFA due to the new oxygen demand.

*Table 7: Overview of the electricity demand of the Hisarna plant and the changed demand of ZUFA (Keys et al., 2019).*

| ***Line*** | **$Q_{BAU}$ [PJ]** | **$Q_{EAF}$ [PJ]** | **Change [%]** |
|---|---|---|---|
| $ZUFA_{electricity}$ | 1.35 | 0.90 | -33 |
| $Hisarna_{electricity}$ | 0 | 0.81 | - |

### *4.3.3.1 Changed nodes*

Figure 11 shows graphically the changed nodes when a Hisarna scenario is implemented. Relative to the EAF scenario, the BOS plant remains at full capacity. Naturally, the EAF is replaced by a Hisarna plant.

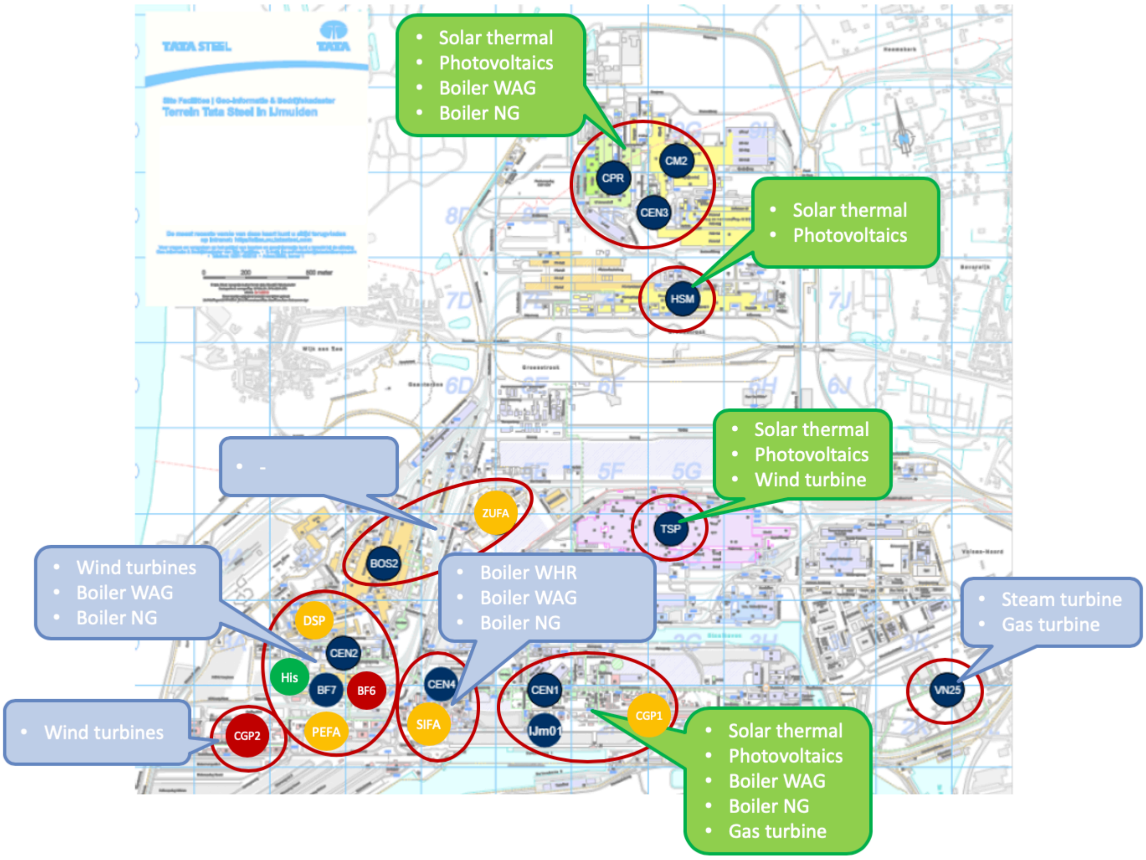


*Figure 11: Overview of TSIJ in a Hisarna scenario. The furnaces which are closed, are represented by a red dot. The furnaces which are reduced, are represented by an orange dot and the Hisarna plant is represented by a green dot. The green boxes are the nodes where renewables could be installed.*

## 4.4 Scenario results

The objective of research question 3 is to display and analyze the scenario results. By doing so, the scenario can be interpreted to pinpoint the differences in utilizing an electrification-, an EAF- and a Hisarna scenario.

To run the alternative scenarios, the EHub tool described in section 4.2.1 is used. However, the input data of the demand profiles are changed. The demand profiles used in the EHub tool are changed based on the scenario analysis described in section 0. The results of the three alternative scenarios are shown separately and are compared with the reference created in the model analysis which is described in section 4.2.

Two outcomes of the EHub tool are compared to show the trends of the three scenarios. First of all, the annual costs and $CO_2$ emission of each scenario are displayed and compared. This is done to evaluate if or how much $CO_2$ is reduced and what annual system cost is implied. Then the technology selection and technology size are compared. This is done to elaborate on where the $CO_2$ reduction is coming from and why this technology selection is chosen. This way, the trends of each scenario can be compared with the BAU.

# 5 Analysis

The following chapter provides an overview of the findings arising from this research. First, it describes the outcome of the EHub tool applied on the current demand profiles of TSIJ to create a reference for the decarbonization routes. This is followed by the changed demand profiles for the three scenarios. Lastly, the changed demand profiles are implemented in the EHub tool so the decarbonization routes can be explored.

## 5.1 Model analysis

Figure 12 reports a Pareto front of the total $CO_2$ emission relative to the annual energy costs. The Pareto front shows the relative decarbonization, i.e. the point left represents the design minimizing $CO_2$ emissions, and the point right represents the design minimizing costs. It can be observed that the maximum $CO_2$ savings are limited to 8%, due to the limited capacity of renewables on the site of TSIJ. Those savings of 8% come with a cost increase of 20%. Furthermore, decarbonization of 4% and 2% can be achieved with a cost increase of about 3% and less than 1%, respectively. This shows that decarbonization by changing the energy system is only cost-effective towards emission design 1 and 2. Thereafter, the increase in cost relative to the reduced $CO_2$ becomes too high, which makes the viable potential of decarbonization by changing the energy system lower. The limited potential for decarbonization clearly shows the need for process changes if deep decarbonization is aimed for. Scenarios covering such changes are discussed in section 0.

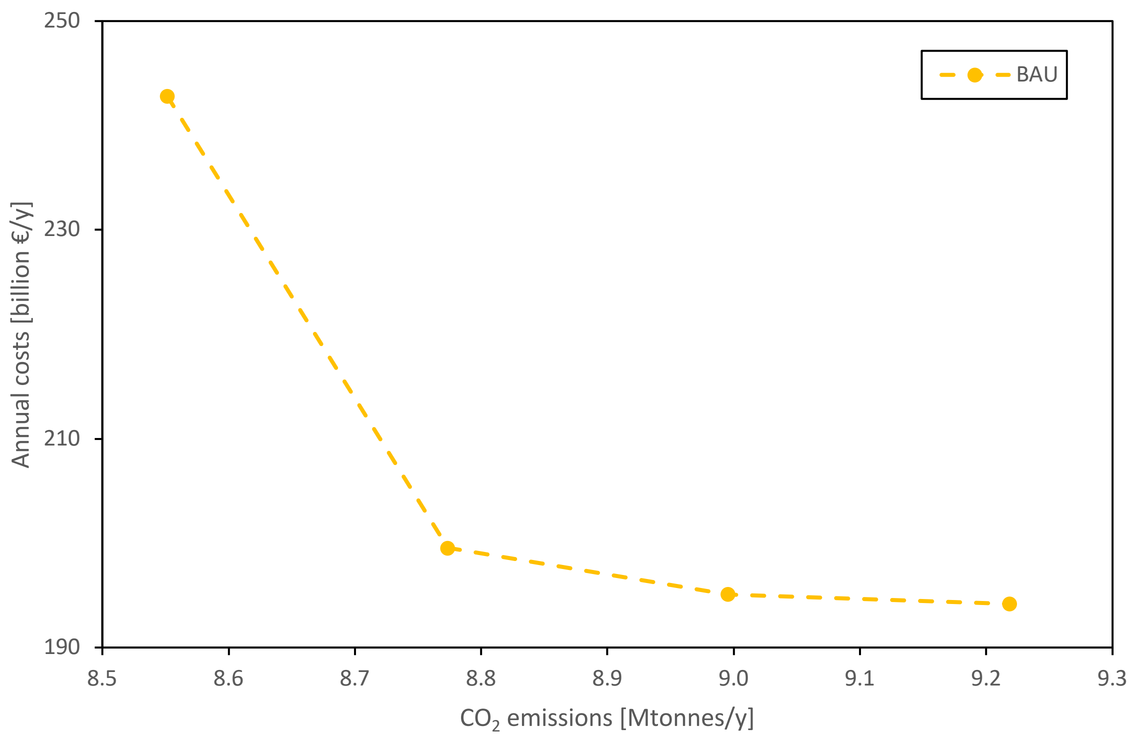


*Figure 12: Pareto front of the total costs relative to the $CO_2$ emissions of the BAU. Along the Pareto front from left to right, the point represents the design minimizing $CO_2$, emission design 1, emission design 2 and the design minimizing costs.*

Figure 13 and Figure 14 report the size and selection of the technologies as a function of the $CO_2$ reduction. This way, better insights where the costs and $CO_2$ savings are coming from can be made. In this figure, the cost minimizing design is equal to 0 and the $CO_2$ minimizing design is equal to 1. A few considerations can be made:

i) The wind turbine is installed at maximum capacity in every optimization. This means that the wind turbine is both in a cost perspective and a $CO_2$ emissions perspective the best technology to generate electricity.

ii) The sharp increase in costs to save the last part of $CO_2$ emissions is equal to the sharp increase in the usage of the boiler WAG and steam turbine. Although these technologies generate emission-free, these are expensive to use.

iii) The GT is used at full capacity in all designs, except for the $CO_2$ minimizing design. Only in this design a small part of the capacity is used for peak demand. The small increase in $CO_2$ emissions in emission design 1, where the GT is used at full capacity, shows that the GT emits a relative low amount of $CO_2$. This means that the GT is a good technology for TSIJ as an alternative for the steam turbine and boiler WAG in more cost-effective designs.

iv) In all designs at least 54% of electricity is imported. This highlights the potential of extra (renewable) electricity generation at the site of TSIJ and decarbonization of grid emissions.

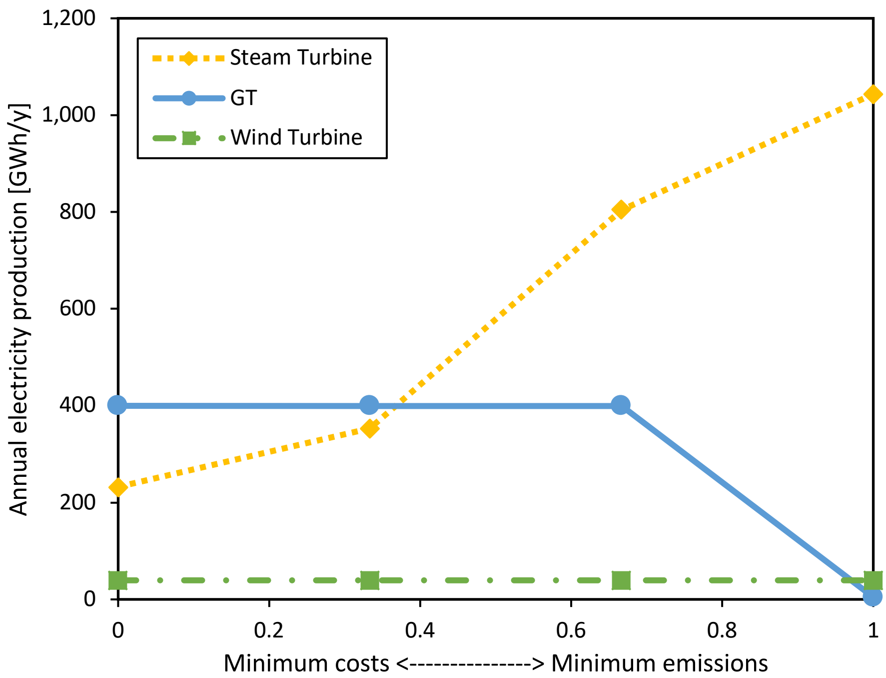


*Figure 13: The Pareto front for electricity generating technologies in an BAU scenario. On the x-axis, 0 represent a design minimizing costs, 1 represents a design minimizing $CO_2$ emission.*

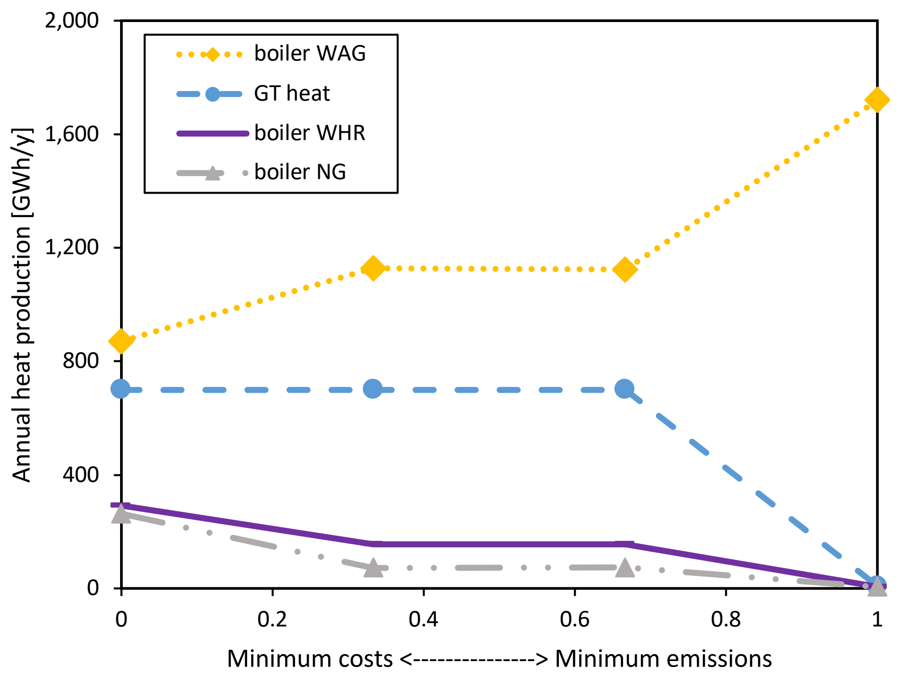


*Figure 14: The Pareto front for heat generating technologies in an BAU scenario. On the x-axis, 0 represent a design minimizing costs, 1 represents a design minimizing $CO_2$ emission.*

To understand the technology size and selection in more detail, the cost and $CO_2$ minimizing design, are analyzed in more detail based on operation graphs. Figure 15 and Figure 16 show the technology size presented in an operation graph. These figures show a cost minimizing design, the current situation at TSIJ. All technologies, currently present at TSIJ, are selected. The GT and the wind turbines are selected at the maximum allowed capacity. The GT is used since it is a CHP plant. This allows the GT to produce electricity and heat at the same time, which makes the GT an efficient and cheap plant. Also, because TSIJ has both a large demand for electricity and heat, the GT is an efficient technology to use. The wind turbines are used at full capacity, as the wind turbine is the cheapest technology available to generate electricity. Considering that both the demand for heat and electricity are not fulfilled with just those two technologies, other technologies are used as well. For electricity generation, the steam turbine is used, and 75% of the total electricity demand is imported. This is pollutive but cheaper than fulfilling the rest of the demand with the steam turbine.

Heat import is not possible. Instead, the boiler NG and the earlier mentioned GT are cheapest and thus used as baseload. The boiler WHR is cheaper to use than the boiler WAG. However, there is not always sufficient waste heat available to fulfill the demand. Therefore, the boiler WAG, which is the most expensive technology, is used to produce the remaining demand. This configuration leads to 27 €/$kg_{steel}$ and 1.3 tonnes $CO_2$/$tonne_{steel}$. Note that the energy costs not only include the variable but also the fixed costs of the technology selection.

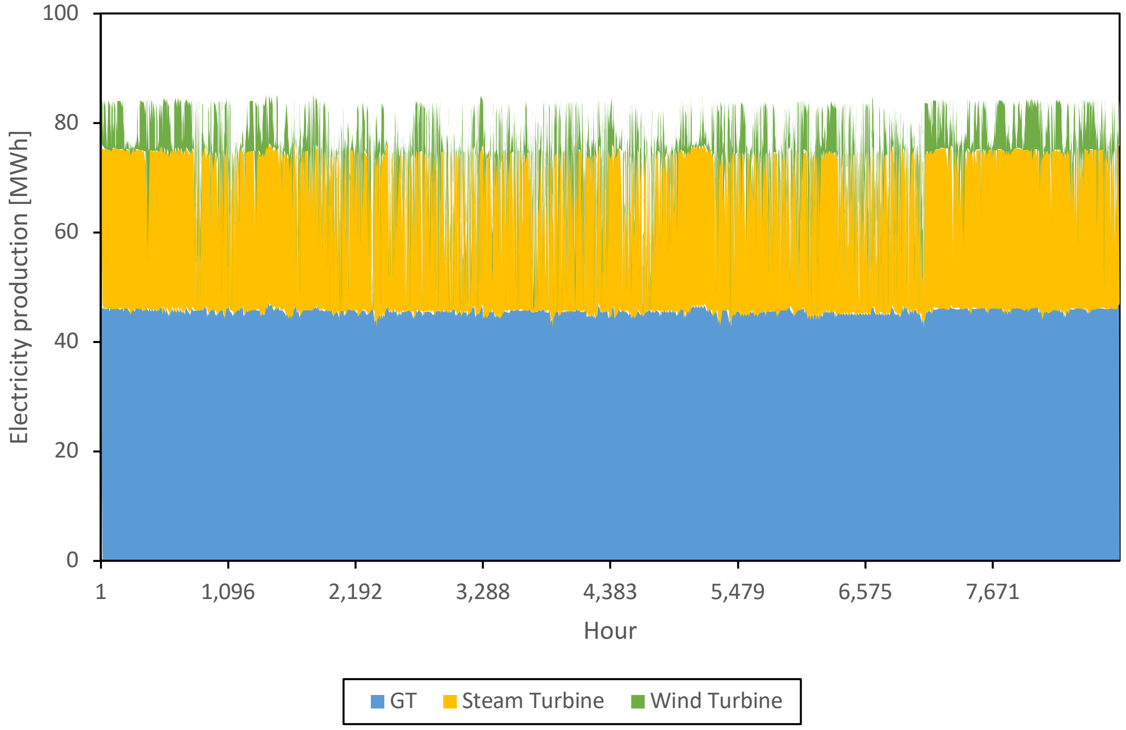


*Figure 15: Operation graph of electricity-generating technologies in a cost optimization.*

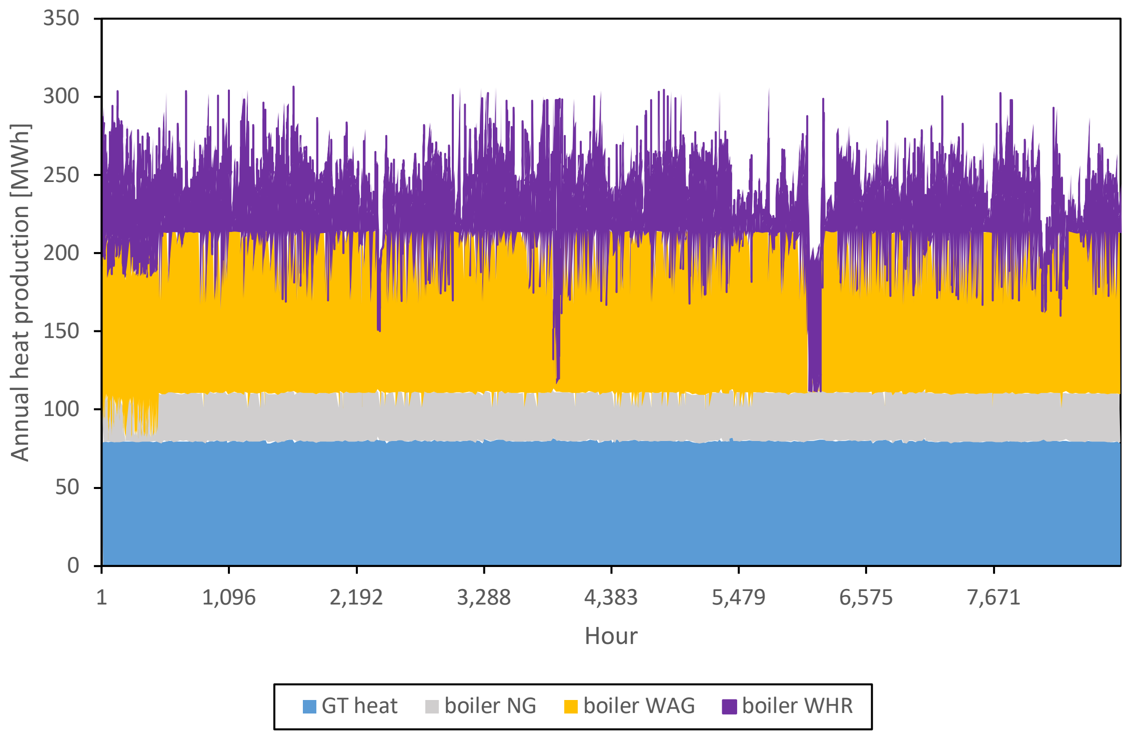


*Figure 16: Operation graph of heat-generating technologies in a cost optimization.*

Figure 17 and Figure 18 illustrate the technology selection for TSIJ in a minimizing $CO_2$ emission design. In contrary to the varying technology selection in a cost minimizing design, the energy in a design minimizing $CO_2$ emission is mainly generated by the steam turbine and the boiler WAG for electricity and heat respectively. The utilization of these WAG utilization technologies does not result in additional emissions since the emissions of WAG are assumed to occur anyway, because WAG is a byproduct of steelmaking. Furthermore, the wind turbine is installed at the maximum allowed value. Aside from that the wind turbine is being cheap, the wind turbine runs on wind and thus emits no $CO_2$. Hence the steam turbine and wind turbine are preferred over the GT in emission low designs for electricity generation. Note that a lot more electricity is generated relative to a minimal costs design. This can be explained through less imported electricity, 1.7TWh, which is 62% of the total demand. This lower import of electricity leads to less $CO_2$ emissions.

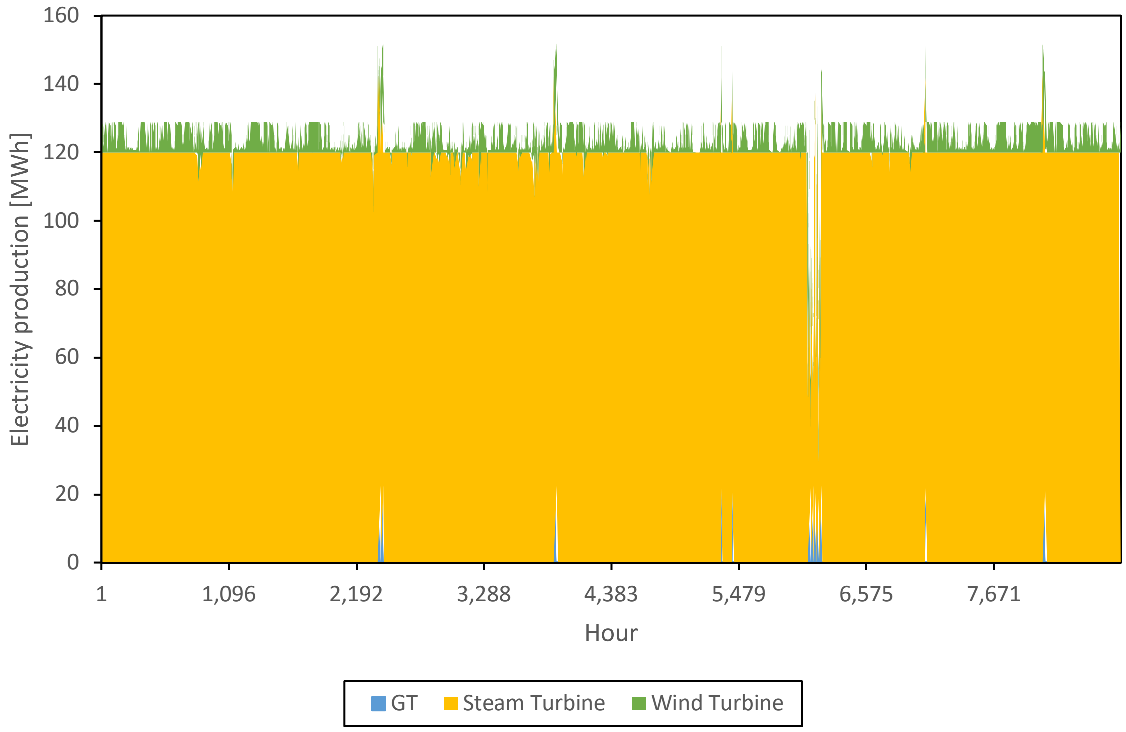


*Figure 17: Operation graph of electricity generating technologies in a $CO_2$ optimization.*

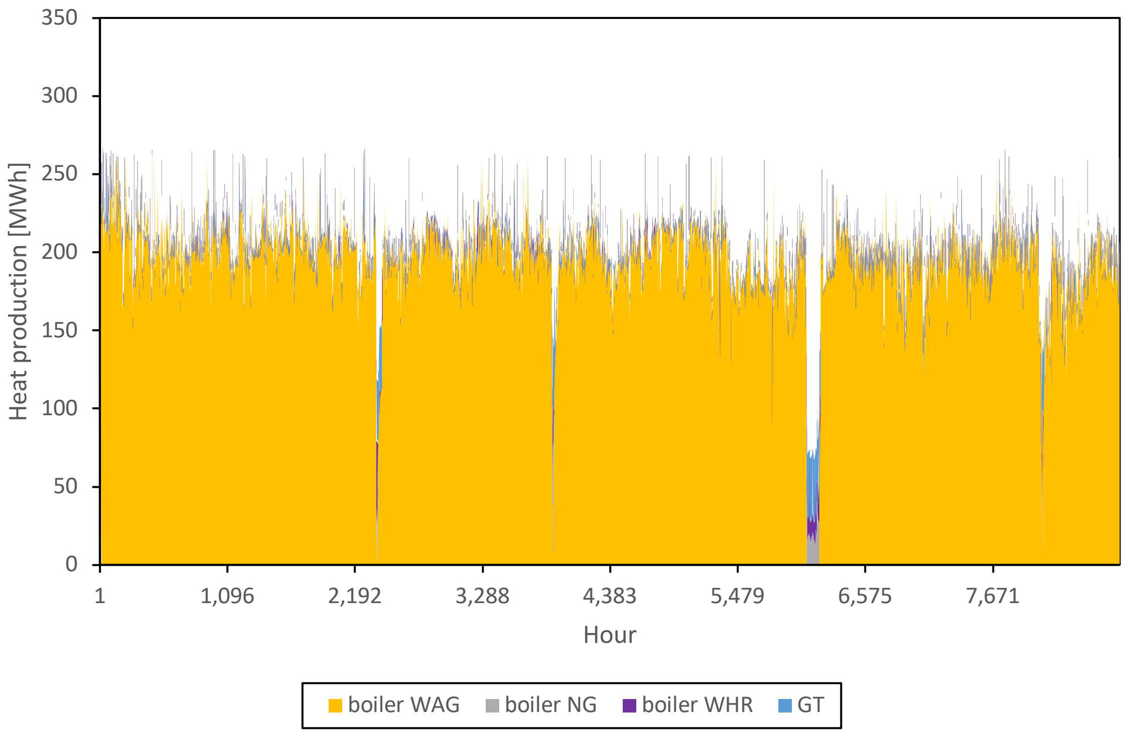


*Figure 18: Operation graph of heat generating technologies in a $CO_2$ optimization.*

Due to that the WAG utilizing technologies are that dominant, less dominant technologies cannot be analyzed properly through these figures. Therefore, Figure 19 and Figure 20 display the technologies other than the boiler WAG and the steam turbine. Figure 19 shows that the wind turbine fluctuates a lot between the rated power of 9,000 MWh and periods when less wind is available, and the output is less. This shows the high intermittency of the wind turbine. Figure 17 shows that the wind turbine follows a seasonal pattern in the fluctuations. In the summer, less peaks are visible, and the peaks are mostly lower. In the winter, more peaks can be observed. This pattern can be explained through more wind in winter relative to the summer.

Figure 20 shows the heat generating-technologies. Remarkable is that the heat demand, next to the boiler WAG, is supplied by the boiler NG. The boiler NG is selected next to the boiler WHR despite the little emission of the boiler WHR. This can be explained through the location of the boiler WHR. The boiler WHR is located at the same node as the boiler WAG. Considering that the boiler WAG produces almost all heat demand, no capacity on the heat distribution network is left for the heat production of the boiler WHR. The boiler NG has multiple locations where it can be installed. Therefore, it is only possible for the boiler WHR to produce heat when WAG is less available. Next to the boiler WHR and boiler NG, the GT is used as a backup. The GT is used as back next to the boiler WHR, because the boiler WHR has no sufficient capacity due to the limited amount of waste heat available. The GT is selected over the boiler NG because the GT produces also electricity. This prevents that electricity needs to be imported, which makes the GT more efficient than the boiler NG.

The planned maintenance hours of the BFs around hour 6,000 makes this design very expensive relative to the other designs. Since heat cannot be imported, it has to be generated. The minimizing $CO_2$ emission design is very dependent on WAG, but WAG is less available during the maintenance hours. Therefore, the GT, boiler WHR and boiler NG need to be installed for small use of their capacity, which is inefficient in terms of cost, but necessary to generate the heat when WAG is less available. All in all, a design minimizing $CO_2$ leads to 34 €/$kg_{steel}$ of costs and 1.2 kg $CO_2$/$tonne_{steel}$.

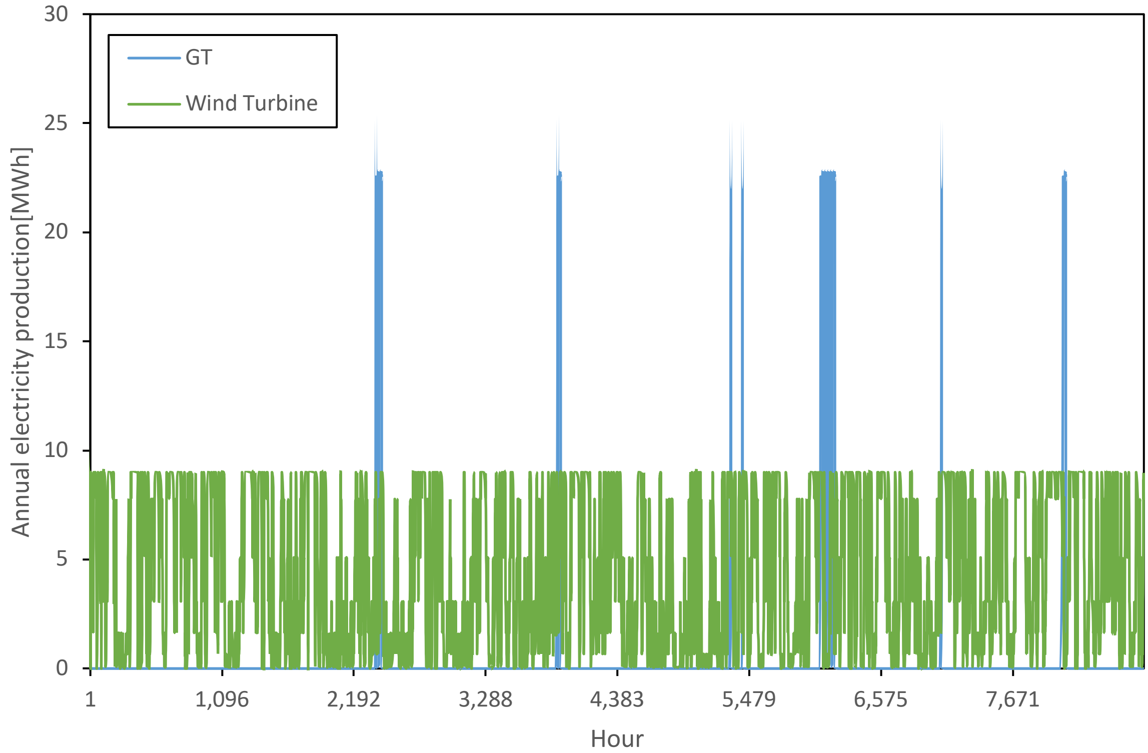


*Figure 19: A detailed representation of the operation graph of electricity showing the GT and the wind turbine. Note that, in the contrary of the full operation graph, this in no stacked diagram.*

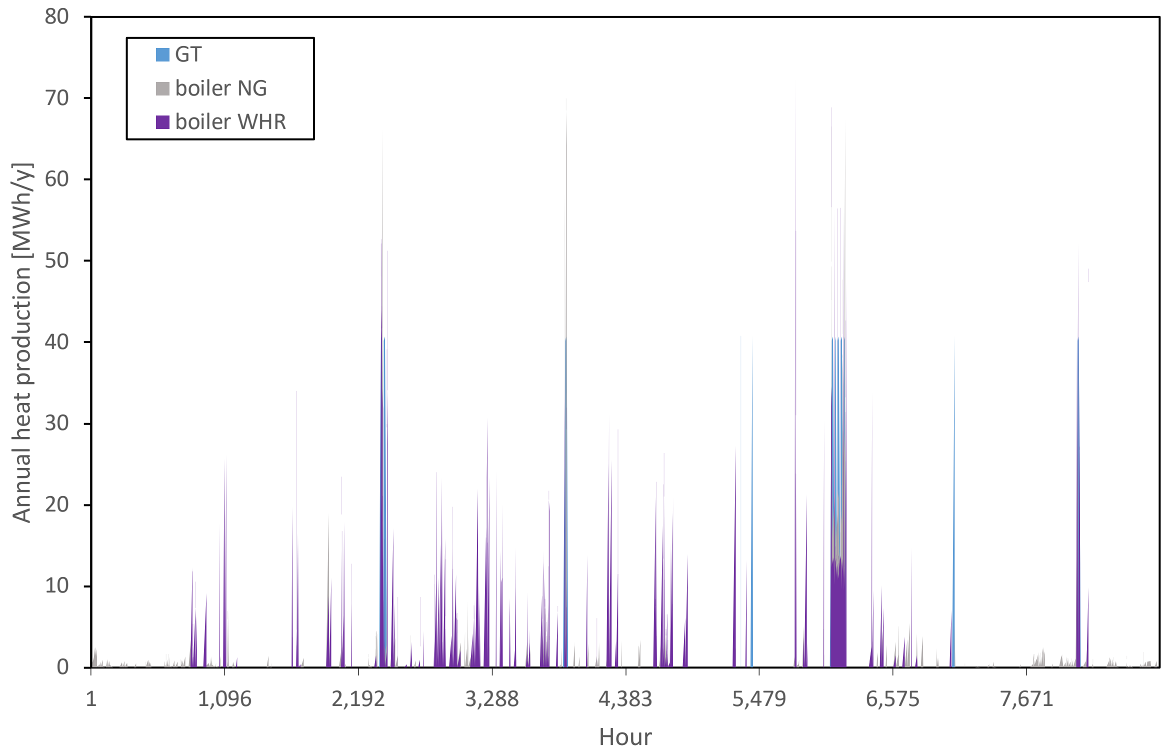

*Figure 20: A detailed representation of the operation graph of heat showing the GT, the boiler NG and boiler WHR. Note that, in the contrary of the full operation graph, this in no stacked diagram.*

## 5.2 Scenario analysis

As seen in the previous section, the decarbonization potential is limited without process changes. Three such process changes, namely electrification of heat, utilization of an EAF, and utilization of the Hisarna process, are considered in this study. In the following section, the effect of those process changes on the demand profiles is discussed.

### 5.2.1 Electrification scenario

The heat of furnaces that are electrified are HSM, TSP and DSP. These furnaces are localized at nodes 2, 4 and 6 respectively. As a consequence, the profiles at these nodes change. All have a lower NG demand and a higher electricity demand. Table 8, Table 9 and Table 10 provides the original in orange and new demand in green of node 2, 4 and 6 respectively:

*Table 8: Average, minimum and maximum electricity and NG demand of node 2. The BAU scenario is shown in orange, the electrification scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | 49.37 | 4.068 | 85.91 |
| *NG* | 104.7 | 18.42 | 313.0 |
| *Electricity* | 56.05 | 6.337 | 98.13 |
| *NG* | 94.13 | 16.56 | 281.3 |

*Table 9: Average, minimum and maximum electricity and NG demand of node 4. The BAU scenario is shown in orange, the electrification scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | *18.15* | *8.037* | *28.03* |
| *NG* | 16.36 | 3.632 | 26.11 |
| *Electricity* | *21.74* | *8.074* | *33.92* |
| *NG* | 9.888 | 0.002 | 24.61 |

*Table 10: Average, minimum and maximum electricity and NG demand of node 6. A negative value means that the node generates more than it consumes. The BAU scenario is shown in orange, the electrification scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | 18.76 | -16.37 | 46.38 |
| *NG* | 22.31 | 0.543 | 69.97 |
| *Electricity* | 24.72 | -16.34 | 53.95 |
| *NG* | 3.705 | -23.45 | 64.75 |

Note that node 2 consists of more furnaces than only DSP. Also, BF 6 & 7, CEN1 and PEFA are localized in this node, which means that the demands of these furnaces are also included.

### 5.2.2 Electric Arc Furnace scenario

The utilization of the Electric Arc Furnace changes the demand profiles of 9 furnaces located at 5 different nodes. Each furnace is lowered by a certain percentage determined in section 4.3.2.1. This percentage accounts for all carriers. The EAF itself is located at Node 6. As a consequence, the demand for this node is higher. Table 11, Table 12, Table 13, Table 14 and Table 15 shows the current demand profiles in orange and the new demand profiles in green.

*Table 11: Average, minimum and maximum electricity, WAG and heat demand of node 3. A negative value means that the node generates more than it consumes. The BAU scenario is shown in orange, the EAF scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | 149.1 | 97.87 | 185.3 |
| *WAG* | 89.89 | 0 | 143.6 |
| *Heat* | -7.556 | -58.25 | 39.27 |
| *Electricity* | 82.41 | 54.08 | 102.4 |
| *WAG* | 42.91 | 0 | 68.55 |
| *Heat* | -4.175 | -32.19 | 21.70 |

*Table 12: Average, minimum and maximum WAG and heat demand of node 5. The BAU scenario is shown in orange, the EAF scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *WAG* | 94.12 | 16.50 | 155.7 |
| *Heat* | 11.00 | 6.868 | 15.21 |
| *WAG* | 0 | 0 | 0 |
| *Heat* | 0 | 0 | 0 |

*Table 13: Average, minimum and maximum electricity, NG, WAG and heat demand of node 6. A negative value means that the node generates more than it consumes. The BAU scenario is shown in orange, the EAF scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | 18.76 | -16.36 | 46.38 |
| *NG* | 22.30 | 0.0543 | 69.97 |
| *WAG* | 827.5 | 44.39 | 1,067 |
| *Heat* | 133.1 | 0 | 165.4 |
| *Electricity* | 72.35 | 2.734 | 92.83 |
| *NG* | 86.40 | 1.465 | 127.5 |
| *WAG* | 495.3 | 43.52 | 670.7 |
| *Heat* | 80.52 | 0 | 106.5 |

*Table 14: Average, minimum and maximum electricity, WAG and waste heat demand of node 7. The BAU scenario is shown in orange, the EAF scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | 15.18 | 1.385 | 17.68 |
| *WAG* | 13.69 | 0 | 19.92 |
| *Heat waste* | 6.676 | 11.61 | 0 |
| *Electricity* | 9.665 | 0.8816 | 11.25 |
| *WAG* | 8.717 | 0 | 12.67 |
| *Heat waste* | 4.249 | 7.392 | 0 |

*Table 15: Average, minimum and maximum electricity, NG, WAG and heat demand of node 8. The BAU scenario is shown in orange, the EAF scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | 40.93 | 18.90 | 67.34 |
| *NG* | 100.9 | 0 | 466.8 |
| *WAG* | 169.0 | 274.2 | 70.95 |
| *Heat* | 29.21 | 18.52 | 51.09 |
| *Electricity* | 40.93 | 18.90 | 67.34 |
| *NG* | 100.9 | 0 | 466.8 |
| *WAG* | 158.1 | 66.36 | 256.5 |
| *Heat waste* | 27.62 | 17.32 | 49.31 |

### 5.2.3 Hisarna scenario

The utilization of Hisarna is in some aspects the same as the utilization of the EAF. In both cases BF6 closes, SIFA, PEFA and CGP reduce with the same amount in both scenarios. Therefore, node 5, 7 and 8 changes in the same manner. These can be found in Table 12, Table 14 and Table 15 respectively.

The nodes that do differ between the two scenarios are node 3 and node 6. At node 3 the BOS runs on full capacity in the Hisarna scenario instead of this installation is reduced in the EAF scenario. Moreover, at node 3 ZUFA increases due to more oxygen demand from the Hisarna relative to the EAF. At node 6, the demand is changed because the Hisarna plant is installed instead of the EAF.

*Table 16: Average, minimum and maximum electricity, WAG and heat demand of node 3. A negative value means that the node generates more than it consumes. The BAU scenario is shown in orange, the Hisarna scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | 149.1 | 97.87 | 185.3 |
| *WAG* | 89.89 | 0 | 143.6 |
| *Heat* | -7.556 | -58.25 | 39.27 |
| *Electricity* | 95.49 | 64.55 | 118.1 |
| *WAG* | 89.89 | 0 | 143.6 |
| *Heat* | -4.175 | -32.19 | 21.70 |

*Table 17: Average, minimum and maximum electricity, NG, WAG and heat demand of node 6. A negative value means that the node generates more than it consumes. The BAU scenario is shown in orange, the Hisarna scenario in green.*

| ***Carrier*** | **Average [MWh]** | **Minimum [MWh]** | **Maximum [MWh]** |
|---|---|---|---|
| *Electricity* | 18.76 | -16.36 | 46.38 |
| *NG* | 22.30 | 0.0543 | 69.97 |
| *WAG* | 827.5 | 44.39 | 1,067 |
| *Heat* | 133.1 | 0 | 165.4 |
| *Electricity* | 35.25 | 2.734 | 49.65 |
| *NG* | 13.15 | 0.0300 | 43.04 |
| *WAG* | 495.3 | -43.52 | 670.7 |
| *Heat* | 80.52 | 0 | 106.5 |

## 5.3 Scenario results

To determine the $CO_2$ potential of the decarbonization routes, the changed demand profiles are implemented as input data in the EHub tool. Next, the results are analyzed based on the reference created in section **Fout! Verwijzingsbron niet gevonden.**. In this section, the reduction potential and changed trends for the electrification-, EAF- and Hisarna scenario relative to the BAU are investigated.

### 5.3.1 Electrification scenario

This section presents the implementation of the new input data of the electrification scenario. Figure 21 compares the cost-emission Pareto front of the BAU and the electrification scenario. The Pareto fronts show the relative decarbonization, i.e. the points left represent the design minimizing $CO_2$ emissions, and the points right represent the design minimizing costs. The Pareto front of the electrification scenario follows the same trend as the Pareto front of the BAU. However, the Pareto front of the electrification scenario is shifted towards the origin, meaning that all designs are cheaper and emit less $CO_2$. The same trends mean that saving $CO_2$ emissions within the electrification scenario, goes in similar steps. The $CO_2$ emission reduction of all designs is 1% relative to the BAU, while the reduction of annual energy costs is slightly more than 1% relative to the BAU.

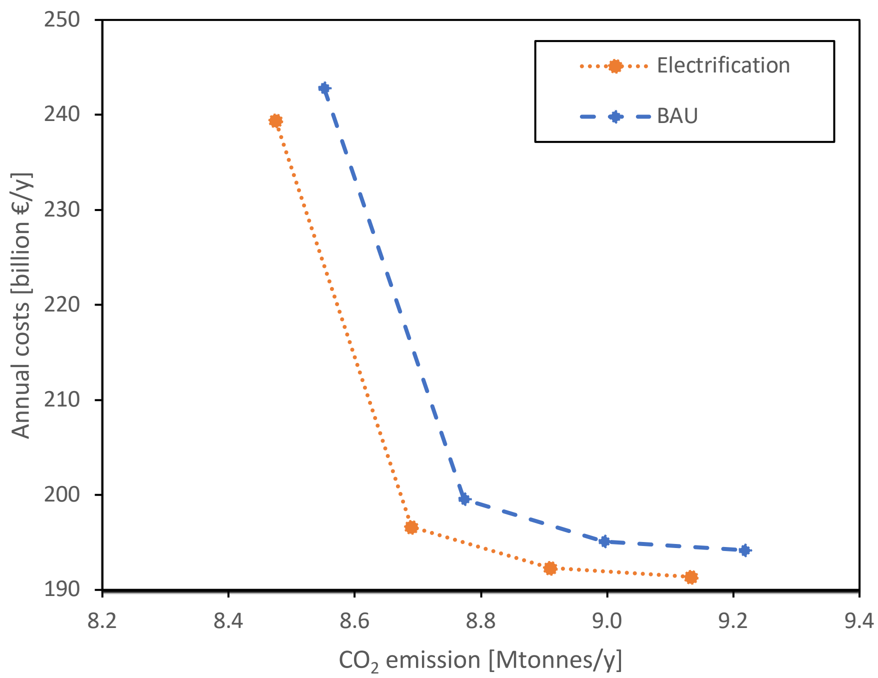


*Figure 21: Pareto front of the costs of the electrification scenario and BAU relative to the $CO_2$ emission of both scenarios. Along the Pareto fronts from left to right, the points represent the design minimizing $CO_2$, emission design 1, emission design 2 and the design minimizing costs.*

Figure 22 and Figure 23 report the size and technology selection of the electrification scenario as a function of the $CO_2$ reduction. Again, the x-axis shows the relative decarbonization, i.e. 0

refers to the minimizing costs design and 1 refers to minimizing $CO_2$ emission design. A few observations can be made:

i) The electricity renewables, PV and wind turbines, are installed and used at full capacity in every design. This means that these renewables are both in a $CO_2$ perspective and in a cost perspective the best technology. On the contrary with the electricity-generating renewables, no renewables to generate heat are installed in any design. This is a result of that PV and solar thermal compete for the same space on the roofs. The heat dissipation, which varies from 2% to 22% for all designs along the Pareto front, shows that significant overproduction of heat occurs. Electricity, however, has to be imported in every design. Hence generating electricity emission-free is favorable over producing heat emission-free.

ii) The trends for the other technologies are the same as in the BAU. This means that the steam turbine is fully used in a $CO_2$ minimizing design and the GT is installed at maximum capacity in all other designs. The steam turbine is used less and less towards the design optimizing costs.

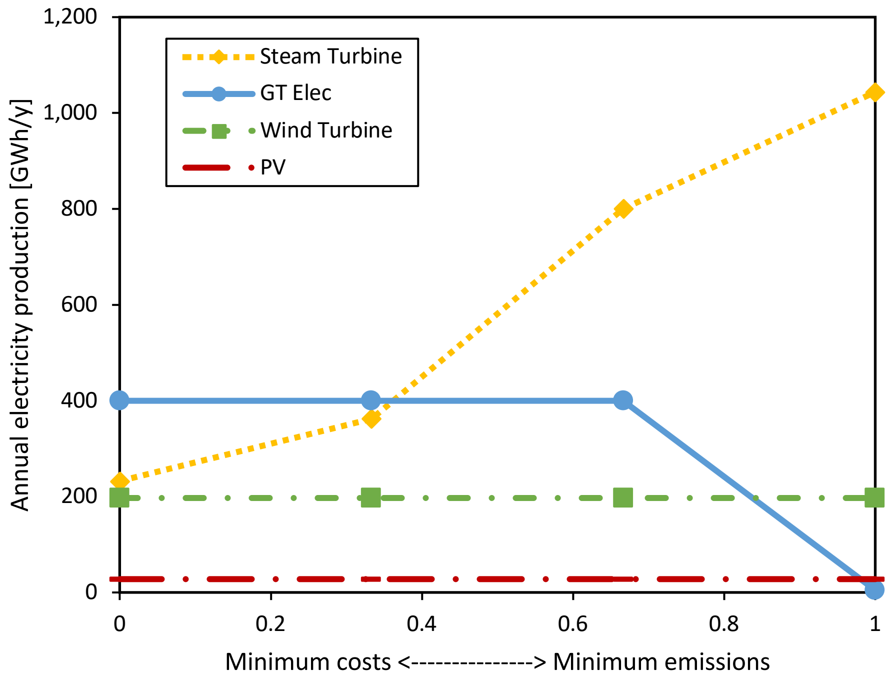


*Figure 22: Pareto front for electricity generating technologies in an electrification scenario. On the x-axis, 0 represents a design minimizing costs, 1 represents a design minimizing $CO_2$ emission.*

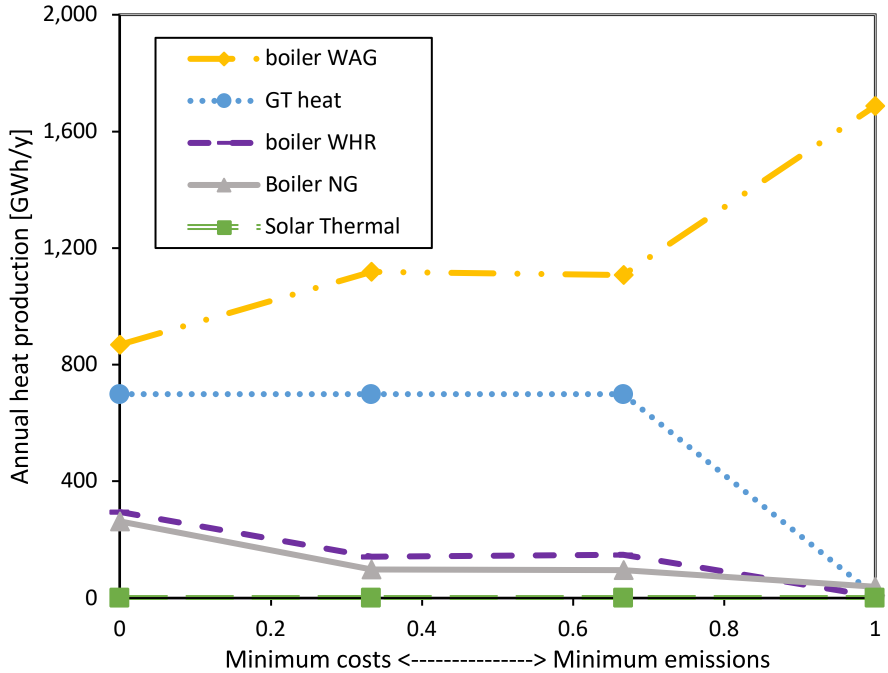


*Figure 23: Pareto front for heat-generating technologies in an electrification scenario. On the x-axis, 0 represents a design minimizing costs, 1 represents a design minimizing $CO_2$ emission.*

To analyze the differences between the BAU and electrification scenario in more detail, the technologies are compared against each other. Figure 24 shows the annual energy production of each technology, which is installed in the two previous figures. From Figure 24 a couple of conclusions can be drawn:

i) The steam turbine, boiler WAG and GT are equally used in both scenarios, which can be seen because all technologies follow the same trend. The line of the renewables differs significantly. However, this has nothing to do with the difference in the input of the electrification scenario, but with the difference in possibilities to install the renewables. What both scenarios have in common, is that the renewables are installed at maximum capacity in all designs.

ii) The other difference between the scenarios can be found in the boiler NG and the boiler WHR. Emission design 1 and 2 of the electrification scenario make more use of the boiler NG and less of the boiler WHR. This has to do with the fact that the electrification scenario has more possibilities to install renewables. Considering this installation, less $CO_2$ is emitted and thus the tool has more room to save on costs while emitting a little more $CO_2$ at other technologies. As a consequence, a slightly higher capacity of boiler NG is installed in an electrification scenario, which is cheaper than the boiler WHR, but emits more $CO_2$.

iii) As expected, the electrification scenario has the same qualitative trends as the BAU, since only minor changes on DSP, TSP and HSM are done. No radical adjustments are implemented, so steel is still made in the way as it was in BAU. At the same time, $CO_2$ emissions are reduced while annual energy cost reduces slightly as well. Although the electrification scenario shows improvement in terms of $CO_2$ emission reduction, the electrification of heat of three furnaces is by far not enough to reach the $CO_2$ reduction target of 2030.

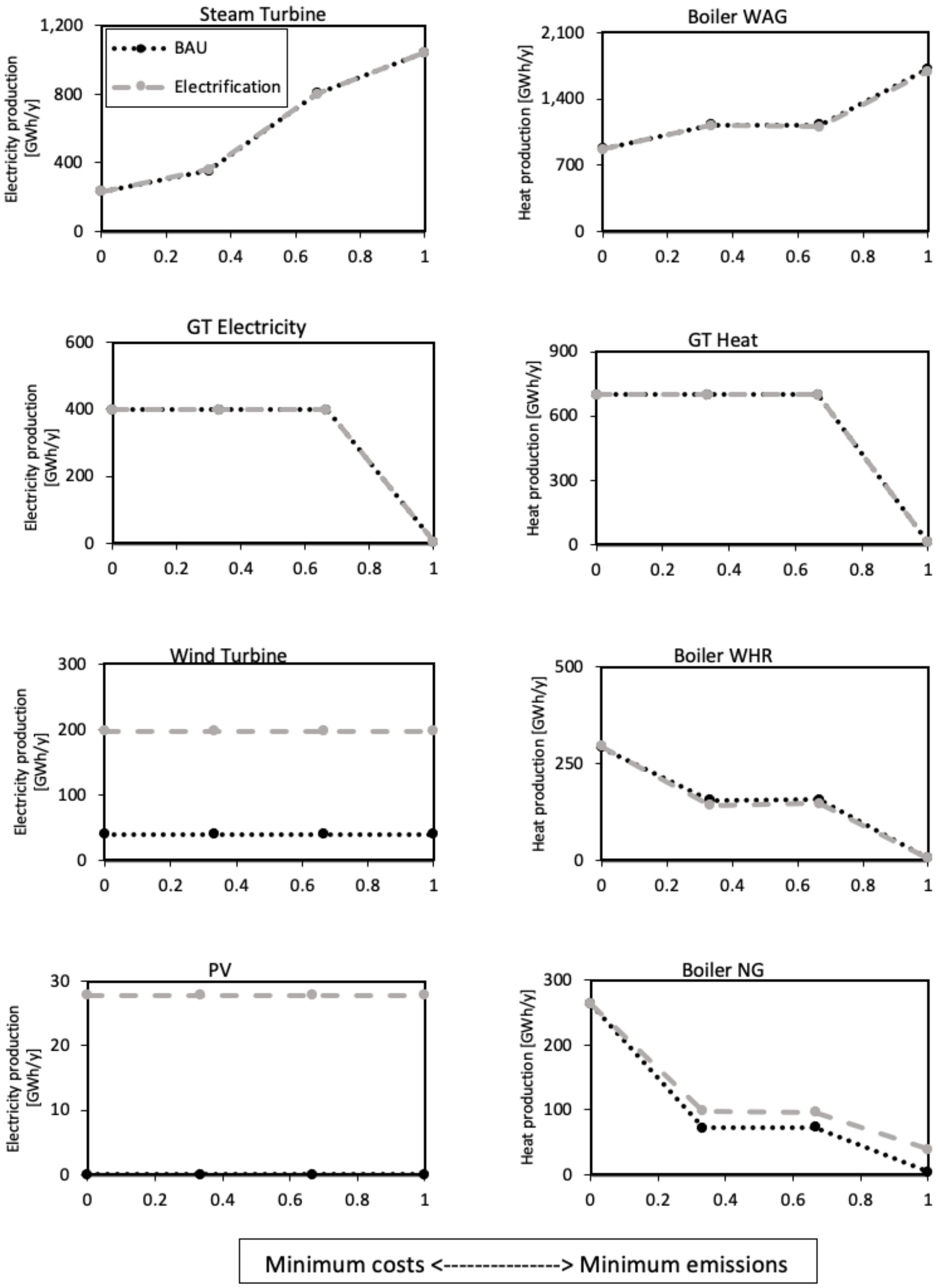


*Figure 24: The Pareto fronts for all electricity (left) and heat (right) generating technologies. On the x-axis, a value of 0 means a design minimizing costs. The value 1 means the $CO_2$ lowest optimization.*

### 5.3.2 Electric Arc Furnace scenario

This section describes the utilization of the Electric Arc Furnace. Figure 25 compares the cost relative to the $CO_2$ emission of the BAU and the EAF scenario. The Pareto fronts show the relative decarbonization, i.e. the points left represent the design minimizing $CO_2$ emissions, and the points right represent the design minimizing costs. This figure shows that utilization of the EAF does lead to a $CO_2$ reduction of 30% and an annual cost reduction of 10%. The $CO_2$ reduction can be explained due to the closure of BF6. As a consequence, WAG is reduced by 40%, so the $CO_2$ emissions are reduced. Also, the energy costs are less due to the more efficient design of the EAF. This compensates for the larger electricity and NG consumption of the EAF. Furthermore, the same trend as the BAU can be seen when changing the design. This means that 4% of the $CO_2$ emission can be reduced with a 0.5% increase in energy costs. Reducing another 4% of the $CO_2$ emission can be achieved with a 3% energy cost increase. The design minimizing $CO_2$ emission emits again 4% while the energy cost increased by 18%.

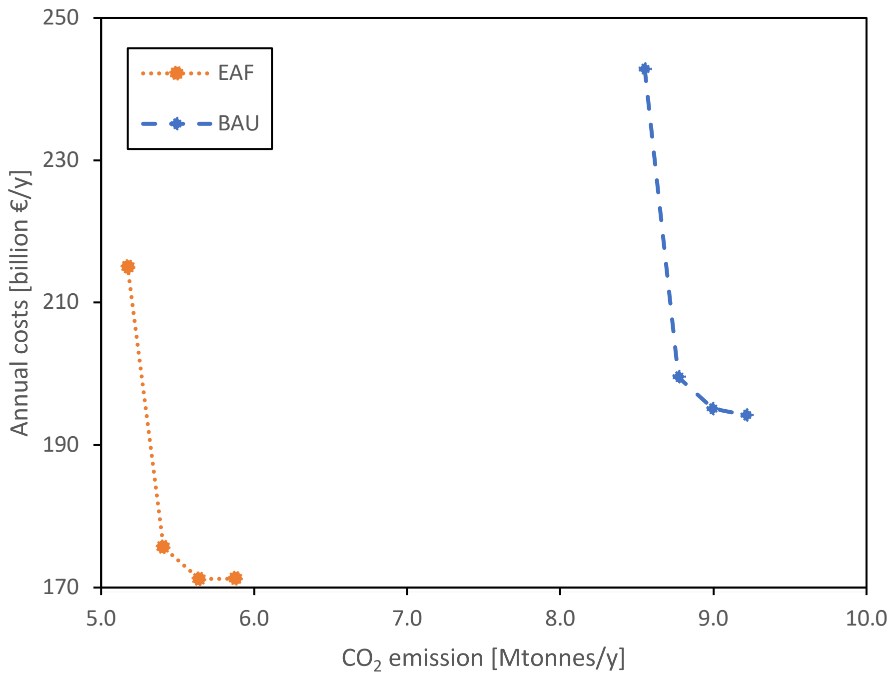


*Figure 25: Pareto front of the costs of the EAF scenario and BAU relative to the $CO_2$ emission of both scenarios. Along the Pareto fronts from left to right, the points represent the design minimizing $CO_2$, emission design 1, emission design 2 and the design minimizing costs.*

Figure 26 and Figure 27 report the size and technology selection of the EAF scenario as a function of the $CO_2$ reduction. Again, the x-axis shows the relative decarbonization, i.e. 0 refers to the minimizing costs design and 1 refers to minimizing $CO_2$ emission design. A few observations can be made:

i) In a design minimizing costs, the electricity is generated by all technologies, whereas the PV, wind turbine and GT produce at full capacity. The share of electricity import is 73%, which is high. The heat is generated by the GT, boiler WHR and the boiler NG, which are the cheapest technologies. Since the total heat demand is lower relative to the BAU, the capacity of the expensive boiler WAG is not needed.

ii) In emission design 2, the way electricity is generated remains the same. The $CO_2$ emission reduction is achieved at the heat generating-technologies. The boiler NG and the boiler WHR decrease while the boiler WAG increases with 800 GWh/y. The switch towards this design comes with a small cost increase of less than 1% and reduces 4% $CO_2$. In other words, using a combination of the boiler WAG and GT as main heat production technologies is a cost-effective design to reduce $CO_2$ emissions even further, while costs increase is minimal.

iii) When emissions are decreased further towards emission design 1, heat-generating technologies produce the same while the size of electricity-production technologies change. The steam turbine increases with 300 GWh/y, and the share of electricity import reduces from 69% to 56%. This design reduces 4% $CO_2$ emissions and increases the costs by 3%.

iv) Towards a design minimizing $CO_2$ emission, the WAG utilizing technologies and the renewables are producing electricity and heat. However, this won't be an attractive design for TSIJ, since the $CO_2$ emission reduce by 4% but the cost increases with 19%. This is significantly more than the abovementioned $CO_2$ reduction, which makes it less cost-effective design for TSIJ.

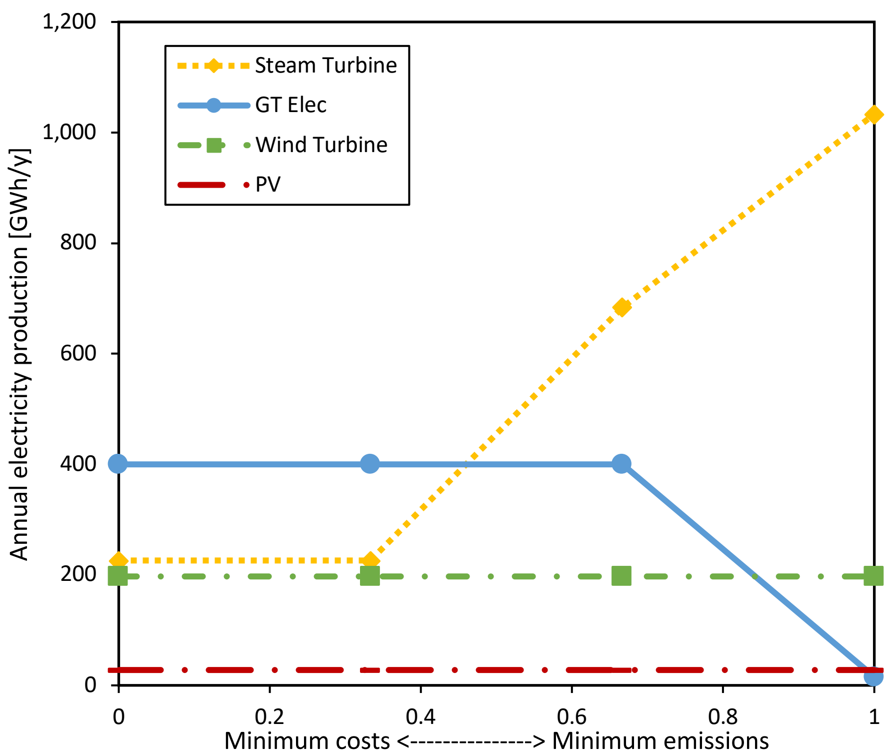


*Figure 26: Pareto front for electricity generating technologies in an EAF scenario. On the x-axis, 0 represent a design minimizing costs, 1 represents a design minimizing $CO_2$ emission.*

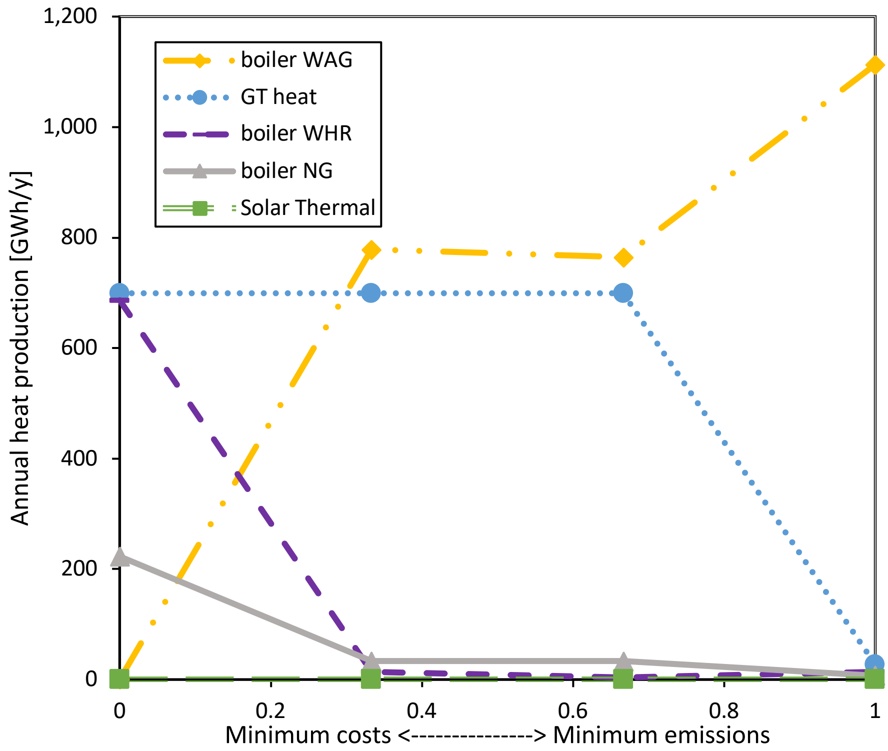


*Figure 27: Pareto front for heat generating technologies in an EAF scenario. On the x-axis, 0 represent a design minimizing costs, 1 represents a design minimizing $CO_2$ emission.*

To compare the technology size of the EAF with the BAU, Figure 28 shows the annual energy production per technology of all designs. The Pareto fronts located left in the figure represent the electricity-generating technologies. The Pareto fronts on the right side show the heat generating technologies. Solar thermal is not taken into account in this figure, because this technology does not produce heat in any design. Further, the x-axis shows the relative decarbonization, i.e. 0 refers to the cost-optimal design and 1 refers to a design minimizing $CO_2$ emission. A few observations can be made:

i) In an EAF scenario, the same growth trends in technology selection as in the BAU can be seen. This means that the steam turbine and boiler WAG increases when more $CO_2$ is reduced and the boiler NG, boiler WHR and GT decrease. Renewables for electricity generation are installed in every optimization.

ii) The technology size diverges from the BAU, mainly at the heat generation. The total heat generation is lower compared to the BAU, which can be explained through the lower heat demand. Utilizing an EAF means a high electricity and NG demand, but the heat demand is less. The boiler WAG is not selected in a design minimizing costs whereas the boiler WHR is not selected in all other designs. Dependent of the emission design, one of these boilers is not needed for TSIJ when utilizing the EAF.

iii) As regards of the size of electricity generation technologies, the steam turbine diverges from the BAU. This can be explained through the EAF scenario has more possibilities to install renewables. As a result of this installation, less $CO_2$ is emitted and thus there is more room to save on costs while emitting a little more $CO_2$ at other technologies. As a consequence, the EAF scenario imports 12% more electricity, which is cheaper than utilizing the steam turbine, but emits more $CO_2$. In an EAF scenario, there is still a lot of room to install renewables since at least 43% of electricity needs to be imported.

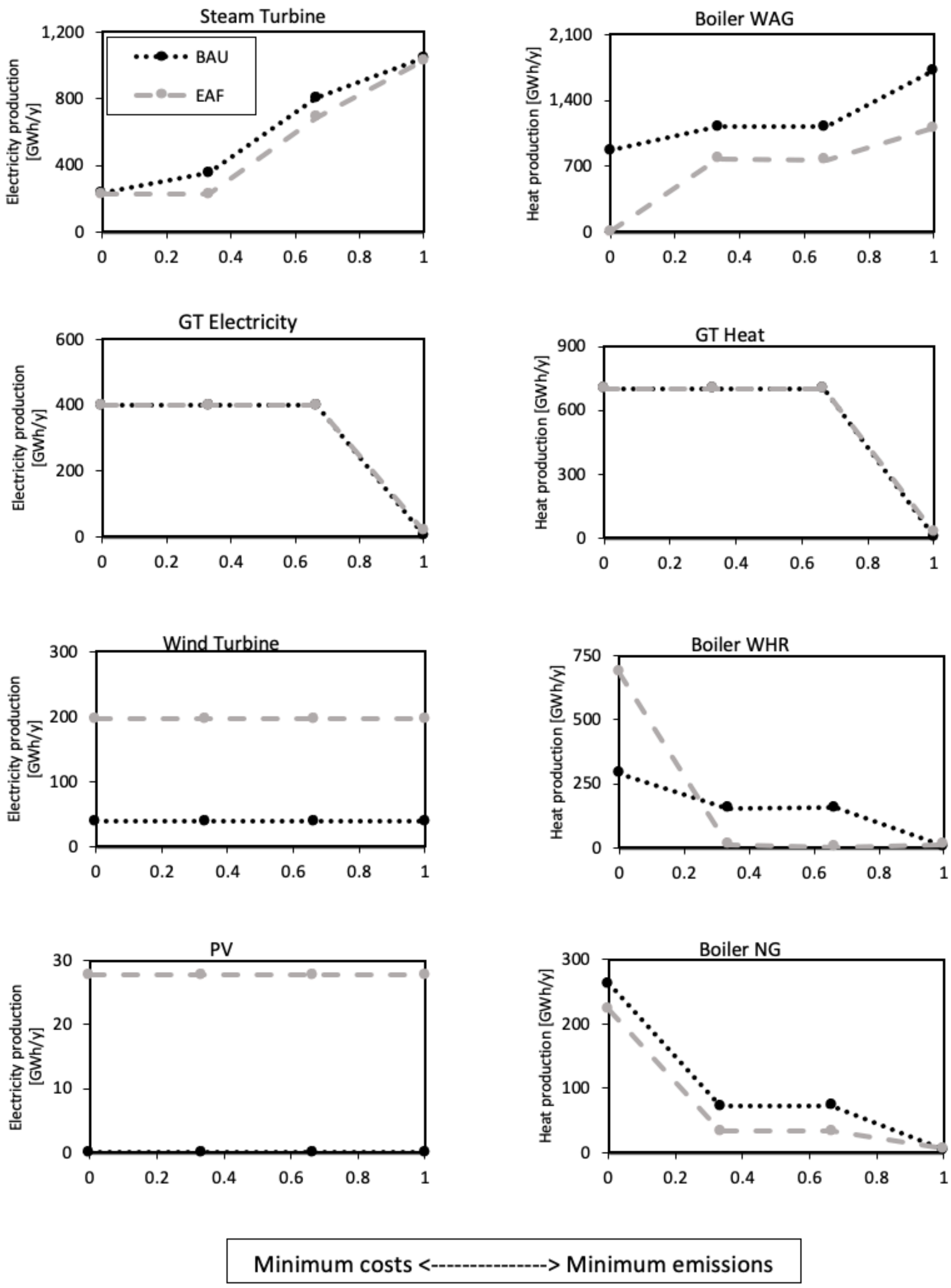


*Figure 28: The Pareto fronts for all electricity (left) and heat (right) generating technologies. On the x-axis, a value of 0 means a design minimizing costs. The value 1 means a $CO_2$ optimizing design.*

### 5.3.3 Hisarna scenario

In this section, the utilization of the Hisarna scenario is discussed. Figure 29 displays the annual costs relative to the annual $CO_2$ emissions of the BAU and the Hisarna scenario in a Pareto front. The Pareto fronts show the relative decarbonization, i.e. the points left represent the design minimizing $CO_2$ emissions, and the points right represent the design minimizing costs. This figure shows that the Hisarna scenario has 20% less annual energy cost than the BAU. Moreover, the Hisarna scenario has 30% less $CO_2$ emissions. This can be explained through the closing of BF6 and the reduction of SIFA, PEFA and CGP. These processes are all included in the Hisarna plant. The combination of furnaces makes the Hisarna an efficient furnace, both in terms of $CO_2$ emission and in terms of annual energy costs. Next to the cost-optimal design an extra 4% or 8% can be reduced by changing the energy system. This would only imply a cost increase of respectively less than 1% and 3%. A design minimizing $CO_2$ emission implies a $CO_2$ reduction of 11% and an annual cost increase of 20% relative to the minimizing costs design.

The annual costs are 10% cheaper than the EAF scenario. This can be explained through 30% less electricity demand. Considering that the EAF requires more electricity, more electricity need to be imported, which has to be bought from the national grid. Despite importing 50% less electricity in a Hisarna scenario, the $CO_2$ emissions do not differ significantly. This can be explained through the Hisarna scenario emits more WAG than the EAF scenario. The $CO_2$ emission resulting from WAG is responsible for circa an equal share as the $CO_2$ emissions of the extra imported electricity.

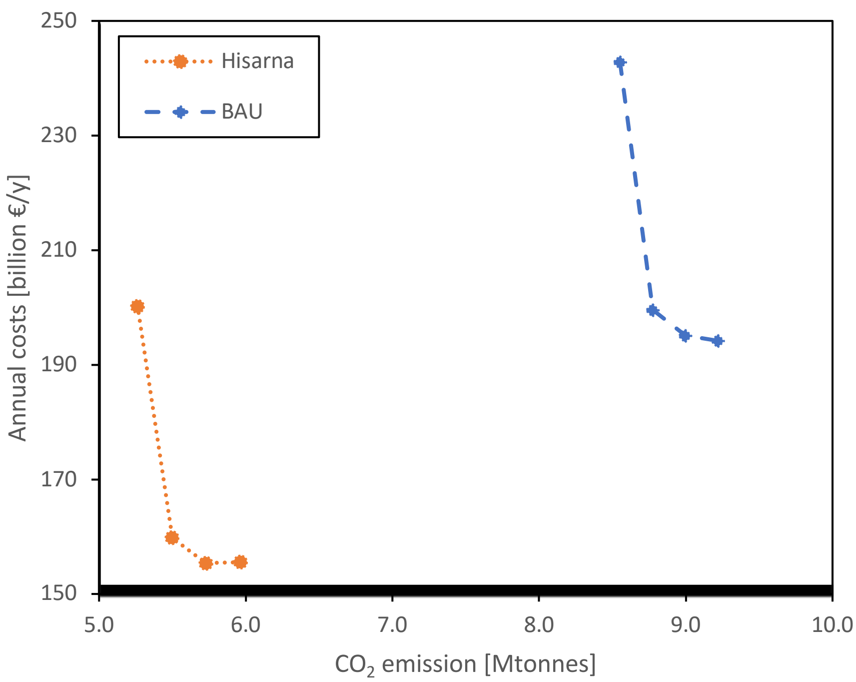


*Figure 29: Pareto front of the costs of the Hisarna scenario and BAU relative to the $CO_2$ emission of both scenarios. Along the Pareto fronts from left to right, the points represent the design minimizing $CO_2$, emission design 1, emission design 2 and the design minimizing costs.*

Figure 30 and Figure 31 show the technology selection and size in a Pareto front. In this figure, a design minimizing $CO_2$ emission is represented by a 1, and a design minimizing costs is represented by a 0. The following considerations can be made:

i) These trends are the same as implementing the EAF in spite that the electricity demand is 40% lower relative to the EAF scenario. This can be explained through the EAF scenario imports almost twice as much electricity as the Hisarna scenario. As a consequence, the trend for electricity-generation is the same. The same trend relative to the heat demand can be explained through that the EAF and the Hisarna reduce with 31% and 37% respectively, which is quite similar.

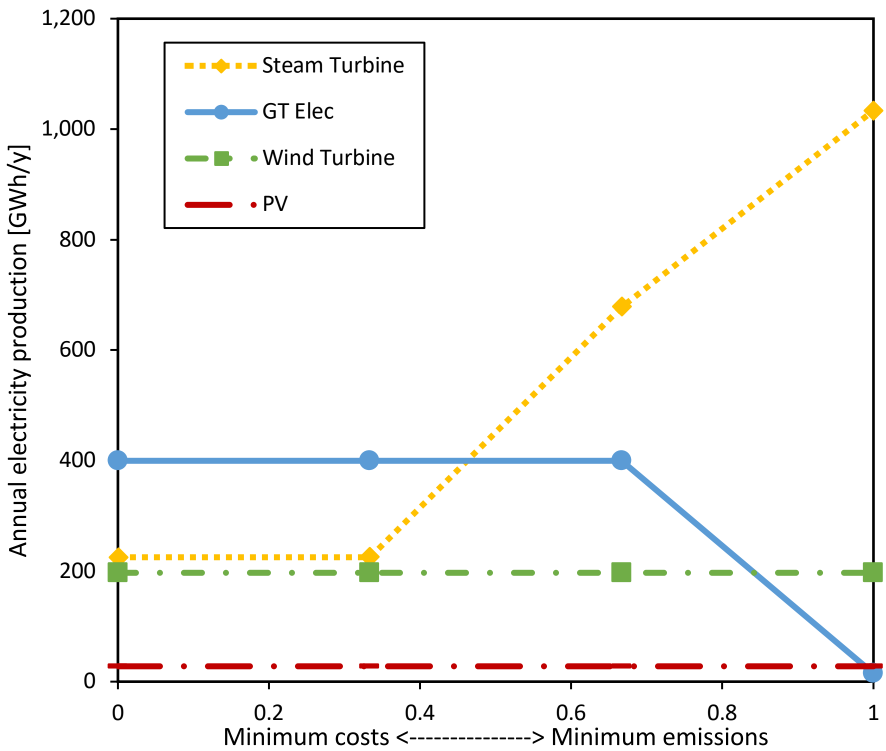


*Figure 30: Pareto front for electricity generating technologies in an Hisarna scenario. On the x-axis, 0 represent a design minimizing costs, 1 represents a design minimizing $CO_2$ emission.*

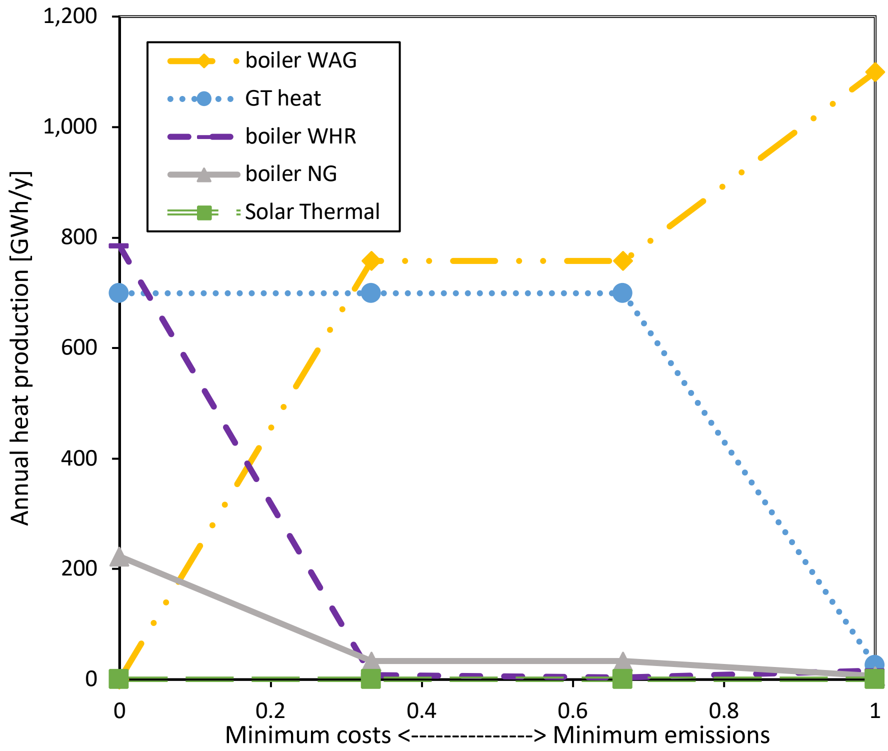


*Figure 31: Pareto front for heat generating technologies in an Hisarna scenario. On the x-axis, 0 represent a design minimizing costs, 1 represents a design minimizing $CO_2$ emission.*

Considering that the trend in technology selection between the Hisarna and EAF are so similar, a closer look between the technology size is needed. Therefore, Figure 32 compares the technology size in a Pareto front. In this figure, a design minimizing $CO_2$ emission is represented by 1 and a design minimizing costs is represented by 0. A couple of considerations should be made:

i) The trends of technology selection and size of the Hisarna are the same as the EAF, except for the boiler WHR at a design minimizing costs. This is remarkable since the Hisarna scenario has a slightly higher heat demand than the EAF scenario. In the design minimizing costs, the boiler WHR produces more heat in the Hisarna scenario. In all other designs this can be explained through the EAF dissipates more heat relative to the Hisarna scenario. This extra dissipation comes with higher costs, which makes the EAF scenario less efficient. The EAF scenario has more room to dissipate heat because the costs of the entire system and the $CO_2$ emissions are higher. Therefore, there is slightly more room to dissipate more and the same trends occur.

ii) The same trends of both technology selection as size implies that the technology selection and size is independent of the choice of the EAF or the Hisarna. This means that the boiler WAG or boiler WHR can be shut down depending on the emission design.

iii) Also, independent of the electricity demand, the same technology selection for electricity generating technologies is required. This means that there is a lot of room for renewable electricity generation since a lot of electricity is imported independently of the demand. Only renewables are favorable to install over importing. This supports the claim of TSIJ that installing renewables for electricity generation is a 'no regret action'.

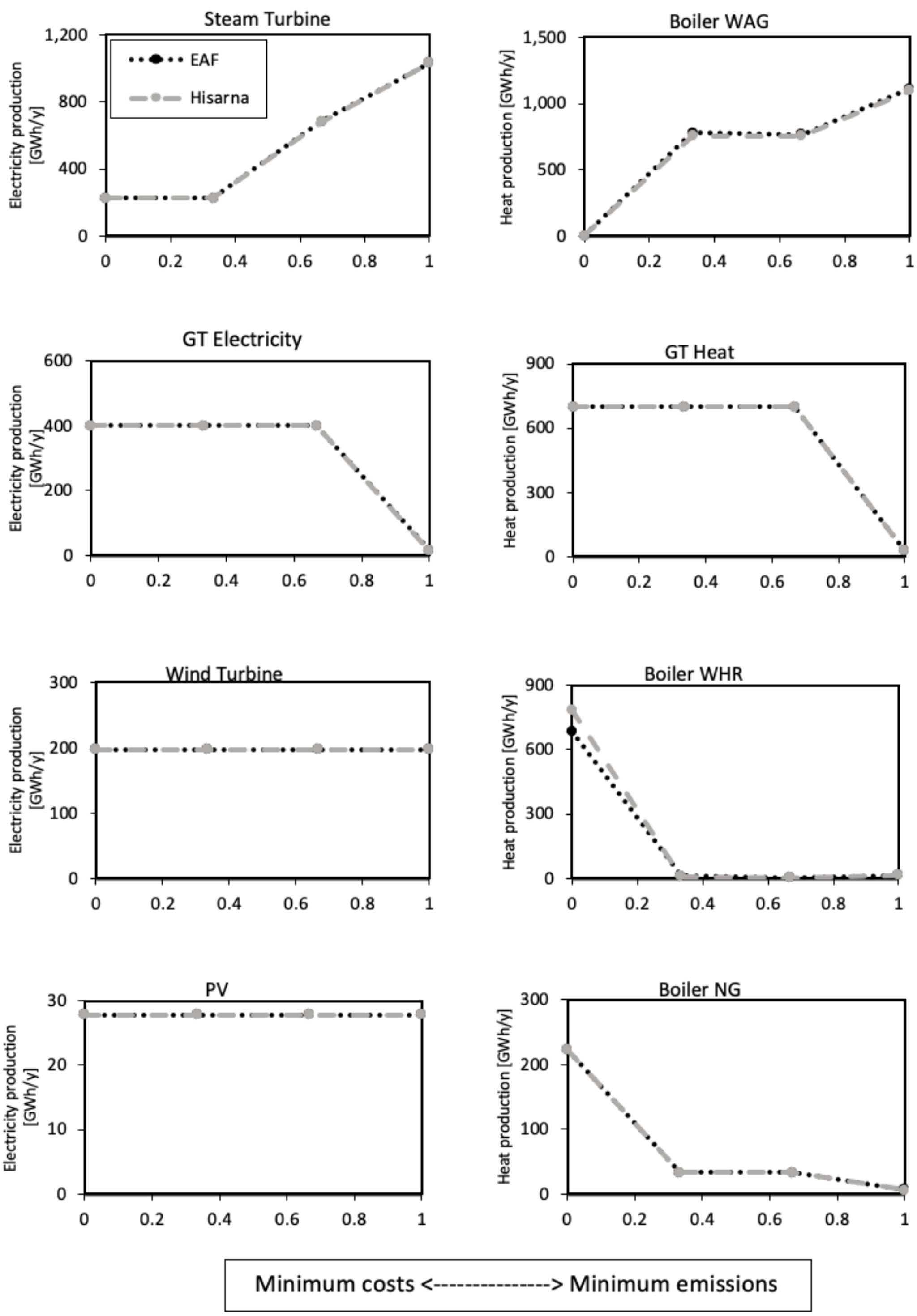


*Figure 32: The Pareto fronts for all electricity (left) and heat (right) generating technologies. On the x-axis, a value of 0 means a design minimizing costs. The value 1 means a $CO_2$ optimizing design.*

# 6 Discussion

This chapter explains the limitations and uncertainties of this research. Moreover, it elaborates on how this research contributes to theoretical insights and how this could be enhanced. Finally, advice for TSIJ resulting from this research is presented.

## 6.1 Limitations and uncertainties

Modeling with the EHub tool brings some advantages as well as some limitations. The first limitation is that the EHub tool only defines a limited amount of energy carriers, because the EHub tool focusses on energy carriers related to energy conversion technologies. Hence, five energy carriers are used in this research. Coal as an energy carrier is not included in the EHub tool, as coal is used as a process-related energy carrier for direct firing, which is not part of the energy system. Considering that coal is a main component of the $CO_2$ emissions coming from TSIJ, the $CO_2$ emissions of the main product of coal, WAG are taken into account. This results in more uncertainty related to the calculated $CO_2$ emissions. Therefore, the total $CO_2$ emission resulting from this research diverges from the actual $CO_2$ emission emitted by TSIJ.

Another limitation of the EHub tool is the way the cost component is determined. The cost component is based on academic literature, which is always off. Moreover, the investments which are needed for implementing the decarbonization routes are not taken into account. Also, the costs arising from importing feedstock are not considered. It is well possible that this component differs between the decarbonization routes. So, based on this research, it is not possible to say which decarbonization route is best in a total cost perspective.

Furthermore, simplifications regarding the changed demand profiles are made. A growth method is used to determine the changed demand profiles. Moreover, the percentage that is used for adjusting the demand profiles, is used for all energy carriers related to each furnace, which also is a growth method. These simplifications lead to less precise determination of $CO_2$ reduction and technology selection. The abovementioned limitations are coming from limitations that are related to theoretical research. Therefore, research needs to be expanded to more practical cases. This could be done by building test installations. However, this is time-consuming and expensive. Hence, it is recommended to narrow down the possibilities of decarbonization routes to 1 or 2 to carry out more practical research.

## 6.2 Theoretical implications

This research has several theoretical implications. First, this research adds insights into the potential for decarbonization of the current steel production processes when only changing the energy system. By only changing the energy design, a limited amount of 8% $CO_2$ emission can be reduced. However, this would not be cost-effective since the reduction becomes more expensive per tonne $CO_2$ reduction. This shows the potential of implementing decarbonization routes for the steel industry to meet the climate goals of 2030.

Therefore, the potential of three decarbonization routes, which are considered at TSIJ, are taken into account as well. Neither of these routes can contribute to enough reduction to meet the goal of 49% $CO_2$ reduction in 2030, not even in the case of a $CO_2$ low emission design. This highlights the need for CCS to realize deep decarbonization to meet the $CO_2$ reduction goal. The extent that CCS needs to be implemented depends on the decarbonization route and design. Approximately 34% can likely be reduced, so 15% of the $CO_2$ emission emitted at TSIJ need to be reduced using CCS. Further research is needed to investigate how CCS can be applied at TSIJ to capture this amount of $CO_2$.

Furthermore, this research can be enhanced by analyzing the addition of a price for $CO_2$. It is likely that, to meet the climate goal in 2030, a price is proposed per tonne $CO_2$ emitted. The implementation of such $CO_2$ price can change the technology selection and size at TSIJ and make scenarios more or less attractive. The EHub tool already has a possibility for implementing a $CO_2$ price. Especially for CCS, the role of $CO_2$ pricing is interesting, because $CO_2$ pricing is the only possibility that CCS can be viable. Therefore, research towards this perspective could be of added value.

## 6.3 Implications for TSIJ

This research has several implications for TSIJ. First of all, it does show how technology selection is changed for three decarbonization routes which are currently considered. Also, this research shows the potential of $CO_2$ emission reduction of these decarbonization routes. The $CO_2$ potential of the electrification scenario is limited while the EAF- and Hisarna scenario reduces approximately 30% each. The electrification scenario can be used to further reduce either of the abovementioned scenarios.

A Hisarna route is recommended when TSIJ wants to change the infrastructure as little as possible. Within the Hisarna route, iron ores are still needed as input, the BOS furnace runs on full capacity, and WAG remains at TSIJ. In other words, the way of steelmaking does not change that much. Moreover, it is worth mentioning that the Hisarna plant produces very pure $CO_2$, which is very appropriate for CCS. The EAF on the other hand reduces emissions circa equal to the Hisarna but the steelmaking process changes a lot. The input is differing, and the capacity of BOS, needs to be halved since it is only needed for BF7.

On the other hand, the lower heat demand is the same for both scenarios. As a consequence, the technology selection, size and operation changes in the same manner. Dependent on the $CO_2$ emission design, the boiler WAG or the boiler WHR is not needed. From this research, it is recommended to generate the heat with the boiler WAG, since this boiler is linked to emission design 2. This design reduces $CO_2$ emissions a further 4% while the annual energy costs are increased by less than 1%. This is considered as a cost-effective way of further reducing $CO_2$ emissions.

CCS is needed in either scenario to meet the $CO_2$ reduction goals. This can be implemented in several ways. Current research at TSIJ focusses mainly on CCUS applied on BF7. However, based on this research, possibilities could be researched to apply CCS on the GT, since the GT is a favorable technology for electricity-generation in all cost-effective designs, in all scenarios. As already mentioned, the exact potential for CCUS needs to be determined with more accurate numbers. It is therefore recommended for TSIJ to make a decision as soon as possible, which way TSIJ is heading to carry out more practical research. Explorative researches like this one can help TSIJ define what the implications of certain choices are and can act as a guideline on how much capacity is needed to make a good estimation.

Furthermore, TSIJ needs to investigate an alternative for WAG utilizing technologies in the strategy towards 2050, where $CO_2$ needs to be reduced to 0. Within this strategy, BF7 needs to be closed since it is not possible to reach a zero-emission goal with a blast furnace route included. This means that WAG reduces significantly at TSIJ, which implies that the steam turbine and boiler WAG cannot run on this energy carrier anymore that intensively. This is extra important because the WAG utilizing technologies are key in low emission designs. Explorative researches applied to TSIJ could be carried out to explore the potential. An example of an alternative is the utilization of $H_2$ for various applications.

This research also shows the potential to use renewables for electricity generation. In every case, wind turbines and PV are favorable over other electricity-generating technologies. Since the room at the TSIJ terrain for renewables is highly limited, it is recommended for TSIJ to look for possibilities to enhance the room for renewables to for example offshore. Especially as TSIJ is located near the coast this may be a good possibility.

Lastly, this research shows the potential for low emission grid emissions to lower the $CO_2$ emission of TSIJ. In every design, TSIJ needs to import at least 30% electricity. As a consequence, a significant share of $CO_2$ emissions is related to the $CO_2$ emissions coming from the national grid. A route towards lower grid emissions could be that TSIJ could act as a sink for moments renewables produce more electricity than the electricity demand. Researches towards this type of utilization of surplus of renewables could be useful to obtain more insights related to this way of $CO_2$ emission reduction from the national grid.

# 7 Conclusion

This research aimed to *''Explore three decarbonization routes for Tata Steel IJmuiden to obtain insights in decarbonizing the steelmaking process to reach the $CO_2$ emission reduction goal of at least 49% in 2030.''* To contribute to this aim, three research questions were formulated. A short answer to each research question is presented below.

1. *What is the potential of $CO_2$ reduction by changing the energy system?*

The potential of decarbonization by only changing the energy system is limited. At TSIJ, it is possible to reduce the $CO_2$ emissions by 8% when a design minimizing the $CO_2$ emissions is applied. However, this would not be cost-effective for TSIJ because this would imply an energy cost increase of 20%, which is not viable. Along the Pareto front, used in this research, it would be more viable to reduce $CO_2$ emission by 2% which implies a cost increase of 1%.

2. *How do the demand profiles of furnaces change when the decarbonization routes are utilized?*

The demand profiles of the electrification scenario change at three places; HSM, TSP and DSP. At all places, NG reduces and electricity increases. The change of demand profiles for implementing the EAF and Hisarna are similar since BF6 and CGP2 are being closed in both scenarios. As a consequence, CGP1, SIFA and PEFA reduce at all energy carriers. The difference between the EAF and Hisarna scenario arises at the new installation. The EAF scenario implies a significant increase in NG and electricity, but the capacity of BOS is only needed for BF7. The Hisarna scenario requires less electricity and NG but emits more WAG. Also, when a Hisarna plant is implemented, BOS is needed with full capacity.

3. *What is the $CO_2$ reduction potential of each decarbonization route and what is the effect on the processes of Tata Steel IJmuiden?*

The electrification scenario has a small effect on the processes of TSIJ. Minor changes are implemented, which means that the existing way of steelmaking does not change. On the other hand, utilizing this scenario reduces the $CO_2$ emissions by only 1% relative to the BAU. The EAF scenario has a major impact on the processes at TSIJ. The electricity demand is higher, and the heat demand and WAG production are lower relative to the BAU. To supply the high electricity demand, a lot of electricity need to be imported from the grid. To supply the lower heat demand, the boiler WAG or boiler WHR can be closed, dependent on the $CO_2$ emission design. The $CO_2$ reduction is approximately 30% relative to the BAU, mainly due to the lower WAG production. Utilizing the Hisarna scenario has a smaller impact on the processes at TSIJ than utilizing the EAF scenario. Due to the more efficient design, the electricity and heat demand are lower relative to the BAU. The WAG production remains the same. Despite the different design, the Hisarna scenario has the same effect on the technology selection and size as utilizing the EAF scenario. This can be explained through the bigger share of electricity import in an EAF scenario. The heat demand lowers approximately the same in both scenarios, which explains the same technology selection for heat production. The $CO_2$ reduction of the Hisarna scenario is approximately 30% relative to the BAU, mainly due to the more efficient design.

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# Appendix

## I) Electrification

To electrify the heat demand, three plants at TSIJ are considered as feasible: TSP, DSP and HSM. All three are currently using NG which is replaced by electricity. Vrijlandt et al. (2019) used Sankey diagrams to determine the energy balance. For each furnace, the first figure displays the current demand, the second figure shows the new demand. After there is explained how the demand profiles change, the possibilities of generating renewable electricity generation are elaborated.

### i) TSP

Within TSP, The Continuous Annealing line 11 (CA11) is currently using NG to heat up. In an electricity scenario, this heating can be replaced with Electric Resistive Heating Tubes (ERHT). This is an interesting way of heating, because it has an efficiency of nearly 100%. The adjustment to the CA11 to adopt the ERHT is expected to be minor, since the CA11 already uses radiative tubes. As a consequence, it is just a matter of replacing the current system. Therefore this part of TSP is considered to electrify (Vrijlandt et al., 2019).

From Figure 33 it can be seen that the NG input in 25.5 GJ/h while the load is 11.5 GJ/h. The other components are losses.

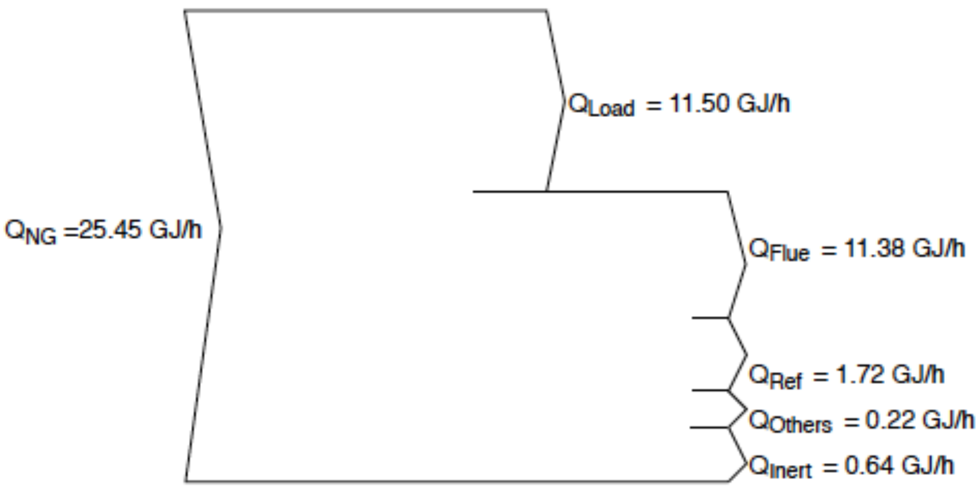


*Figure 33: Sankey diagram of CA11 in the current situation (Vrijlandt et al., 2019).*

When NG is replaced by electricity, the Sankey diagram of Figure 34 is obtained:

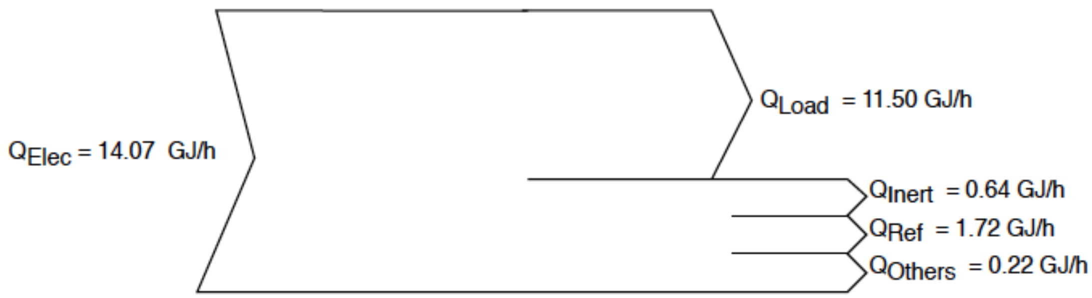


*Figure 34: Sankey diagram of CA11 when the electricity scenario is applied (Vrijlandt et al., 2019).*

From Figure 34 it becomes clear that each 25.45 GJ/h NG can be replaced by 14.07 GJ/h NG. Due to the electrification, the efficiency is improved from 46.08% to 83.3%.

### ii) DSP

To heat up the DSP, a TFX inductor is used. The TFX inductor is more expensive than the ERHT, but it can reach a quicker heating per second which is important in the DSP. Due to the electrification, the amount of oxygen in the furnace will increase and thus the oxidation. This must be counteracted by pumping nitrogen gas in the DSP (± 400m$^3$/h). Pumping the extra nitrogen might even result in lower oxidation than in the situation when NG is used. This leads to more yield of steel, because less steel is oxidized (Vrijlandt et al., 2019).

The original demand can be found in Figure 35:

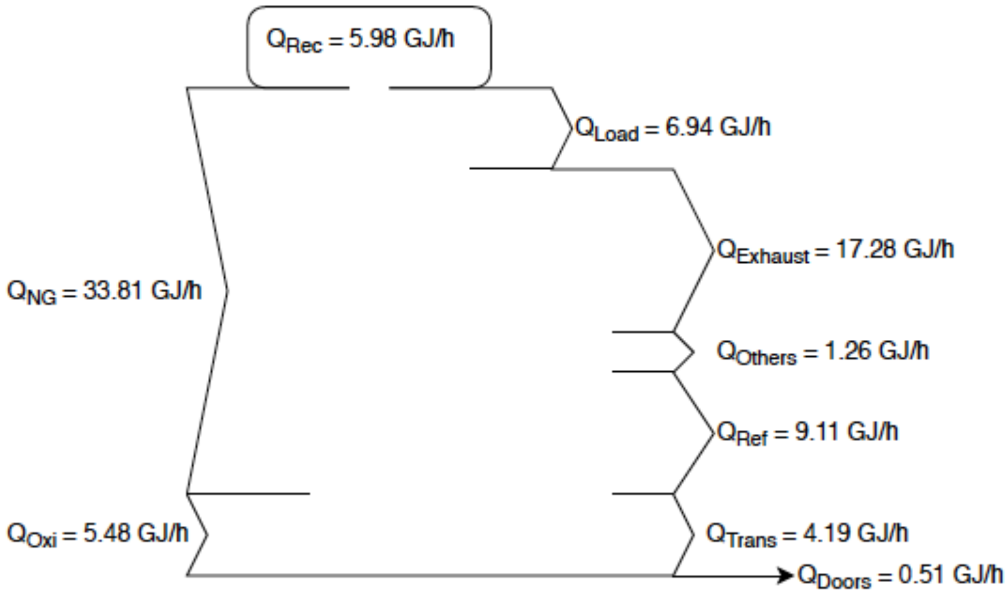


*Figure 35: Sankey diagram of DSP in the current situation (Vrijlandt et al., 2019).*

The demand when NG is used is 33.8 GJ/h, while the oxygas requires 5.48 GJ/h. The load is 6.95 GJ/h which results in a low efficiency of 20.21%.

In Figure 36 the Sankey diagram of the electrification scenario of the DSP is displayed:

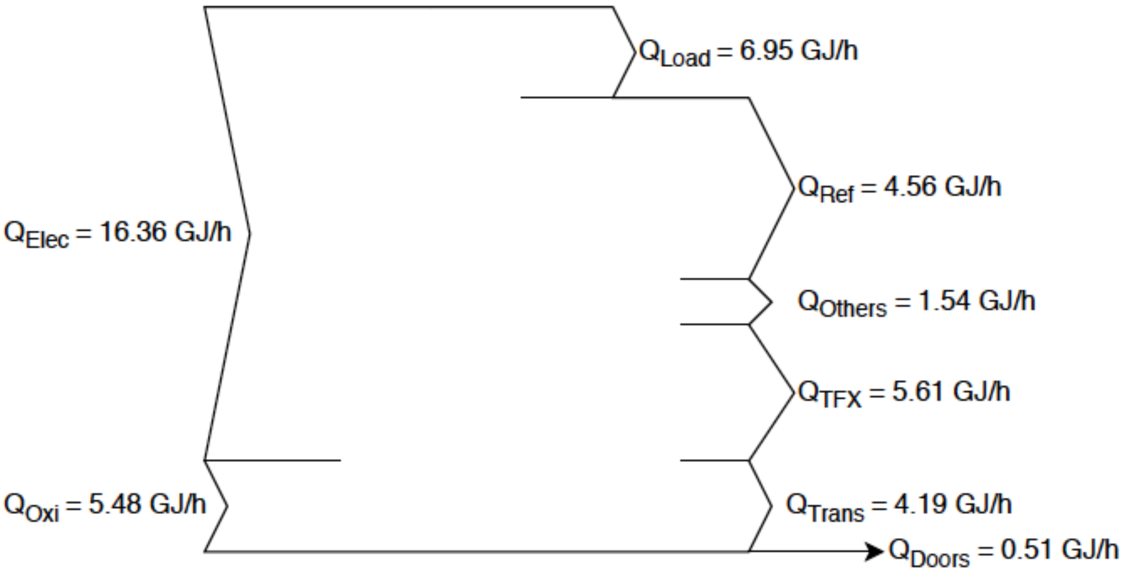


*Figure 36: Sankey diagram of DSP when the electricity scenario is applied (Vrijlandt et al., 2019).*

From Figure 36 it can be concluded that the electricity demand is 16.36 GJ/h and there is still 5.48 GJ/h oxygas required. The oxygen level is equal to the previous level. However, because there is less electricity relative to NG, the relative oxygen level increases. This leads to more oxidation, as previously mentioned. The use of less electricity compared to NG means that the electrification delivers a big efficiency win of 42.5% (Vrijlandt et al., 2019).

#### iii) HSM

The HSM implements the preheating of slabs before entering the HSM. Therefore, it is not needed to adjust the current furnaces. As a result of the inlet temperature is very constant due to the preheating, the slabs have a very constant inlet temperature. This makes it possible to switch off one furnace, which runs on NG. This also leads to a better quality of steel (Vrijlandt et al., 2019).

In Figure 37 the original demand of the HSM is shown:

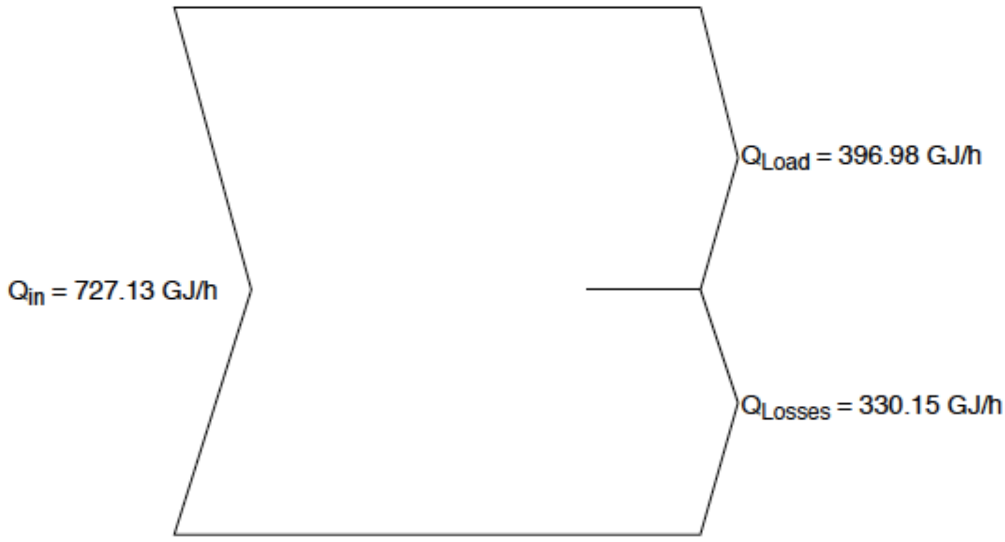


*Figure 37: Sankey diagram of HSM in the current situation (Vrijlandt et al., 2019).*

The original NG demand is 727.31 GJ/h which leads to a load of 396.98. The efficiency of the HSM is therefore 54.60%.

In Figure 38 the Sankey diagram of the electrification scenario is shown:

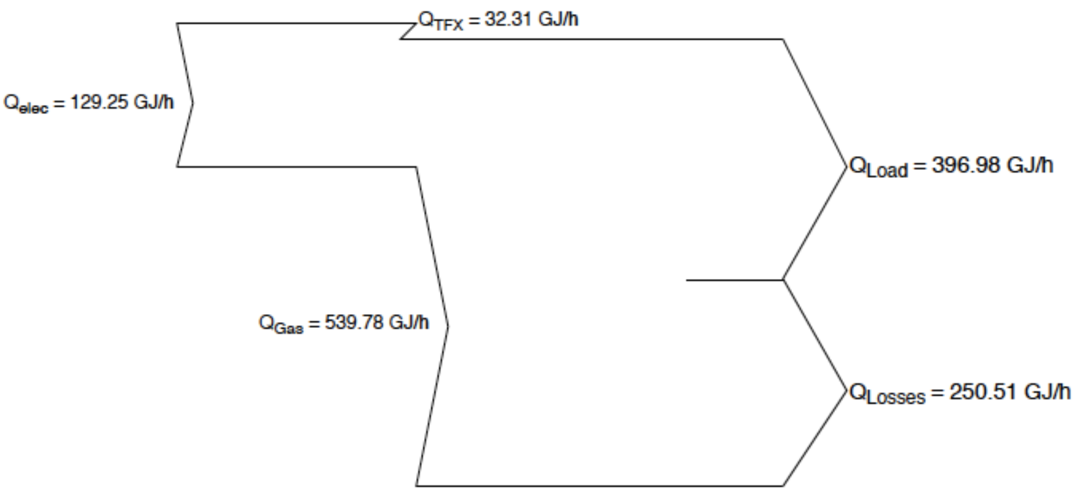


*Figure 38: Sankey diagram of HSM when the electricity scenario is applied (Vrijlandt et al., 2019).*

From Figure 38 it can be seen that 539.78GJ/h NG and 129.25GJ/h electricity is needed to obtain the same load of 396.98 GJ/h. A small loss of 32.31 goes to the TFX. This led to an efficiency of 59.34%. This is a smaller efficiency win compared to the other two furnaces, because the electricity demand of the HSM is just a share of the total demand, whereas the other two furnaces can be electrified completely. On the other hand, because the HSM has more load than the other two, the absolute saving is higher (Vrijlandt et al., 2019).