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# D5.2.5
# Evaluation of the potential for hydrogen and CCS in the decarbonization of the Dutch steel industry

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## Abstract

The iron and steel industry accounts for 5 % of worldwide $CO_2$ emissions. With 13 $Mt_{CO2eq}$ annually, TATA Steel, which employs the traditional blast furnace – basic oxygen furnace steel making route, is one of the largest single point emitters in the Netherlands (and EU). Given the role of steel in present and future society, decarbonizing the steel industry is of paramount importance for a $CO_2$ net-zero society. Traditional research on integrated steelworks decarbonization via CCS focuses on (few) specific carbon capture technologies. In such approaches, the performance of a technology is established via dedicated experimental campaign and techno-economic modelling. With this research we instead adopted a different approach: we show the role of carbon capture and clean hydrogen in decarbonizing the steel industry by proving the limited decarbonization potential on measures that do not rely on hydrogen or carbon capturing. In particular, we investigate the effect of (a) decarbonization measures which target the process emissions on (b) the energy-system and therefore the power-supply related emissions. It is important to note that such approach is technology-agnostic, i.e. we are not investigating (and supporting) a specific carbon capture or hydrogen technology, but we are demonstrating the necessity of going beyond renewable-based electrification and efficiency improvement. The quantitative analysis reported here has the foundations in the thorough analysis of the TATA Steel Ijmuiden production, including reconciled production profiles and energy demand profiles at hourly resolution. Three decarbonization measures were considered, namely electrification of heat, implementation of an electric arc furnace, and implementation of the Hisarna process without carbon capture. Implementation of an electric arc furnace or the Hisarna process both lower the $CO_2$ emissions significantly due to a decrease in energy demands; however, the potential is found to be limited to about -40 %. Heat electrification has low decarbonization

potential, especially when coupled to non-renewable electricity. Overall, this work clearly shows that without CCS or hydrogen, decarbonizing the steel industry is an unnecessary rocky road.

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# 1 INTRODUCTION

In the Netherlands, about 155 million tonnes of $CO_2$ are emitted annually and the industrial and energy sectors jointly account for 61 % of those emissions (see Figure 1) [1]. Furthermore, the two sectors not only make up the majority of emissions, but with 38 % and 73 % for the industrial and energy sector respectively, they are also the furthest away from their 2030 emission target [2].

With 13 $Mt_{CO2eq}$ annually, TATA Steel, representing the Dutch steel industry, is one of the largest single point emitters. Together with the associated power plant, its emission density - 5 $kg_{CO2}/m^2$ - is the highest in the Netherlands [2]. On the other hand, the plant delivers 7.2 Mt of crude steel annually (4 % of the total production in the EU), which is produced at an average $CO_2$ intensity of 1.8 $t_{CO2eq}/t_{steel}$, in line with the global average for integrated steelworks. World-wide, the iron and steel industry accounts for 5 % of all $CO_2$ emissions. Amplifying these concerning numbers is the fact that steel is arguably a product of high societal relevance, giving rise to a dire need for decarbonization of this industry.

Zooming in on the emissions of TATA Steel (see Figure 2), an almost even split of emissions between process related and power-supply related emissions is observable. Conservative decarbonization measures like increased energy efficiency and electrification of heat have the potential to tackle both sides and are rightly subject of continuous research. However, an intrinsic problem of the steel industry is the use of coal as both energy carrier and reactant. This leads to the trivial conclusion that deep decarbonization is only possible if coal is replaced, e.g. by hydrogen, and/or if the carbon emissions are dealt with, e.g. by carbon capturing technologies. The former comes with significant changes to how steel is produced, while the latter could be retro-fitted and therefore potentially minimize the number of process changes. However, public perception is always an issue that has to be dealt with for carbon capture technologies. Either way, aiming for deep decarbonization results in a situation where steel companies will have to adopt one – or possibly both – solutions.

With this research, we aim at supporting aforementioned trivial conclusion by showing quantitatively that both hydrogen and carbon capturing are plain necessities for a zero-carbon steel industry. In particular, we investigate the effect of (a) decarbonization measures which target the process emissions on (b) the energy-system and therefore the power-supply related emissions. The focus lies on measures that do not rely on hydrogen or carbon capturing. Their limited decarbonization potential will be shown and therefore, by proof-of-negation, the importance of hydrogen or carbon capturing technologies underlined. It is important to note that such approach is technology-agnostic, i.e. we are not investigating (and supporting) a specific carbon capture or hydrogen technology, but we are demonstrating the necessity of going beyond electrification and efficiency improvement.

In 2019, about 1.87 billion tonnes of crude steel were produced world-wide. The traditional blast furnace – basic oxygen furnace (BF-BOF) route accounts for 72 % globally and 59 % in the EU-28. TATA Steel, the production of which relies on two blast furnaces, is therefore a representative test case. While the steel emission factor reported earlier confirms this, it should be noted that a vast variety of steel qualities and products exist throughout the industry and therefore no two production sites are perfectly alike. Hence, the qualitative findings of this report can be considered valid for the majority of the steel industry while quantitative findings are case specific and only transferrable within certain limitations.

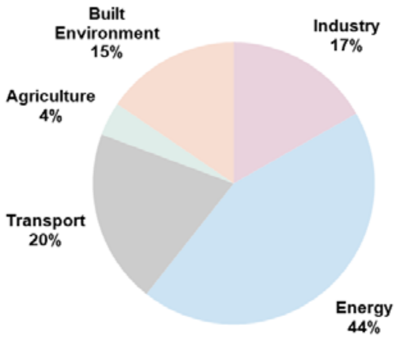


*Figure 1: Dutch $CO_2$ emissions by sector* [1]

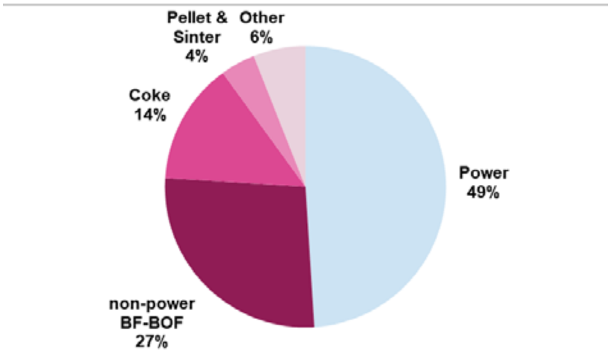


*Figure 2: $CO_2$ emissions of TATA Steel IJmuiden by origin* [3]

## 1.1 Steel production at TATA Steel

An overview of the steel production at TATA Steel Ijmuiden is shown in Figure 3. At the beginning of the process stand the coke and gas factory (CGF), the sinter factory (SIFA), and the pellet factory (PEFA). In the CGF, ground coal is heated to 1100 °C which removes impurities while producing coke and coke oven gas (CO-gas), both of which are inputs to the blast furnaces. The SIFA and PEFA both process iron ore. SIFA processes coarse iron ore into a homogeneous clay which is backed at 1600 °C and subsequently broken, giving the sinter. The PEFA uses finer iron ore which is, aided by water and chemical additives, baked to form pellets. Pellets are smaller and of circular shape and thus structurally stronger than sinter.

The coke, sinter, and pellets are fed into the blast furnaces (BF), which are heated to 1100 °C with CO-gas and blast furnace gas (BF-gas). At the top, the continuously produced (BF-gas) is captured and cleaned so it can be used as combustible gas. Pig iron and slag are retrieved from the bottom and the former is transported to the basic oxygen furnace (BOF).

In the BOF, the carbon content of the steel is lowered well below 2.1 % through oxidation with oxygen. The temperature is controlled by adding scrap metal. About 80 % of the liquid steel undergoes continuous casting. The resulting slabs are transported to the hot strip mill (HSM) where they are reheated, milled, and coiled. The other 20 % if liquid steel go directly to the direct sheet plant (DSP). Here, continuous casting, milling, and coiling are combined. Finally, the steel is further processed, e.g. galvanizing or paint coating, to suit the product specification.

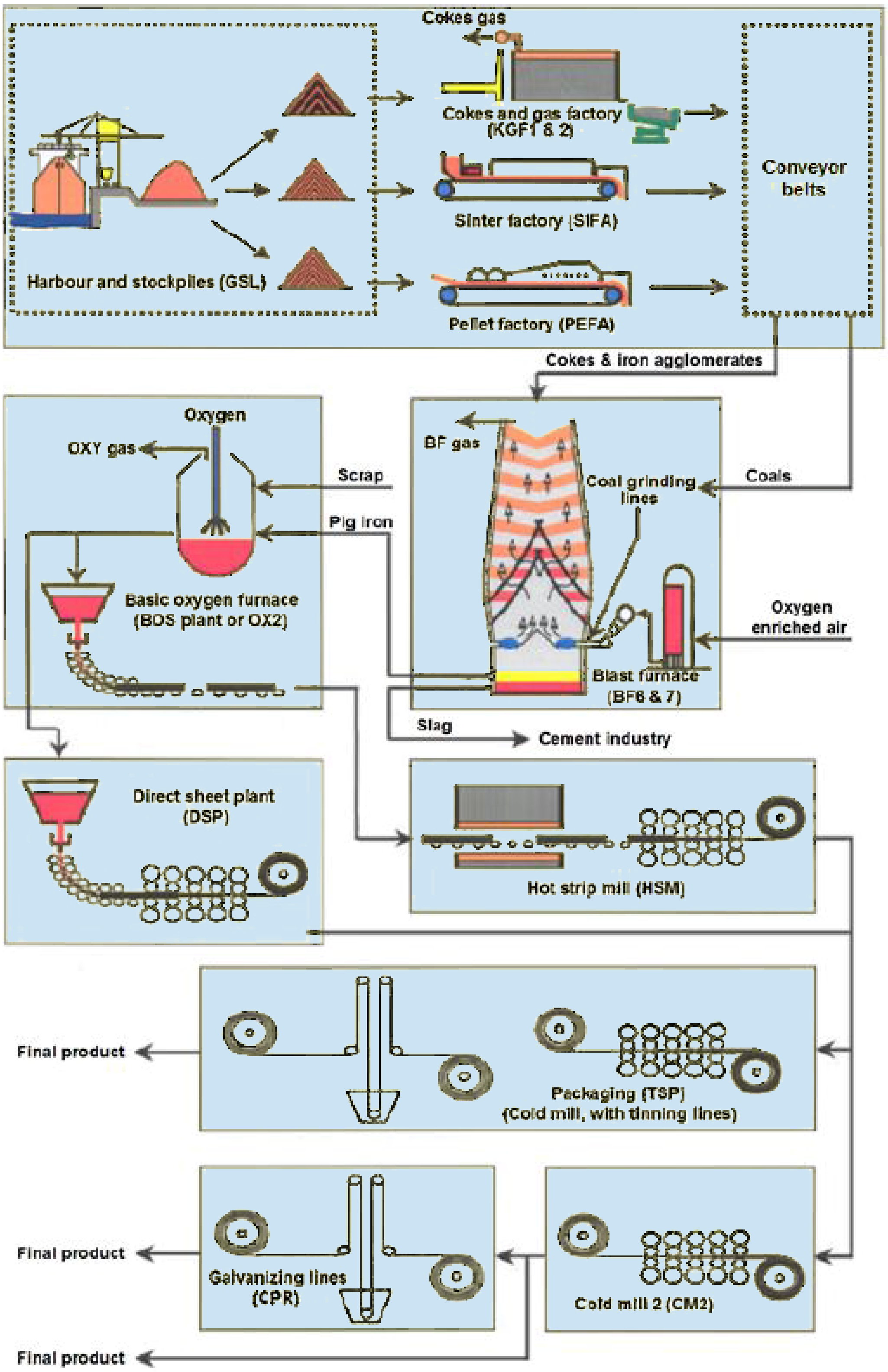


*Figure 3: Overview of the steel making process at TATA Steel IJmuiden*

# 2 METHODOLOGY

In this section, the methodological approaches found in this research are elaborated upon. Subsection 2.1 describes the research design in detail and thus helps putting the different scenarios analyzed in the course of this work into context. Subsection 2.2 gives a brief introduction into the modeling tool used.

## 2.1 Research design

The research presented in this report was designed with the aim of showing for a real case study, i.e. Tata steel Ijmuiden, that deep decarbonization is hardly possible without carbon capture (and storage) and/or hydrogen technologies. We therefore proceeded through proof by negation, i.e. starting with the assumption that it is indeed possible and proofing this assumption wrong. To do so, a focus was put on decarbonization measures which don't rely on CCS/$H_2$. Those measures were compared to the business as usual case to show their limited decarbonization potential.

Figure 4 shows a graphic summary of the research design. The analysis is divided into two types of scenarios, *Business as usual (BAU)* and *Decarbonization Scenarios*. For each of the scenario types, *data analysis* provided the information for the subsequent *energy system design*. The results of those designs were compared to establish the decarbonization potential. Based on this potential, conclusions about the importance of $H_2$ and CCS can be drawn. The detailed process analysis including the gathering and cleaning of demand and production profiles with hourly resolution was conducted in collaboration with experts from TATA Steel and is the foundation of this work. The process is explained in section 3. The decarbonization measures were selected based on feasibility, which was assessed through a combination of knowledge arising from the initial process analysis as well as consultations with experts from TATA Steel. Details about the analyzed measures and a brief overview about other measures discussed for the steel industry are provided in section 4.

It is worth mentioning that this work focuses entirely on the impact of the decarbonization measures on the energy system design. The costs of putting the measures in place as well as the direct impact on process emissions, i.e. not energy system-related emissions, is not considered in the final conclusion.

## 2.2 Modeling framework

The mixed integer linear programming (MILP) based tool used in this work was first developed by Gabrielli *et al.* [4], [5]and further adapted in the course of the ELEGANCY project by both ETH Zurich and Utrecht University. The tool is designed to optimize the design and operation of multi-energy systems and has a strong focus on energy conversion and storage technologies. Its main scope is to understand the complex interactions between technologies in integrated energy systems. This determines the analysis time horizon of one year at hourly resolution. While technology cost data are indeed considered in the model, they are estimates (class IV-V) and economic conclusions are to be interpreted as rough guidelines or indications only.

Figure 5 shows the flow of information within the tool and how the physical domain relates to the computational domain; most notably, the energy demands are to be supplied and hence are an output in the physical domain but an input in the computational domain. Focusing on the computational domain, other inputs are (i) weather profiles, i.e. wind speed, solar irradiance, and ambient temperature, and (ii) industry-typical energy prices and carbon rates for energy flows crossing the system boundaries. These three types of data are spatially resolved and specific for each application case. Technology cost and performance parameters are also required as input but are specific for a certain technology rather than for a certain application case and hence are readily available in the tool for a vast portfolio of technologies.

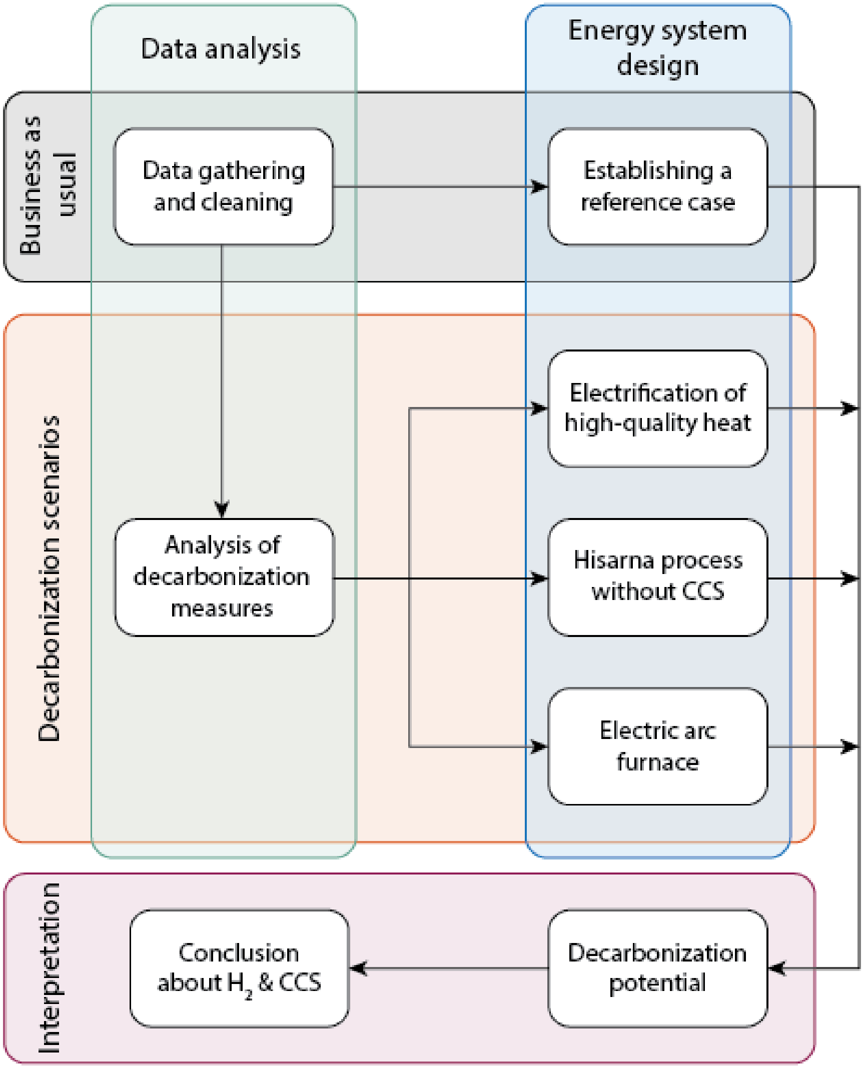


*Figure 4: Schematic representation of the research design for the study presented in this report.*

The mathematical problem is generally formulated as

$$\min_{x,y,z}(d'x + e'y + f'z)$$
$$s.t.$$
$$Ax + By + Cz = b$$
$$x \geq 0 \in \mathbb{R}^{N_x}, y \in \{0,1\}^{N_y}, z \in \mathbb{N}^{N_z}$$

where $d$, $e$, and $f$ are the cost vectors with respect to continuous $x$, binary $y$, and integer variables $z$, respectively. $A$, $B$, and $C$ are their respective constraint matrices and $b$ is the constant term of the constraints. $N$ represents the dimensions of $x$, $y$, and $z$ (indicated as subscript). The constraints describe the technology and network behavior as well as the energy balances. For details about that matter, the reader is referred to [4]–[6].

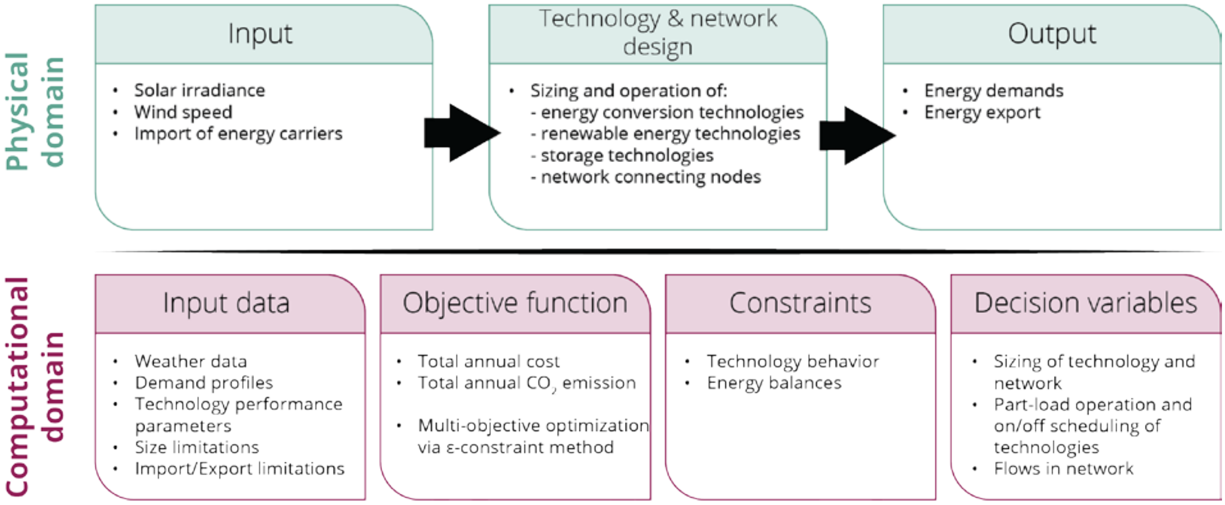


*Figure 5: Simplified representation of the physical information flow (top) and its translation into the MILP framework (bottom)*

# 3 PROCESS ANALYSIS

The foundation of this work is a thorough process analysis of the Tata Steel Ijmuiden plant. This step helps to define the most suitable model complexity, i.e. an appropriate compromise between level of detail and computational tractability, but also provides a reference scenario which all other cases will be compared against.

## 3.1 System boundaries and spatial resolution

An in-depth analysis of both the manufacturing processes and the energy system was conducted to appropriately define system boundaries and spatial resolution. For the system boundaries, physical flows and level of integration was considered more relevant than business units. Hence, the on-site power plant was included within the system boundaries, albeit operated by an external company, because its power output is mostly dedicated to covering the steel plant's demand. For the same reasons, the on-site air separation unit operated by an external company was included as well. Therefore, the considered system boundaries include the steel production plant, the power plant and the air separation unit.

The criteria applied to choose the right spatial resolution are threefold. Firstly, the spatial resolution should be kept as coarse as possible to keep the computational complexity low. Secondly, significant transportation losses of energy carriers should be represented in the simulation, i.e. process units far apart from each other should be modeled as distinct nodes in the network. However, no constellations with significant transportation losses (>1%) were found. Lastly, the ability to model potential process changes like replacement or discontinuation of process units, especially in view of the decarbonization measures considered in this work, has to be maintained. This entails the separation of some nodes, despite them being in close proximity.

The transportation losses of electricity are negligible given the small distances (< 5 km) on site. Gas distribution losses can arise due to pressure drop and condensation losses. The pressure drops are compensated with compressors whose electricity demands are added to the total electricity demand, while the condensation losses reported at 0.1 % of mass flow were deemed negligible. The losses of transporting steam is estimated at 0.01 %/m. Radiative losses, however, are negligible due to low surface temperature. Those effects in combination render the second criterion unimportant and leads to the decision of spatial resolution being mainly based on the first and third criterion. The most important considerations regarding the latter are:

- Some plants may be subject to process electrification in the future and are therefore treated as separate nodes.
- One of the blast furnaces is considered to be replaced by novel technologies and is therefore treated as separate node.
- Currently, $O_2$ required for the blast furnaces is provided by an air separation plant. However; in the future, $O_2$ may be produced as a by-product of green hydrogen. Hence, the air separation plant is treated as separate unit to highlight the electricity consumption that may decrease if $O_2$ becomes available from another source.
- Manufacturing plants that are also net energy producers are maintained separate to highlight internally supplied energy flows the current integrated energy system. An exception to this are perfectly integrated sub-clusters.

## 3.2 The current energy system

### 3.2.1 Energy carriers

Before identifying relevant technologies and processes, the energy carriers of interest need to be defined. Besides electricity and natural gas, works arising gases (WAGs), steam, and waste heat are the most important carriers for the analyzed system.

The WAGs can be further distinguished into three different gas streams; (i) blast furnace (BF) gas arising from the blast furnace operation, (ii) OXY-gas arising from the basic oxygen furnace (BOF), and (iii) CO gas arising from the coke oven. For simplicity, those three were lumped and treated as single carrier, i.e. WAG.

Steam is currently used at 44 bar, 15 bar, and 3.5 bar, i.e. 470 °C, 230 °C, and 145 °C, respectively. In this work a lumped *steam* energy carrier was considered, regardless of temperature. Being a strong assumption, this is subject to refinement for future studies.

Waste heat is defined for off-gas streams with low heating values but significant enthalpy, which are used to pre-heat streams via heat exchange before entering the boiler.

Finally, an important material for steel making is coal. While coal has a significant heating value and could therefore be considered an energy carrier, it cannot be directly substituted since it acts as a reactant in the steel making process. Hence, coal was not considered as energy carrier in this study.

### 3.2.2 Energy conversion technologies

For the energy conversion technologies already in place, a differentiation must be made between technologies whose replacement can be modeled and those whose replacement cannot be modeled by the optimization framework. The former consist of technologies with the exclusive purpose of generating energy for the system. The fuel they use and the way they are operated do not directly influence the manufacturing processes. This set of technologies consists of boilers, gas turbines, steam turbines (listed in Table 1) and storage tanks for WAG (listed in Table 2).

There are three technologies that are considered irreplaceable since they are coupled to production processes. Firstly, the BF-gas produced in the blast furnace is expanded through an expansion turbine, which is an integral part of the BF process. Furthermore, a steam expansion turbine is used to expand steam from its transportation pressure of 80 bar[1] to 15 bar. Finally, the heat to be removed from the OXY-gas produced is utilized in a steam generator.

### 3.2.3 Networks

In the real site as well as in the optimization, each carrier, namely electricity, natural gas, and WAG, can be transported through a dedicated network. The current pipelines follow a main header, from which shorter pipes connect to users and generators. The representation in the model is an approximation of the real network directly connecting the different nodes. Figure 6 shows the network design. The networks are considered to be in place at sufficient capacity already. Hence, the optimization decides upon the hourly flows but not the network design. Furthermore, transportation losses are not included for the reasons discussed in section 3.1.

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[1] The mismatch in pressure of produced/transported steam and utilized steam is due to legacy systems

*Table 1: Summary of existing energy conversion technologies subject to change during the optimization process*

| Technology | Fuel | Number of units | Capacity [Unit] | Unit | Specification |
|---|---|---|---|---|---|
| Steam turbine | WAG | 1 | 300 | $MW_{el}$ | - |
| Gas turbine | Natural gas | 1 | 130 | $MW_{el}$ | - |
| | | 1 | 12 | | |
| Boiler | WAG or natural gas | 3 | 12 | tph | 10 bar/175 °C |
| | | 1 | 80 | | 44 bar/470 °C |
| | | 1 | 80 | | 64 bar/440 °C |
| | | 1 | 80 | | 80 bar/520 °C |
| | | 1 | 100 | | 44 bar/470 °C |
| | | 1 | 110 | | 44 bar/470 °C |
| | | 2 | 110 | | 80 bar/520 °C |

*Table 2: Summary of available WAG storage tanks. Above the flaring point, stored gas is flared off. All values in $Nm^3$*

| Number of units | Min | Max | Flaring Point | Working volume |
|---|---|---|---|---|
| 1 | 80,000 | 175,000 | 155,000 | 75,000 |
| 1 | 8,000 | 80,000 | 72,000 | 64,000 |
| 1 | 6,000 | 60,000 | 55,200 | 49,200 |

## 3.3 Energy demand and production profiles

The analysis in section 3.2 gives a characterization of the data to be gathered, i.e. which carriers for which process lumped in which nodes. The data gathering includes data validation by comparing different sources. Once reliable data sets were obtained, they were cleaned to create typical patterns.

### 3.3.1 Data gathering

TATA steel maintains three databases with different scopes and levels of detail. For simplicity, they are called DB1, DB2, and DB3 in this report.[2] First, annual energy consumption profiles from DB1 were analyzed for each carrier and the share of consumption of a certain node over the total

[2] Internal names of the databases are MoniCA, PI datalink, and ISE, respectively

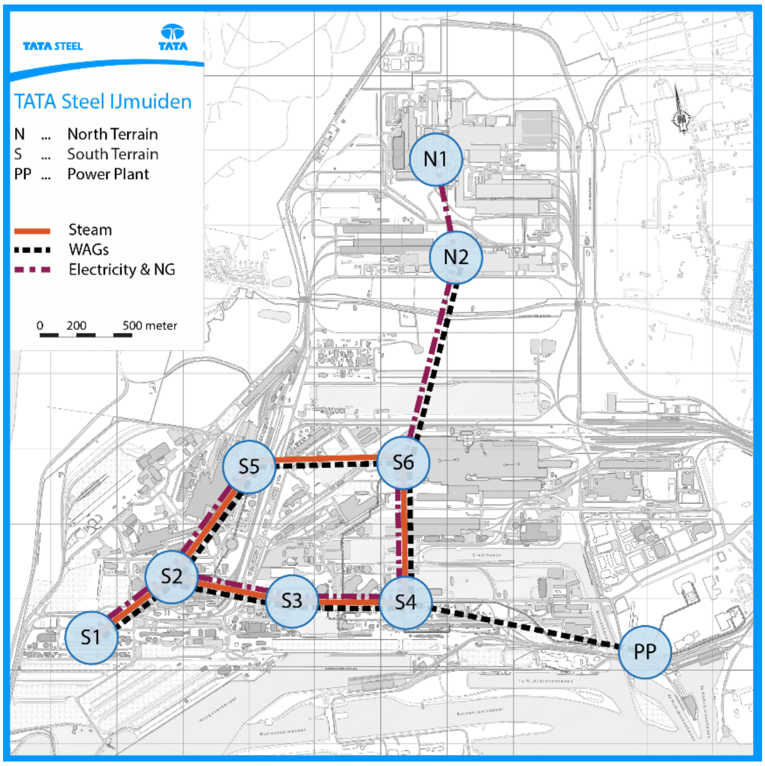


*Figure 6: Representation of the production site in the model. The blue circles represent the various nodes (an overview of the manufacturing processes at each node can be found in Table A-2). The lines represent the networks.*

consumption of the production site was calculated. Focusing on the major consumers, it was decided that profiles are only gathered at hourly resolution if the share of consumption is greater than 5 %. To avoid the underestimation of total consumption, the remaining consumers' demands (< 5%) were lumped into one profile. The detailed findings of this analysis are found in the appendix in Table A - 3.

After determining which profiles are of relevance, hourly data was gathered from DB2 & DB3 and the yearly energy consumption and production were compared for validation. A significant amount of data shows a variation between any two databases of more than 5 %, which was defined as acceptability threshold. Reasons for data variation are measurement errors or measurements at different points of the plants. For example, DB1 records the total natural gas consumption for plants including natural gas used for building heating whereas DB2 records the consumption for the individual manufacturing processes. For cases in which the choice of an appropriate dataset was not obvious, experts on-site were consulted. Furthermore, in case of doubt, overestimation of demand was preferred over underestimation. In this respect, two assumption are worth being mentioned specifically:

- The air separation unit's main purpose is to supply $O_2$. The by-product $N_2$ is sold to external users. Unused $O_2$ is flared throughout the year whenever a larger amount of $N_2$ must be supplied. Therefore, allocating the entire electricity demand of the air separation unit to the steel making process is an overestimation.

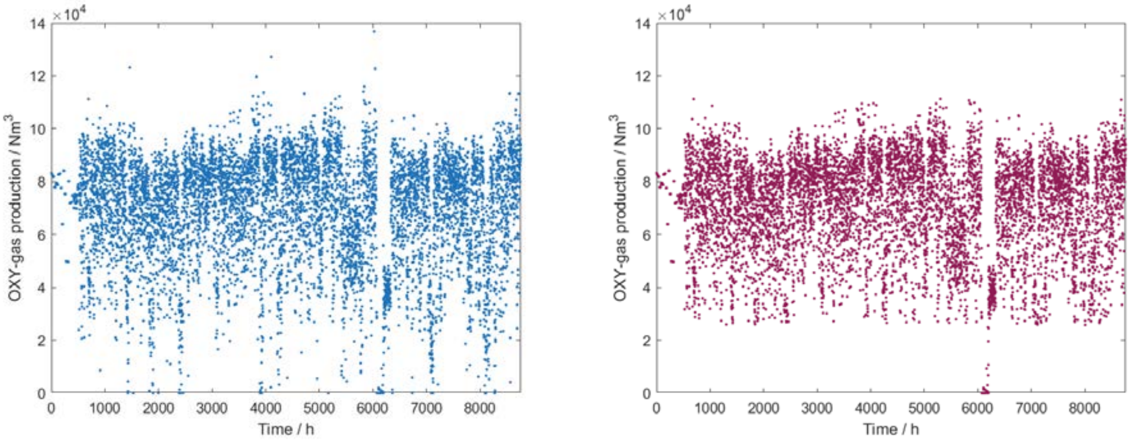


*Figure 7: Exemplary result of the data cleaning process. The plot shows the 2018 OXY-gas production of the basic oxygen furnace. (left) raw data, (right) processed data.*
*$\mu$ = 68.8 Nm$^3$/h, 2$\sigma$ = 43.1 Nm$^3$/h*

- The demineralization water treatment process required for boilers comes with a certain electricity demand which was obtained from the databases. As a conservative estimate, this demand is assumed to remain unchanged, even if boilers are replaced.

### 3.3.2 Data cleaning

The data was gathered for the year 2018. However, representative data irrespective of the particular year was desired. Hence, after the completion of data gathering, the data are cleaned from measurement errors and atypical trends.

First, profiles with irregular trends were compared with previous years, also obtained from DB2 and DB3. Furthermore, experts were consulted to (a) collect information about planned maintenance and known interruptions, and (b) investigate the causes for unexplained disturbances. For confirmed atypical events, e.g. unplanned interruptions or measurement errors, a trend interpolation or substitution with data from previous years was performed.

Then, values outside a confidence range of two standard deviations ($\mu \pm 2\sigma$) of the respective data set are replaced by trend interpolation. This method was not applied for profiles following an expected but strongly varying trend where the confidence interval would result in misleading conclusions. An example for data cleaning using this method is shown in Figure 7.

Finally, planned maintenance times, which are excluded by the $2\sigma$ confidence interval since the demand/production is zero, were imposed on the profiles.

For two processes, none of the aforementioned methods were deemed appropriate and therefore required custom processing

- Due to a technical problem in the expansion turbine of one of the blast furnaces, its electricity production was not representative. To reconstruct the profile, the turbine conversion factor in $\mathrm{kW_e}$ per $\mathrm{Nm^3_{BF\text{-}gas}/h}$ was calculated based on 2017 profiles and applied to 2018.
- The profiles of the pellet plants are highly irregular. However, the causes for the irregularities were still being investigated by experts at the time of the research execution. These profiles are therefore directly used in the analysis, without further pre-processing.

## 3.4 Potential for renewable energy conversion technologies

The renewable energy conversion technologies considered in this study are wind turbines, photovoltaic panels, and solar thermal panels. The former are significantly constrained by the land availability and suitability. The photovoltaic and solar thermal panels are assumed to be limited to suited rooftops. The maximum potential has been assessed by TSIJ. A summary of the study's finding is shown in Table 3.

*Table 3: Maximum potential of renewable energy technologies on site as assessed by TSIJ*

| Location | Wind turbines [units] | PV/solar thermal [$m^2$] |
|---|---|---|
| TSP | - | 2250 |
| HSM2 | - | 37101 |
| CM2 | - | 92530 |
| CPR | - | 9704 |
| CGP2 | 2 | - |
| CEN1 | - | 14749 |
| CEN2 | 3 | - |

# 4 DECARBONIZATION MEASURES

The decarbonization measures usually associated with the steel industry can be divided into two categories. The first one entails measures that can be retrofitted to existing plants and do not significantly change the way steel is produced today. The most prominent examples of this category are electrification of heat, post-combustion capture applied as end-of-pipe or to specific streams within the process, and end-of-pipe Sorption Enhanced Water-Gas-Shift (SEWGS) (though before combustion). The second category is a collection of novel steel making processes, namely Hisarna, direct reduction through hydrogen, and Electric Arc Furnace (EAF). The latter is not a new technology but constitutes a significant change compared to the classic blast furnaces and is hence listed in the same category here.

In the course of this work, the aforementioned decarbonization measures are distinguished by yet another criterion; whether they utilize hydrogen and/or carbon capture technologies or not. The modeling work focuses on the technologies that do not, i.e. electrification of heat, EAF, and stand-alone Hisarna (i.e. not coupled to carbon capture). These three are explained in detail in sections 4.1 - 4.3. Section 4.4 provides a summary of the other technologies important for the steel industry but not covered in this work.

For the focus technologies, implementation scenarios were created and the new demand profiles determined. Table 4 shows an overview of the technologies' effects on the energy demands.

## 4.1 Electrification of heat

A thorough study [7] has been conducted on the potential of electrification of heat at TATA steel. This study found that the hot strip mill (HSM), direct sheet plant (DSP), and packaging facilities (TSP) show the highest potential.

Within TSP, the continuous annealing line is currently heated by combustion of natural gas. This process could be replaced by electric resistive heating tubes. Figure B - 1 (Appendix) shows Sankey diagrams for heating with natural gas and with electricity. It can be seen that electrification increases the efficiency from 46 % to 83 %.

The natural gas used for heating in DSP is considered to be replaced by a transverse flux inductor. While being more expensive than resistive heating, this technology suits the requirements of the DSP better since it can provide steeper temperature gradients. The Sankey diagram in Figure B - 2 (Appendix) shows that electrification increases the efficiency from 20 % to 42 %.

For the hot strip mill, the conventional heat provision for the furnace with natural gas is not replaced but an electric pre-heating step is added. Again, heating by induction is considered. Preheating the slabs leads to a more constant temperature in the furnaces since all slabs enter with the same temperature. This in turn opens up the possibility of shutting down one furnace which decreases the natural gas consumption. Furthermore, the study [7] showed that this measure prevents overheating, i.e. unintended heating above the target temperature, which increases the overall energy efficiency. The Sankey diagram in Figure B - 3 (Appendix) shows the increase in efficiency from 54 % to 62%. Compared to TSP and DSP, the efficiency improvement is small. This is because HSM is not entirely electrified.

In conclusion, the aforementioned changes lead to an increase in electricity demand and a decrease in natural gas demand. Figure 8 illustrates which nodes would be affected by the electrification plans.

*Table 4: Overview of the effect of different decarbonization measures on energy demands*

| | Electrification of Heat | Electric Arc Furnace | Hisarna |
|---|---|---|---|
| Electricity | + 5 % | - 5 % | - 15 % |
| Natural Gas | - 10 % | + 20 % | - 5 % |
| Steam | - | - 35 % | - 35 % |

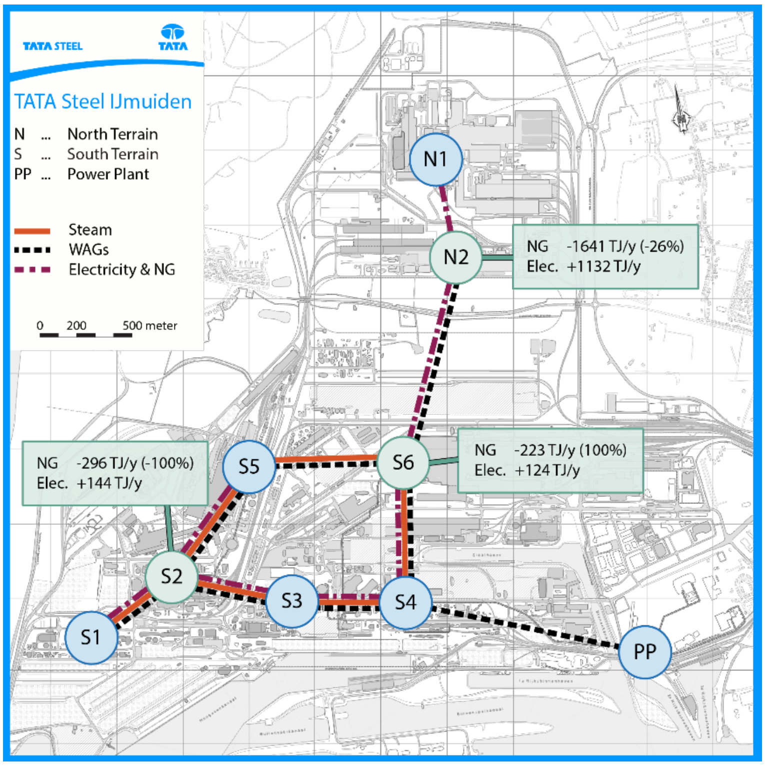


*Figure 8: Overview of process changes related to the implementation of electrification measures*

## 4.2 Electric arc furnace

The electric arc furnace uses mostly scrap metal and can therefore be seen as a recycling process. A sketch of an EAF is shown in Figure 9. The ferrous scrap is melted and refined using electrical energy. While melting, oxidation of phosphorous, silicon and other materials occur. A slag, containing some of these oxidation products forms on top of the molten steel, which is decarburized using oxygen. The heat necessary for the melting process comes from an electric arc arising when graphite electrodes get in contact with the charged metal and wall-mounted gas burners oxy-fuelled with natural gas. While vast amounts of electricity are needed to run this process, no WAGs are associated with an EAF. [8]

Due to the limited availability of scrap metal, it is unrealistic to assume that both blast furnaces are replaced by EAFs. Instead, it is assumed that one blast furnace with an output of 3 Mt/y is replaced by an EAF while the other one (4.2 Mt/y) continues operation.

Implementation of an EAF comes with significant changes to the rest of the integrated site. First of all, not only the blast furnace (BF6) but also its associated coke oven (CGP2) is shut down. Furthermore, the sinter and pelleting plants, the other coke oven, the direct sheet plant, and the basic oxygen furnace are lowered in capacity. [3]

The main task of the coke oven to be scaled down (CGP1) is to deliver CO-gas to the blast furnaces. Hence, it was scaled based on the change in CO-gas demand as

$$S_{new} = S_{old} \cdot \frac{\sum P_i^{\text{CO-gas}}}{P_1^{\text{CO-gas}}} \cdot \frac{C_7^{\text{CO-gas}}}{\sum C_j^{\text{CO-gas}}}$$

where $S_{new}$ and $S_{old}$ are the new and old scales of CGP1, respectively, $P_i^{\text{CO-gas}}$ is the production of CO-gas in coke plant CGP-$i$ (CGP1 and CGP2), and $C_j^{\text{CO-gas}}$ is the consumption of CO-gas in blast furnace BF-$j$ (BF6 and BF7). This results in a 7 % downscaling of CGP1.

As opposed to the coke oven, the sinter factory cannot be scaled arbitrarily due to a more modular architecture. One of the sinter ovens is stopped such that the supply of the other blast furnace is still ensured but approached as close as possible. This leads to a decrease in scale of 36 %. [9]

Similar to the sinter factory, the pellet factory cannot be scaled arbitrarily either. The maximum achievable scale-down which still requires the remaining demand is 36 %.

The direct sheet plant and basic oxygen furnace, both being downstream of the blast furnace, are simply scaled based on the pig iron output of the blast furnaces, resulting in a reduction of 45%.

Finally, the oxygen demand of an EAF is lower compared to a blast furnace. Hence, the electricity demand of the air separation unit is lowered by 43 %. Note that this assumption neglects potential constraints from external users of the air separation's by-product nitrogen.

Based on literature values, it was estimated that the energy demands to produce 3 Mt/y of steel with EAFs are 2.3 PJ/y of natural gas and 2.0 PJ/y of electricity. [3]

Figure 10 summarizes the changes to the different processes graphically.

## 4.3 Hisarna process

Another alternative to a blast furnace is the Hisarna process. A significant advantage is that it can utilize fine raw materials directly, while the blast furnace relies on various preprocessing steps for its material inputs. In particular, the pellet factory, sinter factory, and coke oven are not needed for the Hisarna process. This leads to a significant increase in energy efficiency. [10]

Figure 11 shows a sketch of the Hisarna process. Iron ore is injected at the top and liquefied in a high temperature cyclone. Combustion process promoted by the injected oxygen are the main source of heat. The liquified ore then drips to the bottom of the reactor where power coal is injected to reduce the iron ore. The top gas is rich in $CO_2$, which favors carbon capturing. [11] This is one of the main selling points of this technologies. In this work, however, the carbon capturing contribution was not considered.

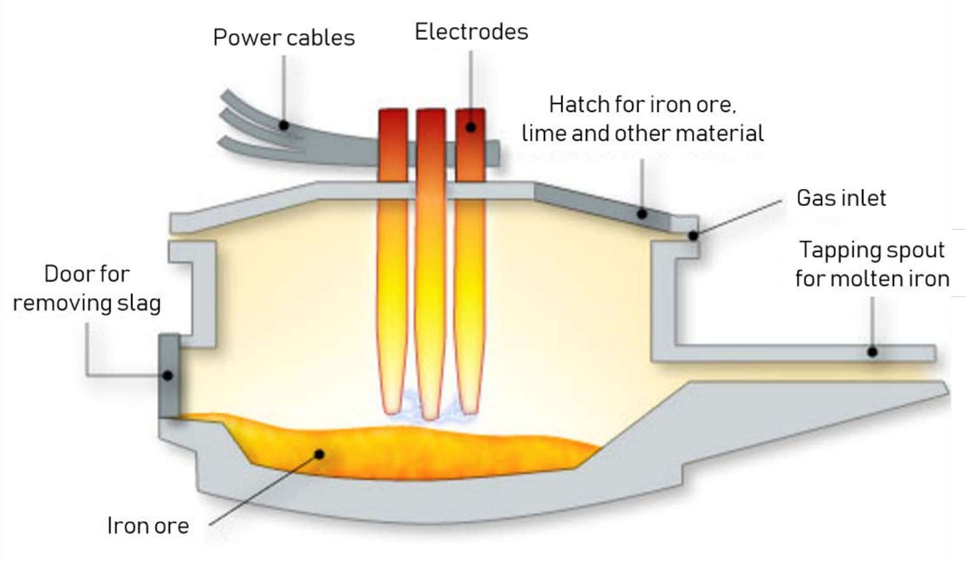


*Figure 9: Sketch of an electric arc furnace (EAF) adapted from* [12]

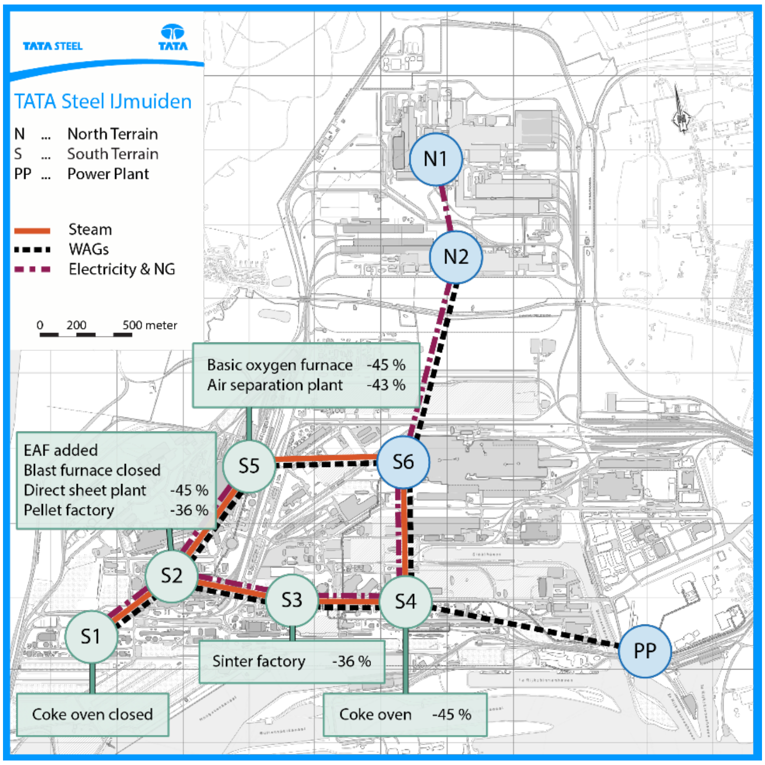


*Figure 10: Overview of process changes related to the implementation of an electric arc furnace*

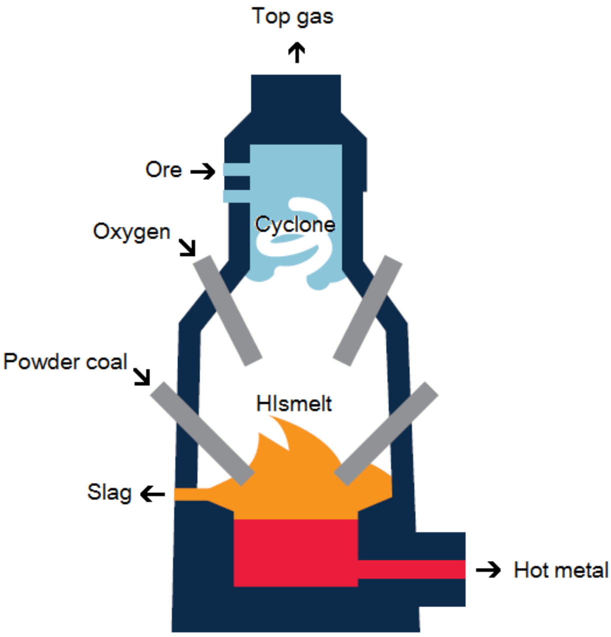


*Figure 11: Sketch of the Hisarna process* [11]

In order to keep the different decarbonization scenarios comparable, the replacement of only one blast furnace was assumed for the Hisarna process as well. The changes to the upstream process, i.e. pellet factory, sinter factory, and coke ovens, are identical to the EAF scenario (see section 4.2). Nevertheless, a significant difference exists in downstream processing. While EAF produces

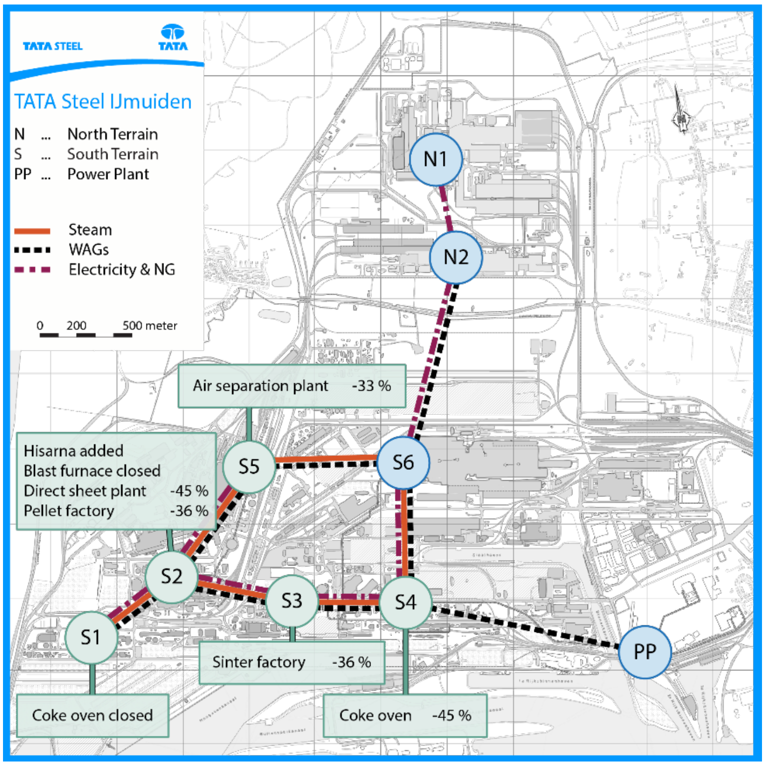


*Figure 12: Overview of process changes related to the implementation of the Hisarna process*

crude steel directly and renders the basic oxygen furnace unnecessary, the Hisarna process produces pig iron similar to the blast furnace. Hence, the blast oxygen furnace remains in place.

The electricity demand of the air separation plant is lowered by 33 % due to lowered oxygen demand.

Of the energy carriers considered in this work, the Hisarna process itself only requires 0.8 PJ/y of electricity.

Figure 12 summarizes the changes to the different processes graphically.

## 4.4 Other decarbonization measures for the steel industry

Several processes exist that make use of carbon capture for decarbonization of the steelworks. Indeed, the complexity of the plant and the variety of process units open doors for applying carbon capture at different positions, with different levels of integration within the plant, and via different technologies and principles. A comprehensive revision of these different possibilities is not in the scope of this report, and an interested reader can refer to the growing scientific and grey literature [13]–[15]. However, we would like to briefly introduce here four different possibilities that are particularly relevant in the context of Elegancy but that have not been considered for the quantitative analysis presented in this report.

- VPSA for BF top gas recycling. The blast furnace gases can be decarbonized sending the stream at the top of the BF to an adsorption unit, where $CO_2$ is separated from the remaining components. The adsorption unit consists of several fixed bed filled with (a mixture of) physical sorbents that undergo a cyclic process comprising adsorption and regeneration. While $CO_2$ is sent to storage or utilization, CO, $H_2$ and other diluents are recirculated to the BF. In order to do so, the lowest cycle pressure needs to be below ambient conditions, lest the purity and recovery of $CO_2$ would be very low. Given the multicomponent nature of the BFG and the amount of CO compared to $CO_2$, the VPSA developed within Elegancy (see WP1) could offer a potential promising candidate for application in the top gas recycling. However, dedicated research work would be necessary to prove this both computationally and experimentally. Overall, the BF top gas recycling could achieve a reduction of 55-60% of $CO_2$ emissions [14].
- SEWGS. The sorption enhanced water gas shift has proven as an effective technology for decarbonizing the different varieties of gas present in an integrated steel mill. Thanks to its versatility in processing CO rich gases, which are abundant in a steel mill plant, and converting CO to $CO_2$, the SEWGS has proven to be an effective technology for $CO_2$ reduction in steelworks. [15], [16] Notably, the SEWGS could be used in an integrated fashion, where its deployment would require modifications in the steel production line, or in an end-of-pipe, yet pre-combustion, fashion. The latter would not affect the steel production, but would not fully exploit the energy saving potential. The application of SEWGS to steel plant has the potential of achieving ultra-low $CO_2$ emissions, i.e. the $CO_2$ remaining in sleep streams from the SEWGS.
- Post-combustion flue gas amine scrubbing. The removal of $CO_2$ from flue gas products is a ready commercial solution for carbon capture. Therefore, steel plants can be equipped with end of pipe flue gas scrubbing (typically using chemical solvents), which would remove $CO_2$ after the steel gas are mixed and used in a combustion (in boilers or power plants associated to the steelworks). However, thanks to the high CO and $CO_2$ content in the gases inside the steelworks battery limits, most of steel producers do not regard this solution as particularly promising. It is finally worth noting that this solution could deliver a steel plant with ultra-

low $CO_2$ emissions, provided that all CO available in the plant gases is converted to $CO_2$. Recent research has shown that post-combustion capture in combination with biomass feeding could lead to net-negative steelworks. [17]

- Direct reduction with hydrogen. Here, the main concept is to replace the blast furnace-basic oxygen furnace process with the ensemble of (i) a hydrogen reduction process, which produces direct reduced iron, and (ii) an electric arc furnace, which turns the reduced iron into steel. In such configuration, high $CO_2$ reduction can be achieved provided that $H_2$ is produced without $CO_2$ emissions, i.e. via fossil+CCS or via electrolysis from renewable electricity. Recent literature about this route showed that it is cost competitive with an integrated steel plant at a carbon price of 34–68 EUR per tonne CO2 and electricity costs of 40 EUR/MWh [18].

# 5 ENERGY SYSTEM DESIGN

In this section, the outcomes of the energy system designs for the scenarios described in section 4 are presented and discussed. Table 5 summarizes the technologies considered for the design.

For a clear understanding of the results, the role of works arising gases needs to be clarified here. WAGs are of process related nature and their production is therefore not affected by the energy system design. As a result, the emissions due to WAGs always occur – unless treated with CCS, no matter how large the share utilized within the energy system. Hence, all results include the emissions that correlate to the combustion of the whole amount of WAGs produced.

## 5.1 Reference design

The energy system currently in place is significantly different from what an optimization would result in. The reasons for this are: (i) the performance and cost parameters for technologies do not perfectly reflect the specificities of the case study (e.g. suppliers quotations might significantly deviate from literature costs), and (ii) the green field approach used in the optimization does not represent the organic growth in time of the real site. Although the latter was taken into account to a certain extent by considering existing technologies, it is hardly possible to simulate organic growth in the modeling framework used.

For consistency, the cost-optimal system design found by the tool for the current process situation was used as a references case, rather than the actual system in place. This is a crucial step to ensure that relative changes of emissions and costs are representative and comparable. To bring this change into focus, all results are reported relative to the reference design.

The pareto front for the multi-objective optimization on $CO_2$ emissions and total annual system cost is displayed in Figure 13. It can be observed that the decarbonization potential is rather limited with a maximum of about 6 %. This minor decrease in emission comes with a significant increase in cost of 25 %.

Figure 14 shows the contribution of the different technologies to the electricity and heat delivered for each design along the pareto front in Figure 13. Most notably, the WAG utilization increases for decreasing emissions (see steam turbine and boiler (WAG)), while renewables play a minor role due to their limited on-site potential.

## 5.2 Electrification of heat

The electrification of heat reduces the natural gas demand and increases the electricity demand. As can be seen in Figure 15, both emission and cost are lower for all pareto optimal designs. Comparing the minimum cost design of the reference scenario with the minimum emission design for electrified heat, a decrease in emissions of about 8 % for a cost increase of 23 % can be observed. Figure 16 reveals the reason for the limited effect of the electrification of heat, namely the limited renewable potential and the high share of imported electricity. Hence, it can be concluded that a larger potential of renewables or greener grid electricity is necessary to exploit the full potential of this measure.

On a different note, it can be observed that the entire area dedicated to PV and solar thermal is used for PV. This indicates that the benefit of replacing grid electricity and/or conventional conversion technologies for electricity is more beneficial than replacing boilers. The main reason for this is the high utilization of WAG for heat generation, especially in the minimum emission design.

*Table 5: Summary of available energy conversion technologies for the energy system design. For boilers, the fuel used is given in parentheses.*

| Node | Conventional technologies | Renewable technologies |
|---|---|---|
| N1 | Boiler (WAG), Boiler (NG) | Solar thermal, Photovoltaics |
| N2 | - | Solar thermal, Photovoltaics |
| S1 | - | Wind turbines |
| S2 | Boiler (WAG), Boiler (NG) | Wind turbines |
| S3 | Boiler with waste heat recovery, Boiler (WAG), Boiler (NG) | - |
| S4 | Boiler (WAG), Boiler (NG), Gas turbines | Solar thermal, Photovoltaics |
| S5 | - | - |
| S6 | - | Solar thermal, Photovoltaics, Wind turbines |
| PP | Steam turbines, Gas turbines | - |

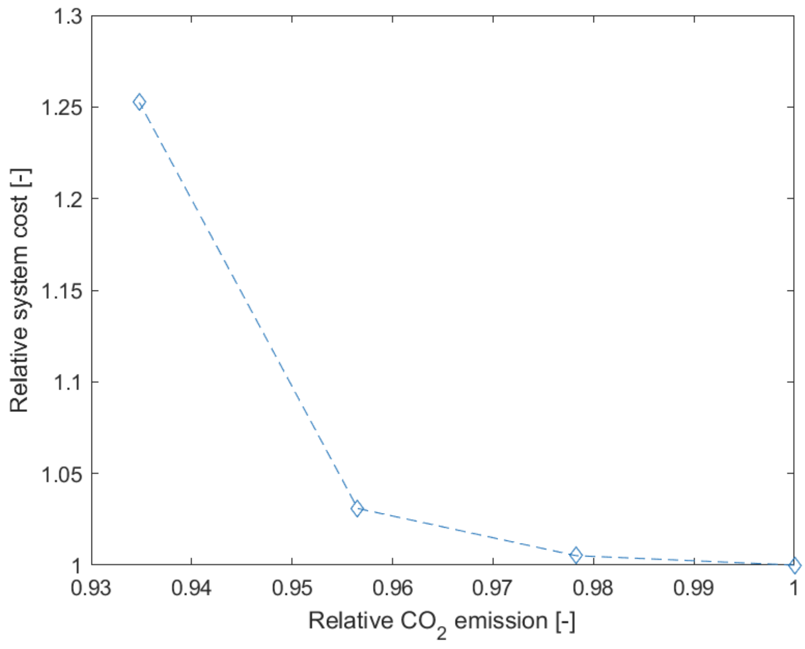


*Figure 13: Pareto front of $CO_2$ emissions and system cost, relative to the minimum cost design, for the reference scenario*

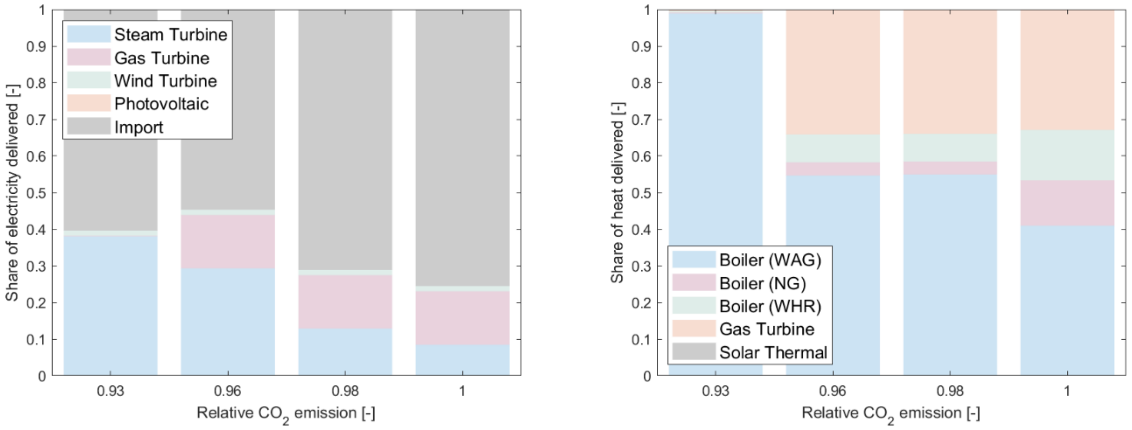


*Figure 14: Contribution of the different technologies available to the total delivered electricity (left) and heat (right) for the reference scenario.*

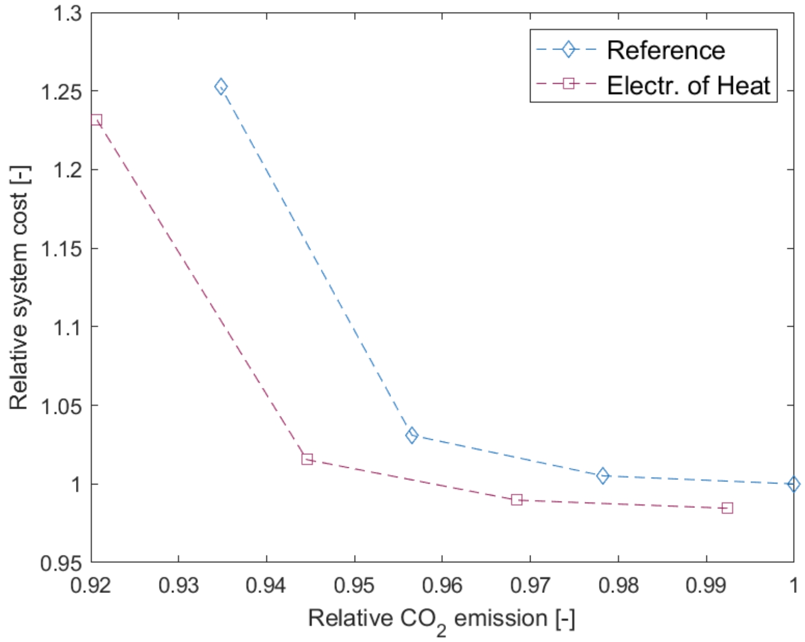


*Figure 15: Pareto front of $CO_2$ emissions and system cost, relative to the minimum cost design of the reference scenario, for the electrified heat scenario*

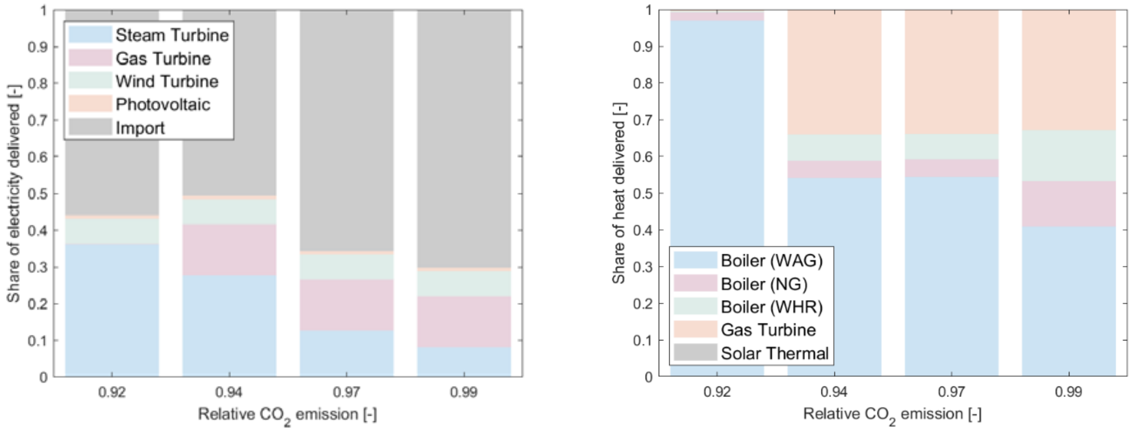


*Figure 16: Contribution of the different technologies available to the total delivered electricity (left) and heat (right) for the electrified heat scenario*

## 5.3 Hisarna process

As discussed in earlier parts of this report, the Hisarna process reduces the demand of all energy carriers significantly. This is reflected in both costs and emissions of the energy system, as can be seen in Figure 17. The maximum achievable emission reduction of about 45 % comes with a cost increase of just about 3 %. Furthermore, the cheaper energy system designs reduce the costs by roughly 20 % while still reducing the emissions by 35 – 40 %.

Figure 18 shows that the basic trend of the technologies along the pareto curve is similar to the other designs, indicating that the main driver for the observed decarbonization here is the reduced energy demand. However, this observation also implies that a greener grid or extended potential for renewables could further decrease the emissions.

## 5.4 Electric arc furnace

The energy system design for the EAF scenario is very similar to the one for the Hisarna scenario as shown by both Figure 19 and Figure 20. However, since the Hisarna process is overall more energy efficient than the EAF (all upstream and downstream process changes included), the system design for the EAF is overall slightly more expensive. The increase in imported electricity compared to the Hisarna scenario as a result of the higher electricity demand. Furthermore, it’s important to note that the higher natural gas demand for the EAF scenario (see Table 4) leads to higher process emissions which is not represented in this study due to its focus on the energy system.

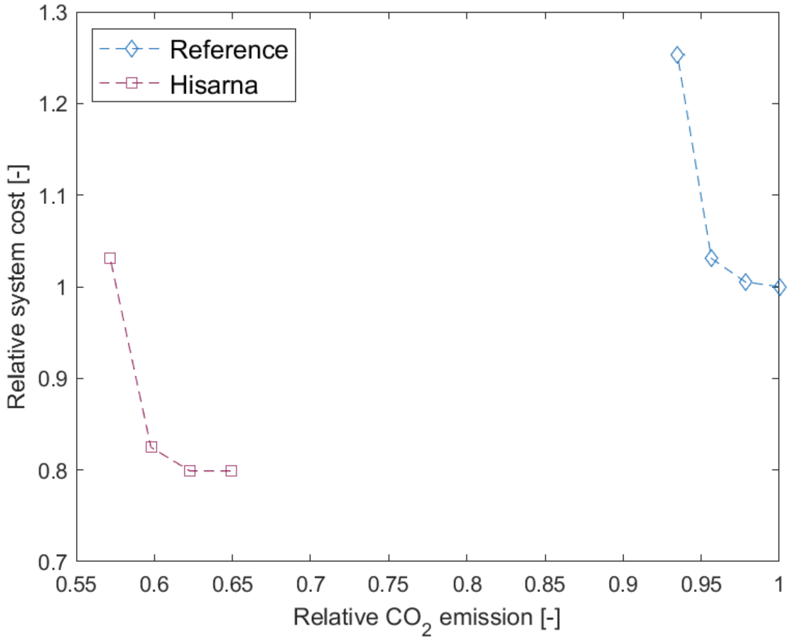


*Figure 17: Pareto front of CO2 emissions and system cost, relative to the minimum cost design of the reference scenario, for the Hisarna scenario*

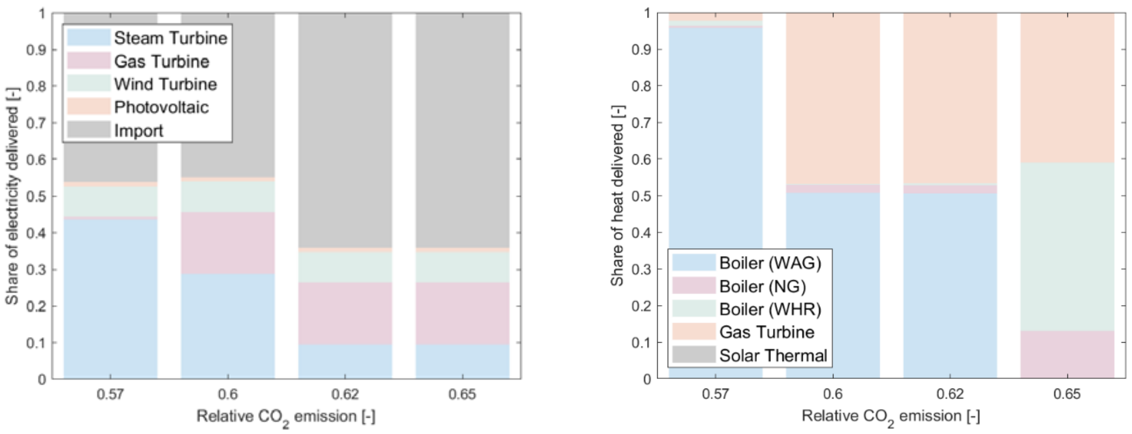


*Figure 18: Contribution of the different technologies available to the total delivered electricity (left) and heat (right) for the Hisarna scenario*

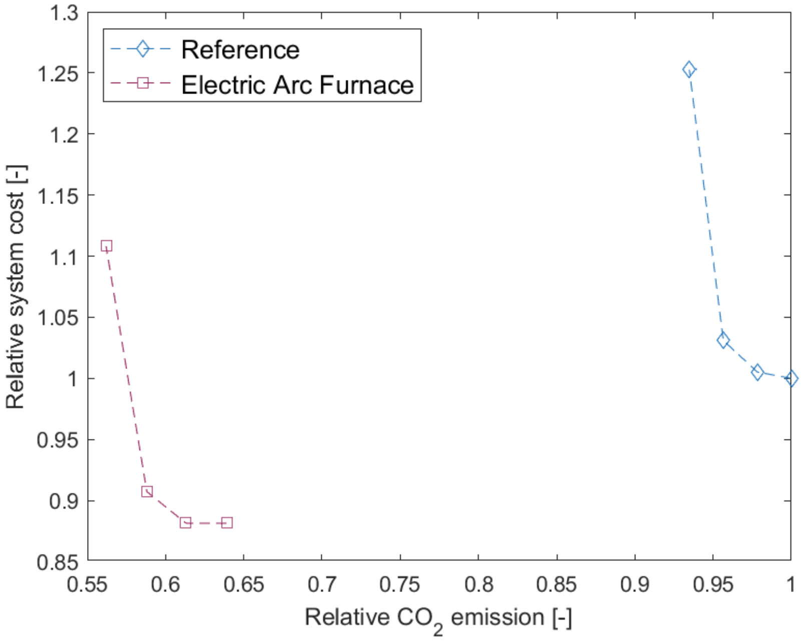


*Figure 19: Pareto front of CO2 emissions and system cost, relative to the minimum cost design of the reference scenario, for the Electric Arc Furnace scenario*

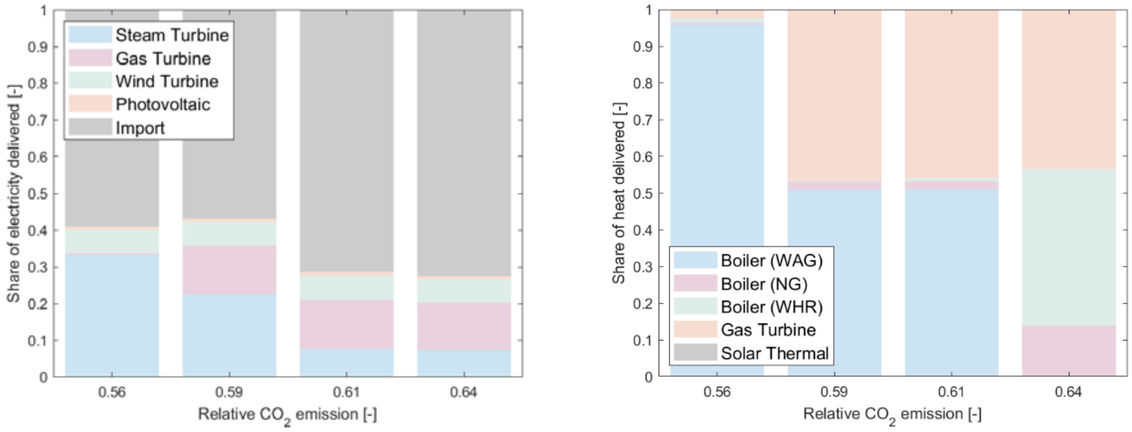


*Figure 20: Contribution of the different technologies available to the total delivered electricity (left) and heat (right) for the Electric Arc Furnace scenario*

# 6 DISCUSSION

The comparison of the minimum emission designs for all four scenarios (see Figure 21) clearly shows that the energy system itself does not show much room for emission reduction. Electrifying the heat demand changes this only marginally. The reason for it lies in the limited potential for renewables and the high emission factor of electricity from the grid. Having abundant (i.e. cheap) and green electricity from the grid would improve this scenario, but would not substantially change the limited decarbonization potential. As opposed to electrification of heat, both the Hisarna process and the EAF have a significant impact on the energy system. Both reduce the emissions by more than 40 % while increasing the costs only by 5-10 %. The Hisarna process leads here to the cheaper designs due to its lower energy demands.

Although all measures reduce the emissions related to the energy system, none of them enable deep decarbonization on their own. It is therefore reasonable to conclude that additional measures are necessary.

Post-combustion carbon capture and storage is an option that can be combined with the measures investigated in this work. The clear advantage is that this technology is able to tackle the emissions related to the energy system but also remaining process related emissions. Especially for the Hisarna process, capturing and storing the $CO_2$ rich off-gas stream is an essential part of the technology. Therefore, the required infrastructure would facilitate broader utilization of carbon capture technologies.

Another option for achieving deeper decarbonization levels is the use of carbon-neutral hydrogen. The main applications of hydrogen are threefold. Firstly, it can replace natural gas for heating purposes. Secondly, it can be used as a fuel in gas turbines. This application, however, is not yet state of the art and only sensible if WAGs are avoided or treated. Finally, direct reduction through hydrogen, the third application of hydrogen, is a novel way of producing steel and is therefore regarded an alternative rather than a supplement to the measures analyzed in this work.

In the transition phase to an energy system with redundant green electricity, carbon neutral hydrogen will rely on carbon capture. Hence, similar to the Hisarna process, the CCS infrastructure required for carbon-neutral hydrogen could facilitate the application of carbon capture to decarbonize the steel industry. Furthermore, both hydrogen and CCS allow to produce carbon-free electricity on-site, which makes the process of decarbonizing the energy system less reliant on the emission factor of the national grid.

It is important to note that neither hydrogen nor CCS have been quantitatively investigated in this study. It merely shows the need for any of the alternatives proposed in this section if deep decarbonization is the goal. Also, whether CCS or hydrogen are to be preferred, and which application in particular, is influenced by many factors like political and societal situation (e.g. public acceptance of technologies) or infrastructural conditions.

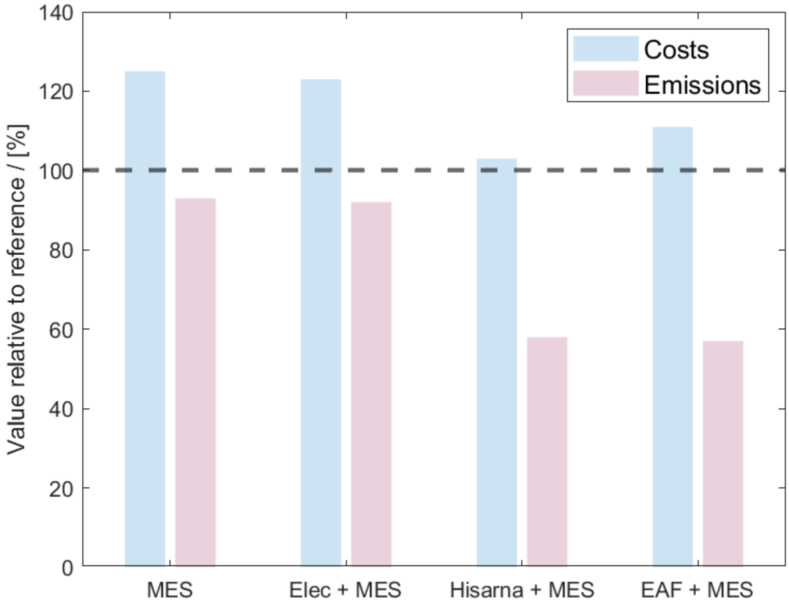


*Figure 21: Comparison of the costs and emissions of the energy system for different decarbonization measures. 'MES' refers to an optimization of the multi-energy system for minimum emissions*

# 7 CONCLUSION

This work aimed at quantifying the role of carbon capture and/or clean hydrogen in decarbonizing steel production from integrated steelworks. To do so, an approach of proof-by-negation was used. This means that the starting point for this study was the assumption that decarbonization measures which do not rely on CCS or hydrogen would suffice. This assumption was then proven wrong.

The foundation is a thorough analysis of the TATA Steel Ijmuiden production site in collaboration with on-site experts. In the course of this activity, production profiles as well as energy demand profiles at hourly resolution were gathered, critically analyzed, and cleaned of measurement errors and other disturbances to obtain representative profiles. Furthermore, the impact of three decarbonization measures, namely electrification of heat, implementation of an electric arc furnace, and implementation of the Hisarna process, on the energy demands was assessed.

With this vast set of data, optimal energy systems for the three different decarbonization measures and for a reference case were designed using an inhouse optimization framework. The designs were optimized for pareto-optimal conditions of $CO_2$ emissions and costs. Furthermore, system constraints imposed by the topography of the site, e.g. available land for renewable energy conversion technologies, but also existing technologies have been considered in the simulations. Throughout this whole process, discussions with on-site experts were used to ensure the reasonability of the findings.

The energy system designs reveal that the limited potential for renewable energy conversion technologies in terms of land availability significantly constrains the decarbonization of the energy system. Another issue with the same effect is the lack of a green national grid. This is especially true for electrification of heat. While the measure itself is certainly reasonable, it only makes sense if the electricity can be provided in a low- or no-carbon manner, which is currently not the case. Implementation of an electric arc furnace or the Hisarna process both lower the $CO_2$ emissions significantly due to a decrease in energy demands. However, the potential is here limited to about -40 % as well; again due to the lack of green electricity.

In conclusion, none of the investigated measures allow for deep decarbonization without additional efforts. An obvious, yet not straight forward, way of increasing the level of decarbonization is to increase the capacity of renewables. Since this can only be done off-site due to spatial constraints, it is synonymous with decreasing the emission factor of the national grid. Hence, the plant operator can influence this only to a certain extent.

An alternative is the use of CCS and/or hydrogen. Both CCS and hydrogen would allow to decarbonize the process side as well as the energy system side. Furthermore, the full potential of the Hisarna process can only be exploited with carbon storage infrastructure in place. Therefore, another logical extension would be the utilization of this infrastructure for further carbon capture applications. Finally, delivering carbon-free hydrogen relies on carbon capturing and its associated infrastructure until redundant green electricity is available.

This work did not quantify the effect off CCS or hydrogen and the exact selection and design of the associated technologies has to be assessed on a case-by-case basis since legal, political, societal, and infrastructural conditions can vary drastically between steel production plants. However, this work clearly shows that without CCS or hydrogen, decarbonizing the steel industry is an unnecessary rocky road.

# 8 ACKNOWLEDGEMENT

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# A TABLES

*Table A - 1: List of works within TATA Steel Ijmuiden and their abbreviations*

| Abbreviation | Name/Description |
|---|---|
| BF6/7 | Blast furnace |
| BOS or BOF (used synonymously) | Basic oxygen steelmaking plant or basic oxygen furnace |
| CEN1/2/3 | Central heat and power production, mostly agglomeration of boilers |
| CGP1/2 | Coke and gas plant |
| CM2 | Cold mill plant |
| CPR | Coating facility |
| DSP | Direct sheet plant |
| HSM | Hot strip mill |
| IJm01 | Ijmond01, location of CHP plant |
| PEFA | Pellet factory |
| SIFA | Sinter factory |
| TSP | Tata Steel Packaging |
| VN25 | Velsen, Nuon power plant utilizing process gases |
| ZUFA | Air separation plant operated by Linde |

*Table A - 2: Summary of processes at each node*

| Node | Processes |
|---|---|
| N1 | CPR, CM2, CEN3 |
| N2 | HSM |
| S1 | CGP2 |
| S2 | DSP, CEN2, BF6, BF7, PEFA |
| S3 | CEN4, SIFA |
| S4 | CEN1, IJm01, CGP1 |
| S5 | BOS2, ZUFA |
| S6 | TSP |
| PP | VN25 |

*Table A - 3: Processes identified as relevant consumers and producers of energy carriers. Production and demand profiles were gathered at hourly resolution.*

| Carrier | Consumer | Producer | Consumption ratio |
|---|---|---|---|
| Steam (3.5 bar) | CM2, CPR | CPR | 0.90 |
| Steam (15 bar) | CGP1, TSP, ZUFA | BOS2 | 0.91 |
| Steam (44 bar) | BF6, BF7, BOS2, CGP2 | BOS2 | 1.00 |
| Waste heat | - | SIFA | - |
| BF-gas + OXY-gas | BF6, BF7, CGP1, PEFA | BF6, BF7, BOS2 | - |
| CO-gas | BF6, BF7, CGP1, CGP2, HSM, PEFA, SIFA | CGP1, CGP2 | - |
| Natural gas | CPR, DSP, HSM, PEFA, TSP, CEN1 | - | 0.77 |
| Electricity | BOS2, CM2, DSP, HSM, PEFA, SIFA, TSP, ZUFA, CEN1 | BF6, BF7, CEN1 | 0.74 |

# B FIGURES

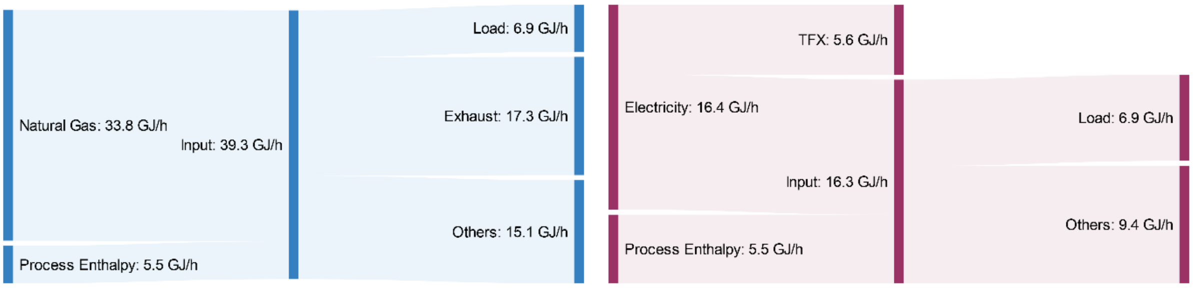


*Figure B - 1: Sankey diagram for the direct sheet plant. (left) current situation (right) electrified situation. Figure adapted from* [7]

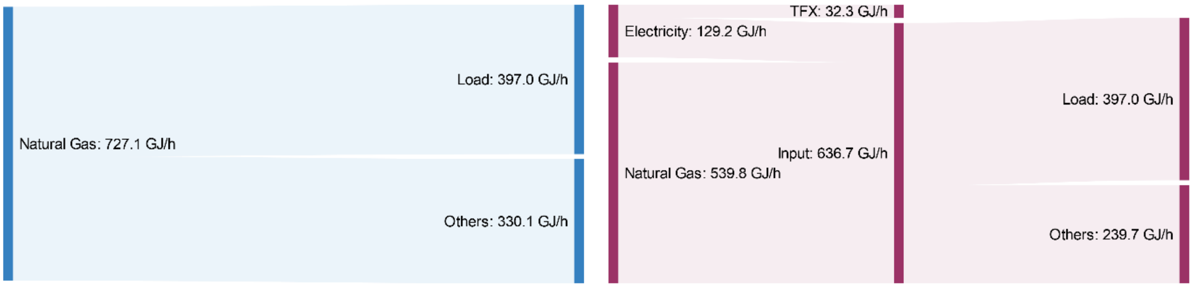


*Figure B - 2: Sankey diagram for the hot strip mill. (left) current situation (right) electrified situation. Figure adapted from* [7]

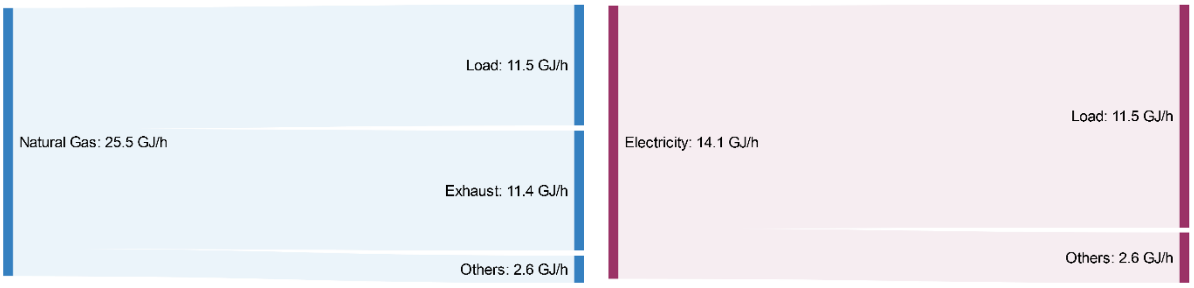


*Figure B - 3: Sankey diagram for the packaging facility. (left) current situation (right) electrified situation. Figure adapted from* [7]