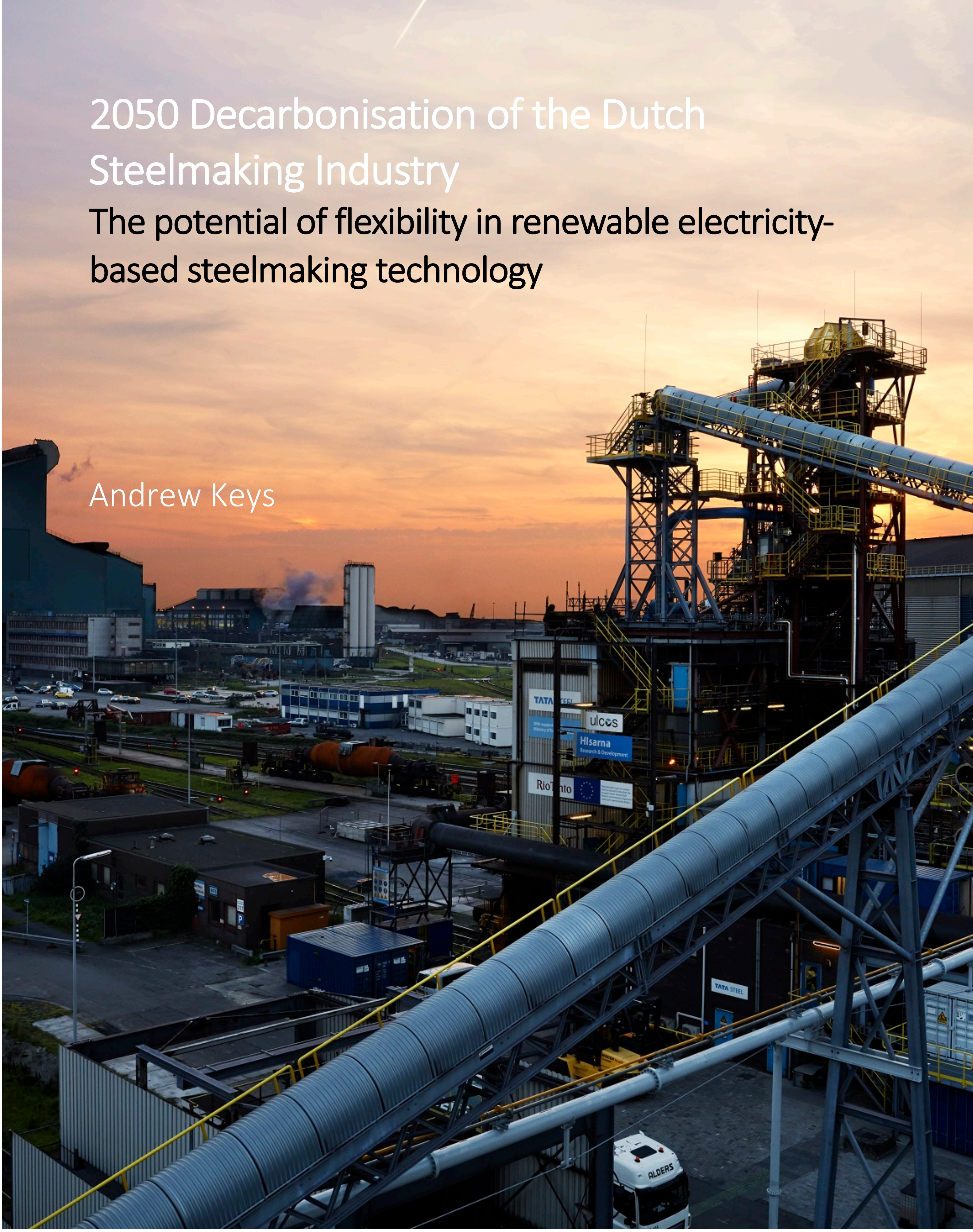
2050 Decarbonisation of the Dutch Steelmaking Industry

The potential of flexibility in renewable electricity-based steelmaking technology

Andrew Keys



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2050 DECARBONISATION OF THE DUTCH STEELMAKING INDUSTRY: THE POTENTIAL OF FLEXIBILITY IN RENEWABLE ELECTRICITY-BASED STEELMAKING TECHNOLOGY

A thesis submitted to the Delft University of Technology in partial fulfilment
of the requirements for the degree of

Master of Science in Sustainable Energy Technology

by

Andrew Keys

October 2019

Andrew Keys: *2050 Decarbonisation of the Dutch steelmaking industry: The potential of flexibility in renewable electricity-based steelmaking technology* (2019)

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PREFACE

This thesis has been carried out as part of the masters degree of Sustainable Energy Technology at Delft University of Technology. The thesis research has stemmed from my involvement in the MIDDEN project, a joint initiative between the Netherlands Environmental Agency (PBL) and the Energy Research Centre of the Netherlands (ECN part of TNO). My work on the MIDDEN project involved a full-time six month internship within the Department of Climate, Air and Energy at PBL. The MIDDEN project serves to create a dynamic knowledge base for decarbonisation options in Dutch industry that can be shared and recognised by all relevant stakeholders. The purpose of which is to provide up-to-date relevant information to aid further research and decision-making that can benefit the Netherlands as a whole. My thesis research builds upon the work I carried out for the MIDDEN project, gaining deeper insights to the role and opportunities of electrification in the steelmaking industry.

I would like to take this opportunity to thank those who have helped me through this research and complete the final stage of my life in education. Firstly, I would like to thank my supervisors at PBL, Marit and Bert, for their persistent support and help beyond what is required of them. My support at PBL is equally owed to my colleagues; Carina, Marco, Vincent, Ioannis and Yasmin, with whom many great memories were shared and still continue to be shared. I would also like to thank my TU Delft supervisors, Andrea and Wiebren, for their invaluable advice from the academic viewpoint in which I often unintentionally veered from. Finally, I would like to thank all of my friends and family who continually put everything into perspective. I look forward to continuing my work at PBL and making an impact, no matter how small that may be.

Andrew Keys
Delft, October 2019

EXECUTIVE SUMMARY

Since the birth of industrial steelmaking in the Netherlands in 1918, the blast furnace production process has been used and is now capable of producing almost 7 Mton of crude steel annually. This level of steel production has brought significant employment and economic growth to the Netherlands, but has came at a cost to the environment. The Dutch steelmaking industry was responsible for producing 12.6 Mton of CO_2 in 2017, making it the greatest CO_2 emitting entity within Dutch industry.

The Dutch government has set an ambitious target of reducing greenhouse gases by 49% by 2030 (compared to 1990 levels) and by 95% reduction by 2050 in line with the Paris Agreement goals [37]. For industry, a CO_2 reduction target of 14.3 Mton, in addition to the existing policy of 5.1 Mton, has been set to be achieved by 2030.

This target provides the steelmaking industry with a significant responsibility to reduce their CO_2 emissions to meet these goals. Therefore, radical technological and infrastructural change must take place to replace the current coal-based blast furnace steelmaking process. Changing the status quo requires significant investment and research if steel production is to remain at today's level. This research aims to aid this transition to a more environmentally-friendly industry that can continue to provide quality products to prosper both the Netherlands and the rest of the world.

By 2050, the electricity system in the Netherlands is expected to be primarily based on renewable energy sources (RESs). The shift towards intermittent sources of electricity is expected to increase the fluctuation and uncertainty of electricity prices and this will prove to be a great challenge if an electricity-based steel production method is to be implemented in the future.

ULCOWIN is an example of an electricity-based steelmaking technology, based on the electrochemical reduction of iron oxide, often referred to as iron ore electrolysis. This technology claims to be flexible in its production rate. For a steel producer, this opens up the possibility of responding to electricity prices through ramping up and down of production to avoid peak prices and capitalise on low prices. Alongside the potential cost benefits, this may also serve to increase the integration of RESs. Hence, the overall objective is to assess how operational flexibility can potentially support the electrification of the Dutch steelmaking industry in a system with high RES penetration.

The following research questions serve to guide the objective:

1. Which are the most energy and CO_2-intensive processes in the Dutch steelmaking industry?
2. Which technologies are the most promising to decarbonise the Dutch steelmaking industry?
3. To what extent can electrification support the future decarbonisation of the Dutch steelmaking industry compared to other decarbonisation options?
4. How can operational flexibility potentially support the electrification of the Dutch steelmaking industry?

To assess the potential cost advantage of operating electricity-based steel production flexibly in the future, a 2050 scenario is used based on the Distributed Generation scenario created by ENTSO-E and ENTSOG. This scenario assumes 46%, and 35% installed capacity of wind and solar PV in the Netherlands, respectively. Alongside this scenario, two fuel and CO_2 price scenarios are inputted into the European electricity system model, COMPETES, yielding hourly electricity prices per European country[1]. The resulting electricity prices of the scenario form the basis of the flexibility assessment, in which an electrolyser system is oversized to different extents with the ability to change production level based on hourly electricity prices with the overall objective of maximising profit margin. Maximising profit margin is essentially a trade-off between achieving electricity cost savings from operating flexibly, and the increased capital cost of oversizing the system.

The main results and conclusions of the study are as follows:

- Steel production in the Netherlands is based on the blast furnace (BF) process and directly emits 7 Mton of CO_2 from the onsite steelmaking processes (primarily from the BF and coke plants), and 5.7 Mton from the combustion of works arising gases in power plants.
- There are a broad range of decarbonisation options that have the potential to significantly reduce CO_2 emissions from steelmaking by 2050. These fall into several main categories of technologies: revamped BF (coal or biomass-based), direct reduction (coal, natural gas, biomass or hydrogen-based), smelting reduction (coal- or biomass-based) and iron ore electrolysis (electricity-based). Alongside these technologies, carbon capture and storage (CCS) and carbon capture and utilisation (CCU) are also necessary additions for those options relying on fossil fuels, with some allowing for easier CO_2 capture than others.
- The decarbonisation options production costs vary significantly, namely in terms of energy costs, with those options based on electricity expected to have the highest energy costs.
- Electricity-based steel production options consequently have a significantly high electricity demand. ULCOWIN technology is estimated to require 25 TWh of electricity annually to maintain current steel production levels, 16% of the total electricity demand expected in the Netherlands in 2050. This is likely to require signification additional investment in generation and transmission capacity. However, there is also expected to be around 10 TWh of wind curtailment in 2050, thus some of this may be able to be utilised to provide low cost electricity during periods of high wind capacity.
- Under the assumption that direct electricity-based technologies do not benefit from economies of scale, operating flexibility in all cases is found to be unprofitable compared to inflexible operation. However, these results also show that if economies of scale are realised as the technology is developed further then there is potential for benefiting from implementing flexible operation. The results rely heavily on several other uncertain factors, including the $CAPEX$ and fixed $OPEX$ of the technology, and these also have a great impact on the potential benefits that operating flexibly may

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[1] More precisely, COMPETES calculates electricity prices per defined node. Most EU countries are represented by a single node, with the exception of: Denmark, which is split in two nodes since it belongs to two non-synchronous networks; Luxembourg, which is aggregated to Germany since there is generally no congestion between them. Furthermore, Balkan area (Greece, Romania, Bulgaria, Hungary, Bosnia-Herzegovina, Albania, Croatia, Slovenia, Macedonia, Montenegro and Serbia) and Baltics (Estonia, Latvia, Lithuania) are aggregated in a single node in order to reduce run times. Overall, COMPETES covers EU28 and Norway, Switzerland and Balkan countries. This will be further referred to as EU28+.

have. As time progresses closer to 2050, the value of these factors will become more clear and thus the potential benefits of operating flexibly will converge to a more accurate representation.

- Under the assumption that there is some economy of scale for the concerned technology, the Netherlands is found to benefit greater from operating flexibly than the majority of other EU countries. This is likely owed to the high penetration of offshore wind in the electricity generation mix in the Netherlands. Offshore wind typically has a higher capacity factor compared to other RESs, and thus provides longer periods of low electricity prices that can be capitalised on by ramping up steel production levels.

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ACRONYMS

BF	blast furnace
BFG	blast furnace gas
BOF	basic oxygen furnace
BOFG	basic oxygen furnace gas
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CHP	combined heat and power
COG	coke oven gas
CS	crude steel
DG	distributed generation
DRI	direct reduced iron
E-BF	experimental blast furnace
EAF	electric arc furnace
EOR	enhanced oil recovery
EV	electric vehicles
EU	European Union
H-DR	hydrogen direct reduction
HP	heat pump
HM	hot metal
HRC	hot rolled coil
LS	liquid steel
MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network
MEA	monoethanolamine
NG	natural gas
NG-DR	natural gas direct reduction
PSA	pressure swing adsorption
RES	renewable energy source
TRL	technology readiness level
TSIJ	Tata Steel IJmuiden
TGR-BF	top gas recycling blast furnace
ULCOS	ultra-low CO_2 steelmaking
vRES	variable renewable energy sources
VPSA	vapour pressure swing adsorption
WAG	works arising gas

1 INTRODUCTION

The transition to an energy system based on sustainable energy technologies, such as wind and solar power, impacts all aspects of the economy and society. The primary focus of achieving this transition thus far has focused on capitalising on the so-called lower hanging fruits — namely decarbonising the electricity sector. As the share of sustainable energy technologies in many countries is increasing, the focus on the decarbonisation of other sectors is gaining ever-increasing attention. One such sector is industry, in which steelmaking is presently one of the most polluting. This chapter serves to introduce the Dutch steelmaking industry, the role it must play to achieve national climate goals, and the research gap that this report aims to fulfil within the subject of the decarbonisation of the Dutch steelmaking industry.

1.1 RESEARCH BACKGROUND

The end of the 19^{th} century marked the start of the steel revolution in which the investment potential of producing low cost, high quality steel for buildings, railroads and transport systems was recognised [6]. Steel was at the heart of the second industrial revolution and has shaped life as we know it today.

The Dutch steelmaking industry was founded in 1918 as Koninklijke Nederlandse Hoogovens to reduce the reliance of imported steel to the Netherlands. The original steelmaking site in IJmuiden remains the site of today's only steel producer in the Netherlands, now under the management of India's Tata Steel. Since the birth of industrial steelmaking in the Netherlands, the blast furnace production process has been the dominant production method and is now capable of producing almost 7 Mton of crude steel annually [69] [68]. However, this level of steel production comes at cost to the environment with Tata Steel in the Netherlands responsible for producing 12.6 Mton of CO_2 in 2017[1], making it the greatest CO_2 emitting entity within the industry [54].

1.2 NETHERLANDS CLIMATE AGREEMENT

The current Klimaatakkoord (Climate Agreement) proposed by the Dutch government sets out their ambitious target of reducing greenhouse gases by 49% by 2030 (compared to 1990 levels) and by 95% by 2050 in line with the Paris Agreement goals [37]. For industry, a CO_2 reduction target of 14.3 Mton, in addition to the existing policy of 5.1 Mton, has been set to be achieved by 2030 [16]. This provides Tata Steel with a significant responsibility to

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[1] This includes CO_2 emissions from Vattenfall-owned power plants based primarily on derived gases from steel production.

reduce their greenhouse gas emissions to meet these goals. Thus, radical technological and infrastructural change must take place to replace or modify the current coal-based blast furnace steelmaking process.

Changing the status quo requires significant investment and research if steel production is to remain at today's level. This research project aims to aid this transition to a more environmentally-friendly industry that can continue to provide quality products to prosper both the Netherlands and the rest of the world.

1.3 ROLE OF THE MIDDEN PROJECT

For Dutch industry to achieve such ambitious targets, a great deal of collaboration between government agencies, research institutions and private companies will be required. This necessity has led to the creation an initiative known as Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN) to facilitate the collaboration between such parties. MIDDEN is joint initiative between the Netherlands Environmental Assessment Agency (PBL) and the Energy Research Centre of the Netherlands (ECN part of TNO).

The MIDDEN project serves to create a dynamic knowledge base for decarbonisation options in industry that are shared and recognised by all relevant stakeholders. The purpose of which is to provide up-to-date relevant information to aid further research and decision-making that can benefit Dutch industry as a whole. As part of this, extensive research has been carried out for the steelmaking industry in which information and data regarding both current production process and decarbonisation options were collected with the assistance of Tata Steel IJmuiden. This information has been utilised in this report to provide a solid foundation to conduct further analysis on. The collaboration directly with industry helps to gain a deeper, more realistic insight into the challenges that the industry faces and how decarbonisation can be achieved in practice.

1.4 RESEARCH GAP

There are a range of options currently being explored to decarbonise the steelmaking industry. The main options fall into or across three broad categories: (i) increased scrap steel utilisation, (ii) an alternative for carbon input (e.g. hydrogen, biomass), (iii) alternative for carbon output (carbon capture and storage/utilisation), or a combination of these [50]. There is relatively extensive literature on the possible low-carbon steelmaking technologies within these categories. The most advanced and relevant research program in the context of the Netherlands is within the ultra-low CO_2 steelmaking (ULCOS) program supported by 48 partners including the European Union (EU), research institutions and steelmaking companies. The program aims to develop breakthrough steelmaking technologies that can achieve CO_2 reductions of 50% or greater [8].

Several of the options being developed by the ULCOS program are based either directly on electricity or indirectly through the production of green hydrogen[2]. These options have the potential to produce zero-emission steel, but would require a significant quantity of electricity to operate, posing both physical and economic challenges.

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[2] Green hydrogen refers to hydrogen produced by electrolysis powered by renewable energy sources RESs.

Electricity-based technologies are quoted in literature to have the potential to operate flexibly [49], however, no research can be found to explore how much potential there could be. Operating flexibly can potentially increase the profitability of such a system is by ramping-up and -down production in response to electricity prices, to avoid peak prices and capitalise on low prices. An example of direct electricity-based steelmaking technology is by iron ore electrolysis. Direct electrolysis-based steel production is still in a premature phase of development, however the design of one such technology, ULCOWIN[3], claims to be flexible in production rate [49]. The ability to operate flexibly may support the electrification of the Dutch steelmaking industry if flexibility can help reduce costs of operation and thus become more competitive with other steelmaking technologies with less CO_2 reduction potential.

Beyond potential cost savings, flexibility may also potentially serve to increase the integration of RESs, lower the cost of network capacity investments and thus benefit society as a whole. Hence, this research serves to investigate the potential benefits that electricity-based steelmaking technologies may be able to capitalise on, that is not possible in other low-carbon steelmaking technologies which are not directly based on electricity.

1.5 OBJECTIVE AND RESEARCH QUESTIONS

The main objective of this research is to assess how operational flexibility can potentially support the electrification of the Dutch steelmaking industry. A number of research questions are answered to help fulfil this objective. Firstly, the current situation of the steelmaking industry in the Netherlands is described to identify the most energy and CO_2-intensive processes. This allows for the identification of so-called "hot-spots" that need to be prioritised for decarbonisation.

Following from this, a literature review of the most promising decarbonisation options are presented with the associated energy and CO_2 flows. This part is aligned to the aim of the MIDDEN project, as described in Section 1.3. The decarbonisation options are compared to assess how the energy requirements and CO_2 reduction potential of electrification-based options differ from the other options. Alongside this, the energy costs are compared using both historic prices and future prices in 2030 and 2050, when the energy system is expected to have greater RES penetration.

The fluctuating, uncontrollable nature of RESs yields uncertain consequences for future electricity prices, and so the ability to operate an electricity-intensive system flexibly may help reduce such uncertainty in energy costs for a steel producer if steel production is to move from a broadly global energy source (coal) to more localised sources (RESs). Hence, the potential cost benefit of operational flexibility to aid in the electrification of the Dutch steelmaking industry is assessed based on two 2050 scenarios of the EU electricity system. The main objective is thus attempted to be fulfilled following four chronological research questions:

1. Which are the most energy and CO_2-intensive processes in the Dutch steelmaking industry?

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[3] ULCOWIN technology is now being developed further under the name ΣIDERWIN, however, most literature still makes refers to this as ULCOWIN and thus this report will also do so for consistency.

2. Which technologies are the most promising to decarbonise the Dutch steelmaking industry?
3. To what extent can electrification support the future decarbonisation of the Dutch steelmaking industry compared to other decarbonisation options?
4. How can operational flexibility potentially support the electrification of the Dutch steelmaking industry?

2 | METHODOLOGY

To answer the research questions, a pragmatic step-by-step approach is followed involving both qualitative and quantitative analysis. The MIDDEN project acts as a strong starting point in which the current situation of the Dutch steelmaking industry is clearly mapped out. This forms a realistic starting point in which further analysis can build upon to yield meaningful results specifically to the Netherlands. This is achieved through the collaboration with experts in the field, carrying out a thorough literature review and collecting and cross-checking data from a range of sources. The methodology by which the overall objective of assessing how operational flexibility can potentially support the electrification of the Dutch steelmaking industry is presented in this chapter.

2.1 RESEARCH FRAMEWORK

The methodology applied to this report follows a research framework chronologically comprising of a literature study, empirical research, model design, results analysis and finally conclusions and recommendations. This framework provides a structure in which findings in one part are implemented in consecutive parts to achieve the overall objective.

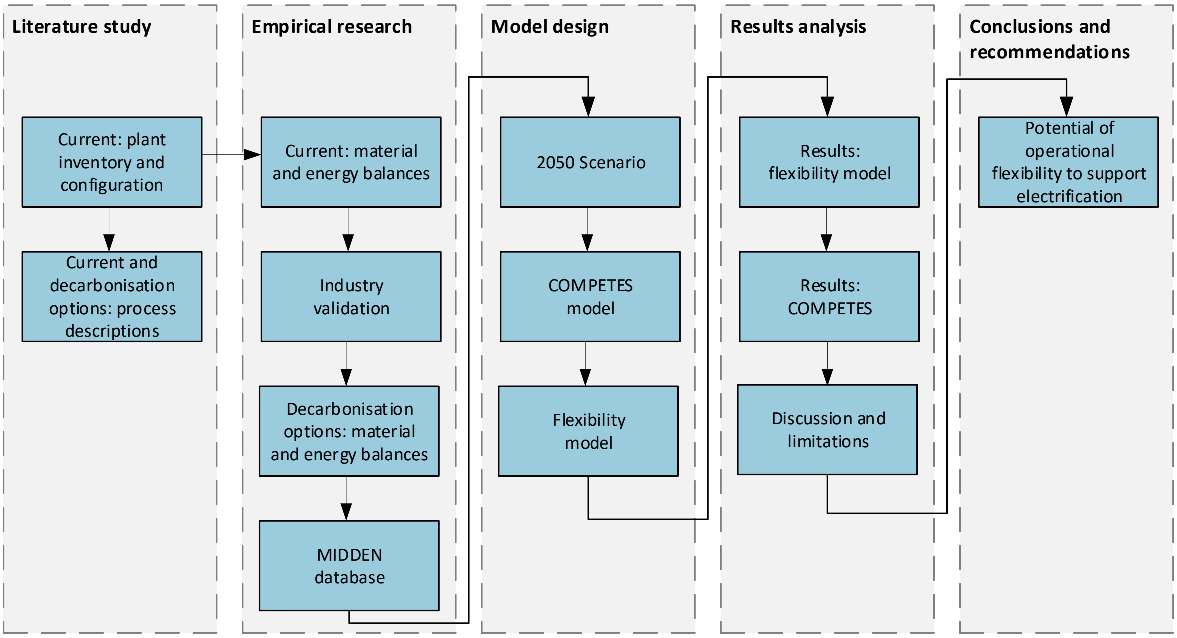

Figure 2.1: Research framework schematic

Chapter 3 provides a literature review of the current steelmaking process in the Netherlands as well as empirical results of the material and energy balances that exist. Chapter 4 provides a literature review of decarbonisation options and empirical results of the respective material and energy balances. This allows for a comparison of electrification options as compared to other decarbonisation options. Chapter 5 implements a 2050 energy system scenario into the COMPETES model to produce projections of hourly electricity prices in 2050. A model simulating flexibility in electricity-based steelmaking is then conducted using the results of COMPETES. These results are then analysed alongside additional outputs (electricity system characteristics) from the COMPETES model. Chapter 6 discusses the results and limitations. Finally, Chapter 7 draws conclusions and recommendations of the results.

2.2 EMPIRICAL RESEARCH

The empirical nature of this report comes primarily in the form of material and energy balances, capital and operating costs and CO_2 emissions. These are supported by expert judgements and validation.

2.2.1 Material and energy balances

Material and energy balances are fundamental methods to form a basis for analysing a process or entire industry. They are based on the law of mass and energy conservation, respectively, and help understand both inputs, intermediate processes and outputs. For the steelmaking industry, generic material and energy balances are widely available in literature. Instead, this report attempts to formulate material and energy balances that are specific to the Netherlands. Looking at the generic data, and gradually moving towards a complete, an accurate representation of the Dutch steelmaking industry is made based on nationally available data and expert validation. Material and energy balances of decarbonisation options are then based upon the current situation in which some processes remain the same and data in literature is used for newer technologies.

2.2.2 CO_2 emission calculation

The material and energy flows allow for the calculation of the associated CO_2 emissions per process. The emission calculations are based on the mass balance approach. The basis of this approach involves measuring the carbon entering and exiting each process and assumes the difference in values is owed to the release of CO_2. The carbon entering and exiting each process is determined using generic national emission factors found in [17]. The aggregated emissions are then validated by comparison with the overall reported CO_2 emissions for the steelmaking industry, stated in [54].

2.2.3 Expert guidance and industry validation

Throughout the period of research, a combination of expert guidance and validation from industry have helped to improve research through opening new insights and data validation. Expert review comes in the form of industry experts in PBL and ECN part of TNO who are involved in the MIDDEN project. Industry validation took place through a series of meetings and emails with senior staff at Tata Steel IJmuiden alongside several seminars.

2.2.4 MIDDEN database

The empirical research is compiled to comply with the MIDDEN database. The MIDDEN database serves to provide detailed data of the majority of Dutch industry for both the current situation and for potential decarbonisation options. The database consists of four main data sets, as follows:

1. **General plant data**: plant name, address, electricity, gas and heat requirements.
2. **Plant configuration data**: process-specific technology, capacity and capacity utilisation.
3. **Technology characteristics**: main inputs and outputs per process, capital and operating costs and CO_2 emissions.
4. **Commodity data**: main commodities market price.

2.3 MODEL DESIGN

To assess if operational flexibility can potentially support electrification in the future, the impact of implementing operational flexibility must be compared to a base case of inflexible operation. To assess such a situation, assumptions about both the technology in question as well as the future energy scenario must first be formulated. Based on the formulated scenario, a model of the EU28+ electricity market, COMPETES, determines hourly electricity prices in 2050. These prices enable an assessment to be made that compares the profitability of an inflexible electricity-based steelmaking system compared to a flexible system. A flexible system is defined as a system that is oversized and able to operate flexibly in response to electricity prices to avoid peak prices and capitalise on low prices when there is a high penetration of RESs. There is essentially a trade-off between electricity cost savings from operating flexibly and increased capital costs from having an oversized system. This assessment attempts to find the most optimal point in this trade off for the Netherlands as well as comparing results with other EU28+ countries.

2.3.1 2050 Scenario

To assess the potential of flexibility of electricity-based steelmaking in an electricity system heavily based on RESs, the year 2050 has been selected. By this year it is anticipated that RESs will account for the greatest electricity generation source in the Netherlands, namely from wind and solar energy. Another important decision factor is that the technology to be simulated, electricity-based steelmaking, is still currently being developed at a laboratory scale and thus is not expected to be able to be deployed at an industrial scale until at least 2040 [28]. For the assessment, a scenario primarily based on the 2018 ENTSO-E and ENTSOG distributed generation (DG) scenario is utilised [27]. The DG scenario assumes high availability of flexibility from demand side (e.g. electric vehicless (EVs), hybrid heat pumps) and from the supply side (e.g. hydro power pumped storage), whilst also considering significant volatility due to high shares of intermittent RESs (primarily wind and solar). This scenario provides data for electricity demand in 2030 and 2040 the number of hybrid heat pumps (HPs) EVs per European country. Thus extrapolation until 2050 and further assumptions for the entire energy system are required to be made. These are detailed below.

Electricity demand

An estimation of the EU28+ electricity demand in 2050 is based on the linear extrapolation of the trend in electricity demand between 2030 and 2040 in the DG scenario. This scenario assumed a relative high share of flexible demand, mainly determined by hybrid HPs and EVs. ENTSO-E only provides data on the total electricity demand, the number of EVs, and the number of hybrid HPs per country, hence, additional assumptions are made to derive the flexible and inflexible share in total electricity demand. These assumptions are described in Appendix C.

Installed capacity

Installed capacity in the EU is dominated by solar (47%) followed by wind (23%). There are no new investments in coal and lignite power plants. 57.9 GW hydro pumped storage is installed in total in 2050, providing flexibility and attempting to maximise profits by arbitraging between low and high prices hours. Thus electricity is both consumed and produced. The DG scenario does not distinguish between centralised and decentralised generation. Figure 2.2 displays an overall of the breakdown of installed capacity by energy source in the EU28+.

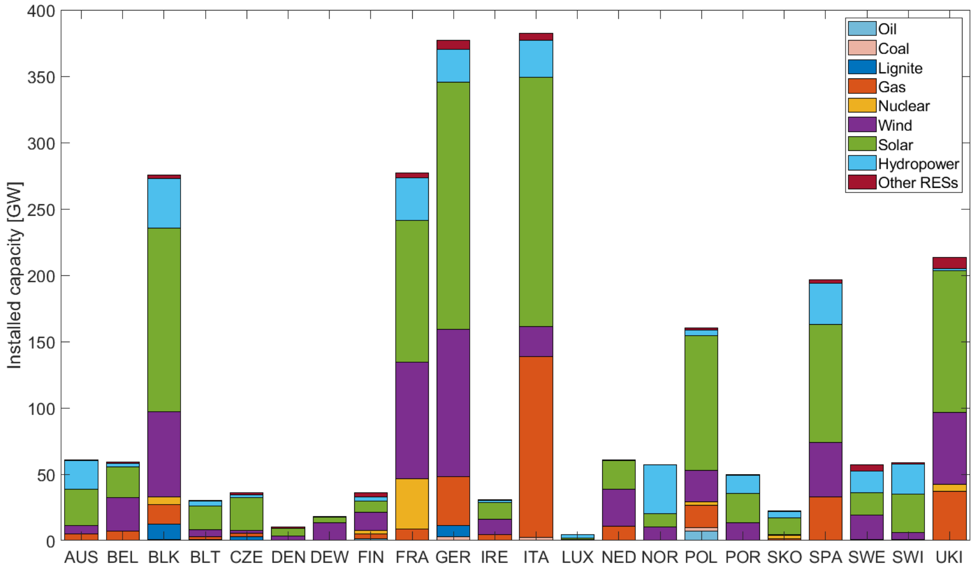

Figure 2.2: Installed capacity in the EU28+ (2050)

Transmission capacity

Consistent with [27], including more uncertain projects for 2050, such as BritNed II.

Fuel and CO2 prices

Two sets for fuel prices (WLO low & WLO high) are assumed based on [19], providing two different scenarios for the assessment.

Table 2.1: Fuel price scenarios for 2050

	Unit	WLO low	WLO high
Oil	€$_{2010}$/GJ	18.4	9
Gas	€$_{2010}$/GJ	10.0	5
Coal	€$_{2010}$/GJ	3.6	2.4
Biomass	€$_{2010}$/GJ	9.8	20
CO_2 EU ETS	€$_{2010}$/ton CO_2	37.2	149

Generation and demand profiles

The generation profile for wind, solar and electricity demand are based on the climate year of 2015. Wind and solar profiles are extracted from [26], demand and hydro pumped storage are extracted from [14] and [58].

2.3.2 COMPETES

COMPETES is a model of the EU28+ electricity market. It is a power optimisation and economic dispatch model that aims to minimise the total power system costs. The model is constrained by power generation technical limits, transmission capacities and by the expansion limits of transmission lines and generation capacity for conventional generation units. COMPETES consists of two sub-models that perform hourly simulations, each with a different purpose [33]:

1. Least cost capacity expansion and economic dispatch with perfect competition, formulated as a linear program to optimise generation and transmission capacity additions in the system.
2. Least-cost unit commitment and economic dispatch with perfect competition: formulated as a relaxed mixed integer program taking into account flexibility and minimum load constraints and start-up costs of generation technologies.

COMPETES uses input data and assumptions from all EU28+ countries, to model country-specific information of factors such as: electricity supply characteristics, flexibility assumptions (e.g. ramp rate) and electricity demand. COMPETES is capable of providing the following main outputs [61]:

- The allocation of generation and cross-border transmission capacity.
- Yearly generation mix and emissions in each country.
- Hourly competitive electricity prices per country.

- The supply of flexibility from generation, transmission, and storage.
- Investments in conventional generation.

2.3.3 Flexibility model

A model to simulate the hourly electricity demand of direct electricity-based steelmaking technology is created to allow for cost benefits of different operating conditions be compared. The model relies upon several key assumptions that must be considered when analysing the results:

1. The electrification technology is commercially available on an industrial scale by 2050.
2. The production rate is flexible and can switch between its capacity limit or seize operation in any given hour.
3. Electricity prices are not affected by the implementation of electricity-based steel production. The assessment is based on the theoretical production of 1 ton-HRC per year which will have low electricity demand. In reality this may still impact prices on an hourly basis, however, for the purpose of this study this is not considered for simplicity and interpretability of results.

Assessment parameters

A model is set-up to calculate potential cost savings of operating flexibly in electricity-based steelmaking. This is based around the principle of capitalising on low electricity prices by means of oversizing system and reduction production rate during periods of high electricity prices. The assessment is made with reference to the base case of operating at a constant production rate (constant electricity demand) to produce 1 ton-hot rolled coil (HRC). The assessment is performed at one hour intervals and hence, assuming 8760 hours of operation per year (100% availability).

Three different scenarios of flexibility (base, low and high) are simulated with the constraint of producing 1 ton-HRC per year in all cases.[1] Low flexibility assumes oversizing the capacity to 150% compared to the base case. High flexibility assumes oversizing the capacity to 200% compared to the base case. Table 2.2 displays a summary of the flexibility scenarios and assumptions for the assessment. The flexibility assessment only concerns the electrolysis part of the process and hence electricity demand of the other processes is kept constant.

Table 2.2: Flexibility scenarios and assumptions

Scenario	**Capacity (kW)**	**Minimum operating capacity (kW)**
Base	Base	Base
Low flexibility	Base × 150%	$\leq$ Base (dependant on E_{max} assumed)
High flexibility	Base × 200%	$\leq$ Base (dependant on E_{max} assumed)

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[1] A realistic production capacity, e.g. 7 Mton, would likely impact electricity prices. However, this study does not factor this in for simplicity purposes.

In order to determine when steel production should ramp up or down in response to electricity prices, the maximum electricity price in which it is still profitable for an electrolyser system to run must be determined. Production is set to ramp down to a base capacity when the marginal cost of operation exceeds the electricity price in that period, and vice versa. The operation conditions are displayed in Equation 2.1 and 2.2.

$$E \geq E_{max} \rightarrow production_{base} \tag{2.1}$$

$$E < E_{max} \rightarrow production_{overcapacity} \tag{2.2}$$

where:

E_{max} is the maximum expenditure on electricity to the point of zero profit [€/MWh]

E is the current hourly electricity price [€/MWh]

$production_{base}$ is the base load of production capacity [kWh/h]

$production_{overcapacity}$ is the upper limit of production capacity [kWh/h]

E_{max} is determined by calculating the cost of electricity at the point in which steel production is just at the point of being profitable ($Profit = 0$). This takes into account the anticipated selling price of steel, CAPEX and OPEX (non-electricity related) in 2050, as shown in Equation 2.3 and 2.4. E_{max} can be converted from [€/MWh] to [€/ton-HRC] based on the electricity demand per ton-HRC of the technology.

$$Profit = Sales - CAPEX - OPEX - E_{total} \tag{2.3}$$

$E_{total} = E_{max}$ when $Profit = 0$. This results in:

$$E_{max} = Sales - CAPEX - OPEX \tag{2.4}$$

where:

$Profit$ is the profit achieved by the steel producer [€/ton-HRC]

$Sales$ is the sales price of HRC in Europe [€/ton-HRC]

$CAPEX$ is the capital expenditure [€/ton-HRC]

$OPEX$ is the non-electricity related operating cost [€/ton-HRC]

E_{total} is total cost of electricity [€/ton-HRC]

The price of steel in fluctuates on a daily basis. The future price of steel is highly dependent on future demand and production methods, both of which are very uncertain, meaning that the price of steel in 2050 is also highly uncertain. According to [48], the primary steel demand in Europe is anticipated to decrease by approximately 25% until 2050[2]. However,

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[2] TSIJ sell steel products both inside and outside of Europe and thus future global steel prices are also relevant but these prices also experience great uncertainty as with Europe.

as steelmaking technology is changing, production costs remain uncertain as well as rising CO_2 prices, this leaves great uncertainty as to what the future price of steel will be and thus this report assumes that the price of steel will remain the same as the current level[3].

A flexible electrolyser system, that is oversized, will naturally have higher associated $CAPEX$ costs. This results in lower electricity prices being necessary to maintain a profit. This factor, alongside the intrinsic uncertainty of steel prices, $CAPEX$ and $OPEX$, lead to the necessity of performing the flexibility assessment under different E_{max} conditions to allow for the comparison of results.

Ultimately, the cost benefit or penalty of flexible operation is a trade-off between electricity cost savings and increased capital costs of having an oversized electrolyser system. The relation between plant capital cost and capacity can be linked by a capacity power law, as displayed in Equation 2.5. n is typically in the range 0.4 to 0.9 depending on the considered plant or equipment [53]. However, according to [18], an electricity-based steelmaking via electrolysis is anticipated to not benefit economically from scaling up capacity, i.e. n is close to 1. Due to the premature technological development, this value still holds great uncertainty. Hence, to determine the $CAPEX$ of oversized systems in the assessment, three n values are used for comparison: 0.5, 0.75 and 1.

$$CAPEX_2 = CAPEX_1 \times \left(\frac{Q_2}{Q_1}\right)^n \tag{2.5}$$

where:

$CAPEX_1$ = base cost [€]

$CAPEX_2$ = scaled up cost [€]

Q_1 = base plant capacity [MW]

Q_2 = scaled up plant capacity [MW]

n = capacity cost factor [-]

Given the above-mentioned parameters, a comparison of scenarios based on profit margin is conducted based on electricity prices in the Netherlands. These results are then compared to the same assessment in other EU28+ countries to compare the profitability of such scenarios and aid in explaining the differences in results.

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[3] The consequences of this assumptions will be discussed further in Chapter 6.

3 CURRENT STEELMAKING PROCESS

This chapter provides an overview of the steel production process used in the Dutch steelmaking industry. This begins with qualitative descriptions of the main process steps, describing how they work and how they operate in tandem with each other to create an integrated steelmaking site. Following on from this, material and energy balances are presented for the main processes to find where the most energy-intensive processes are located. This also serves to show the interconnectivity of steel production, in which material and energy flows are often distributed and recycled extensively. Finally, based on the material and energy flows, the associated CO_2 emissions are calculated using the mass balance approach to find the most CO_2-intensive steps of the process. Overall, this chapter serves to answer the first research question, as follows:

> *Which are the most energy and CO_2-intensive processes in the Dutch steelmaking industry?*

3.1 PROCESS DESCRIPTION

There are two main steel production routes used today: (i) Blast Furnace (BF) process and (ii) Electric Arc Furnace (EAF) process. Globally the former accounts for approximately 70% of steel production. The latter, based on secondary materials such as steel scrap, accounts for 30% [74]. TSIJ produces steel via the BF process. Iron ore and coal are the main raw materials, the majority of which are further processed into sinter and pellets (from iron ore) and coke (from coal) before entering the BF. Pig iron is tapped from the BF and is further processed into crude steel via the basic oxygen furnace (BOF) process in which the carbon content is lowered by oxygen blowing. The BOF typically facilitates 16% of scrap steel to increase recycling rates. The level of scrap steel varies with time, depending on price and availability of scrap of sufficiently good quality. The crude steel product leaving the BOF is then processed further into rolls and sheets. However, the processing stages after the crude steel product are outside of the scope of this report. Presented below is the plant inventory within the scope of this research (Table 3.1) and basic descriptions of the these processes, primarily on [21], [24] and [35].

Table 3.1: Inventory of process plants within the scope of research

Inventory	Quantity	Notes
Coke plant	2	-
Pellet plant	1	-
Sinter plant	1	-
Blast furnace	2	-
Basic oxygen furnace	1	-
Oxygen plant	1	(3rd party owned)
Power generation	4	(3 of which are 3rd party owned)

3.1.1 Coke production

Coke (and coke breeze) is a carbon-containing solid material produced in a coke oven by batch pyrolysis of coking coal. The reaction takes place at temperatures above 1000 °C and each batch lasts approximately 16-20 hours. The coke is then cooled by the addition of water before it can be utilised. The main by-product of this process is coke oven gas (COG), which has a typical volumetric composition of H_2 = 57.3%, CH_4 = 23.7%, CO = 6.6%, CO_2 = 2.6%, N_2 = 7.2% and other hydrocarbons = 2.4% [7]. Part of the COG is recycled and combusted to provide heat to the oven, whilst the remainder of the COG is combusted to heat the BF, for electrical power generation and in the downstream steelmaking processes. Raw coke contains valuable by-products including tar, sulfur components, ammonia and light oil (BTX) that are further processed and sold. TSIJ has two coking plants with a coke oven firing system and a process gas treatment unit to recover the emitted COG. The overall thermal efficiency of the coke oven system is approximately 80%. The coking plant is one the most energy intensive parts of the steelmaking process, hence, TSIJ is continually trying to increase the direct intake of pulverized coal into the BF to reduce the coke requirements. Currently, TSIJ produces more coke than it requires, with the excess being sold to third-parties.

3.1.2 Sinter and pellet production

Iron ore occurs naturally as lump ore and fine ore. BFs are not capable of solely using fine ore as the feedstock and so agglomeration of fine ore is necessary. Lump ore may be possible to use solely, however is scarcer and more expensive than producing sinter and pellets from fine ore. The sintering process consists of heating up fine ore, alongside additives such as limestone, causing it to agglomerate into larger aggregates with a porous structure. A porous structure is important as the blast furnace is a counter-flow reactor and so gases must be able to pass through the iron ore material [21]. In the pelletising process, the fine ore is mixed with additives, such as limestone and olivine, in a wet condition and pellets are formed with a binder and subsequently baked [35]. Sinter and pellets are used in the BF, alongside a small proportion of lump ore in some modern BFs, such as at TSIJ.

3.1.3 Blast furnace

The BF is used to reduce (remove oxygen) iron ore to produce a hot liquid pig iron with a carbon content of 4% [3]. Coke, sinter and pellets are the primary components fed into the top of the furnace and hot oxygen enriched air and pulverised coal are blasted from the bottom through the porous structures (tuyeres). This process results in partial combustion of the carbon from coke and coal, producing reducing gases (containing carbon monoxide) that heat the furnace resulting in liquid pig iron which is subsequently tapped off at the bottom and transported to the BOF. The ideal chemical equation of such reducing reaction from haematite (a commonly used iron ore) is presented in Equation 3.1 [35].

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \tag{3.1}$$

Slag is also produced as a by-product and tapped off separately at the bottom of the furnace to be sold on to other industries such as cement and asphalt. Excess reducing gases are used for power generation and recycled for heat generation or for other processes. A basic schematic of the input and outputs are displayed in Figure 3.1 [32].

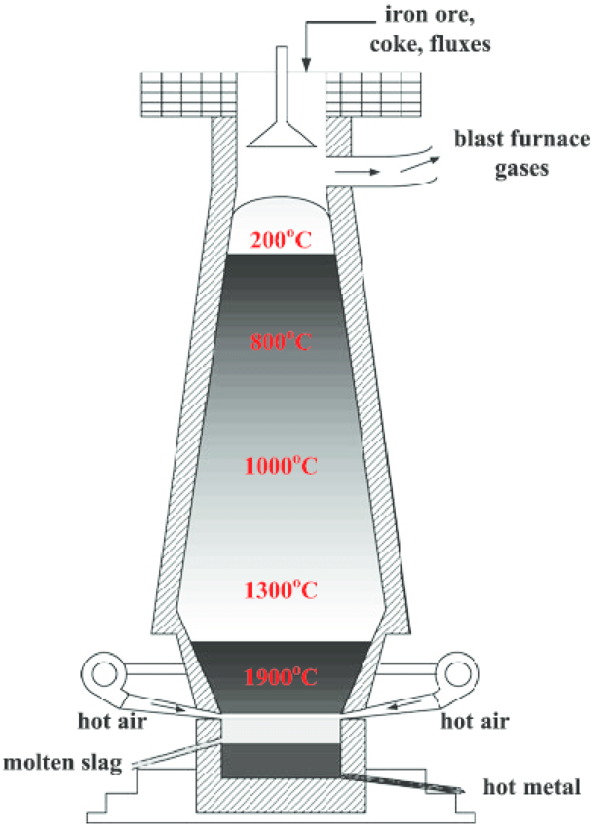

Figure 3.1: Basic schematic of the blast furnace material flow and temperatures

3.1.4 Basic oxygen furnace

The primary reaction in the BOF is the oxidation of carbon in the pig iron by the injection of oxygen. The degree of oxidation of carbon is varied depending on the desired steel product specification. The overall process is exothermic and hence the excess energy allows the possibility of increased levels of scrap steel to be added in the furnace. Scrap steel is also commonly inputted alongside pig iron in the BOF with the purpose of temperature control and to reduce the amount of pig iron required to produce crude steel. Slag is produced as a by-product from the oxidation of impurities such as silicon, manganese, phosphorus and sulphur.

3.1.5 Oxygen production

Oxygen is produced from air by a cryogenic separation unit owned and operated by Linde. Oxygen is required in both the BF and BOF, but at slightly different purities. The BF typically requires an oxygen purity of greater than 95vol% primarily for oxygen enrichment of the hot air blast. The BOF requires an oxygen purity of greater than 99.5vol% for the main process of blowing into the furnace. A higher nitrogen content may adversely affect the steel quality.

3.2 MATERIAL, ENERGY AND CO2 FLOWS

To gain a good understanding of the current steelmaking process, material and energy flows are calculated to match the current situation as closely as possible. This has been achieved by a combination of data provided by TSIJ and publicly available data. Material, energy and CO_2 flows differ somewhat each year. The presence of multiple sources to formulate these flows have left some ambiguity due to different reporting years. Thus, an attempt has been made to scale energy quantities to match the overall energy balance reported for the iron & steel industry in the Netherlands for 2017, as reported in [13]. The overall energy balance separates iron & steel production (including downstream steelmaking processes) and coke production and is displayed in Table 3.2 and 3.3, respectively.

Table 3.2: Energy balance of iron & steel production in the Netherlands for 2017

Label	NG	Cokes	COG	Electricity	Oil	BFG	Coal	Heat
Total Primary Energy Supply	11.4	55.2	8.3	8.8	0.2	-24.9	47	0
Receipts of energy	11.7	57.9	10	11.6	0.2	0	48.1	0
Deliveries of energy	0.3	5	1.7	2.8	0	24.9	0	0
Final energy consumption	10	0.1	7.9	9.3	0.2	10	0	2.8
Electricity and CHP transformation input	1.3	0	0.4	0	0	2.1	0	0
Other transformation input	0	55.1	0	0	0	0	47	0
Net electricity/ CHP transformation	1.3	0	0.4	-0.5	0	2.1	0	-2.8
Net other transformation	0	55.1	0	0	0	-37	47	0
Electricity/CHP transformation output	0	0	0	0.6	0	0	0	2.8
Other transformation output	0	0	0	0	0	37	0	0
Total energy consumption	11.4	55.2	8.3	8.8	0.2	-24.9	47	0
Stock change	0	2.3	0	0	0	0	-1.1	0

Table 3.3: Energy balance of coke production in the Netherlands for 2017

Label	Cokes	COG	Electricity	BFG	Coal
Total Primary Energy Supply	-59	-10	0.3	1.8	78.8
Receipts of energy	0	0	0.3	1.8	83.6
Deliveries of energy	59	10	0	0	0
Energy sector own use	0	5.9	0.3	1.8	0
Other transformation input	0	0	0	0	78.8
Total net energy transformation	-59	-15.9	0	0	78.8
Other transformation output	59	15.9	0	0	0
Total energy consumption	-59	-10	0.3	1.8	78.8
Stock change	0	0	0	0	-4.8

Figure 3.2 and 3.3 display an overview of the material and energy flows respectively for each individual process, including the works arising gass (WAGs) based power generation units. The figure identifies the source from which the value has been derived. Streams that required assumptions to balance the material and energy flows are detailed in A.

Power generation from WAGs is a significant part of the steelmaking processes in terms of electricity generation and subsequent CO_2 emissions. There are four main power generation units at TSIJ: Velsen 24, Velsen 25, IJmond 1 (owned and operated by Vattenfall) and a TSIJ-owned combined heat and power (CHP) plant known as Energiebedrijf Tata for the purpose of this report. Velsen 24 is a combined cycle gas turbine (CCGT) unit that serves as a backup when the other units are out of operation or when there is an excess of acpWAG. Velsen 25 is also a CCGT unit and acts as a base load unit that can run entirely on blast furnace gas (BFG), however natural gass (NGs) is sometimes added to balance fluctuation in BFG supply to avoid significant start-up or -down periods [73]. IJmond 1 is a CHP unit and serves as a base load unit that can run entirely on BFG and produces both electricity and heat [72]. Energiebedrijf is a CHP operated by TSIJ with a mixture of basic oxygen furnace gass (BOFGs), COG and NGs inputted. Table 3.4 states the basic characteristics of these power generation units.

Steam generation and utilisation is difficult to determine and thus ranges based on [24] are used. An exception is the output of the coke plant in which an assumption is been made that coke dry quenching (with heat recovery in the form of steam) is applied and hence a single value is given.

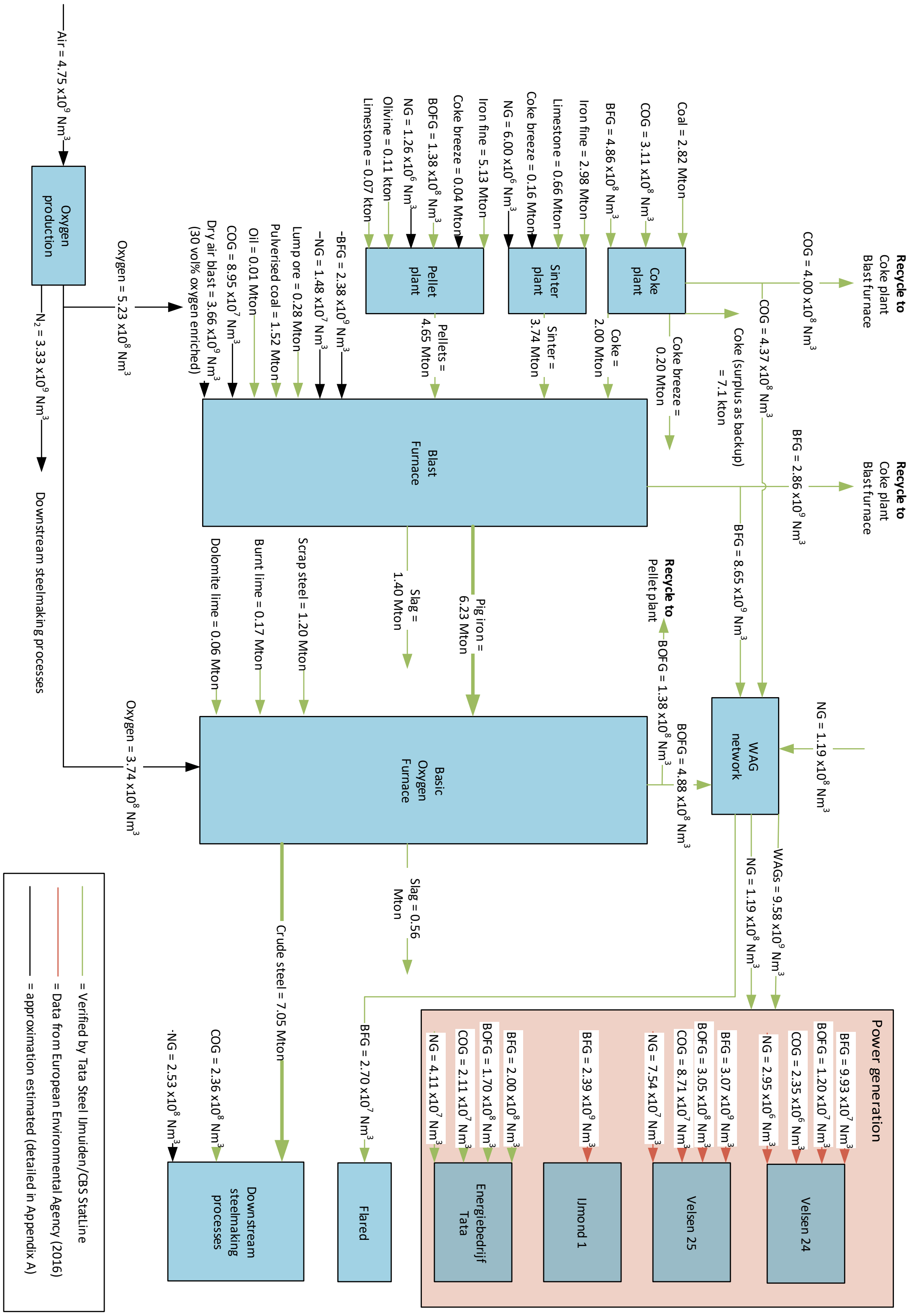

Figure 3.2: Annual material flow overview of the steelmaking process

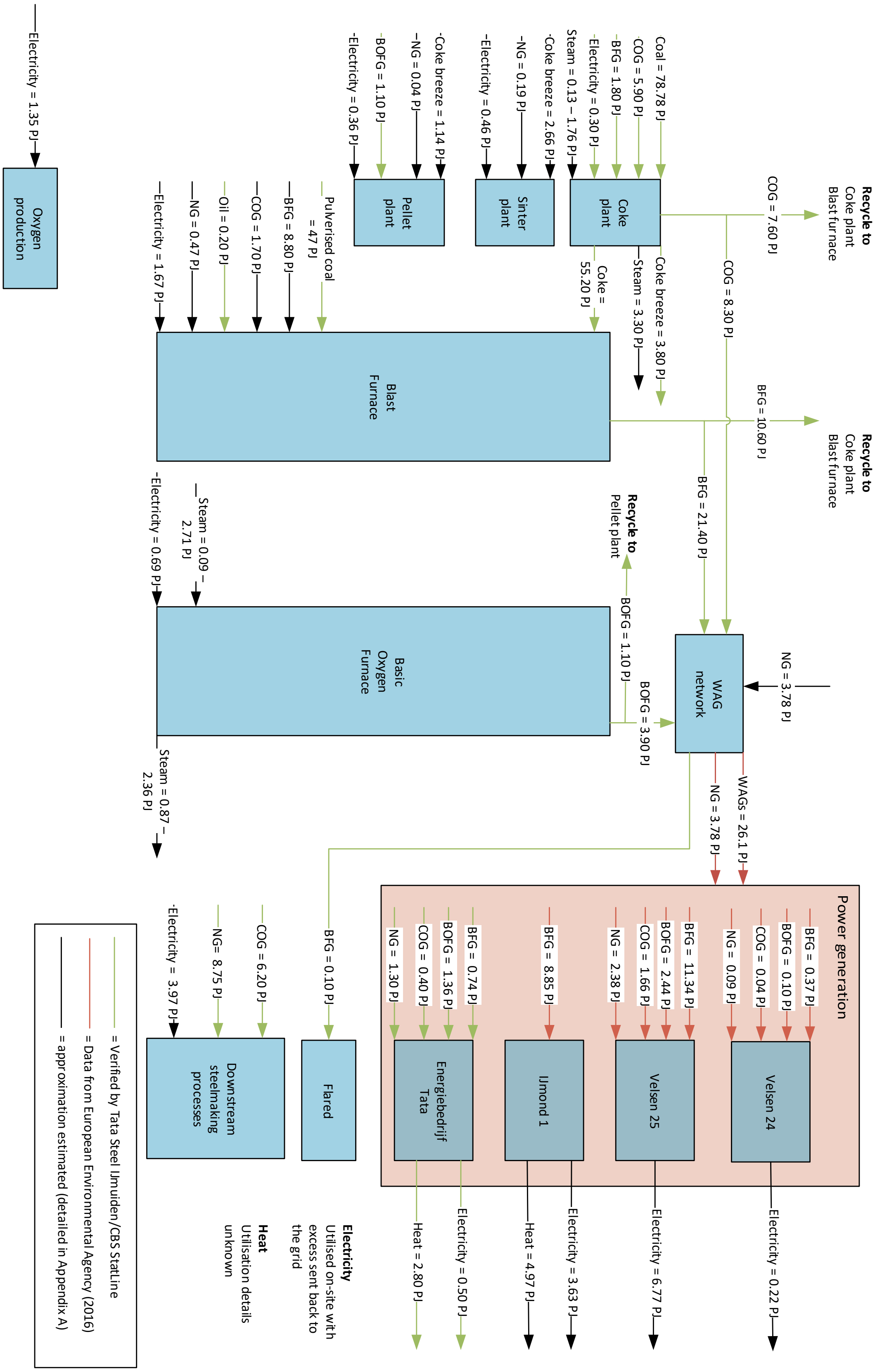

Figure 3.3: Annual energy flow overview of the steelmaking process

Table 3.4: Characteristics of power generation plants

Name	**Technology**	**Electricity capacity (MW_{el})**	**Thermal capacity (MW_{th})**	**Main fuel**	**Other fuel(s)**
Velsen 24	CCGT	460	-	BFG	BOFG, COG, NG
Velsen 25	CCGT	375	-	BFG	BOFG, COG, NG
IJmond 1	CHP	144	105	BFG	-
Energie-bedrijf Tata	CHP	17	97	-	BOFG, COG, NG

Figure 3.4 displays the total final energy consumption of the main steelmaking processes, excluding the power generation units. The blast furnace is the most energy intensive process, due to the large input of both coke and pulverised coal. The coke plant is the second-most energy intensive process with a large input of coking coal to be processed into coke for the blast furnace. Together, the blast furnace and coke plant account for 88% of the total final energy consumption.

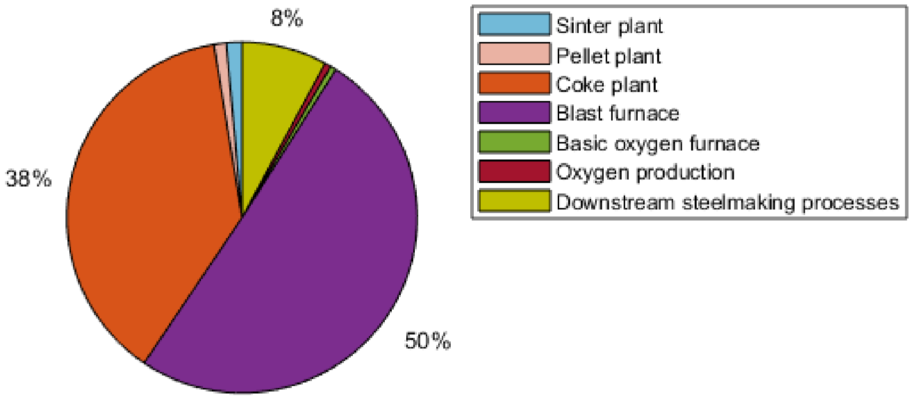

Figure 3.4: Distribution of total final energy consumption in the steelmaking process

Figure 3.5 displays the calculated direct CO_2 emissions per process, divided between those directly emitted by TSIJ and indirectly by the Vattenfall power plants[1]. The total direct CO_2 emissions and specific direct CO_2 emissions are compared to the reported value from TSIJ in 2017 [54]. The calculated values almost match what is reported, with differences likely arising from different values assumed for CO_2 emission factors, carbon content of materials and from using information based on different years other than 2017.

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[1] The excess coke produced is assumed to be stored and used in the blast furnace when needed, e.g. when the coke plant is under maintenance. Hence, its associated CO_2 emissions are calculated as if it is used directly.

It can be seen that the Vattenfall-owned power generation plants are responsible for almost half of the total steel industry's CO_2 emissions. This causes discrepancy as to who is responsible for such emissions, given that the power generation plants solely serve the works-arising gases from Tata Steel processes. This report considers both emissions directly from the steelmaking processes and indirectly through the combustion of works-arising gases to show the impact that various decarbonisation options have on each.

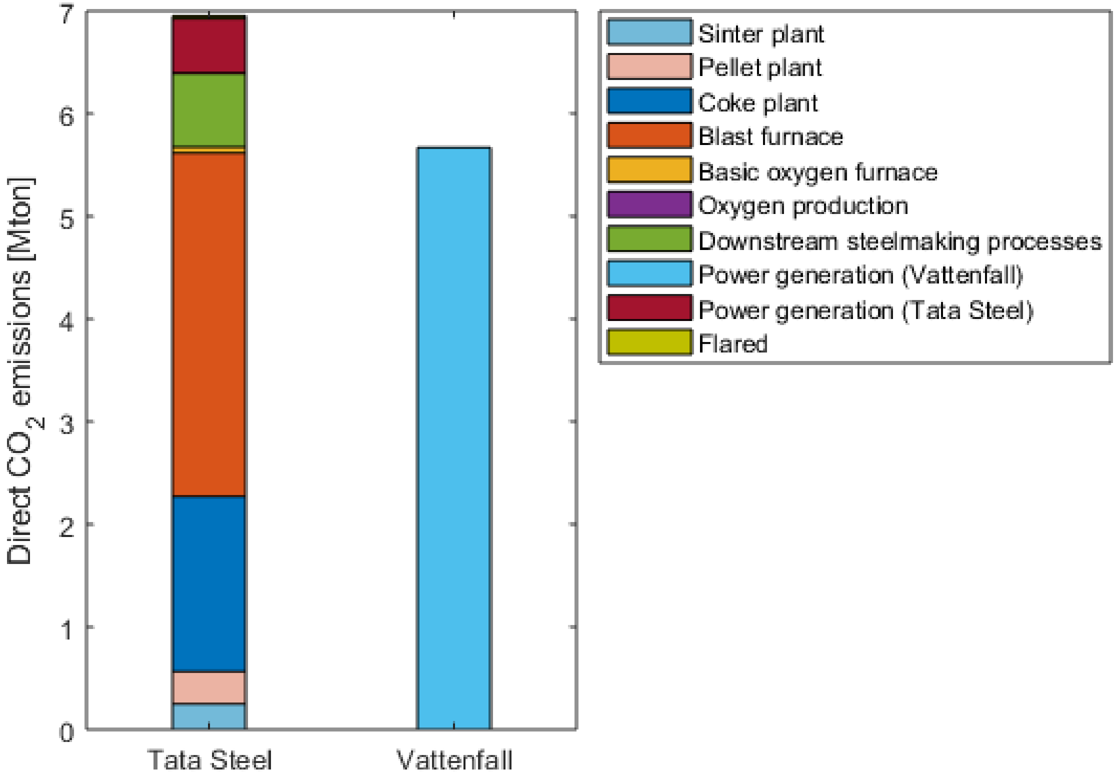

Figure 3.5: Calculated annual direct CO_2 emission distribution of steelmaking processes and power generation plants

This chapter aimed to answer the first question question, identifying the most energy and CO_2-intensive processes in the Dutch steelmaking industry. Through formulating material and energy balances and calculating the associated CO_2 emissions, this is achieved. The blast furnace and coke plants are the two most energy-intensive steelmaking processes, account for 50% and 38%, respectively, of the total final energy consumption (excluding the power generation units). Alongside this, they are also the most CO_2-intensive processes, emitting 48% and 25%, respectively, of the total CO_2 directly accountable by Tata Steel. This is primarily owed to the heavy use of coal, a more CO_2-intensive energy source than natural gas or electricity. The power generation plants, owned by Vattenfall, are responsible for almost half of the total CO_2 emissions associated overall for the Dutch steelmaking industry. The works arising gases produced by the blast furnace and coke plants are two of the main gases combusted in the power generation units. Therefore, they are also indirectly responsible for a large proportional of the overall steel industry CO_2 emissions.

4 DECARBONISATION OPTIONS

This chapter firstly presents the most promising decarbonisation options applicable to the Dutch steelmaking industry to significantly reduce CO_2 emissions. This begins by providing a description of the selected technology options and the current status of implementation. Then, material and energy balances are compiled and presented schematically. Following this, a comparison is made between options based on energy requirements, CO_2 emissions and estimations of production costs. This comparison forms a basis to evaluate to what extent electrification can support decarbonisation, as compared to the other possible options. Overall, this chapter aims to answer the second and third research questions, as follows:

> *Which technologies are the most promising to decarbonise the Dutch steelmaking industry?*
>
> *To what extent can electrification support the future decarbonisation of the Dutch steelmaking industry compared to other decarbonisation options?*

4.1 TECHNOLOGY DESCRIPTION

There are a broad range of technologies that have the potential to significantly reduce CO_2 emissions in steelmaking. Several different programmes have been established to develop these technologies, of which the main programmes are: ULCOS (EU), COURSE50 (Japan), POSCO (South Korea) and AISI (USA). From these programmes, ULCOS has the most extensive research scope [47]. The technologies being developed by these programmes all fall under the following categories and some examples are given:

- Revamped blast furnace: TGR-BF
- Direct reduction ironmaking: ULCORED, MIDREX, HYL
- Smelting reduction ironmaking: HIsarna, COREX, FINEX
- Iron ore electrolysis: ULCOWIN, ULCOLYSIS
- CCS and CCU

For simplicity, and to avoid repetition of similar technologies, only some of the possible technologies are selected for further explanation and analysis. The ULCOS programme is the most relevant for the Netherlands due to its partnership with European steelmakers, including TSIJ, with research covering all of the above-mentioned categories, namely the technologies of: TGR-BF, ULCORED, HIsarna, ULCORED, ULCOWIN and ULCOLYSIS. The ULCOS program has also identified a number of supporting technologies alongside these: H-DR steelmaking, biomass-based steelmaking and CCS. Due to these technologies covering the main technology categories as well as having the most extensive research and available data, these technologies are selected for further consideration. However, this does not go to say that other technologies are not possible or relevant.

ULCOS was set up by the European Steel Technology Platform in 2004. The aim of the program was to develop new low-carbon steelmaking technologies that have the potential to reduce CO_2 emissions per ton of steel by 50% from the 2004 best available technology level of 2 tonnes of CO_2 per tonne of steel to 1 tonne of CO_2 per tonne of steel by 2050 [47]. The first phase (ULCOS I, 2004-2010) involved theoretical research and pilot-scale testing, costed €3.5 million and received €2 million in funding. The second phase (ULCOS II, 2010-present) takes four pilot technology projects that are deemed to have the greatest potential to develop further towards industrial scale [1].

Below, a description and the current implementation progress of the following selected decarbonisation options are presented, with the option of supporting technology such as CCS, hydrogen and biomass for applicable options.

- TGR-BF
- HIsarna
- ULCORED
- Iron ore electrolysis (ULCOWIN and ULCOLYSIS)

4.1.1 TGR-BF

The TGR-BF technology involves modification of the existing BF to include top gas recycling. The reducing agents (CO and H_2) are recycled from the gas leaving the BF top after CO_2 removal. Recycling this stream reduces the demand for coke and hence reduces energy use and carbon emissions from the coking plant. TGR-BF primarily consists of the following modifications as compared to the conventional BF [64]:

- Injection of reducing top gas components CO and H_2 into the shaft and/or hearth tuyeres.
- Lower fossil-based carbon input due to lower coke rates.
- Use of pure oxygen in place of hot air blast at the hearth tuyere (elimination of nitrogen).
- Recovery of high-purity CO_2 from the top gas for underground storage.

Four versions of TGR-BF were originally tested. However, version 2 has been rejected due to a lower carbon saving than expected and challenging technology required to heat the recycle gas in two steps, by a recuperator and by partial oxidation.

The three remaining versions are described below and illustrated in Figure 4.1 [47]. The versions differ mainly with regard to the level of preheating of the CO_2-free top gas and the location of the injection of the top gas in the BF. Note: the top gas exits the furnace at a temperature of approximately 100 °C and the CO_2 removal is achieved by vapour pressure swing adsorption (VPSA) [66].

Version 1 – part of the CO_2-free top gas is recycled, preheated to 900 °C and injected into the BF through the tuyeres in the furnace stack. Another part of the CO_2-free cold top gas (25 °C), alongside oxygen and pulverized coal, are injected into the blast furnace through the tuyeres in the furnace hearth. The expected CO_2 saving from this version is 22% excluding CCS.

Version 3 – the CO_2-free top gas is preheated to 1250 °C and injected into the BF through the tuyeres in the furnace hearth. The expected CO_2 saving from this version is 24% excluding CCS.

Version 4 – part of the CO_2-free top gas is preheated to at 900 °C and injected into the BF through the tuyeres in furnace stack. Another part of the CO_2-free top gas is preheated to 1250 °C and, alongside oxygen and pulverized coal injected at into the BF through the tuyeres in the furnace hearth. The expected CO_2 saving from this version is 26% excluding CCS.

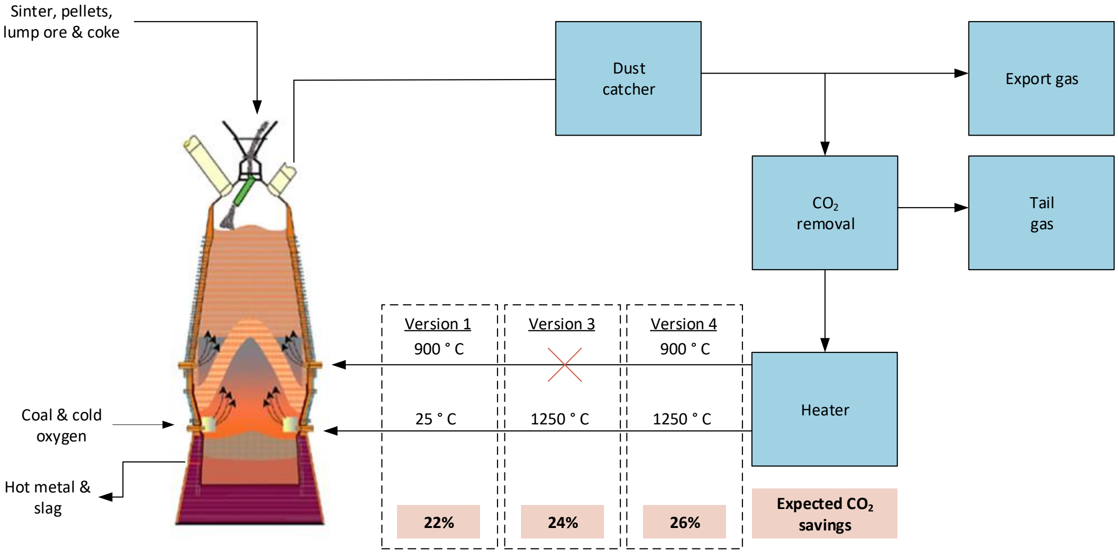

Figure 4.1: Process flow diagram of version 1, 3 and 4 TGR-BF

The operation of the three versions have been tested in 2007 on an experimental blast furnace (E-BF) in the facilities of LKAB, a Swedish iron ore manufacturer and supplier. Some additional technological additions were required to be implemented on the E-BF, this included a VPSA device to remove the CO_2 from the top gas and vertical gas injection devices at the tuyeres of the furnace stack [47].

The most notable results achieved during the tests at these facilities are as follows [47]:

- On average, for the three versions, the carbon input decreased from 470 kg/ton-hot metal (HM) to 350 kg/ton-HM.
- The top gas recovery rate of version 3 can reach 72% , with carbon consumption reduced by 15%. The top gas recovery rate of version 4 can reach 90%, with carbon consumption reduced by 24%. As more CO and H_2 is injected, the reduction rate of iron ore increases and hence the consumption of coal and coke is reduced. The consumption of coal and coke is reduced at a rate of 17 kg for every additional cubic meter of CO and H_2.
- VPSA unit operated stably, processing 97% of the recycled top gas in the blast furnace. The injected gas contained, on average, 2.67vol% of CO_2 with a CO recovery rate of 88%, thus achieving the required composition and quantity for the process.

- In conjunction with CCS units, the quantity of CO_2 is proved to be able to be reduced by 1270 kg/ton-HM with TGR-BF. This is 76% of the total CO_2 emissions in the ironmaking process. However, the version in which this result is achieved is not explicitly stated.

In conclusion, the test results validated the operation, safety, efficiency and stability of the TGR-BF. Version 4 proved to have the greatest emissions reduction potential and hence is the priority of the next round of testing with an industrial-scale BF. TGR-BFalso has the potential to substitute coal with a source of biomass for further emission reduction, although tests have not been carried out for this.

4.1.2 HIsarna

A conventional BF requires the pre-processing of raw materials; iron ore into sinter and pellets and coal into coke. HIsarna is based on a smelting reduction process, eliminating the pre-processing steps by allowing the raw materials to be injected directly into a reactor as powders. Throughout the HIsarna reactor, the temperature is above the melting point of iron, allowing iron ore to instantly melt and subsequently converted into liquid iron. At the top of the reactor (CCF cyclone), the temperature is increased further by the addition of oxygen to react with carbon monoxide present. The cyclone part of the reactor creates a turbulent environment that allows greater contact time for the hot gas to enter at the top and partially reduce and melt the iron ore. The degree of partial reduction in the cyclone is typically in the range of 10-20% [47].

The molten iron ore then falls to the bottom of the vessel (smelter) and comes into contact with powder coal which is injected at a high speed in the bottom after being decomposed and preheated in a coal decomposition furnace. The reaction of carbon from the powder coal with the melted iron ore creates liquid iron. The temperature in the smelter is around 1400-1450 °C with 4vol% dissolved carbon [47].

The partly combusted gas leaving the smelter is then internally circulated to provide hot fuel gas to the cyclone. The pure liquid iron is then tapped off at the bottom for further processing. A simplified schematic of this process (with CCS) is displayed in Figure 4.2 [47].

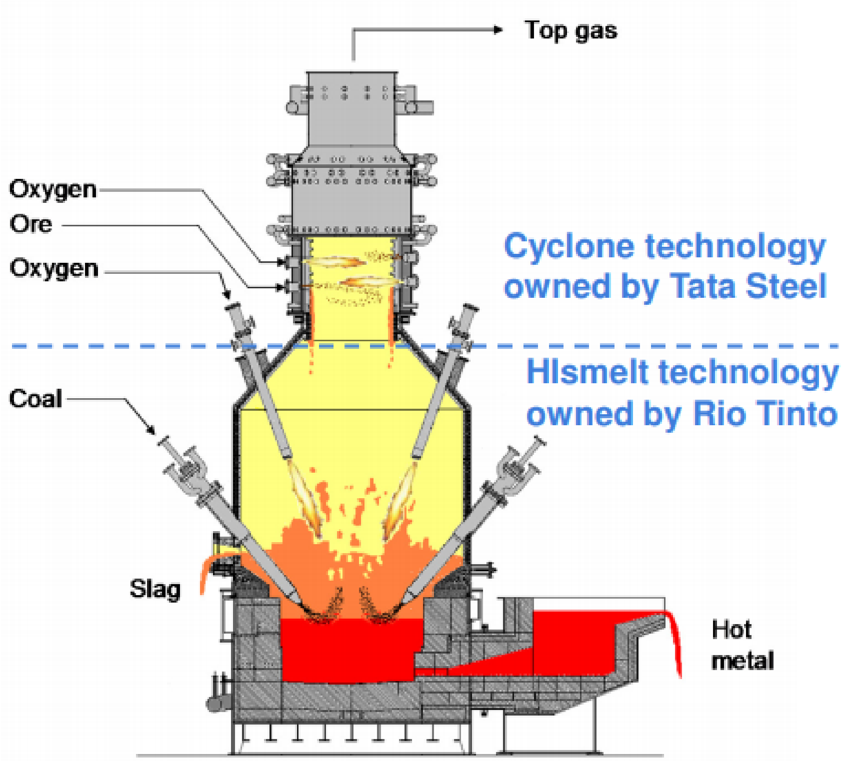

Figure 4.2: Simplified schematic of the HIsarna process with CCS

If implemented on an industrial scale, HIsarna is claimed to produce at least 20% lower CO_2 emissions and use at least 20% less energy compared to conventional steelmaking process. It is also ideally suited for CCS due to the absence of nitrogen in the gases, the compressibility of the gas due to sufficient CO_2 content and the once-through gas flow nature. Taking into account CCS, up to 80% CO_2 reduction can be achieved compared to the conventional steelmaking process. Asides from energy and carbon savings, and hence cost reduction, HIsarna can eliminate 90% of the process phosphorous to slag. This allows the use of cheaper, high-phosphorous iron ore which would not normally be accepted in the conventional process.

A HIsarna pilot plant has been successfully designed and developed at TSIJ since 2011. The project has been jointly developed by Tata Steel and the mining company Rio Tinto. Further testing and development is being undertaken alongside additional partners: ArcelorMittal, ThyssenKrupp, Voestalpine and technology supplier Paul Wurth. In addition to the partner companies, the EU has provided significant funding for the plant and in October 2017, a six-month test campaign was carried out proving that liquid steel can be produced for high running hours. It is estimated that this campaign costed approximately €25 million. Following the success of this campaign, the next stage is intended to design, construct and test a larger-scale pilot plant with an estimated investment of €300 million. It is anticipated that this will have to go through several years of testing 2 to 3 times the size of the current pilot plant at TSIJ with a production capacity up to 10 times greater [67]. In November 2018, it was announced that the new large-scale pilot plant will be built in Jamshedpur, India. The plant is planned to initially produce 400 kton-HM/year with a scale up to 1 Mton-HM/year eventually. The new plant does not signal the closure of the current pilot plant at IJmuiden, which is currently producing 60 kton-HM/year [59].

4.1.3 ULCORED

ULCORED directly reduces of iron ore using reducing gases from coal, natural gas, biomass or hydrogen to produce direct reduced iron (DRI). The main features of ULCORED compared to other direct reduction-based technologies are as follows [63]:

- The use of pure oxygen in the shaft furnace produces a flue gas with no or low nitrogen content, making CO_2 capture easier.
- Reduced natural gas requirements due to the recycle of the flue gas after CO removal to act as a reducing agent.
- Possibility to use alternatives to natural gas: coal, biomass and hydrogen.

A schematic illustration of natural gas-based ULCORED is displayed in Figure 4.3 [62]. With hydrogen as the reducing agent, the only by-product in the shaft furnace is water. This means that zero CO_2 emissions are produced in the ironmaking stage, with the overall emissions being entirely associated with hydrogen-production, pellet plant, EAF and downstream steelmaking processes. The use of hydrogen in the ULCORED process is currently researched to a lesser extent than that of natural gas or coal and thus there is still a lack of knowledge on its potential. A schematic illustration of hydrogen direct reduction, not specific to ULCORED, is displayed in Figure 4.4 [4].

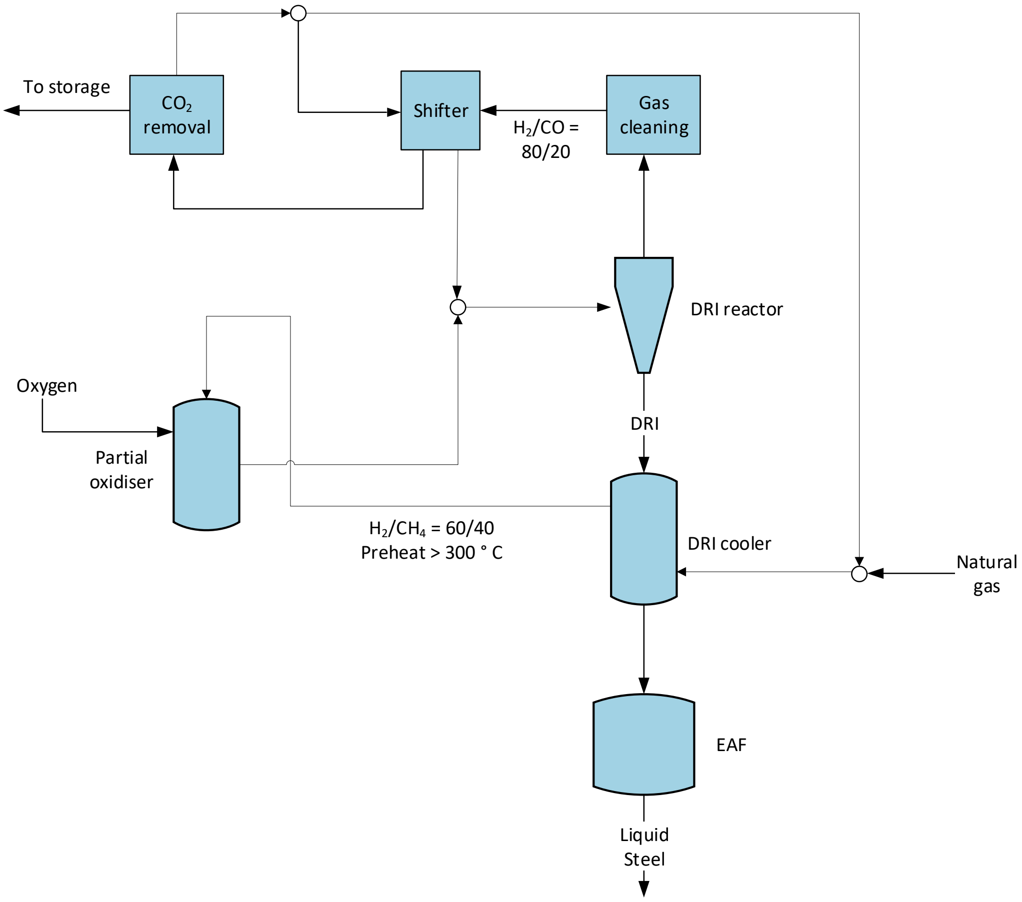

Figure 4.3: Basic schematic of natural gas-based ULCORED

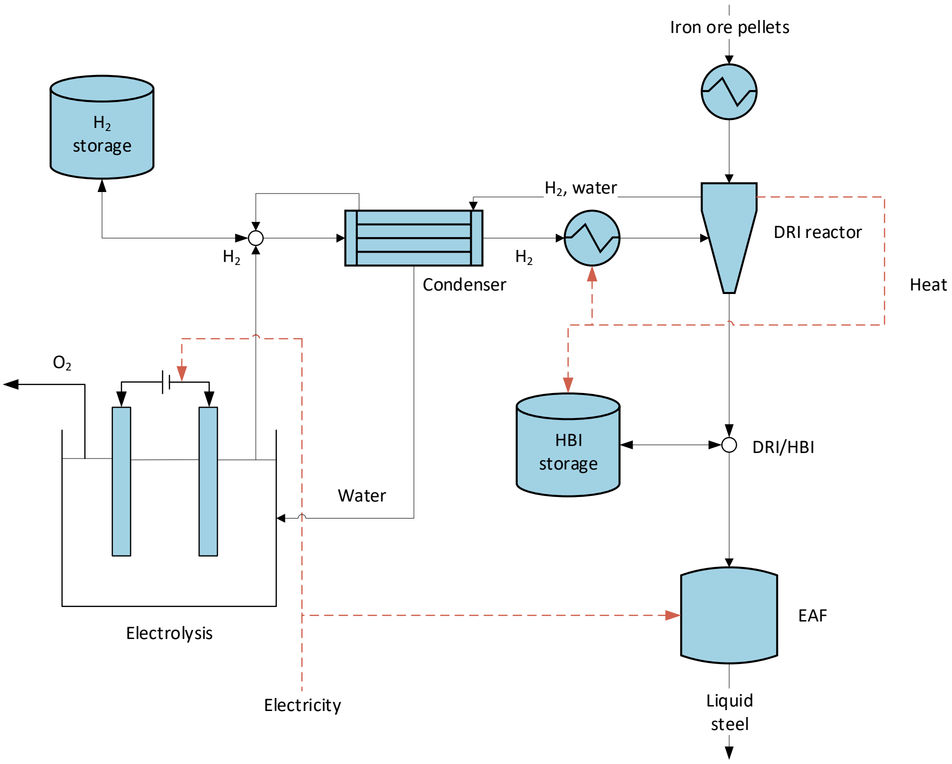

Figure 4.4: Example schematic of hydrogen-based direct reduction

4.1.4 Iron ore electrolysis: ULCOWIN and ULCOLYSIS

Electrochemical reduction of iron oxide forms the basis of both ULCOWIN and ULCOLYSIS technologies. ULCOWIN utilises direct electrolysis powered by electricity to produce iron and oxygen from iron ore particles submerged in an alkaline electrolyte (NaOH) solution at a temperature of 110 °C. A schematic of the basic working principle of the ULCOWIN process is displayed in Figure 4.5 [49]. This electrolysis technology is emission-free when powered by renewable electricity sources. The overall emissions are hence fully dictated by pre-treatment processes, EAF and downstream processes. During the ULCOS I phase, an iron purity of 99.98% was achieved with an energy consumption of 9.36 to 10.8 GJ per ton of pure iron. However, the production rate was very low at around 5 kg pure iron per day.

One solution to overcome the production rate constraint, is to dissolve iron ore in a molten oxide solution at 1600 °C, higher than the melting point of iron, using electrical direct reduction. This technology is known as ULCOLYSIS. The (inert) anode is submerged in the electrolyte solution and electrical current is passed between this anode and a liquid iron pool connected to the circuit as the cathode. This produces oxygen gas at the anode and liquid iron at the cathode. Both technologies based on iron ore electrolysis are currently the least developed of the four ULCOS technologies. However, the electrolysis process itself is very mature with its wide implementation in smelting metal such as aluminium, zinc and nickel [47] [1].

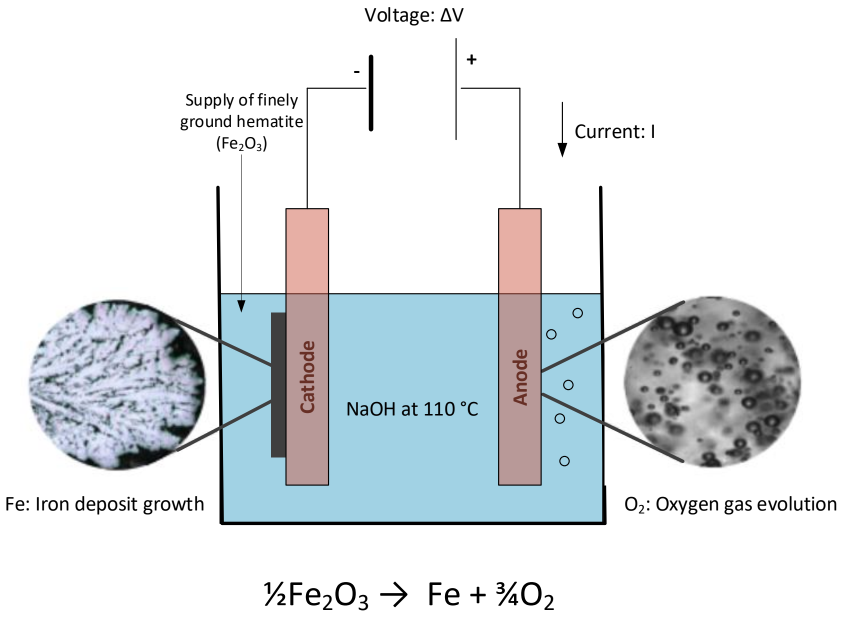

Figure 4.5: Basic schematic of iron production by the ULCOWIN process

4.1.5 Comparison of technology progress

Table 4.1 displays a comparison of the TRL of decarbonisation options[1] to give context to their possible deployment in the Netherlands [45] [44].

Table 4.1: TRL comparison of alternative steelmaking technology progress

Technology	**TRL**
TGR-BF	6–7
HIsarna	5
ULCORED (natural gas)	2–4
H-DR	7
ULCOWIN/ULCOLYSIS	5-6 (ULCOWIN) <5 (ULCOLYSIS)

4.1.6 Use of Biomass

Using biomass as a reducing agent, has the potential to achieve zero and even negative net carbon emissions. This is possible because the carbon cycle is relatively short, the CO_2 is recently extracted from the atmosphere by plants, as opposite to a very long time ago in the case of fossil fuels. Asides from this, the sulphur content in biomass is typically low, meaning that less capital is required for sulphur removal from iron. Although the use of biomass is much less technologically complex than some of the other low-carbon technologies, it has several important conditions to fulfil: (i) the harvesting of biomass does not degrade its environmental conditions (such as soil, water, air and biodiversity)

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[1] H-DR refers to more developed hydrogen-direct reduction technologies (e.g. HYBRIT), rather than hydrogen-based ULCORED

for future use. (ii) The use of biomass does not threaten food prices and the habitation of humans [2]. (iii) the biomass is harvested in a timely manner to meet conditions required to be accounted as net zero emissions overall.

Biomass-based steel production is already in practice on a small scale. Charcoal from eucalyptus trees in Brazil is being used in a small-scale BF as 100% of the feedstock. However, the use of eucalyptus trees in Europe is not realistic, but it does show the potential and thus research and development of other biomass sources which are more feasible in Europe is worth investigating.

Charcoal is cited as the most feasible biomass material for substitution and its possible fossil fuel substitution range are given in [55]. Tests on HIsarna are currently increasing charcoal substitution and a target of 40% charcoal substitution was made for 2017-18. Although this goal has not been seen to be proven yet, it is assumed technically possible for this report. An important consideration is that although it may be technically possible to substitute charcoal 100%, this may only be feasible at a small scale and not on an industrial scale. Infeasibility of such high substitution may arise from lack of spatial requirements (lower energy density of some biomass sources) or the undesirable mechanical properties of the selected biomass material. For simplicity and lack of relevant literature on industrial scale applicability, the upper limits from [55] are used. The possible charcoal substitution rates are summarised in Table 4.2. The possible substitution rate for ULCORED is not cited in literature and thus is not included in further results to avoid making conclusions on very uncertain data.

Table 4.2: Degree of implementation of charcoal per process for applicable steelmaking process plants

Steelmaking process plant	Fossil fuel substitution	Charcoal substitution rate (%)
Sinter plant	Coke breeze	50-100
Pellet plant	Coke breeze	50-100
Blast furnace	Pulverized coal	50-100
Blast furnace	Coke	2-10
HIsarna reactor	Coal	20-40
ULCORED reactor	Coal or natural gas	n/a

4.1.7 CO2 capture and storage

The addition of CCS to the various decarbonisation options can reduce the CO_2 emissions significantly without any major changes in the steelmaking process. The high level of emission reduction is possible because of the presence of single fixed points where CO_2 is released and easily accessible. In some cases the CO_2-containing flue gas has been purified from nitrogen, thus making the separation of CO_2 much easier. After separation, CO_2 must be compressed and in some cases cooled and then transported via pipelines or shipping/road vehicle tankers to an appropriate location for long-term storage (e.g. geological reservoirs in the deep ocean, or by the mineralisation of other compounds, chemical reactants or rocks) [2]. TSIJ have initiated a CCS project called Athos which intends to conduct a feasibility study by 2022 and start storing CO_2 in 2027 alongside another smaller company in the area. It is initially estimated that the initial design will facilitate 5±1 Mton-CO_2/year to be stored in empty gas fields for at least 20 years [11].

CO_2 capture within the steelmaking industry, must be considered differently than to other sectors such as the power sector. Conventionally, CCS can be classified as pre-combustion, post-combustion or oxyfuel combustion. However, CCS in the steelmaking process does not always fall directly into one of these categories. CCS for steelmaking primarily concerns capturing emissions from the reduction of iron ore, rather than combustion or oxidation [36]. Ultimately, the most appropriate method of CCS is dependent upon the particular steelmaking technology used. The main CO_2 capture technologies being explored for steelmaking are discussed below.

Absorption

Absorption can be either physical or chemical and takes place in the bulk of the gas over two main stages. Firstly, a physical or chemical solvent is used to capture CO_2 in the first reactor (absorber) and then in the second reactor (stripper), the solvent is recovered, leaving a CO_2 pure stream. Physical absorption can be carried out using a range of different commercially available solvents which are soluble to CO_2, such as cold methanol [76]. Chemical absorption processes are generally considered the more suitable for removing CO_2 from the BF steelmaking process, however, the process is expensive due to the large amount of thermal energy required to break the strong bonds formed between the solvent and CO_2. Amines, commonly monoethanolamine (MEA), are often used as the solvent in chemical absorption due to its good selectivity and capture efficiency properties. However, MEA has some drawbacks such as equipment corrosion, solvent degradation and low CO_2 loading capacity. Other chemical convents being investigated include ammonia, which has shown to have a higher capture efficiency, higher loading capacity, lower costs and lower energy requirements compared to MEA. Despite these benefits, its high volatility and ability to easily form precipitates cause it to be easily lost in the process and thus this challenge is yet to be overcome [1]. Figure 4.6 illustrates the basic principles of the chemical absorption process [1].

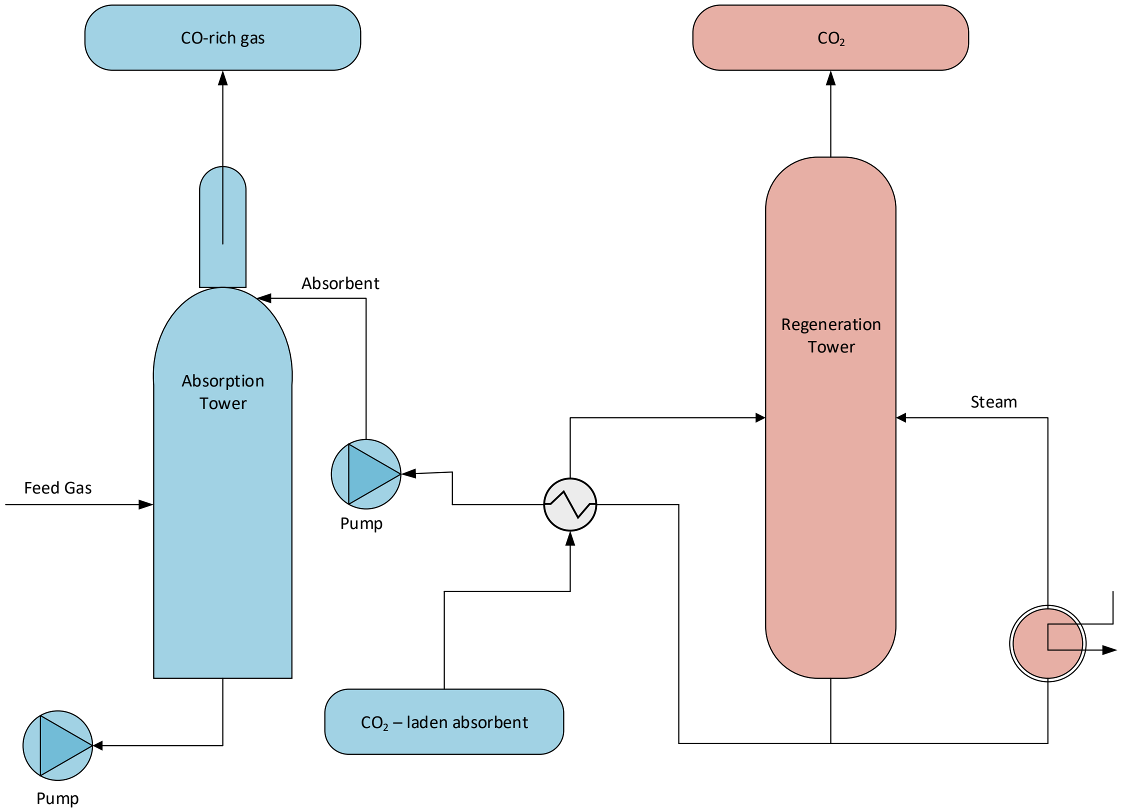

Figure 4.6: Schematic of chemical absorption-based CCS

Adsorption

Adsorption can occur by physical (physisorption) or chemical (chemisorption) bonding. Asides from the type of bonding, the different sorption technologies differ primarily by the nature of the CO_2-absorbing material (such as zeolite or activated carbon) and on the process of absorption and desorption on the respective material (changes in temperature or pressure) [36]. The main commercially available CCS adsorption technologies in the steelmaking industry are pressure swing adsorption (PSA) and VPSA [1]. These technologies separate CO_2 by loading the gas into the adsorption vessel under pressure and then separating it by swinging the pressure to atmospheric or a vacuum, respectively. One of the most promising PSA technologies for the steel sector is Sorption Enhanced Water-Gas Shift technology (SEWGS). This operates at high temperature, is claimed to achieve 90% CO2 removal and has a SPECCA[2] of 1.95 MJ/tCO_2. A basic schematic of the physisorption is displayed in Figure 4.7.

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[2] SPECCA stands for Specific Primary Energy per CO2 Avoided

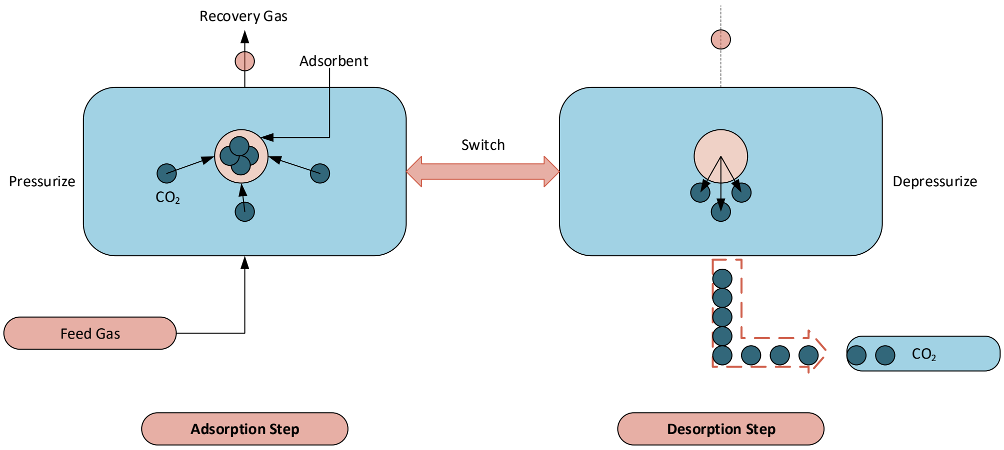

Figure 4.7: Basic process flow diagram of the physical adsorption-based CCS

Cryogenic

Cryogenic CO_2 separation is a distillation process for gaseous mixtures, analogous to a conventional distillation process for liquids. It involves cooling down the feed gas to sublimation temperatures in the range -100 to -135 °C (avoiding condensation) and using high pressures in the range 100 to 200 atm to separate out CO_2 based on the differences in boiling points of the gaseous components. The extreme conditions in this process mean that it is very electricity intensive with an estimated energy requirement of 2.2 to 2.4 GJ per ton of CO_2 to recover in liquid form. Typical recovery efficiency's are in the range of 90 to 95% and suitability is limited to gaseous mixtures with a high CO_2 concentration (>90%vol) [51].

Gas hydrates

Gas hydrate CO_2 separation is a relatively new technology compared to other separation methods. It is based on the principle of reacting the CO_2-containing stream with water under high pressure to form hydrate compounds. At high pressure and low temperature, the CO_2 becomes trapped within hydrate structures easier than other components in the gas. The CO_2 is subsequently removed from the hydrate structure by depressurisation or heating. Gas hydrate separation has been found to have an energy consumption of 2.06 GJ/ton-CO_2. Although gas hydrate separation technology is in its infancy, the US Department of Energy believe that it may be the most promising long term CCS technology [51].

Mineral carbonation

Mineral carbonation utilises the alkaline earth metals (such as silicates and free lime) found in the slag produced by a BF. CO_2 reacts with these compounds to form stable compounds which can subsequently be stored. The two main carbonation processes are classified by either a direct or indirect process. Direct process carbonation reactions occur in the aqueous phase or at the solid-gas interface between the slag and CO_2-containing gas mixture. Indirect processes involve the alkaline earth metals first being isolated from the slag and then reacted with the CO_2-containing gas mixture [1].

Membranes

Gas can be physically separated using membranes such as ceramics and metals configured in such a way that only CO_2 can pass through. This is operated as a continuous process, unlike the previous technologies which all operation in batch mode. A CO_2 capture efficiency of over 80% can be achieved with some membrane materials. Other gas components can also be removed using membranes, such as O_2 and N_2, which can be used for other parts of the steelmaking process or sold to other industries. Membranes are currently relatively infant in their development but may have good future potential. One of the main challenges with membranes is minimising fouling and thus increasing the flux rate. Membranes have proven to be very sensitive to the gas stream properties and thus careful control of this is needed to achieve efficient operation [51].

ULCOS program

The main CCS technologies that are being explored in the ULCOS programme are amine scrubbing, PSA or VPSA and cryogenics. Several factors are taken into account when evaluating the most effective CCS technology: the steelmaking technology, steam and energy prices, CO_2 purity in feed and output, and storage requirements [2]. Another important consideration is that all of these factors are time-dependent and so evaluations must take into consideration factors such as the R&D progress predictions (e.g. decrease in energy intensity) of all technologies as well as future projections of steam and energy prices [36].

In both a conventional BF and TGR-BF, physisorption-based technologies (PSA and VPSA) are found to be the most suitable with both performance and cost considered. natural gas direct reduction (NG-DR) steelmaking processes also are found to be most suitably implemented with physisorption-based technologies. Cryogenic separation may be necessary in a subsequent stage to PSA/VPSA depending on the desired CO_2 purity for BF, TGR-BF and NG-DR technologies. HIsarna produces a high purity CO_2 stream and so CO_2 capture is only required in the cases in where the CO_2 purity is required to be even higher or if the presence of impurities is high, thus requiring cryogenic separation. Overall, each steel mill needs to be evaluated on a case-by-case basis to select and optimise the CCS technology which takes into consideration all CO_2 streams and not only the primary source [36].

As part of the ULCOS program, a TGR-BF pilot plant built by LKAB in Luleå, Sweden has implemented a VPSA system. The VPSA system was built by Air Liquide, a partner of the ULCOS program. An indirect advantage of this CCS system implemented in a BF is that the captured CO_2 from the top gas increases the concentration of reducing gas (mainly CO) that can be recycled back into the vessel and thus improves overall performance. In this pilot plant, the captured CO_2 was not stored [36].

Following the successful implementation of VPSA in the pilot plant as part of ULCOS I, a larger scale CCS system is being planned for ULCOS II with VPSA used in conjunction with cryogenics. This will test the scale-up effect of such a system and will also the ability of cryogenics to achieve high CO_2 purity, as it is planned to store the CO_2 in deep saline aquifers. During the cryogenic step, reducing gas is produced as a by-product that can be recycled back into the BF for improved performance [36].

In the absence of CCS, the HIsarna process requires dust removal, heat recovery and desulfurisation processes. The addition of cryogenic-based CCS still requires these processes but with the addition of drying, separation, compression stages prior to pipeline transport and storage, as displayed in Figure 4.8 [64].

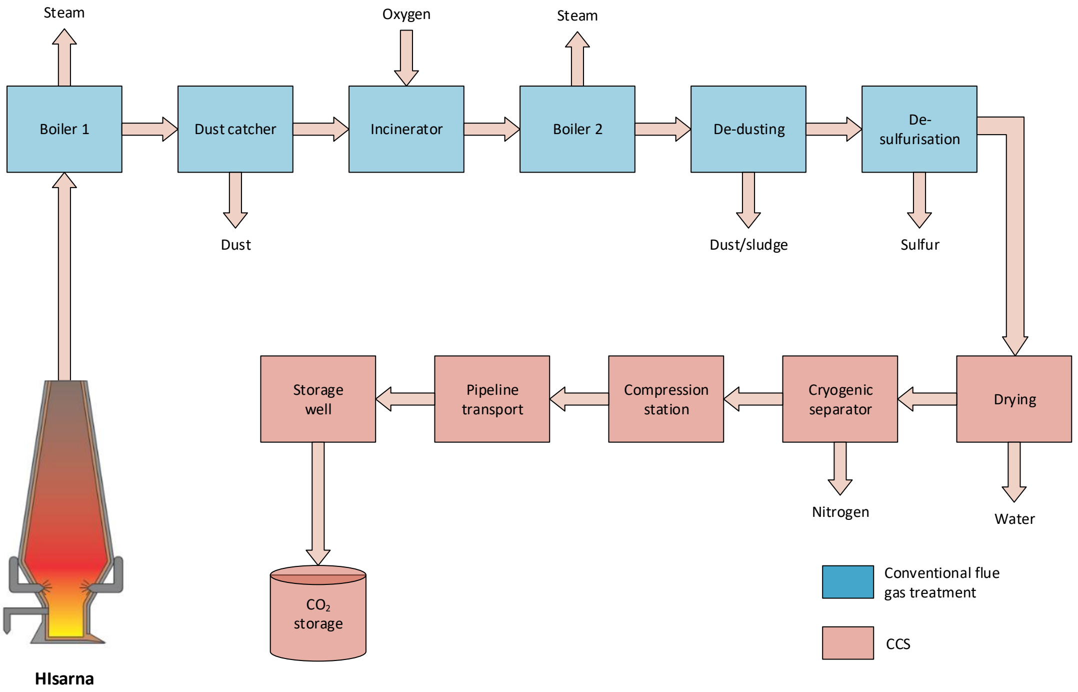

Figure 4.8: Systematic flowchart of cryogenic CCS implemented to the HIsarna process

The composition requirement of different storage basins is specific to each case and thus it is difficult to create universal legislation. Thus the stream specification would need to be specified to all participating parties for each project to ensure compliance. Table 4.3 displays the stream composition in some existing CCS pipelines used for EOR [57]. The CO_2 composition in these pipelines is in the range 85-99.7mol%, this is a good indicator of the stream purity that would be expected to be achieved regardless of the source.

Table 4.3: Stream composition of several different existing CCS pipelines used for EOR [mol%]

	Pipeline 1	**Pipeline 2**	**Pipeline 3**	**Pipeline 4**	**Pipeline 5**
CO_2	95	85-98	96.8-97.4	98.5	99.7
CH_4	1-5	2-15	1.7	0.2	-
N_2	4	<0.5	0.6-0.9	1.3	03
H_2S	0.002	<0.02	-	<0.002 wt	-
C2+	Trace	-	0.3-0.6	-	-
CO	-	-	-	-	-
O_2	-	-	-	<0.001 wt	-
H_2	-	-	-	-	-
H_2O	0.0257 wt	0.005 wt	0.129 wt	0.0257 wt	-

CO2 capture and utilisation

CCU follows the same principles as CCS without the storage aspect. Instead, CCU aims to use the capture CO_2 as a feedstock to make useful products. The products can be broadly categorised into: CO_2-to-fuels, enhanced commodity production, enhanced hydrocarbon production, CO_2 mineralisation chemicals production. Extensive research of CCU potential has been conducted by the European Commission Joint Research Centre. An overview of the main technologies currently being investigated are displayed in Table 4.4 [10]. The global uptake potential is given to put into context the demand that could be available. The research and industrial engagement gives an indication about how much activity is going on within the technology and can give an indication about how much potential a technology is deemed to have. Finally, the technology readiness level (TRL) indicates the maturity of each technology from the basic concept (TRL 1) to being available at a commercial scale (TRL 9) [10]. An important consideration is that in many of these applications, the CO_2 is not permanently stored, but instead is often released again in another process.

Table 4.4: Overview of most promising European technological pathways for CCU

CO_2 re-use technology	**Uptake potential (Mton/year)**	**Research & Industrial engagement**	**TRL**
Methanol production	>300	+++	4-6
(Carbonate) Mineralisation	>300	+++	3-6
Polymerisation	5 – 30	+++	8-9
Formic acid	>300	+++	2-4
Urea	5 – 30	+++	9
Enhanced coal bed methane recovery	30 – 300	+–	6
Enhanced geothermal systems	5 – 30	++-	4
Algae cultivation	>300	+–	3-5
Concrete curing	30 – 300	++-	4-6
Bauxite residue treatment	5 – 30	++-	4-5
Fuels engineered micro-organism	>300	++-	2-4
CO_2 injection to methanol synthesis	1 - 5	+–	2-4

Asides from CO_2, other by-products can be utilised to make useful products. TSIJ and Dow Benelux are currently building a pilot plant that utilises CO from the waste gases of the BFs to produce syngas. Syngas can be used to produce a range of products but this pilot plant will focus on naphtha, a hydrocarbon mixture that Dow use to make chemical products. TSIJ claims that they can supply around 5% of the current naphtha production by Dow. Producing naphtha is a higher value application than the production of electricity and the emissions of doing so would no longer be included within the steelmaking plant, an advantageous attribute for the steelmaker. Several other major European steelmakers are also working on similar projects [23].

Steel recycling

TSIJ recycle approximately 1.4 Mton of steel, both internally and externally sourced, in 2015. Scrap steel is inputted in to the BOF alongside pig iron from the BF. The use of scrap steel significantly reduces CO_2 emissions from production but is subject to significant restraints of availability and cost. EAFs can be run entirely on scrap steel and currently account for 30% of global steel production and so competition for material is rife [74]. Hence, decarbonisation options with an EAF provide the opportunity to greatly increase the level of scrap steel used provided that there is sufficient availability.

Energy efficiency

TSIJ have an energy efficiency program entitled Trias Engergetica which consists of three main goals:

1. Reduce unnecessary energy consumption, e.g. heat insulation, start-up/shut-down procedures, design innovation.
2. Use sustainable energy sources for necessary energy consumption, e.g. wind, solar, biomass.
3. When sustainable energy sources are not possible, utilise more efficient, less pollutant fossil fuel sources, e.g. natural gas instead of coal.

A combination of these energy efficiency measures have helped TSIJ improve their energy efficiency by 32% since 1989. This is illustrated in Figure 4.9 and compared to steel mills deemed 'world class' in terms of energy efficiency, showing that TSIJ is one of the most energy efficient steel mills in the world. However, further incremental energy efficiency measures are becoming more difficult and thus larger, step-change technological investments are required to improve energy efficiency further [46].

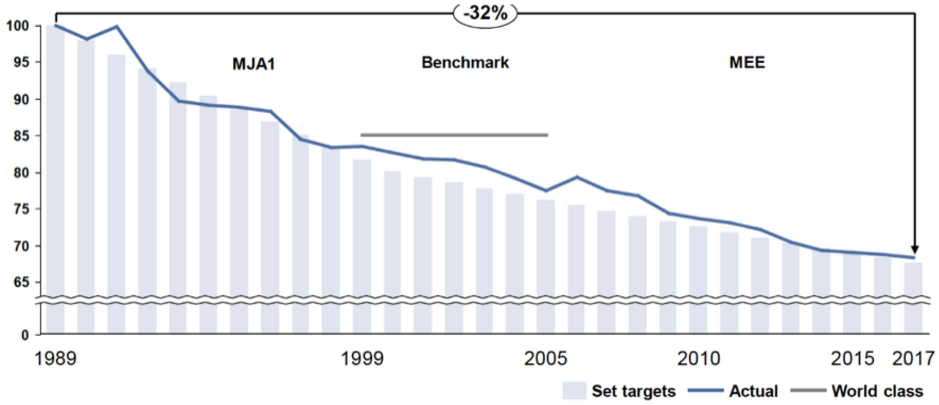

Figure 4.9: Energy efficiency of TSIJ overall processes relative to 1989

4.2 MATERIAL, ENERGY AND CO2 FLOWS

An overview of the material, energy and CO_2 flows for the selected decarbonisation options are formed using a range of sources specifically for each technology. Details of use of hydrogen in ULCORED are not available and hence will be stated as a general H-DR option. Alongside these alternative technologies, the use of existing EAF technology alone is also a valid option and hence is included. An explanation of how the flows have been devised are provided one-by-one in this section. For all options, process plants that are present in the current situation at TSIJ are scaled linearly to meet 1 Mton of crude steel production. See Section 3.2 for an explanation of how these values were devised alongside the CO_2 emission calculation methodology. All excess WAGs are assumed to be combusted in an on-site CHP plant with 40% efficiency and a 1:1 electricity-to-heat ratio. It is also assumed that in the absence of any process gases, they are substituted by natural gas. All options are displayed schematically in Appendix B.

EAF

The flows for an EAF are based on [24] in which it is assumed that the process is based entirely on scrap steel. Average values are taken for all flows.

TGR-BF

The flows from the TGR-BF unit are based on version 4 from [22]. It is assumed that an equal share of sinter and pellets is used, analogous to what is currently practiced at TSIJ. A modification is made in that 90% top gas recycling rate is assumed, in-line with the results in [47]. The remaining 10%, alongside the tail gas of the VPSA, have an energetic content that is assumed to be used for the preheating of the recycled top gas. The energy density of both streams are calculated based on the value per Nm^3 from [22]: 6.9 MJ/Nm^3 for the 10% unrecycled top gas and 1.5 MJ/Nm^3 for the tail gas of the VPSA.

HIsarna

The iron ore requirement is assumed to be analogous to the other processes, in which little variation is present between options. The coal requirement is assumed to be 80% of the stated typical blast furnace coal requirements ($17 \times 80\% = 13.6$ GJ/ton-HRC) from [20]. The oxygen requirements are calculated by performing a basic mole balance calculation based on the equation, $C + O_2 \longrightarrow CO_2$, assuming that the top gas is almost 100% CO_2. Working backwards from the CO_2 emissions arising from the HIsarna reactor, the oxygen requirements are calculated assuming an oxygen density of 1.33 kg/Nm^3. The electricity requirements are assumed to be in the same range as that in the TGR-BF. It is assumed that 100% of the CO_2 is captured.

ULCORED

A ULCORED reactor based on natural gas has been primarily based on a simplified version of [62]. Due to the absence of a coke plant for this option, coke breeze has been substituted for coal in the pellet plant. The DRI and scrap steel flow into the EAF has been based on [21].

H-DR

The flows in this option have been based on [40]. It has been assumed that all iron ore requirements are met with pellets to keep consistency with the source, although it may be also possible to also use sinter. The flows in the water electrolyser to produce the required volume of hydrogen have been devised from a basic mole balance calculation.

ULCOWIN & ULCOLYSIS

All flows in both options are based explicitly on [18].

Carbon capture and storage

CCS plays an important role in several decarbonisation options for emission reduction and its energy requirements differ for each technology, hence, it is important to provide explanation to how the energy requirements have been derived for this report. The addition of CO_2 capture can be applied to the BF, HIsarna and ULCORED and is an integral component to TGR-BF steelmaking technology to achieve significant CO_2 reduction. There are a range of CO_2 capture technologies that can be applied to each steelmaking technology, each with their own pro's and con's. The flue gas from HIsarna differs relatively substantially from the other technologies due to its high CO_2 purity (95%) [12]. Depending on the required CO2 purity for storage, it may or may not be necessary to include a CO_2 separation unit. If a higher CO_2 purity is required then it is likely to only require cryogenic separation alone, otherwise HIsarna only requires pre-treatment stages and compression before storage. A system-level flowsheet of how cryogenic separation and storage can be applied to HIsarna is displayed in Figure 4.8.

The assumptions of the CO_2 capture technology that has been selected for the purpose of this report and the associated characteristics are listed in Table 4.5, based on what is most commonly considered to be most suitable both technically and economically. The CO_2 capture rate in the case of the BF is assumed based on [60] and in HIsarna a 100% capture rate is assumed. The CO_2 capture rate for the other steelmaking technologies has been calculated, rather than assumed, based on the material flows used from literature. The effective CO_2 concentration range in flue gas for each CO_2 capture technology is estimated based on their common applications. For example, cryogenic distillation separation is commonly used to treat high CO_2 purity streams and amine-based separation is commonly used for combustion flue gases with low CO_2 purity. Table 4.6 displays the energy requirements of the selected CO_2 capture technologies, in which data for VPSA is based on [36], cryogenic distillation is based on [51] and SEWGS is based on [34]. Figure 4.10 displays the main stages involved for CCS applied to flue gas sources, beginning with several pre-treatment stages, followed by the main CO_2 separation unit, and finally compression to 100 bar for storage [39]. These general stages are applicable to all capture technologies considered and outlines the scope when energy and costs are considered.

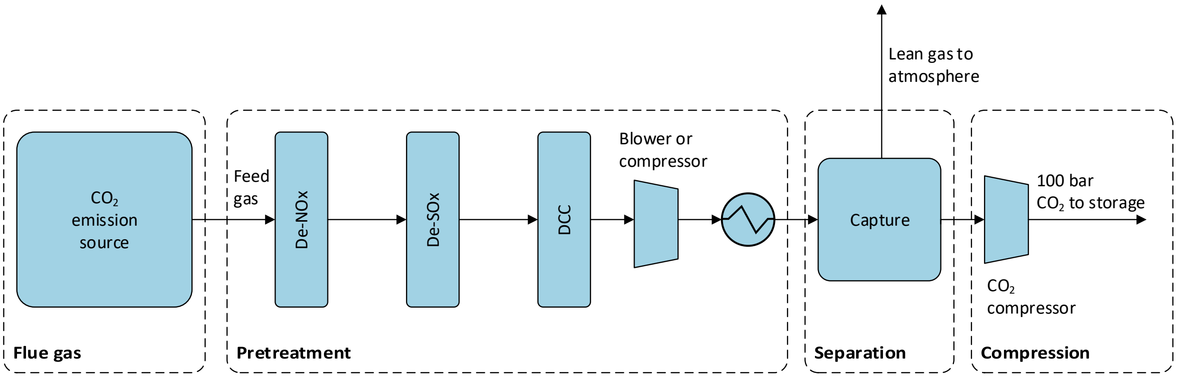

Figure 4.10: Scope of CO_2 capture process

Table 4.5: CO_2 capture technology assumptions for steelmaking processes

Steelmaking process	**CO_2 capture technology**	**Location**	**Capture rate (%)**	**Effective CO_2 concentration in flue gas (%)**
BF	SEWGS, compression	Power plants	90%	Low (<15vol%)
TGR-BF	VPSA, compression, cryogenic flash	TGR-BF	94%	Medium (15-55%vol)
HIsarna	Cryogenic distillation, compression	HIsarna reactor	100%	High (>90vol%)
ULCORED	VPSA, compression, cryogenic flash	ULCORED reactor	94%	Medium (15-55%vol)

Table 4.6: Energy requirements of CCS technology configurations

	VPSA, cryogenic flash, compression	**Cryogenic distillation, compression**	**SEWGS, compression**
Electricity consumption [GJ/ton-CO_2]	1.05	2.16	2.24
Capture process [GJ/ton-CO_2]	0.58	1.75	-
Compression for storage at 110 bar [GJ/ton-CO_2]	0.48	0.41	-
Total energy requirement [GJ/ton-CO_2]	**1.05**	**2.16**	**2.24**

Considering the energy flows constructed for the selected decarbonisation options, a comparison of the total energy consumption and generation is calculated. This not only includes energy consumed as a fuel but also the energy of chemical feedstocks, e.g. coke as a reductant in the blast furnace. The total energy consumption and generation is divided into coal, natural gas and electricity for each option. The comparison is displayed in Figure 4.11. Electricity-based options may have the potential to operate solely on electricity, however, this report does not consider the decarbonisation of downstream steelmaking processes after crude steel and thus natural gas-based processes remains from the current situation. Note: the steam requirements for CCS in the BF configuration is accounted for by assuming an electric boiler efficiency of 100% to produce low pressure steam. It is also possible that high temperature heat pumps that inhibit a higher efficiency could be used instead, depending on the temperature required. It is likely that there is waste heat available on-site that could be utilised instead to produce steam, however the quantity is not known.

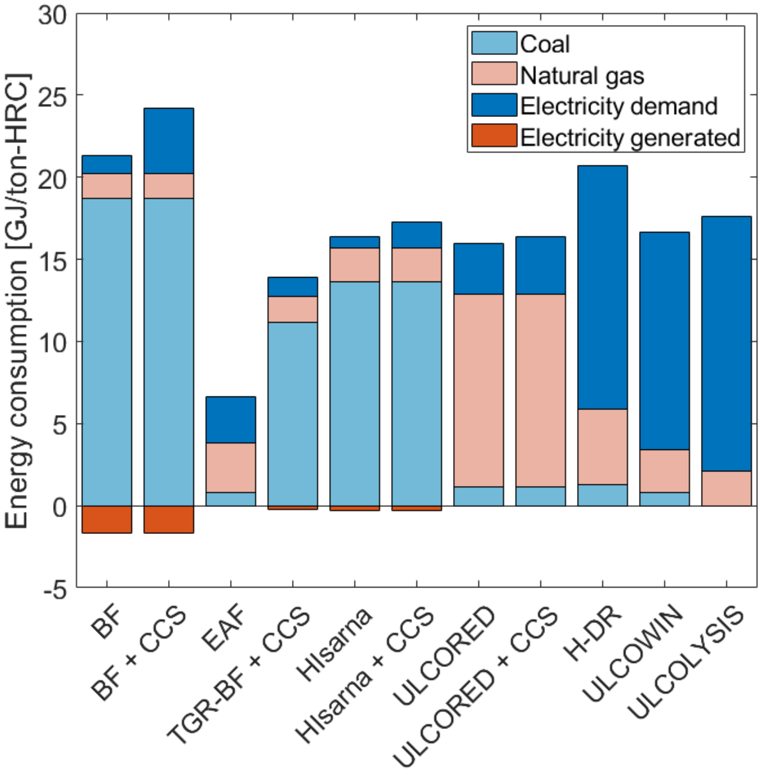

Figure 4.11: Annual energy consumption of decarbonisation options relative to the current BF process

The resulting CO_2 emissions are calculated with the same methodology as in Section 3.2. To allow for more consistent comparison, all results are given per Mton product of HRC of steel. Electricity-based options may have the potential to have zero emissions, however, this report does not consider the decarbonisation of downstream steelmaking processes after crude steel and thus natural gas-based processes remains from the current situation. Figure 4.12 displays a comparison CO_2 emissions emitted for decarbonisation options including CCS where applicable. Figure 4.13 displays the CO_2 emissions emitted calculated for the relevant decarbonisation options with charcoal substitution at both a lower and upper limit. Table 4.7 displays the charcoal substitution limits based on Table 4.2.

Table 4.7: Assumed upper and lower limit of charcoal substitution per process for applicable decarbonisation options

Steelmaking process	**Fossil fuel substituted**	**Lower charcoal substitution rate (%)**	**Upper charcoal substitution rate (%)**
Sinter plant	Coke breeze	50	100
Pellet plant	Coke breeze	50	100
Blast furnace	Pulverized coal	50	100
Blast furnace	Coke	2	10
HIsarna reactor	Coal	20	40

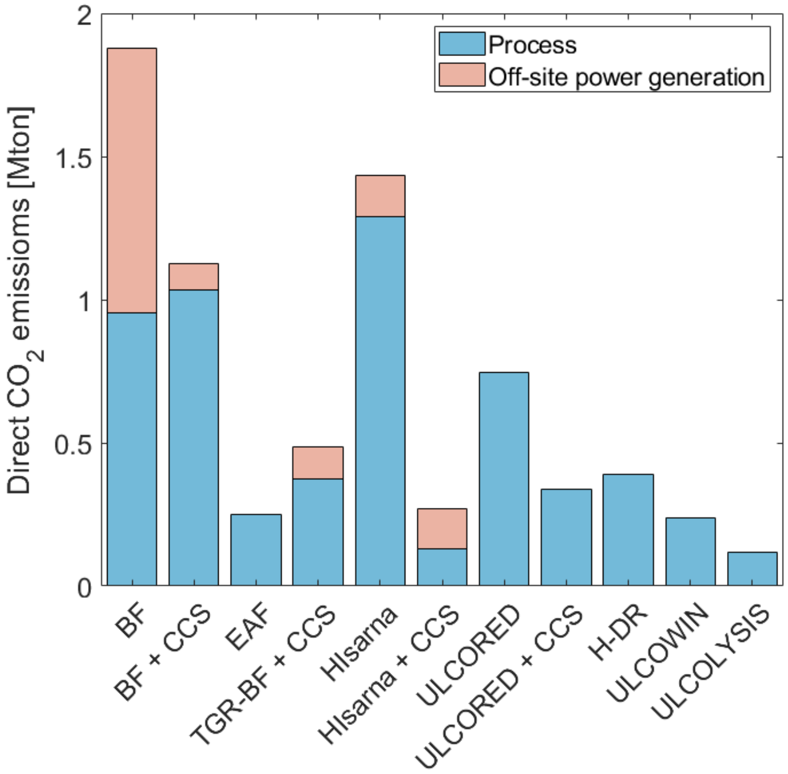

Figure 4.12: Comparison of CO_2 emission estimates for steelmaking technologies (excl. biomass implementation)

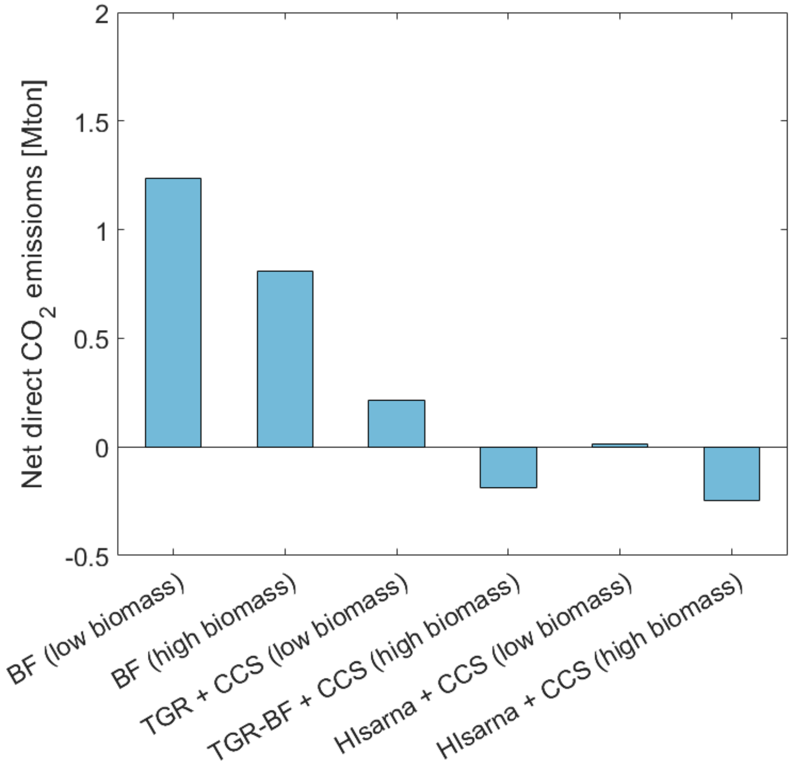

Figure 4.13: Comparison of CO_2 emission estimates with charcoal substitution in the most feasible steelmaking technologies

4.3 PRODUCTION COSTS

A comprehensive production cost comparison of the concerned technologies of this report are sourced from [18]. The production costs are divided into capital, raw materials, energy and other non-energy costs and this forms the basis on the production cost analysis. The assumptions behind the capital, raw material and non-energy costs (such as equipment lifetime, raw material costs and CCS technologies) are unknown from the data. However, the consistency and scope of the data is the most suitable available literature and so the data is utilised. Please note that all costs are in terms of ton-HRC and so are also assumed to include post processing stages.

BF with CCS retrofit is missing from this data and so an estimate of the total cost of CCS to the baseline cost of BF is estimated from [39] where the overall cost of CO_2 capture for this configuration with amine CCS technology at a WAG power plant is €56/t-CO_2. The source also provides a breakdown of the overall CO_2 capture costs into capital, raw materials and other is shown in Figure 4.14. Therefore, an estimate of these costs can be derived from this information alongside the calculated CO_2 reduction potential, as shown in Equation 4.1.

$$\begin{aligned}&\text{specific cost of CCS retrofit}\left[\frac{€}{ton_{HRC}}\right]\\&=\text{overall CO}_2\text{ capture cost}\left[\frac{€}{ton_{HRC}}\right]\times\text{cost breakdown }[\%]\\&\qquad\times\text{CO}_2\text{ reduction}\left[\frac{ton_{CO_2}}{ton_{HRC}}\right]\end{aligned}\tag{4.1}$$

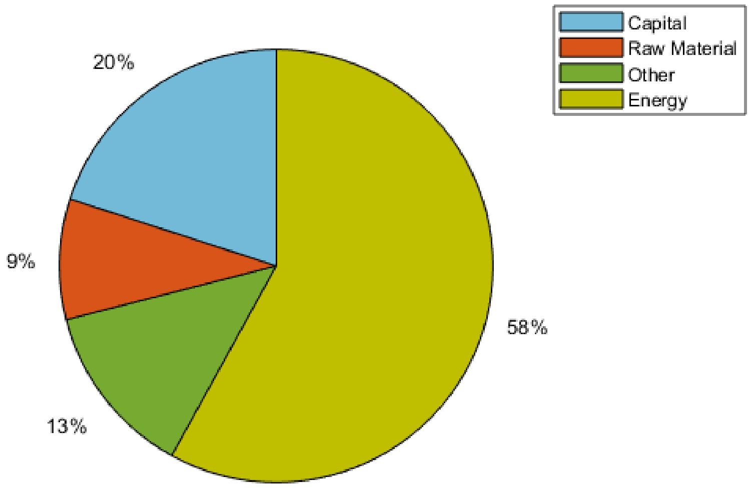

Figure 4.14: Cost breakdown for CO_2 capture (MEA solvent) at a conventional steel mill power plant

Figure 4.15 displays the annualised capital costs for each of the options. Notably EAF has the lowest annualised capital cost primarily owed to less processes required compared to most of the other options which require several pre-processing steps. Figure 4.16 displays the non-energy related operating costs. The assumptions behind other operating costs are not explicitly known but can be assumed to primarily represent fixed operating costs. The scrap-based EAF option notably has the highest operating costs owed to its reliance on relatively expensive scrap steel.

To estimate the associated energy costs for each option, average national energy costs in 2017 [70] and two different national energy cost scenarios (high and low) for 2030 and 2050 [19] are used to calculate the range of annual energy costs that are expected. The impact that these scenarios have on the total annual energy costs for each option are displayed in Figure 4.16 to 4.21. For steelmaking processes primarily based on electricity (H-DR, ULCOWIN and ULCOLYSIS), the energy costs are relatively high in all cost scenarios. This is one of the most significant factors that must be taken into account when considering the implementation of these technologies.

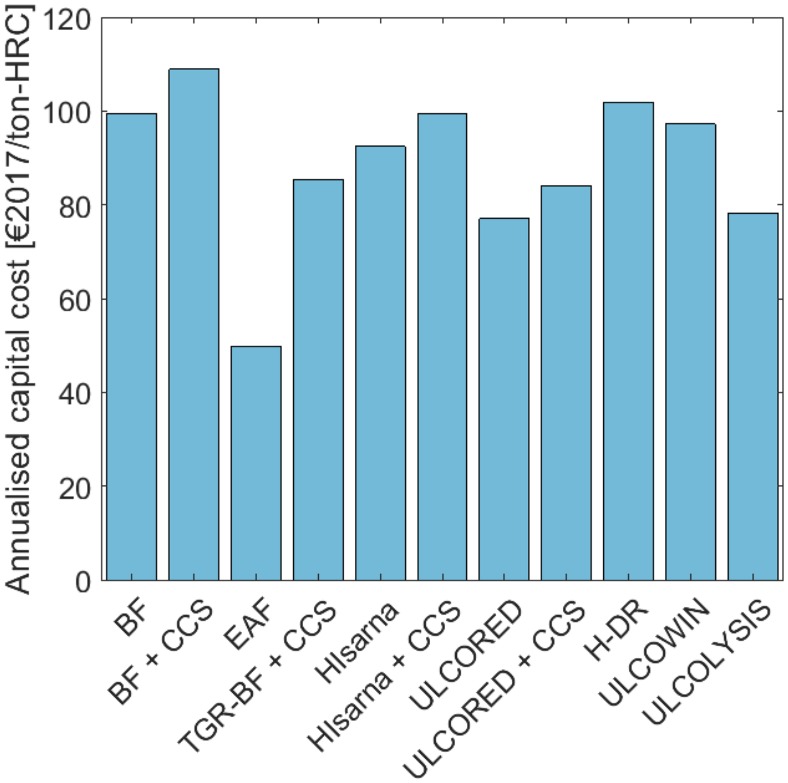

Figure 4.15: Annualised capital costs of decarbonisation options

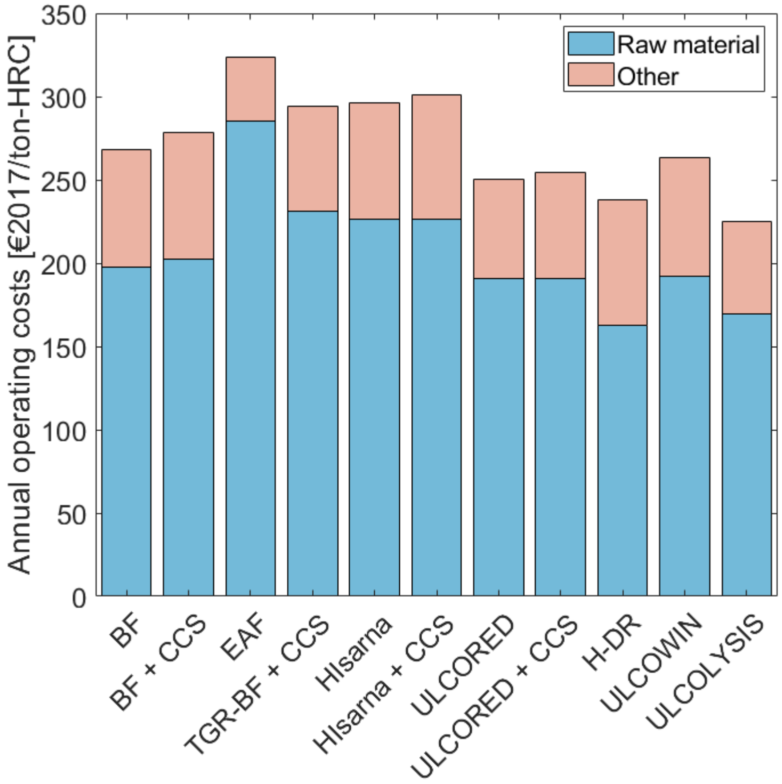

Figure 4.16: Annual operating costs of decarbonisation options (excl. energy)

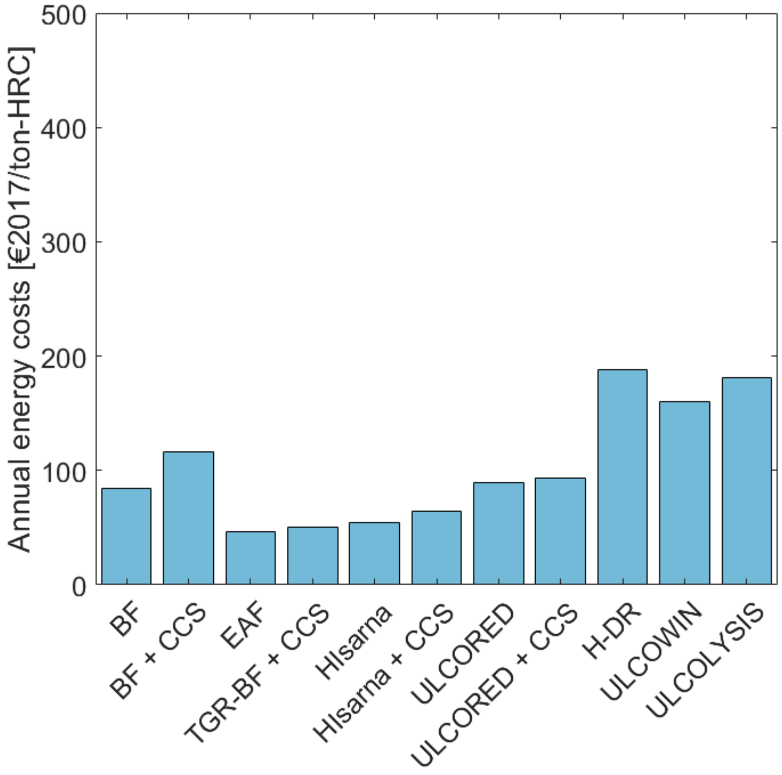

Figure 4.17: Annual energy costs for decarbonisation options based on 2017 historical prices in the Netherlands

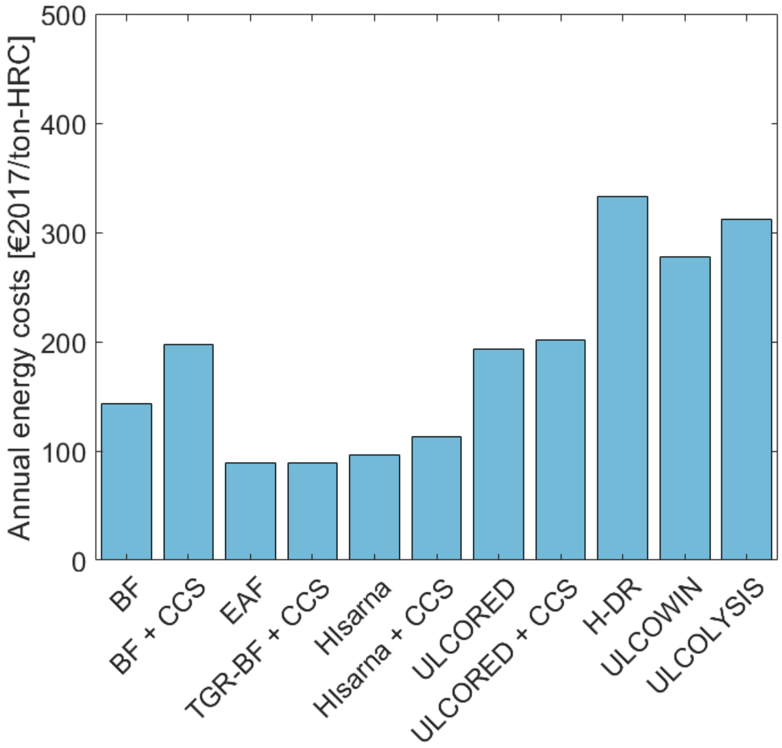

Figure 4.18: Annual energy costs for decarbonisation options based on a 2030 low energy cost scenario in the Netherlands

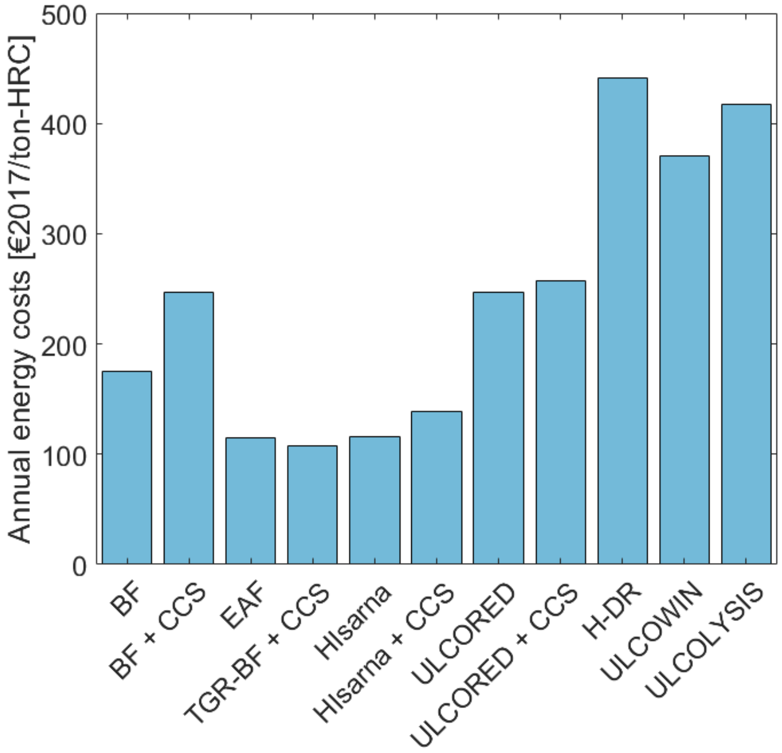

Figure 4.19: Annual energy costs for decarbonisation options based on a 2050 low energy cost scenario in the Netherlands

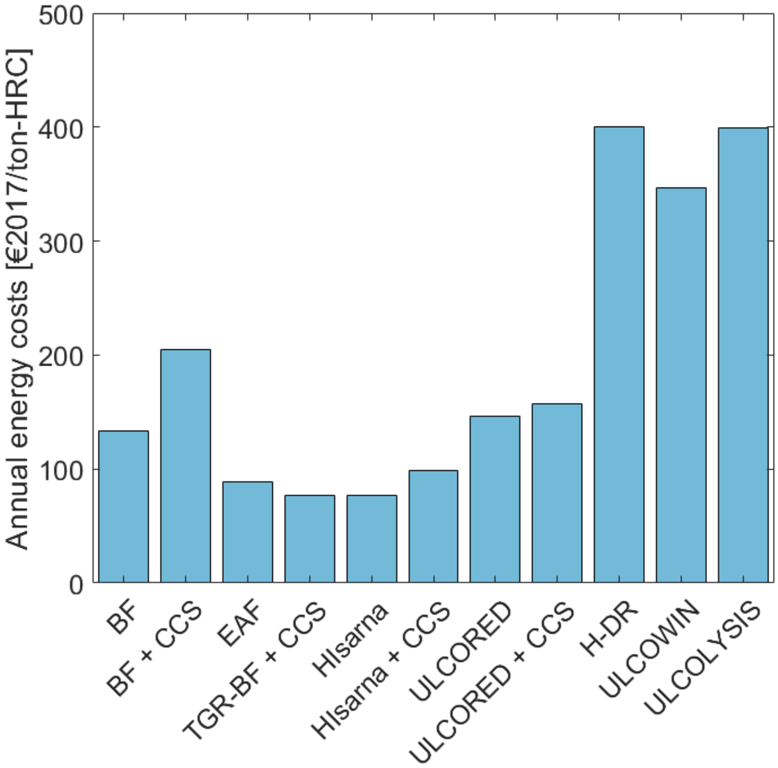

Figure 4.20: Annual energy costs for decarbonisation options based on a 2030 high energy cost scenario in the Netherlands

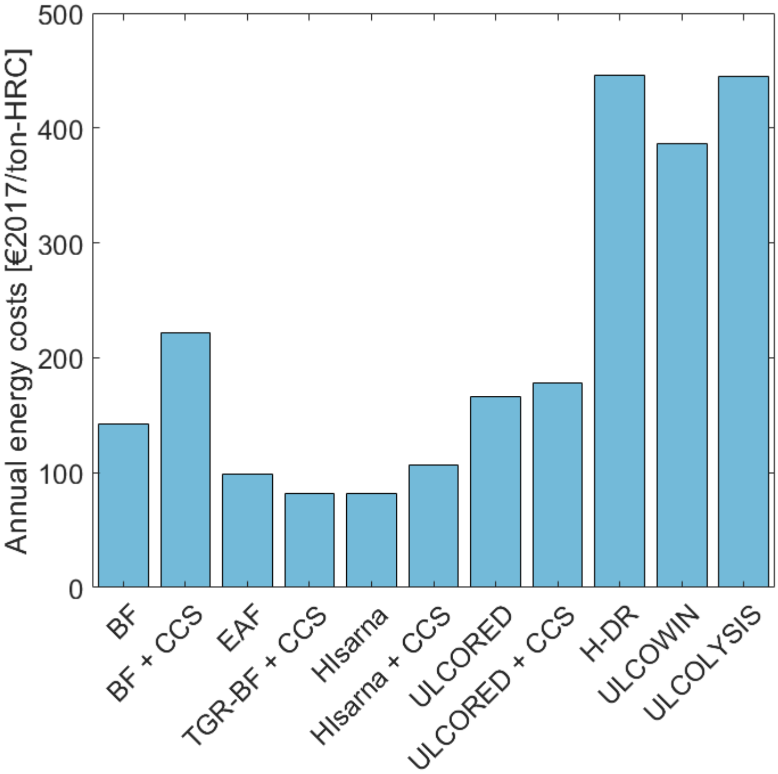

Figure 4.21: Annual energy costs for decarbonisation options based on a 2050 high energy cost scenario in the Netherlands

The production costs give an indication as to which factors are most important when comparing how promising a decarbonisation options will be in the future. The annualised capital cost is less significant compared to the operating costs for all options. The raw materials and other operating costs (excluding energy) are relatively similar for all options. The most significant difference in production cost between options is the energy cost. In 2017, the energy cost for electricity-based options (H-DR[3], ULCOWIN and ULCOLYSIS) are almost double the cost of the other options. Given that these technologies are estimated to become available commercially by approximately 2050, the energy cost difference in both 2050 scenarios are expected to become up to four times more expensive than all non-electricity-base options. The implications that this anticipated energy cost has on electrification of steelmaking and possibilities for overcoming such a challenge are discussed further in Subchapter 4.4.

4.4 ROLE OF ELECTRIFICATION

Each of the most promising technologies for decarbonisation have their own advantages and challenges, as discussed in the previous section. One of the most notable trade-offs that emerges from the results of this chapter is between energy costs and CO_2-reduction potential. The main direct[4] electrification options, ULCOWIN and ULCOLYSIS are able to achieve almost zero CO_2 emissions[5]. However, the anticipated future energy costs when the technology is expected to become available commercially in 2050 are generally much higher than that of other decarbonisation options which are not based on electricity.

In a future electricity system based primarily on RESs, electricity prices are expected to fluctuate depending on many factors, such as RES availability, demand and storage availability. Steel production directly based on electricity is exposed to such electricity prices. The current coal-based steel production process in the Netherlands is based on the global coal market and hence, changes in coal price will generally affect other international steelmakers similarly. A shift towards electricity-based steel production in the Netherlands would likely mean that energy prices for a steel producer would shift to becoming based on the EU electricity market. Unlike the coal market, the electricity market is largely unaffected by global developments. Instead the electricity market is affected by many more local, regional and national factors (including: electricity demand, network investments, congestion, and generation portfolio). This shift in markets will change the largely level playing field currently experienced in the steel industry, alongside likely making it harder to anticipate how future energy (electricity) prices will develop. This not only includes whether electricity prices will on average increase or decrease, but also how their volatility develops.

One such method that may have potential to reduce energy costs for electrification options is by implementing operational flexibility. Operational flexibility means to ramp-up and -down production (and hence, electricity demand) in response to electricity prices. This typically also means to oversize a system to compensate for periods when the system is

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[3] When hydrogen is produced by electricity-based electrolysis.

[4] Direct refers to steel production powered directly by electricity as opposed to hydrogen-based options in which hydrogen is produced via electricity-based electrolysis and then used for steel production. In essence, hydrogen is likely to be traded as a commodity in the future and hence the H-DR option would not be considered an electrification option from the perspective of a steel producer.

[5] This could potentially be zero, however, this report does not consider the decarbonisation of the downstream steelmaking processes, currently based on natural gas, and thus it is refrained from stating zero emissions.

operating at a lower production rate and steel production demands are still met. Operating electricity-based steel production flexibly is both a technical challenge (i.e. the ability to ramp-up and -down) and an economical challenge (i.e. magnitude and volatility of electricity prices as well as the geographic difference in prices). The main objective of flexible operation is to avoid electricity price peaks and thus reduce overall production costs.

Direct electrification options have the potential to decarbonise the Dutch steel industry but this still poses many technical and economic challenges. The ability to operate flexibly may have the potential overcome some of the economic challenges by reducing the overall energy costs. The next section will explore both qualitatively and quantitatively the extent at which operational flexibility may have the potential to support electrification of the Dutch steel industry.

5 ELECTRIFICATION: POTENTIAL OF OPERATIONAL FLEXIBILITY

In the previous section, electrification technologies are described and compared to other decarbonisation options. Electrification technologies are shown to have greater CO_2-reduction potential compared to other decarbonisation options. One of the main challenges identified with electricity-based technologies, relative to other technologies are the anticipated high energy costs. In an attempt reduce the energy costs of this technology, this chapter aims to assess the potential of operational flexibility to avoid peak electricity prices and capitalise on low electricity prices when there is an abundance of RESs. This is to be assessed in 2050 for two reasons: (i) the technology is expected to become commercially available by this year, and (ii) the electricity system is expected to have a greater penetration of RESs and thus the intermittent nature of such sources may yield more opportunity capitalise on volatile prices.

The methodology in Chapter 2 lays out the parameters used to assess the potential of operational flexibility. Based on the the previous chapters, specific data for the parameters are given in Appendix D. This chapter aims to answer the fourth, and final, research question:

> *How can operational flexibility potentially support the electrification of the Dutch steelmaking industry?*

5.1 MODEL SET-UP

The direct electrification options identified in the previous chapter are based on iron ore electrolysis. The two specific technologies discussed, ULCOWIN and ULCOLYSIS, are relatively new concepts still in early development. Of these two technologies, ULCOWIN is selected for the analysis for two main reasons. Firstly, the development of ULCOWIN technology is the most developed of the two with a TRL of 5–6. Secondly, ULCOWIN operates at 110 °C, as opposed to 1600 °C for ULCOLYSIS. The high operation temperature for ULCOLYSIS technology is likely to pose greater challenges when ramping-up and -down production levels. Therefore, is seems more realistic for ULCOWIN to have near-future potential to technically operate in such a nature.

The electrolysis process requires 9.34 GJ/ton-HRC (9.15 GJ/ton-liquid steel (LS)), equating to 2595 kWh/ton-HRC[1]. The assessment is performed at one hour intervals and hence, assuming 8760 hours of operation per year (100% availability), the electricity demand per hour in the base case equates to 0.296 kW to produce 1 ton-HRC.

Table 5.1 displays a summary of the flexibility scenarios and assumptions for the assessment. The flexibility assessment only concerns the electrolysis part of the process and hence electricity demand of the other processes is kept constant. The scope of the overall process is displayed in Figure 5.1.

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[1] The overall process production process requires 3950 kWh/ton-HRC

Table 5.1: Flexibility scenarios and assumptions

Scenario	**Capacity (kW)**	**Minimum operating capacity (kW)**
Base	0.296	0.296
Low flexibility	0.444 (1.5×0.296)	0–0.296 (dependant on E_{max} assumed)
High flexibility	0.592 (2×0.296)	0–0.296 (dependant on E_{max} assumed)

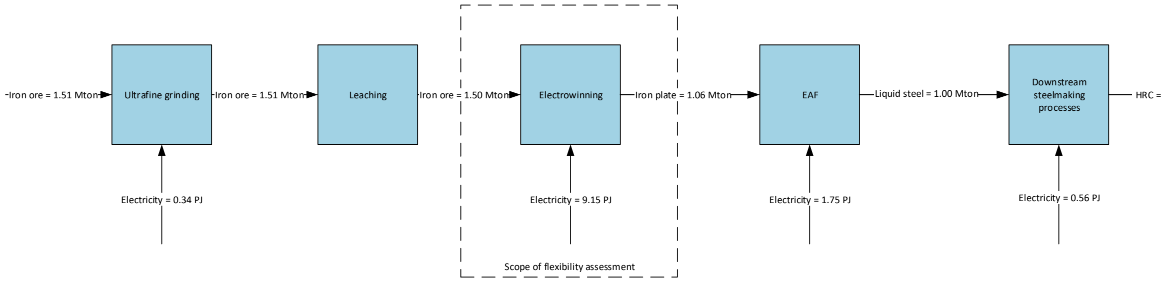

Figure 5.1: Electricity demand and scope of flexibility assessment of electrolysis-based steel production

The model is based on comparing the profit margins of implementing different scenarios of operational flexibility compared to the base case of inflexible operation. The parameters and assumed values used to calculate the profitability for each scenario are detailed in Appendix D.

5.2 RESULTS

This section begins by presenting results from the two COMPETES model scenarios, including generation mix and average hourly electricity prices in 2050. The results of the flexibility model are then displayed for the Netherlands based on the scenarios. The aim is to assess if operating flexibly, via oversizing an electrolyser system, for electricity-based steelmaking can prove to be be beneficial. These results are then compared to other EU28+ countries and considered alongside the COMPETES results. An analysis is made based on how the future electricity system characteristics affect the potential of flexible operation.

5.2.1 COMPETES model

The COMPETES model both provides data for electricity prices in 2050, but also characteristics of the electricity systems per country and for the EU28+ as a whole entity. The ever-increasing interconnectivity of the European electricity system means that electricity systems in each country have a large affect on other countries. Therefore, when considering the future electricity prices in the Netherlands, the generation mix across the EU28+ (particularly the north-west region) must be considered, rather than only the generation mix in the Netherlands. Figure 5.2 and 5.3 display the generation mix for the EU28+ as computed by COMPETES. It can be seen that in both scenarios solar PV makes up the largest share of generation. However, the generation from other sources differs between scenarios. This has an impact on the resulting electricity prices and their volatility.

Figure 5.4 displays the average hourly electricity prices in the Netherlands for both scenarios. It can be seen that the WLO low scenario, on average, has higher electricity prices than the WLO high scenario. These figures do not display the volatility of such prices and thus a sample week is displayed in Figure 5.5 and 5.6 for both scenarios in a given week in winter and summer to display the difference in electricity price volatility. It can be seen that the volatility in both scenarios, for both given weeks follow a relatively similar trend.

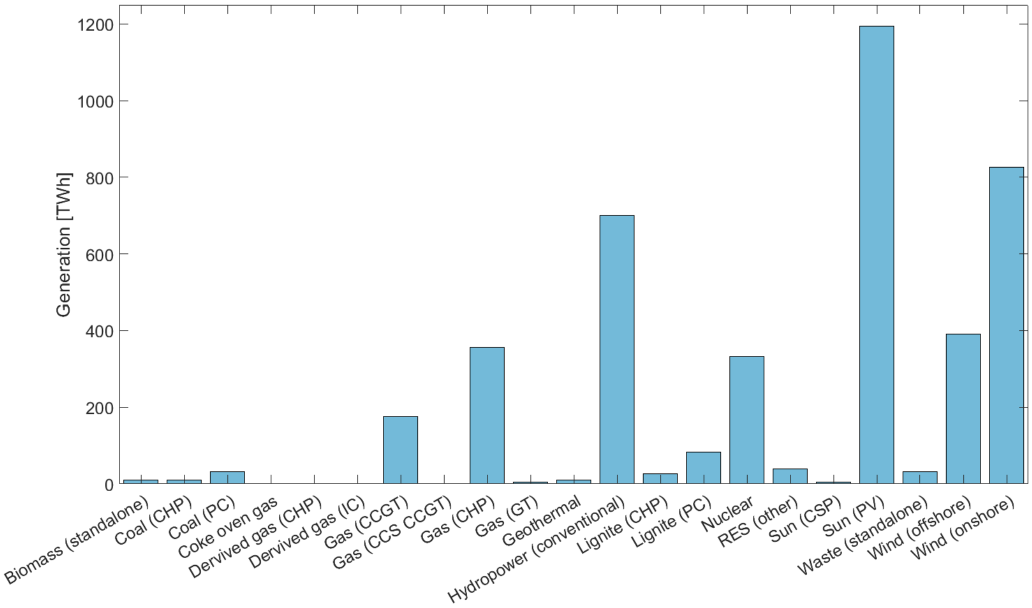

Figure 5.2: Overall generation mix for the EU28+ in the WLO low price scenario for 2050

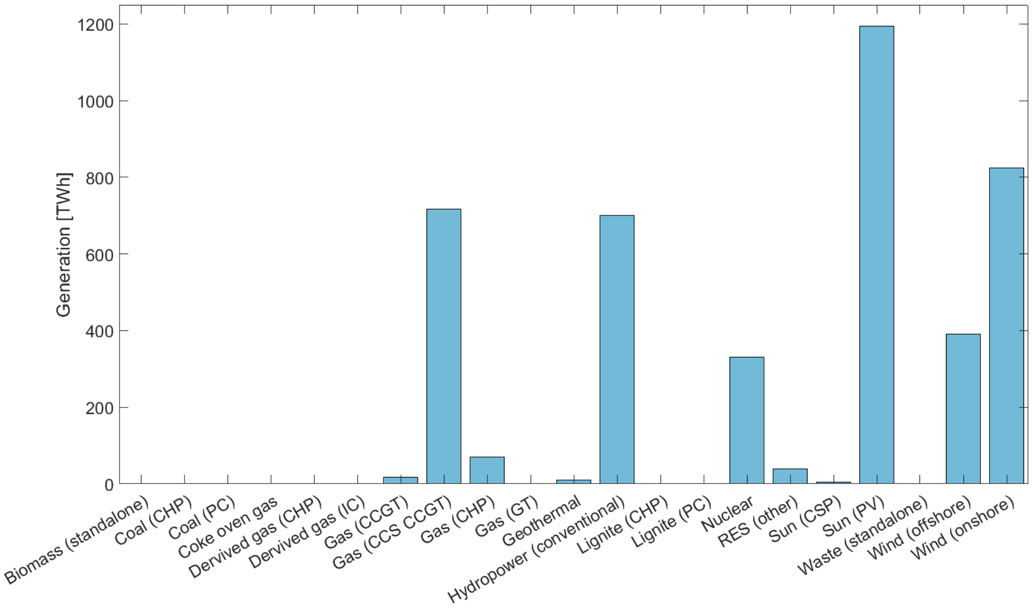

Figure 5.3: Overall generation mix for the EU28+ in the WLO high price scenario for 2050

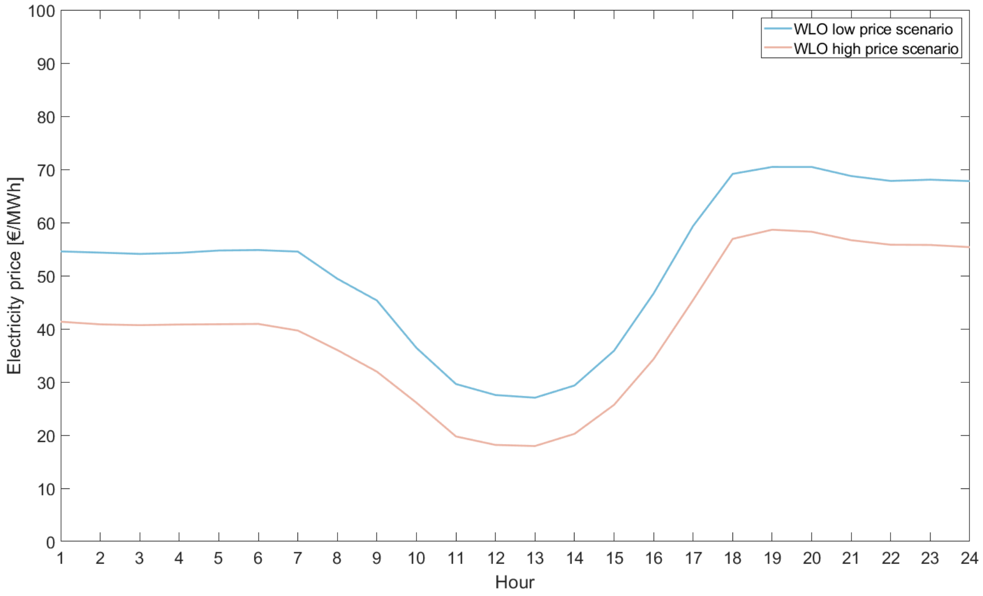

Figure 5.4: Average hourly electricity prices in the WLO low and high price scenario in the Netherlands for 2050

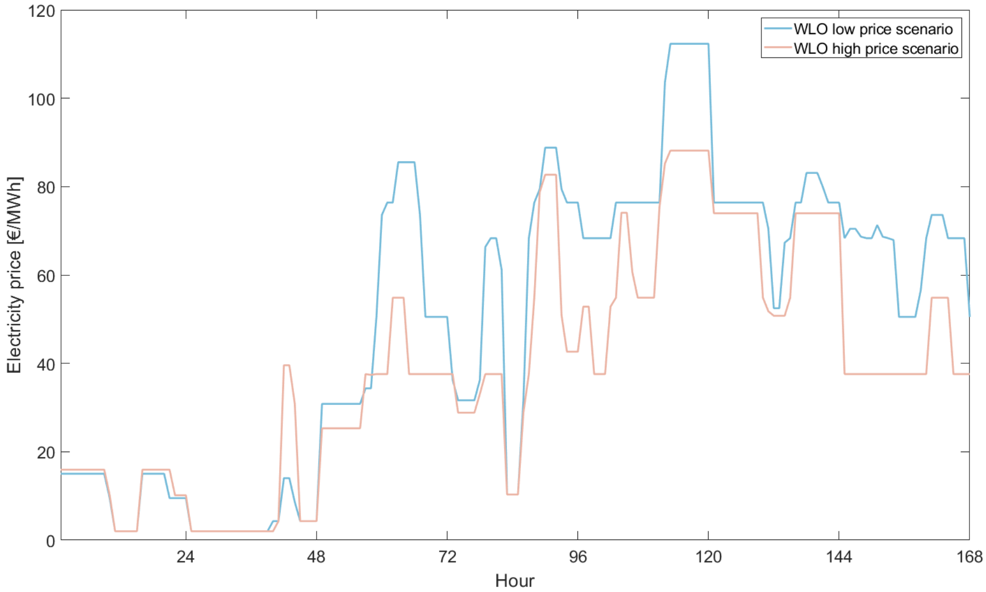

Figure 5.5: Electricity prices for the week of 1 January in the WLO low and high price scenario in the Netherlands for 2050

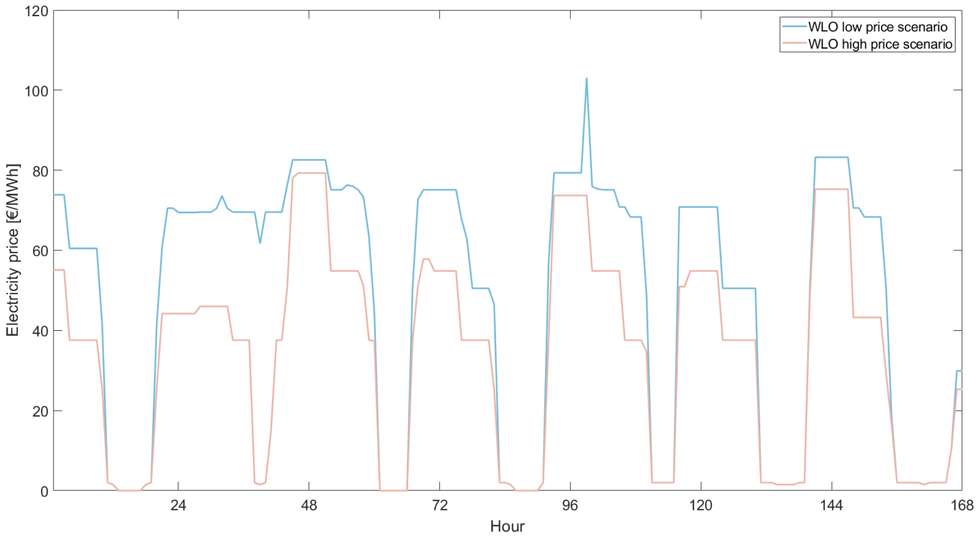

Figure 5.6: Electricity prices for the week of 1 July in the WLO low and high price scenario in the Netherlands for 2050

5.2.2 Flexibility model

Figures 5.7 – 5.9 display how the electrolyser system operates in the base case, low flexibility and high flexibility. It can be seen that in Figure 5.7 that regardless of the electricity price, the electricity demand always remains constant. In Figure 5.8 and 5.9, the electrolyser system ramps down for three periods and thus operates at a higher level than in the base case for the majority of time, capitalising on almost zero electricity prices.

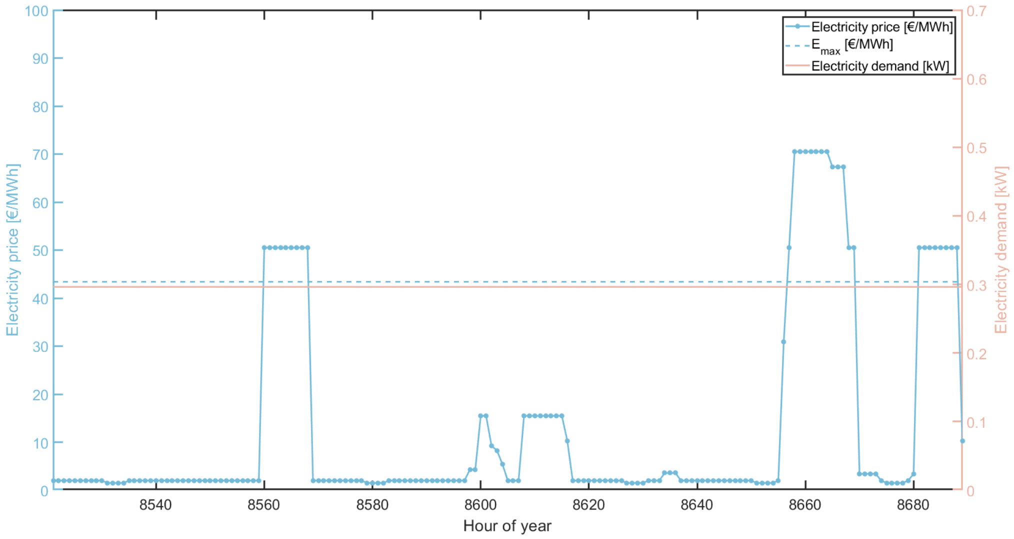

Figure 5.7: Base scenario electricity demand of electrolyser operating under low price scenario in a given sample week in 2050

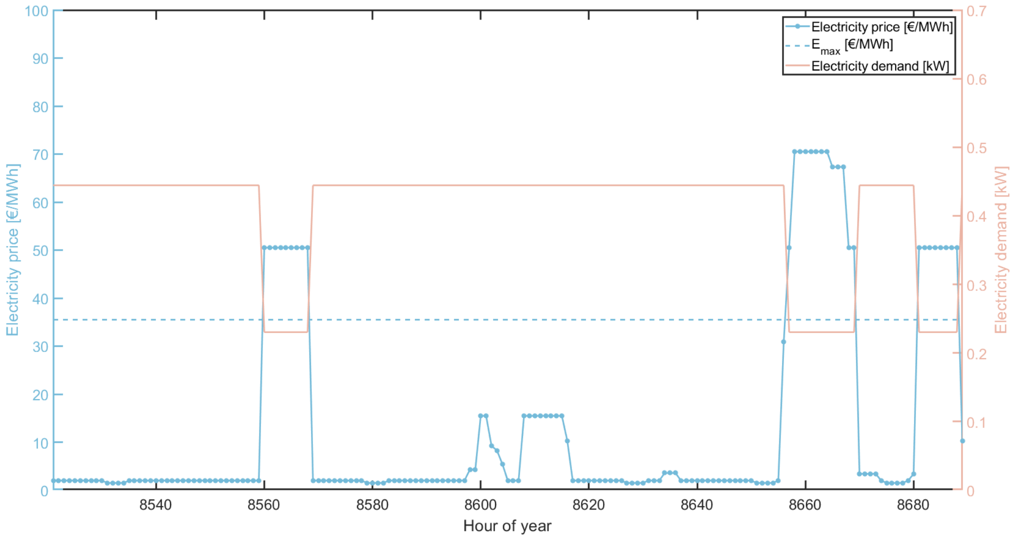

Figure 5.8: Low flexibility scenario electricity demand of electrolyser operating under low price scenario in a given sample week in 2050

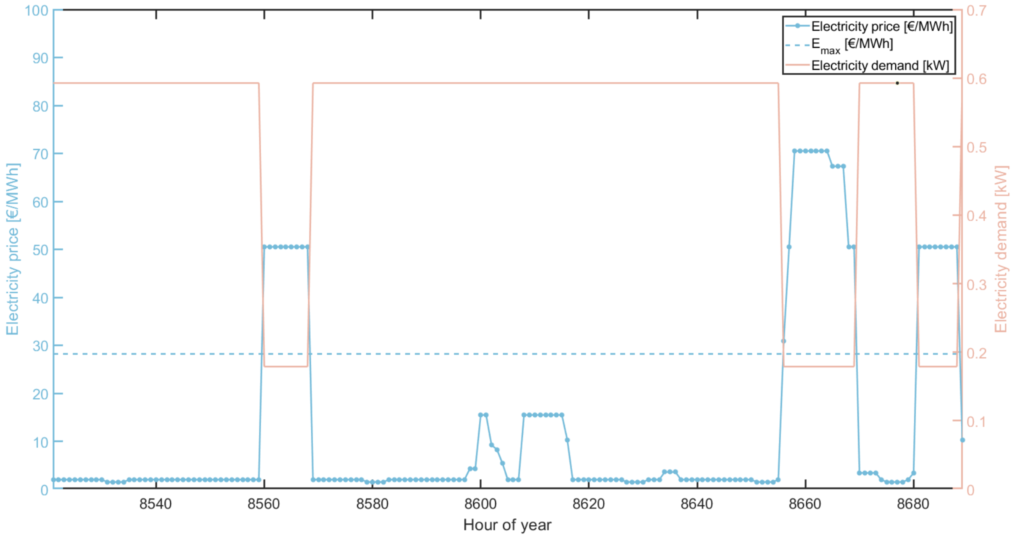

Figure 5.9: High flexibility scenario electricity demand of electrolyser operating under low price scenario in a given sample week in 2050

To assess the potential benefit of flexible operation, the profit of each scenario is calculated as detailed in Equation 2.1. The profit has been standardised to the base case, hence, all positive values show a benefit to flexibility, and negative values imply that flexibility is disadvantageous. This has been assessed for capacity cost factors, n, of 0.5, 0.75 and 1 to show the importance that this factor has on benefiting from oversizing a system to operate flexibility. Figure 5.10 and 5.11 display the results for the WLO low and high price scenarios respectively. In the low price scenario, only in the case when n is 0.5 does operating flexibly result in a benefit, marginally more with high flexibility rather than low. In the high price scenario, operating flexibly is again beneficial when n is 0.5 as well as when $n = 0.75$, but only in the case of low flexibility. Given that n is expected to be closer to 1, this suggests that flexibility is disadvantageous under both scenarios.

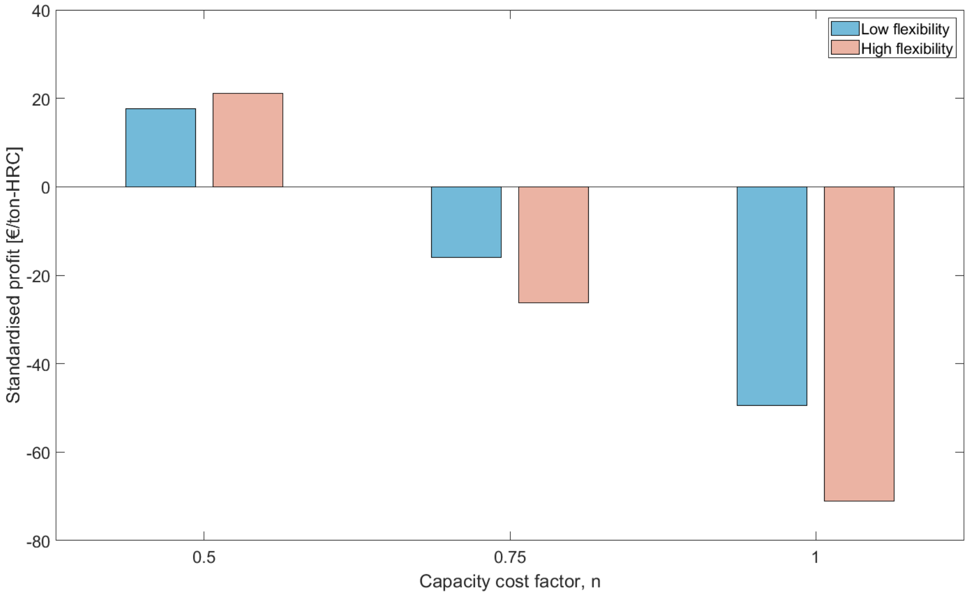

Figure 5.10: Standardised profit for low and high flexibility for a range of capacity cost factors under the WLO low scenario in the Netherlands

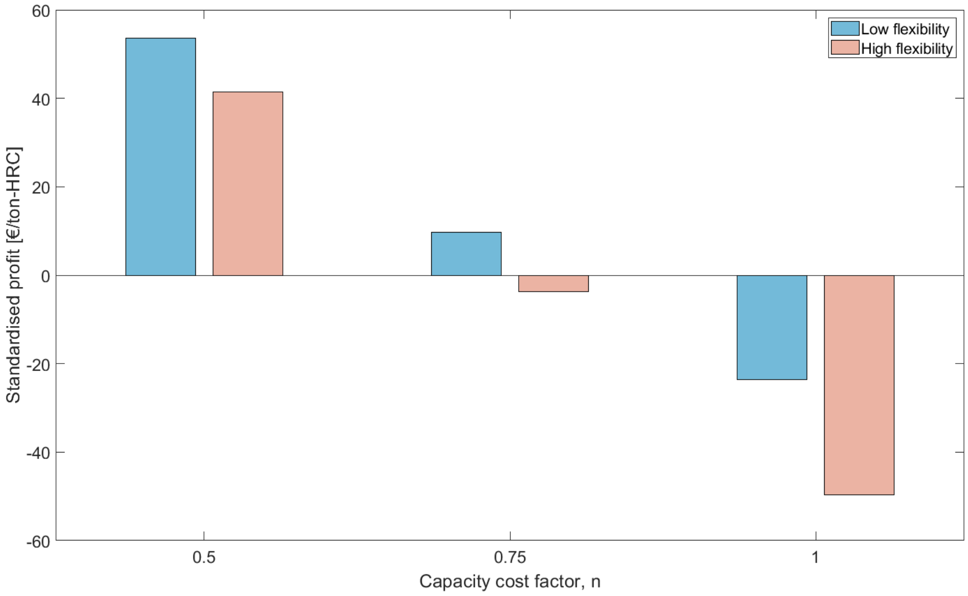

Figure 5.11: Standardised profit for low and high flexibility for a range of capacity cost factors under the WLO high scenario in the Netherlands

The flexibility assessment of other EU28+ countries is carried out for both the WLO low and WLO high scenarios with a constant E_{max} of 28.8 €/MWh, n = 0.75 and again for same two degrees of flexibility, low and high, as with the Netherlands assessment. Performing the assessment with n equal to 0.75 is selected based on the previous results in Figure 5.10 and 5.11 in which a higher n is likely to result in flexible operation being disadvantageous in all cases. Thus, an n of 0.75 allow for a better comparison in which some countries may benefit and some may not, if this capacity cost factor holds in the future. A constant E_{max} is selected for uniform simplification, and in reality this price must be determined in advance by a steel producer in advance without knowing future electricity prices or the optimal level of oversizing. Based on Table D.2, an average value of E_{max} when $n = 0.75$ is calculated to be 26.1 €/MWh. The results of the standardised profits w.r.t. the base case scenario are displayed in Figure 5.12 and 5.13 for the low and high price scenarios, respectively. The majority of countries in both price scenarios benefit from operating with low flexibility, with some also benefiting from high flexibility. In both price scenarios, France benefits the greatest from flexibility and Finland benefits the least. In the case of Finland, the base case is the mode beneficial mode of operation.

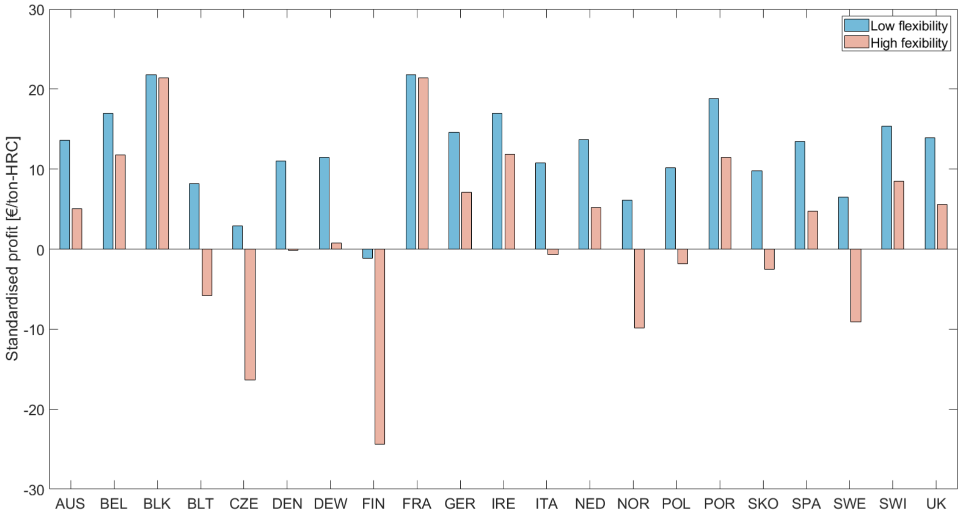

Figure 5.12: Standardised profit w.r.t. the base case of low and high flexibility implemented to an electrolyser system in the EU28+ under low price scenario in 2050

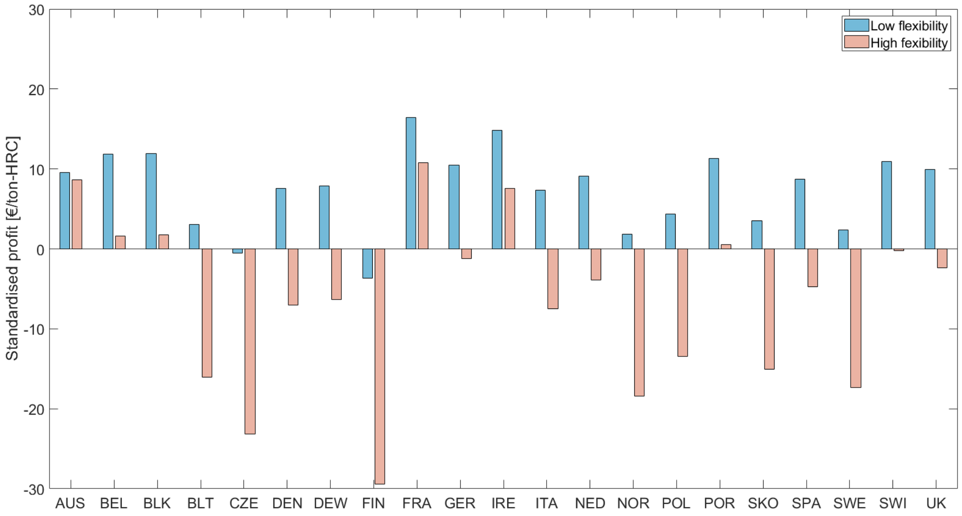

Figure 5.13: Standardised profit w.r.t. the base case of low and high flexibility implemented to an electrolyser system in the EU28+ under high price scenario in 2050

5.2.3 Electricity system characteristics

In order to interpret and explain the results of profit margin from operating flexibly in the Netherlands and compared to other EU28+ countries, it is useful to compare their electricity system characteristics from the COMPLETES model. To gain a deeper insight into which system characteristics affect the profitability of flexibility, several contrasting countries are selected alongside the Netherlands. From the results, it can be seen that Finland (FIN) and the Czech Republic (CZE) experience the least profit from operating flexibly, and thus are analysed further to attempt to explain why this is. In addition, Slovakia (SKO) is selected because it is an example of one of the countries benefits from low flexibility but not high flexibility, and thus makes for an interesting analysis also. Firstly, the average hourly prices of the respectively countries, including the Netherlands, are compared. This is then followed by comparing the generation mixes, and finally the capacity factors of solar and wind capacities that have been assumed in the scenarios in the respective countries.

Average hourly electricity price

The average hourly electricity price profile for the Netherlands, Czech Republic, Finland and Slovakia provides a good overview of how the basic generation mix per country impacts the electricity price. Figure 5.14 and 5.15 display the average hourly electricity price profiles, under the COMPETES 2050 WLO low and high price scenarios respectively. The price profiles under both scenarios display a similar trend. The Netherlands benefits from the lowest overall prices with a moderate price drop during the middle of the day. The general trend of low prices may be owed to the more consistent offshore wind generation that is not present in the other countries. Offshore wind has zero variable cost and thus the higher, more consistent capacity contributes to yielding lower prices. Both Czech Republic and Slovakia experience a significant price drop during the middle of the day but experience relatively high prices at other times. Finland experiences the flattest of all profiles but with relatively high prices throughout the day. The flat price profile is likely owed to the majority of energy generation coming from dispatchable sources such as nuclear, gas and hydropower plants.

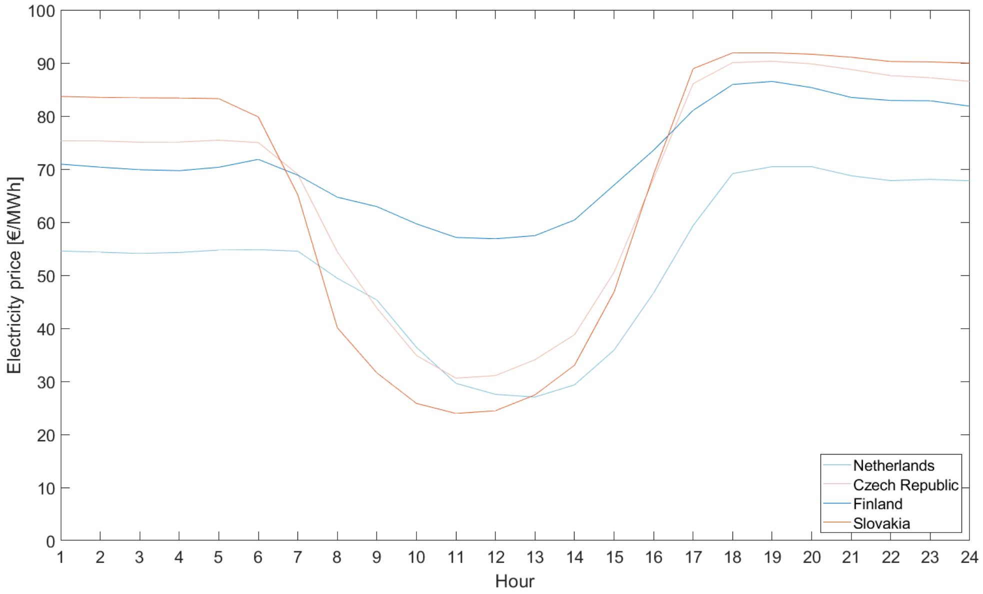

Figure 5.14: Average hourly electricity price in the Netherlands, Czech Republic, Finland and Slovakia in 2050 under the COMPETES WLO low price scenario

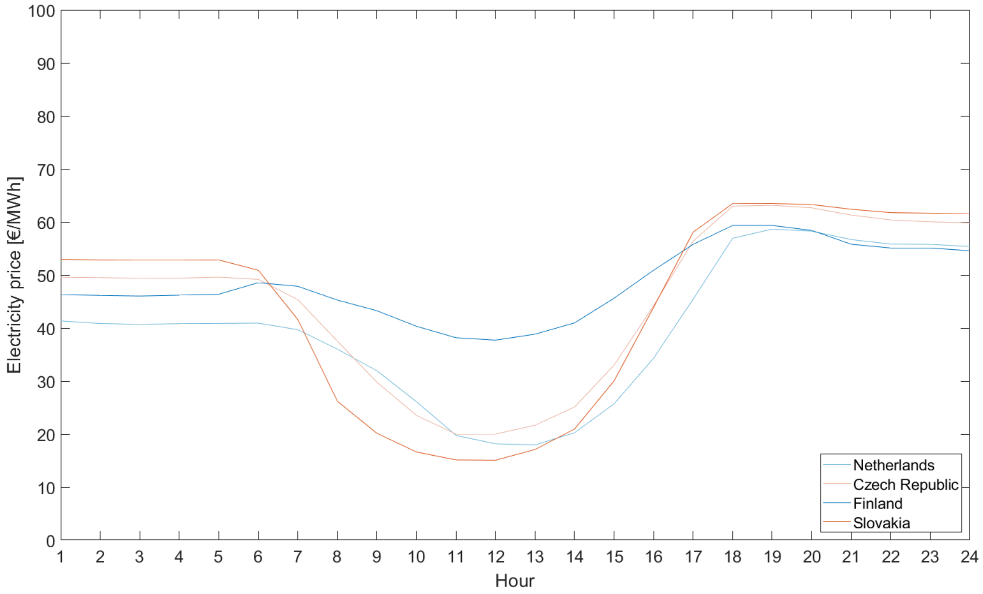

Figure 5.15: Average hourly electricity price in the Netherlands, Czech Republic, Finland and Slovakia in 2050 under the COMPETES WLO high price scenario

Electricity generation mix

The electricity generation mix of a country has huge influence on the characteristics of the respective electricity price profiles. For example, a generation mix with a high share of solar PV is likely to yield low electricity prices during peak sun hours, whereas a generation mix primarily based on nuclear energy is likely to have more stable electricity prices throughout the day. Electricity generation mixes with high amounts of dispatchable sources (e.g. nuclear, natural gas (CCGT) and biomass), are expected to have flatter electricity price profiles. These systems are thus excepted to benefit less from operating flexibly for steel production. To verify the above-mentioned claims, the electricity generation mix of the three different countries that are not based on offshore wind are examined and compared to the Netherlands. The selected countries electricity generation mix are displayed in Figure 5.16 from COMPETES 2050 low price scenario. The main characteristics per country under this scenario scenario are as follows:

- **Netherlands**: offshore wind (41%), onshore wind (19%) and solar PV (18%).
- **Czech Republic**: solar PV (31%), gas power plants (34%) and lignite power plants (20%).
- **Finland**: onshore wind (28%), nuclear (26%) and hydropower (20%).
- **Slovakia**: nuclear (44%) and solar PV (31%).

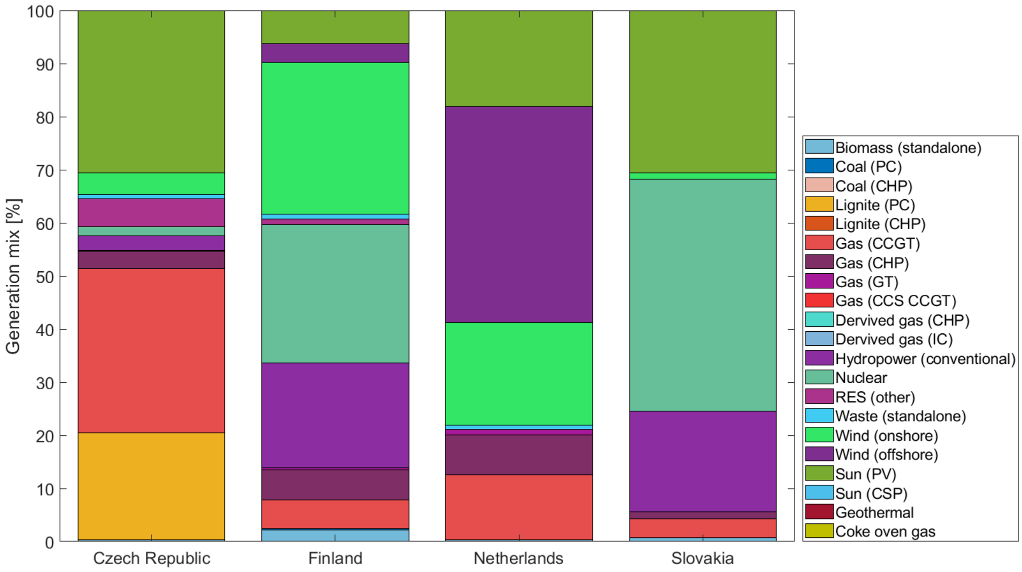

Figure 5.16: Electricity generation mix of Czech Republic, Slovakia, Finland and the Netherlands in 2050 under the COMPETES WLO low price scenario

The selected countries electricity generation mix are displayed in Figure 5.17 from COMPETES 2050 high price scenario. The main characteristics per country under this scenario are as follows:

- **Netherlands**: gas power plants (40%), offshore wind (31%), onshore wind (15%) and solar PV (14%).
- **Czech Republic**: gas power plants (60%) and solar PV (28%).
- **Finland**: Onshore wind (26%), nuclear (24%), gas power plants (22%) and hydropower (18%).
- **Slovakia**: nuclear (42%), solar PV (29%) and hydropower (18%).

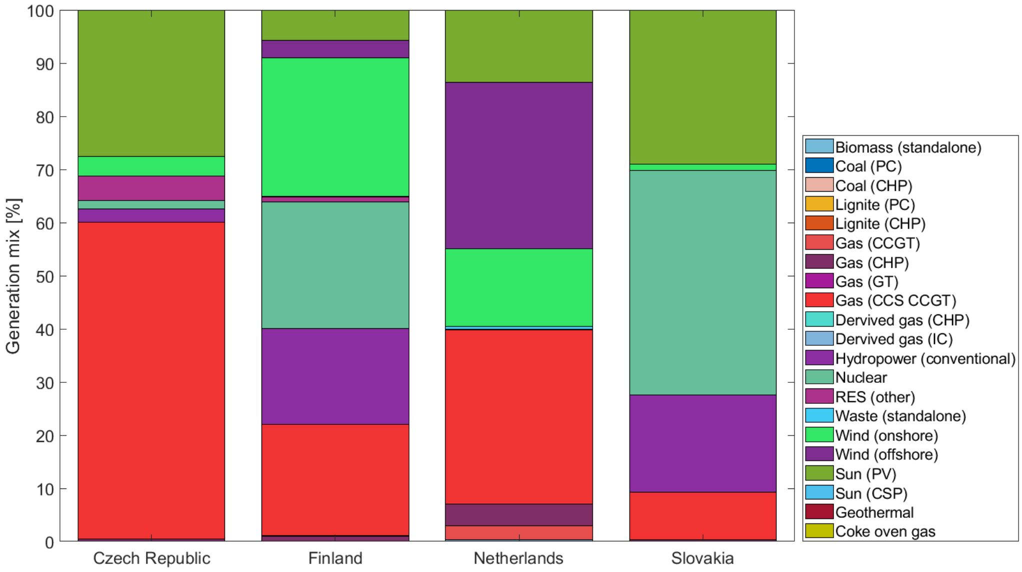

Figure 5.17: Electricity generation mix of Czech Republic, Slovakia, Finland and the Netherlands in 2050 under the COMPETES WLO high price scenario

To begin to understand how the generation mix effects the electricity price profile, it is useful to also analyse the capacity factor profiles for different energy sources to see how their generation profiles differ. Electricity generation from dispatchable energy sources generally run at a constant production level, regardless of external environmental factors such as wind speed, and only ramp down when the marginal cost of operation is higher than the market clearing price or during periods of maintenance. Dispatchable electricity generation sources include gas power plants, nuclear and hydropower.

vRESs are renewable energy sources that fluctuate based on environmental conditions such as wind speed and solar irradiance. This primarily includes solar (PV and CSP) and wind (offshore and onshore). The typical generation profiles of these energy sources differ significantly from each other. Figures 5.18 - 5.22 display the hourly capacity factors of the primary vRESs inputted to the COMPETES model for the Netherlands, Czech Republic, Finland and Slovakia[2]. In all cases, solar PV capacity factor fluctuates consistently with daylight hours, logically emphasised in the summer period, and does not generate during darkness. In the Netherlands, both offshore and onshore wind experience stable, high capacity factors in the winter period and a more spontaneous fluctuating pattern during summer months. In Finland, onshore wind produces relatively fluctuating capacity factors in both summer and winter periods, compared to that of offshore wind patterns in the Netherlands.

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[2] Only the vRESs that form the majority of the electricity generation in each country are displayed to enhance clarity.

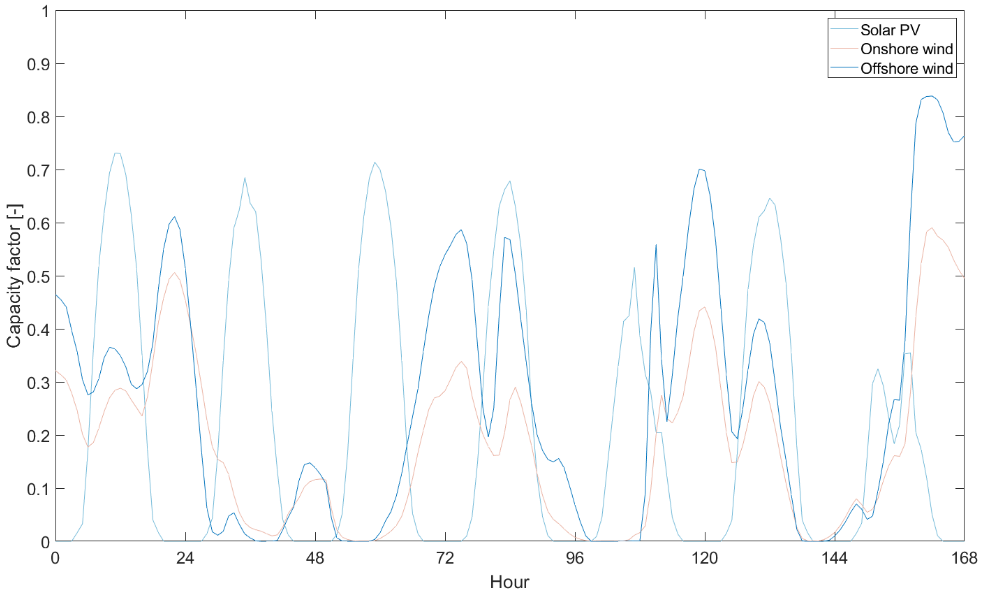

Figure 5.18: Capacity factor of vRESs in the Netherlands used for the COMPETES model on a typical week in summer

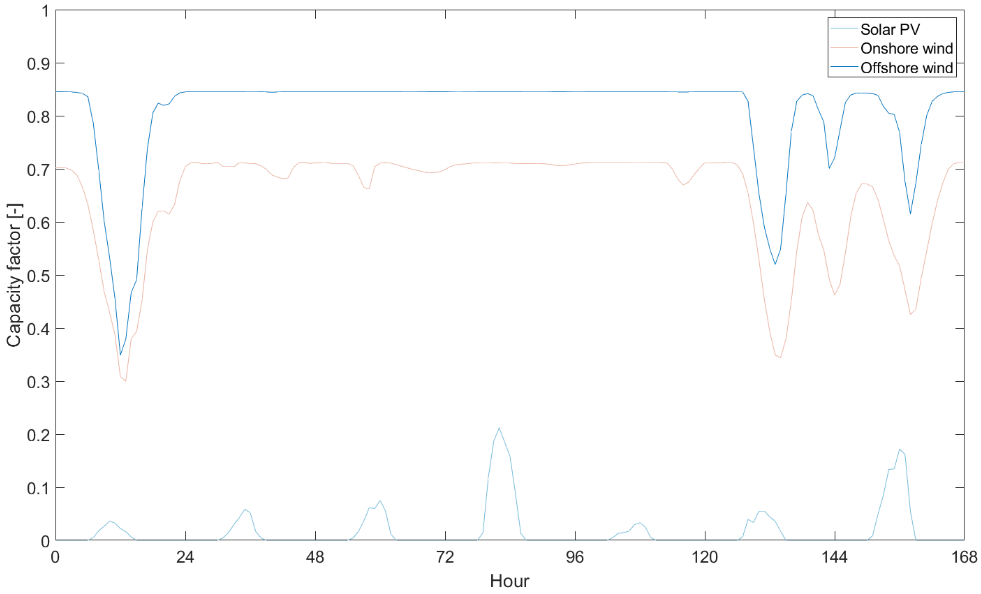

Figure 5.19: Capacity factor of vRESs in the Netherlands used for the COMPETES model on a typical week in winter

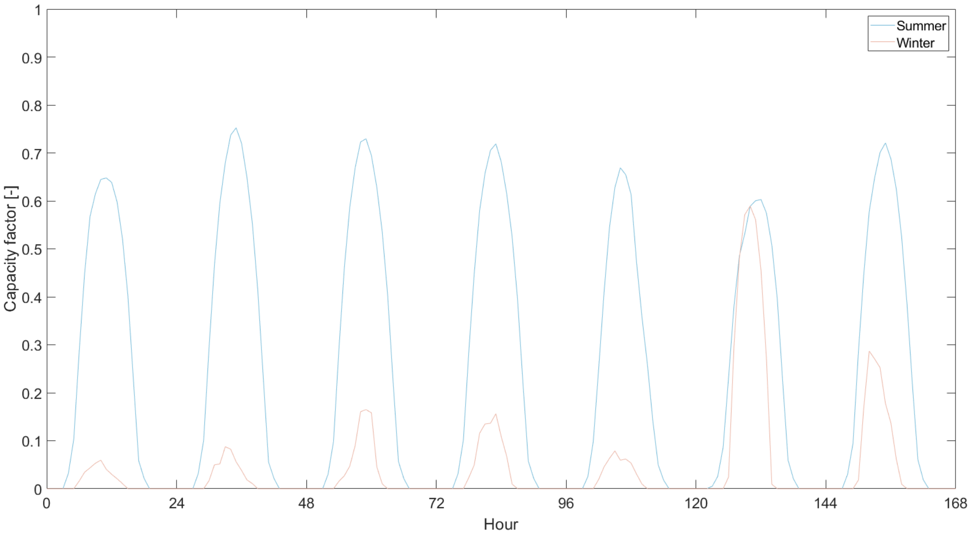

Figure 5.20: Capacity factor of solar PV in Czech Republic used for the COMPETES model on a typical week in summer and winter

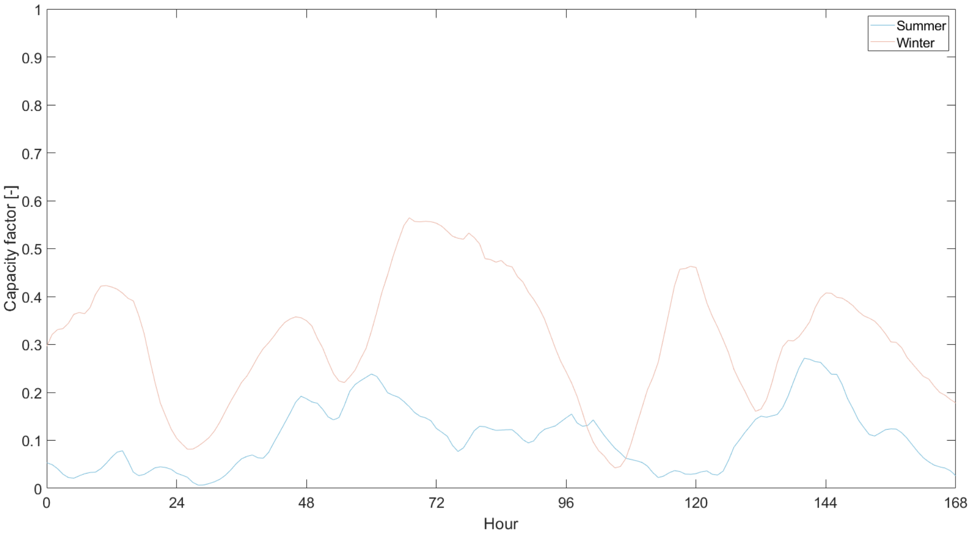

Figure 5.21: Capacity factor of onshore wind in Finland used for the COMPETES model on a typical week in summer and winter

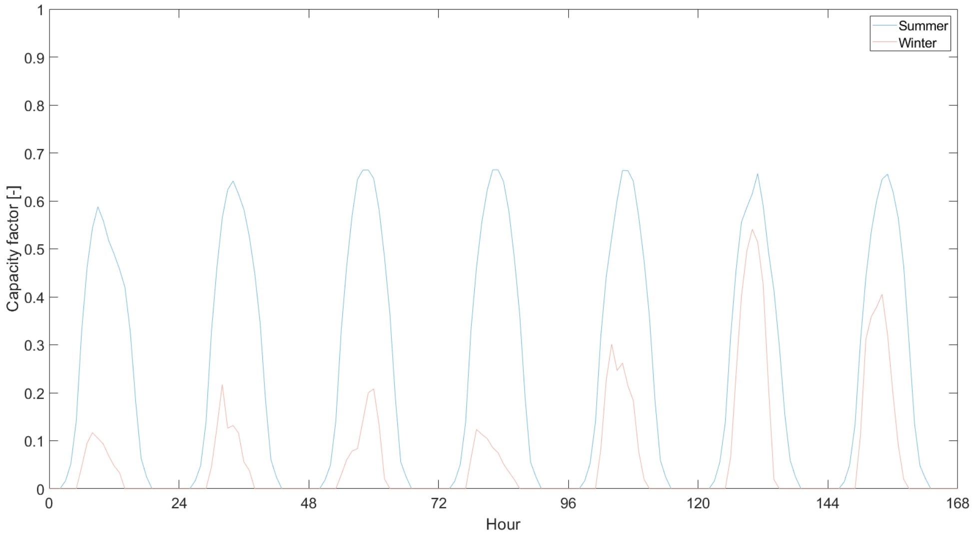

Figure 5.22: Capacity factor of solar PV in Slovakia used for the COMPETES model on a typical week in summer

The annual consistency of offshore wind production in the Netherlands appears to help yield greater potential in operating flexibility through more consistent low price electricity. Countries with a high penetration of solar PV can benefit from some periods of low prices electricity but this lacks the consistency in the winter periods to compare with that of offshore wind. The presence of nuclear and hydropower power generation generally exhibits stable and higher priced electricity relative to RESs and thus does not promote the case of operation flexibility.

5.2.4 Electricity demand

One of the feasibility challenges for the deployment of an electricity-based steel production, will be electricity availability. Figure 4.11 presents the electricity demands of the current steel production process compared with other decarbonisation options, including the iron ore electrolysis-based options, ULCOWIN and ULCOLYSIS. The current steel production process in the Netherlands requires 1 GJ/ton-HRC, this significantly less compared to the estimated 13 and 16 GJ/ton-HRC for the ULCOWIN and ULCOLYSIS options, respectively. It is useful to scale these values up to the current production levels to get an idea of the current overall electricity demand from steel production and how this compares with the electricity demand that would be requirement if electrolysis-based steel production is alternatively implemented. The current steel production level as displayed in Figure 3.2 is 7.05 Mton-crude steel (CS), translating to 6.71 Mton-HRC (1 ton-HRC = 1.05 ton-CS). Under the assumption that the production output will remain constant until 2050, Figure 5.23 displays a comparison of electricity demand that would be required to meet this production output for all considered decarbonisation options included in this report, including both iron ore electrolysis-based options. The current BF process generates its own electricity by burning WAGs, generally meeting all electricity demand in the current process. The implementation of electrolysis-based technology would thus both make the WAG-based power plants redundant alongside dramatically increasing the electricity demand from the electricity grid to almost 90 PJ (25 TWh) in the case of ULCOWIN for a given year.

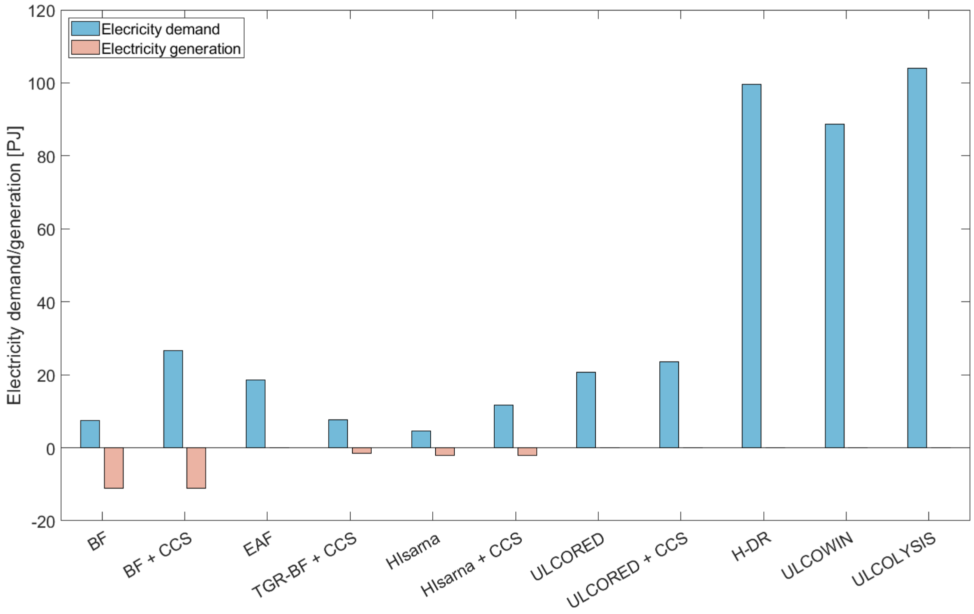

Figure 5.23: Electricity demand and generation comparison of decarbonisation options to meet the current steel production level in the Netherlands

Based on the COMPETES model, the total electricity demand of the Netherlands in 2050 is estimated to be 153 TWh. This means that the electricity demand of adopting ULCOWIN technology would thus require 16% of this demand to maintain current production levels. This may appear to be an unrealistic amount of electricity generation that would be required to support such technology. However, COMPETES also estimates that a significant amount of vRES will need to be curtailed in 2050. The increased penetration of RESs into the generation mix of all EU countries has the consequence of increase RES curtailment levels. Curtailment can be defined as as a reduction in the output of a generation source to an output less than its capacity value. Curtailment is typically deployed for two main reasons: reducing transmission congestion and reducing excess generation to match demand [9].due to the lack of demand and/or transmission capacity largely due to RES peak production periods and low demand.

From the countries being focused on in this assessment, the Netherlands is the only country with a significant amount of wind curtailment (10 TWh). Czech Republic and Slovakia are expected to have 0.8 TWh and 1.5 TWh of sun curtailment, with only a negligible amount expected in both the Netherlands and Finland. The implications of RES curtailment on resulting electricity prices cannot be concluded explicitly. However, during periods where curtailment is deployed due to oversupply of energy, it is expected that electricity prices will also fall significantly.

The curtailment estimate of 10 TWh in the Netherlands represents a significant fraction of the estimated electricity demand that ULCOWIN would require. Given that the majority of this curtailment occurs from offshore wind power in the North Sea, this may be advantageous to the current steel production site on the coastal area of IJmuiden. Strengthening the transmission infrastructure to try and take advantage of as much of the anticipated curtailment as possible may be a more viable option than in other landlocked countries in Europe. The utilisation of curtailed energy would serve to strengthen the potential benefits of operating flexibly in steel production due to increased usage of low priced electricity that is expected in these periods. The curtailment levels in the EU28+ for wind and solar under the low price scenario are displayed in Figure 5.24 and 5.25[3].

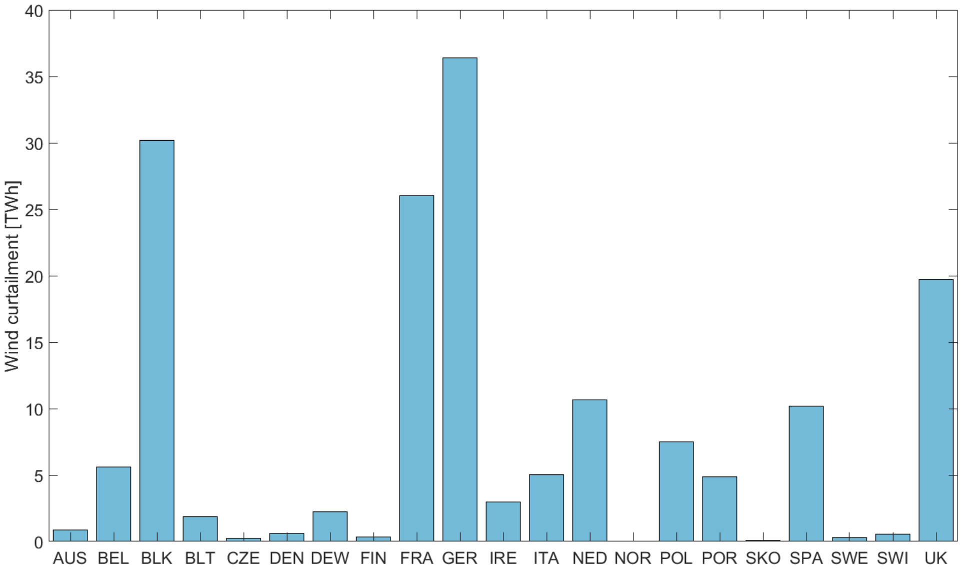

Figure 5.24: Wind curtailment levels in EU countries under the 2050 COMPETES WLO low price scenario

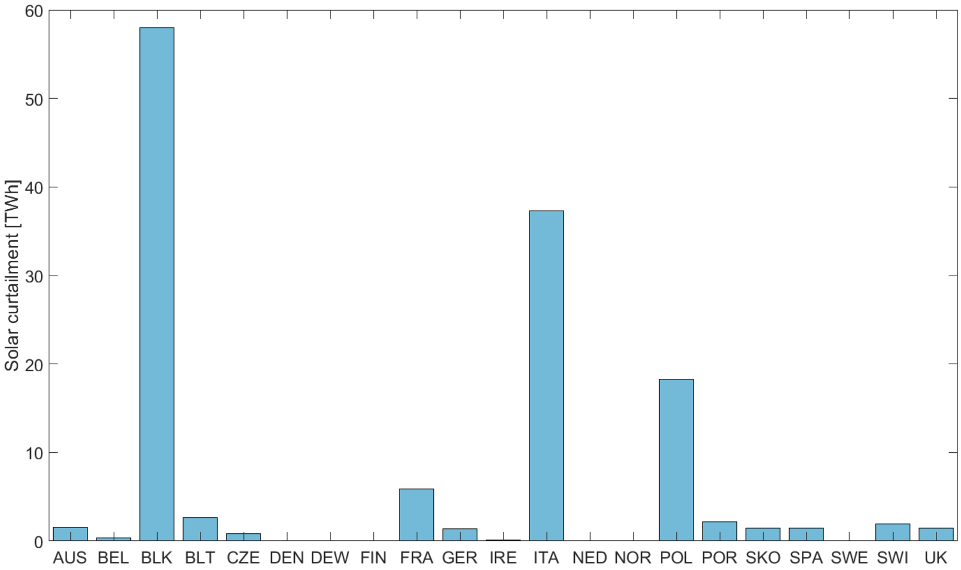

Figure 5.25: Solar curtailment levels in EU countries under the 2050 COMPETES WLO low price scenario

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[3] Curtailment levels from the WLO high price scenario yield very similar results and are thus not included for conciseness.

6 DISCUSSION

This chapter aims to discuss the findings and results from Chapter 3 to 5. Implications that these results may mean specifically for the Netherlands are explored further. This brings insights from a series of meetings with Tata Steel in which their opinions and strategies for decarbonisation are discussed. This chapter also discusses some of the limitations of this research that should be kept in mind.

6.1 DECARBONISATION: GOING DEEPER

Decarbonisation options require varying levels of infrastructure change, some options eliminate the need for some pre-processing units and others require an entirely new infrastructure, especially in the case of the hydrogen and direct electricity-based options. At the current site, operation is relatively independent with most raw materials being processed on-site. Some decarbonisation options require materials and infrastructure that may decrease independence and make Tata Steel more vulnerable to external factors. The current dominant primary energy carrier is coal, the price of which follows the global market and thus changes in the price affects all primary steel producers in a relatively similar way. A shift to natural gas or electricity-based options would potentially create a less level playing field with natural gas prices following European trends and electricity following a more national/cross-national trend. So the price risks of Dutch steel making will deviate from those of foreign competing companies. Hence, there is greater probability of steelmaking having geographical migration if high and low priced areas can be defined throughout Europe.

The economics of decarbonisation is often the focal point in discussion. However, the social acceptance of different options is often a trumping factor. Regardless of the reality of a situation, how it is perceived from the outside is extremely important. Decisions are not solely made by the steel producer, they require a great deal of acceptance both within the government, EU, non-governmental organisations and the local community. Resistance from any of these parties can put an end to a project, regardless of it being the best economically or logistically. This stresses the importance of Tata Steel to involve a wide range of stakeholders in the decision making process. Below, some technology-specific factors that are important when considering the implementation of decarbonisation options at the current steelmaking site in the Netherlands are discussed.

TGR-BF

The TGR-BF process utilises all of the current site processes with only modifications to the blast furnace required achieving a lower coking rate and a more concentrated CO_2 waste stream for CCS. However, in practice, carrying out major modifications to the blast furnace will cause a long outage period which is highly undesirable given the profit margin and steel output rate aims. Alongside this, a TGR-BF pilot plant operated by ArcelorMittal in Florange (France) has since been shut-down and so speculation around the technologies industrial scale-up remains. Hence, this option is not looked at favourably at the time of publication of this report [52].

HIsarna

The smelting reduction process refers to HIsarna technology in which the only pilot plant is currently operating at TSIJ with a yearly maximum potential production capacity of 60,000 ton-HM/year. The scale-up of this pilot plant will be built in Jamshedpur, India. The plant is planned to initially produce 400,000 ton-HM/year with a scale up to 1 Mton-HM/year eventually. The relocation decision is likely owed to cheaper labour and increasing demand for steel in Asia, whereas growth is more stagnant in Europe. This does not necessarily mean that it will not also be built in the future in IJmuiden but it may act as a trial in which its success could determine whether a similar scale-up will replace the blast furnaces in IJmuiden. The HIsarna process eliminates the need for the pre-processing plants and does not require significant electricity demand. The flue gas has a high CO_2 purity making it more suitable for CCS, an ultimately necessary step for this technology to achieve significantly low CO_2 emissions.

ULCORED

Directly reduced iron production already accounts for approximately 7% of global iron production and EAFs are required to process further into crude steel [74]. Current directly reduced iron is entirely produced with natural gas as the reducing agent. The substitution of hydrogen as the reducing agent is gaining significant attention in research and projects such as HYBRIT in Sweden are gaining momentum. HYBRIT is a project jointly led by Vattenfall, LKAB and SSAB with the aim of producing fossil-free steel by 2035 [43]. For this option Tata Steel would need to either produce hydrogen themselves or gain connection to the Dutch hydrogen grid. In both cases an enormous quantity of hydrogen would need to be available to continue to produce the current level of steel production. Due to the lower carbon intensity of natural gas compared to the current coal-based blast furnace process and the option of combining with CCS, this may be an option to sufficiently reduce CO_2 emissions with the option of switching to (green) hydrogen at a later date when it becomes more economically and sufficient quantity can be supplied. This technology is estimated to use 75 PJ/year of natural gas to meet TSIJ current production levels, hence the price of energy is of high importance for this option.

ULCOWIN & ULCOLYSIS

The development of iron ore electrolysis technologies is still relatively premature with only very small-scale demonstration production being achieved currently. With approximately 88 and 106 PJ/year of electricity required for each option respectively to meet current production levels at TSIJ, a low electricity price is essential to make this option economically feasible. This magnitude of electricity is currently very unrealistic in the Netherlands and so significant electricity generation and transmission must be planned if this option is to be considered in the future. Due to this, these options are not being considered at this moment at TSIJ [52].

CO2 capture and storage

CCS is an essential technology for many of the decarbonisation and the initiation of the Athos project may signify a preference towards these technologies. The initial estimated CCS potential of 5±1 Mton-CO_2/year is a significant quantity compared to the current total emissions. Further details, including costs, of this project are yet to be released. Porthos is another CCS project, based in the Port of Rotterdam, on an even larger scale with more industrial partners compared to Athos. It primarily intends to transport CO_2 from industrial partners via pipelines to be stored in offshore gas reservoirs. CCS in this project is claimed to be both technically feasible and cost effective compared to other climate mitigation measures to meet the Netherlands climate goals [71]. There are many concerning questions that arise in regards to the use of CCS, such as: what happens if CCS capacity is not available at a certain time (e.g. due to unexpected maintenance)? Tata Steel does not consider it feasible to invest in a CCS infrastructure themselves [52]. And as mentioned at the start of this chapter, if society is not willing to accept such a project then this may put an end to the idea completely. Something that has already happened to onshore CCS projects in the Netherlands and Germany.

CO2 capture and utilisation

CCS can be complimented with CCU by alleviating some of the burden from storage and creating products of value, forming a more circular economy. Nouryon (formerly AkzoNobel Speciality Chemicals), Port of Amsterdam and Tata Steel have partnered together to study the feasibility of a hydrogen cluster in the Amsterdam region. The parties see hydrogen as an essential feedstock for CCU by combining it with emissions to make useful products for the chemical industry. The first step of the study will study the feasibility of a 100 MW water electrolyser with a H_2 production capacity of 15 kton/year alongside oxygen production for steelmaking processes at TSIJ. With renewable energy sources, the electrolysis is claimed to save up to 350 kton CO_2/year and the partner companies intend to scale up the capacity if successful. The final investment decision on the project is expected in 2021 after evaluation of the feasibility study [56]. The partnership with Dow Chemical to produce naphtha from blast furnace gas, alongside CCS, is anticipated to be able to achieve a CO_2 reduction of approximately 4.5 Mton/year [52]. It is clear than not one solution is necessary to meet these goals, but a wide range of collaborations and technologies will be vital.

Biomass

There is potential to use biomass as a carbon input substitution, either completely or partially. This primarily concerns the BF, TGR-BF, HIsarna and ULCORED and has the theoretical potential to even provide negative emissions in some cases. The total energy requirement that biomass (namely charcoal or biogas) would need to cover to completely replace the carbon source (coal, coke breeze or natural gas) of these options is up to 107 PJ. To put this into perspective, the Netherlands is estimated to have a biomass potential of 270 PJ, of which 150 PJ is still unused. Of this total, it is unsure as to how much of these biomass sources are suitable for use in steelmaking and can be supplied sustainably. It is predicted that the total demand for biomass will rise to 430 – 600 PJ in 2030 and to 670 – 1470 PJ in 2050 [65]. Hence, it is fair to say that there would be a high reliance on imports if biomass is required as a feedstock, either partially or completely.

6.2 ELECTRIFICATION: SCALE AND LOCATION

Electrification is often seen as a logical step towards decarbonisation in many sectors. However, this is often not so simple for industry, particularly the steelmaking industry. Steelmaking is based on a chemical reaction and so the process does not just require power. Electricity, via iron ore electrolysis, to carry out such a chemical reaction is required at great quantities. Due to the huge scale that the steelmaking industry in the Netherlands operates at, this has major infrastructure and cost implications. It was found that the ULCOWIN and ULCOLYSIS technologies required 13 and 16 times more electricity than what is currently used in the blast furnace process.

The COMPETES model outputted that there will be around 10 TWh of curtailment in the Netherlands in 2050, compared to an anticipated demand of 25 TWh to maintain today's steel output with ULCOWIN technology. The level of curtailment throughout Europe differs greatly. In terms of wind curtailment, Germany, France, UK and the Balkan countries are expected to have more than the Netherlands in the range of 20 – 35 TWh. In terms of solar curtailment, Italy, Poland and the Balkan countries are expected to have 40, 20 and almost 60 TWh, respectively. The significant difference in curtailment levels per country provides opportunities to utilise such excess electricity in some places much more than others. This emphasises the shift that could occur for steel producers from the current global coal market, to more regional electricity markets in which some countries will have a competitive edge over others due to an abundance of RESs providing more periods of low-cost electricity.

To utilise a significant quantity of potentially curtailed electricity, steel production would logically have to inhibit flexible operation to ramp up production significantly during the excess generation periods. Alternatively, the excess electricity could be stored through another medium, such as hydrogen, until it is required. However, this comes with significantly efficiency loses. Overall, for electricity demand to be met at this magnitude, innovative strategies must be explored for electrification to become feasible. This further reinforces the importance of this research for supporting electrification.

6.3 FLEXIBILITY: ECONOMIES OF SCALE AND IMPACT OF RENEWABLES

The results in Chapter 5 highlight the importance that economies of scale have in the trade-off between increased capital costs and electricity savings from operational flexibility. For both the low and high price scenarios, a capacity cost factor of 0.5[1] is needed to achieve any significant profitability with respect to the base case.

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[1] A capacity cost factor of 0.5 means a plant that has twice the capacity of another, the cost will be to the power $2^{0.5}$ times the price. Further details of capacity costs factors are detailed in Appendix D

Water electrolysis, as opposed to iron ore electrolysis, can be said to exhibit "economies of number" rather than "economies of scale". What this means is that the system is of such a modular nature that scaling up does not provide an economic benefit, but rather an extra unit of capacity costs the same as the previous units of capacity. Because iron ore electrolysis technologies are still in a pilot/demonstration phase of development, it remains speculative if they can be operated on an industrial scale with such modularity. Once of the most extensive sources on this technology, [18], claims that ULCOWIN and ULCOLYSIS technology are expected to have a capacity cost factor close to 1, hence exhibit economies of numbers. As the technology becomes scaled up commercially and is found to have no economies of scale benefits then the results of this report with the given assumptions and parameters suggest that oversizing a system and operating flexibility will not be more cost beneficial than inflexible operation. However, the assumptions and parameters used in this report come with some severe limitations and uncertainties. The next subsection will discuss these further and what they mean for the conclusions of this research.

Results from the comparison of implementing operational flexibility in several EU28+ countries yielded some interesting observations. The presence of high penetration of offshore wind provided more consistent low price electricity than other RESs. Greater periods of low price electricity prices allow for greater capitalisation if operational flexibility is implemented. The seasonal fluctuation of solar PV generation appears to yield fewer periods of low price electricity considering both summer and winter. Finally, nuclear and hydropower generation appear to contribute to making electricity prices higher and more stable, with less opportunities for a flexible steel production system to capitalise on low electricity prices. Overall, the implication that different RESs have on benefiting from operational flexibility are clearly apparent but can be difficult to define due to mixtures of several sources in every country. However, the generation consistency and zero marginal cost of offshore wind that the Netherlands is expected to have in the future is likely to only strengthen the case of implementing operational flexibility.

6.4 LIMITATIONS OF RESEARCH

This research has attempted to analyse and makes conclusions based on a number of parameters and assumptions. Some of the limitations of this research can be traced back to these factors. The first limitation to be discussed surrounds the cost data used for the decarbonisation options. The estimation of costs for technology that is still in development stages yields much uncertainty, especially compared with established technologies such as the BF and EAF. The interpretation of such data is made even more difficult due to the lack of transparency of the assumptions behind the cost data. Such questions that still remain include: to what extent do the capital costs include on-site infrastructure? What CCS technology is assumed? And what is the CO_2 capture rate assumed?

The next limitation surrounds the 2050 scenario assumed for assessing the potential of operational flexibility. Assuming one scenario for a distant year will directly affect the results of further analysis but is a necessary choice to make. The energy system by 2050 can evolve in many different ways and thus invalidate much of the results. The limitation of using only a single scenario, combined with uncertainty in the parameters used to calculate the profitability of different levels of flexibility implementation enhances the uncertainty of results. However, as time progresses towards 2050, more will become known about the energy system scenario and cost data on electricity-based technologies and their economy of scale will converge towards more representational values. The results of this research can thus be built upon and continually improved in the future.

Finally, this research is also limited by a number of technology assumptions. It is assumed that the technology can ramp-up or -down at any given moment. Given that an operating temperature of 110 °C is required, this seems reasonable but in reality there may be other operating conditions that must also be met that cannot be achieved in such a dynamic fashion. This research is also limited by the assumption that iron ore electrolysis-based technologies will be commercially available by 2050. As time progresses, some of the other decarbonisation options may prove to become more advantageous both technically and economically. Thus, there is the possibility that not all of the current potential decarbonisation options will reach commercial scale up in the form that they are envisioned now.

No research is without limitations and it is hoped that this research at least sparks thought into different parameters which will become important in the future in the road to decarbonisation of the steel industry in the Netherlands and further afield.

7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 CONCLUSIONS

The objective of this research is to assess how operational flexibility can potentially support the electrification of the Dutch steelmaking industry. This objective is aimed to be fulfilled by a series of consecutive research questions. This section summarises the findings of the four research questions and then provides some recommendations for future research.

> *Which are the most energy and CO_2-intensive processes in the Dutch steelmaking industry?*

Steel production in the Netherlands has been based on the BF production process since its origin in 1918 on the same site as it is today in IJmuiden. The BF production process is based on iron ore and coal as the main raw materials, which are subsequently further processed into sinter and pellets (from iron ore) and coke (from coal) before entering one of two BFs to produce pig iron. Pig iron then enters a BOF to produce crude steel which is then processed further into rolls and sheets to make a range of products. The BF process produces a significant amount of WAGs, which are inputted into four different power plants (three of which owned and operated by Vattenfall) close-by the site in IJmuiden to produce electricity and heat for re-use in the steelmaking process.

Material and energy balances are created for each part of the process and the resulting CO_2 emissions are calculated from this. The BF is found to account for 50% of the total energy consumption, namely in the form of coal and coke. Next to this, the coke plant is found to account for 38%, and the downstream steelmaking processes (post-crude steel processing) accounting for 8%. The overall process directly emits 7 Mton of CO_2 from the onsite steelmaking processes (primarily from the BF and coke plants), and 5.7 Mton from the combustion of works arising gases in power plants. The total associated CO_2 emissions from the steelmaking processes make one of the most CO_2-intensive industries in the Netherlands.

> *Which technologies are the most promising to decarbonise the Dutch steelmaking industry?*

There are a broad range of options that have the potential to significantly reduce CO_2 emissions in steelmaking by 2050. These fall into several main categories of technologies: revamped BF (coal or biomass-based), direct reduction (coal, natural gas, biomass or hydrogen-based), smelting reduction (coal or biomass based) and iron ore electrolysis (electricity based). Alongside these technologies, CCS and CCU are also possible for those options still relying on fossil fuels, with some allowing for easier CO_2 capture than others. Most of these technologies are still in the demonstration phase of research but all are expected to be commercially available at an industrial scale by 2050. The energy requirements of each of these options varies between 14 - 20 GJ/ton-HRC, compared to 21 GJ/ton-HRC for the current BF process. The resulting CO_2 emissions from each option differs greatly, with CCS/CCU required to significantly reduce CO_2 in all options except hydrogen-based direct reduction and iron ore electrolysis-based options.

The production costs of the decarbonisation options are found to be relatively similar in terms of capital and non-energy related operating costs. However, they differ greatly in terms of energy costs, with options based on electricity and hydrogen produced by electricity, found to have the greatest energy costs. Furthermore, energy costs are expected to increase in the future. Some of the decarbonisation options require more infrastructure changes than others, depending on the necessity of pre-processing units and WAGs power plants. A shift away from coal as a primary energy source also shifts the costs to more localised electricity prices, away from the global coal market where most companies are on a more level playing field. Options based on electricity also have large implications on the electricity system as they would require significantly more generation and transmission capacity to become available for large-scale steel production.

> *To what extent can electrification support the future decarbonisation of the Dutch steelmaking industry compared to other decarbonisation options?*

One of the most notable trade-offs that emerges from analysing the most promising decarbonisation options is between energy costs and CO_2-reduction potential. Direct electrification options, such as ULCOWIN and ULCOLYSIS, are able to achieve almost zero CO_2 emissions. However, the anticipated future energy costs when the technology is expected to become available commercially in 2050 are generally much higher than that of other decarbonisation options which are not based on electricity.

In a future electricity system based primarily on RESs, electricity prices are expected to fluctuate depending on many factors, such as RES availability, demand and storage availability. Steel production directly based on electricity is exposed to such electricity prices. Unlike the coal market, the electricity market is affected by many more local, regional and national factors (including: electricity demand, network investments, congestion, and generation portfolio). This shift in markets will change the largely level playing field currently experienced in the steel industry, alongside likely making it harder to anticipate how future energy (electricity) prices will develop. This not only includes whether electricity prices will on average increase or decrease, but also how their volatility develops. Overall, electrification has a huge potential to support the future decarbonisation of the Dutch steelmaking industry by providing a greater CO_2 potential than other decarbonisation options. However, the uncertain and potentially high energy costs of implementing such a technology is one of the major challenges to be overcome for electrification options to become commercially implemented.

> *How can operational flexibility potentially support the electrification of the Dutch steelmaking industry?*

One such method that may have potential to reduce energy costs of electrification options is by implementing operational flexibility. Operational flexibility means to ramp-up and -down production (and hence, electricity demand) in response to electricity prices. This also implies oversizing the system to compensate for periods when the system is operating at a lower production rate so that steel production demands are still met. Operating electricity-based steel production flexibly is both a technical challenge (i.e. the ability to ramp-up and -down) and an economical challenge (i.e. magnitude and volatility of electricity prices as well as the geographic difference in prices).

The potential benefits of operational flexibility are assessed under two future scenarios of the electricity system in Europe, computed using the COMPETES model: (i) high fuel prices with a low CO_2 price, (ii) low fuel prices with a high CO_2 price. Two different levels of flexibility are assessed, low (150% oversizing) and high (200% oversizing) and compared to the base case of operating with no flexibility.

The results based on electricity prices in the Netherlands find that under the assumption that the electrolyser system does not benefit from economies of scale, operating flexibility in all cases is found to be unprofitable compared to inflexible operation. However, these results also show that if economies of scale are realised as the technology is developed further then there is potential for benefiting from implementing flexible operation. The results rely heavily on several other uncertain factors, including the $CAPEX$ and fixed $OPEX$ of the technology, and these also have a great impact on the potential benefits that operating flexibly may have. As time moves closer to 2050, the value of these factors will become more clear and thus the potential benefits of operating flexibly will converge to a more accurate representation.

To compare if the Netherlands could potentially benefit from operational flexibility to a greater extent that other European countries, the analysis is performed again but assuming some level of economies of scale. Assuming some level of economies of scale is a plausible assumption due to the unknown nature of this parameter thus far. The results of this assessment indicate that some countries benefit from operating flexibly and others do not. The Netherlands is found to benefit more than the majority of other EU28+ countries. An explanation is sought by comparing the energy system characteristics of the Netherlands to three less-benefiting countries: Slovakia, Finland and the Czech Republic. It appears that the expected high penetration of offshore wind generation in the Netherlands appears to help provide more stable, low-priced electricity hours likely due to the highly consistent capacity factor relative to other energy sources. This provides the Netherlands with more opportunities for low-priced electricity to be capitalised on compared to the other three countries. The other three countries are based more on lower annual capacity factor sources such as solar PV and onshore wind, based-load sources such as nuclear and hydropower, with higher resulting electricity prices, or a combination of both.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Naturally, focusing on previously mentioned limitations are a good starting point for conducting future research. One of the main limitations is the reliance on cost assumptions for premature technologies. A recommendation for future research could be to work in the opposite way, assessing what the capital, and fixed OPEX costs would need to be for operational flexibility to be beneficial. This has the advantage when the costs of premature technologies become know then the results are more applicable. However, this still comes with the shortfall that the assessment is highly dependant on the assumed 2050 scenario. Perhaps it is useful for the assessment to be conducted under more contrasting scenarios to give a wider range of results that increases the likelihood that one will become realised in the future.

Another recommendation for future research could be to explore the technical challenges of implementing operating flexibility to a greater extent than this research. Relevant aspects could include exploring the consequences and constraints of ramping-up and -down operation, operational strategies to maximise the use of potentially curtailed electricity, and comparing the technology development and future potential of low-temperature (ULCOWIN) versus high temperature (ULCOLYSIS) iron ore electrolysis technologies.

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A CURRENT STEELMAKING PRODUCTION PROCESS CALCULATIONS

MATERIAL AND ENERGY CALCULATIONS FOR CURRENT STEEL PRODUCTION PROCESS

This section intends to explain the calculations and assumptions for data unverified by Tata Steel IJmuiden, these values are coloured in black font in the material and energy balances in Figure 3.2 and Figure 3.3. For flows that can be classified as both a weight/volume and as an energetic value, Table A.1 displays the energy density values that allows for conversion between these units. Hence, it is only necessary to explain the calculations below in one of the interchangeable units. The energy and material flows are calculated to match as best as possible the data reported by [13] for the year 2017.

Table A.1: Energy density of fuels used in the current steelmaking processes

Name	Value	Unit	Reference
BFG	3.7	MJ/Nm^3	[30]
BOFG	8	MJ/Nm^3	[30]
COG	19	MJ/Nm^3	[30]
Natural gas	31.65	MJ/Nm^3	[17]
Coke breeze	28.5	MJ/kg	[17]
Coking coal	28.7	MJ/kg	[17]
Pulverized coal	28.7	MJ/kg	[17][1]
Oil	42.7	MJ/kg	[77]
Coal Tar	41.9	MJ/kg	[77]
BTX[2]	42.7	MJ/kg	[77]

Coke breeze *input to* sinter plant
Value = 0.16 Mton
Assumption: Based on [24] the average ratio of coke breeze used in the sinter plant to pellet plant is 3.7:1 respectively. It is known that 0.2 Mton of coke breeze is produced from the coke plant and hence it can be derived that 0.16 Mton and 0.04 Mton coke breeze are inputted to the sinter plant and pellet plant respectively.

Natural gas *input to* sinter plant
Value = 0.19 PJ
Assumption: Tata Steel IJmuiden verified that the natural gas usage in the 'heavy side' (pellet plant, sinter plant and blast furnace) is 0.7 PJ. Based on [24] the ratio of average natural gas consumption of the pellet plant, sinter plant and blast furnace is 1:4.8:12 respectively. The total use of 0.7 PJ is divided among these processes in this ratio.

Coke breeze *input to* pellet plant
Value = 0.04 Mton
Assumption: Based on [24] the average ratio of coke breeze used in the sinter plant to pellet plant is 3.73:1 respectively. It is known that 0.2 Mton of coke breeze is produced from the coke plant and hence it can be derived that 0.16 Mton and 0.04 Mton coke breeze are used in the sinter plant and pellet plant respectively.

Natural gas *input to* pellet plant
Value = 0.04 PJ
Assumption: Tata Steel IJmuiden verified that the natural gas usage in the 'heavy side' (pellet plant, sinter plant and blast furnace) is 0.7 PJ. Based on [24] the ratio of average natural gas consumption of the pellet plant, sinter plant and blast furnace is 1:4.8:12 respectively. The total use of 0.7 PJ is divided among these processes in this ratio.

Blast furnace gas *input to* blast furnace
Value = 8.80 PJ
Assumption: [13] states that 10 PJ of BFG and BOFG is reused within the process (excluding coke production) and Tata Steel IJmuiden verified that 1.10 PJ of BOFG is inputted into the pellet plant, and 0.10 PJ of BFG is flared and hence the remainder is assumed to be utilized in the blast furnace.

Natural gas *input to* blast furnace
Value = 0.47 PJ
Assumption: Tata Steel IJmuiden verified that the natural gas usage in the 'heavy side' (pellet plant, sinter plant and blast furnace) is 0.7 PJ. Based on [24] the ratio of average natural gas consumption of the pellet plant, sinter plant and blast furnace is 1:4.8:12 respectively. The total use of 0.7 PJ is divided among these processes in this ratio.

Coke oven gas *input to* blast furnace
Value = 1.70 PJ
Assumption: [13] states that the total final consumption of COG is 9.7 PJ in the steelmaking processes (excluding coke production). Tata Steel IJmuiden have verified that 6.2 PJ and the remainder is assumed to be consumed in the blast furnace.

Oxygen *input to* blast furnace
Value = 5.23 x10^8 Nm^3
Assumption: based on [24], an average value of oxygen consumption in 'tuyere injection' and 'other' is taken.

Oxygen *input to* basic oxygen furnace
Value = 3.74 x10^8 Nm^3
Assumption: based on [24], an average value of oxygen is taken.

Air *input to* oxygen production
Value = 4.75 x10^9 Nm^3
Assumption: calculated backwards from oxygen requirements (blast furnace, basic oxygen

furnace) assuming 90% separation efficiency and 21% oxygen content in air.

Nitrogen *output of* oxygen production
Value = 3.33 x10^9 Nm^3
Assumption: nitrogen content of 78% in air with separation efficiency of 90%. Nitrogen is widely used in downstream steelmaking processes for applications such as laser cutting of steel and oxidation protection [5].

Natural gas *input to* downstream steelmaking processes
Value = 8.00 PJ
Assumption: Tata Steel IJmuiden verified that the natural gas usage in the 'light side' (classified as downstream steelmaking processes in this report) is 7.5 PJ. However, this value has been increased to meet the total natural gas usage (excluding coke production) as reported in [13].

Electricity *input to* sinter plant
Value = 0.46 PJ
Assumption: Based on [24], the lower value in range is used.

Electricity *input to* pellet plant
Value = 0.46 PJ
Assumption: Based on [24], the average consumption value is used.

Electricity *input to* blast furnace
Value = 1.67 PJ
Assumption: Based on [24], the average consumption value is used.

Electricity *input to* basic oxygen furnace
Value = 0.69 PJ
Assumption: Based on value in [75].

Electricity *input to* oxygen production
Value = 1.35 PJ
Assumption: Based on value in [15].

Electricity *input to* downstream steelmaking processes
Value = 3.97 PJ
Assumption: [13] states that total final electricity consumption for steelmaking processes (excluding coke production) is 9.3 PJ, hence the electricity required for downstream steelmaking processes is assumed to be the remainder from what is assumed to be used in all other processes.

Electricity *output of* Velsen 24
Value = 0.22 PJ

Calculation: total fuel input · efficiency of 36.3% [25].

Electricity *output of* Velsen 25
Value = 6.77 PJ
Calculation: total fuel input · efficiency of 38% [25].

Electricity *output of* IJmond 1
Value = 3.63 PJ
Calculation: total fuel input · efficiency of 41% [25].

Heat *output of* IJmond 1
Value = 4.97 PJ
Calculation: calculated based on an electricity-to-heat ratio of 1.37 [72].

CO_2 EMISSION FACTORS AND CARBON CONTENTS FOR CURRENT STEEL PRODUCTION PROCESS

Presented below are the emission factors for all relevant material and energy flows in the process (Table A.2) and the carbon content of steel products (Table A.3). These are used in all CO_2 emission calculations in this report with the methodology described in 3.2.

Table A.2: Emission factors for steelmaking materials and fuels

Material/fuel	Value	Unit	Source
BFG	247.4	kg-CO_2/GJ	[77]
COG	42.8	kg-CO_2/GJ	[77]
BOFG	191.9	kg-CO_2/GJ	[77]
Natural gas	56.6	kg-CO_2/GJ	[77]
Coke/coke breeze	89.8	kg-CO_2/GJ	[77]
Coking coal	95.4	kg-CO_2/GJ	[77]
Pulverised coal	98.3	kg-CO_2/GJ	[77]
Oil[3]	73.3	kg-CO_2/GJ	[77]
Limestone	0.4	kg-CO_2/$CaCaO_3$	[17]
Dolomite	0.5	kg-CO_2/dolomite	[17]
Coal tar	80.7	kg-CO_2/dolomite	[77]
BTX	73.3	kg-CO_2/dolomite	[77]

Table A.3: Carbon content of steelmaking products

Material	**Assumed value**	**Unit**	**Source**
Pig iron	0.04	wt-C/wt	[24]
Crude steel	0.0004	wt-C/wt	[31]
Scrap steel	0.0009	wt-C/wt	[31]
DRI/HBI	0.02	wt-C/wt	[24]
Carbon steel	0.03	wt-C/wt	[42]
Stainless steel	0.01	wt-C/wt	[29]

B DECARBONISATION OPTIONS: MATERIAL, ENERGY AND CO2 FLOWS

An overview of the material, energy and CO_2 flows for the selected decarbonisation options are formed using a range of sources specifically for each technology. The assumptions and sources of such diagrams are stated in Section 4.2.

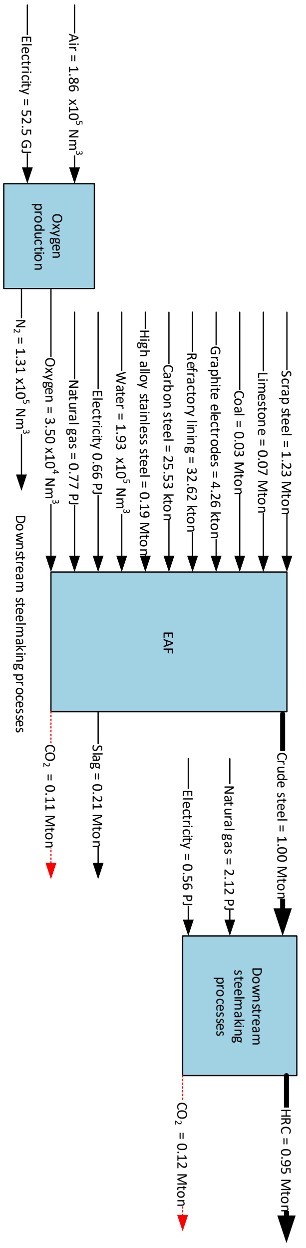

Figure B.1: Flowchart of the EAF steelmaking route

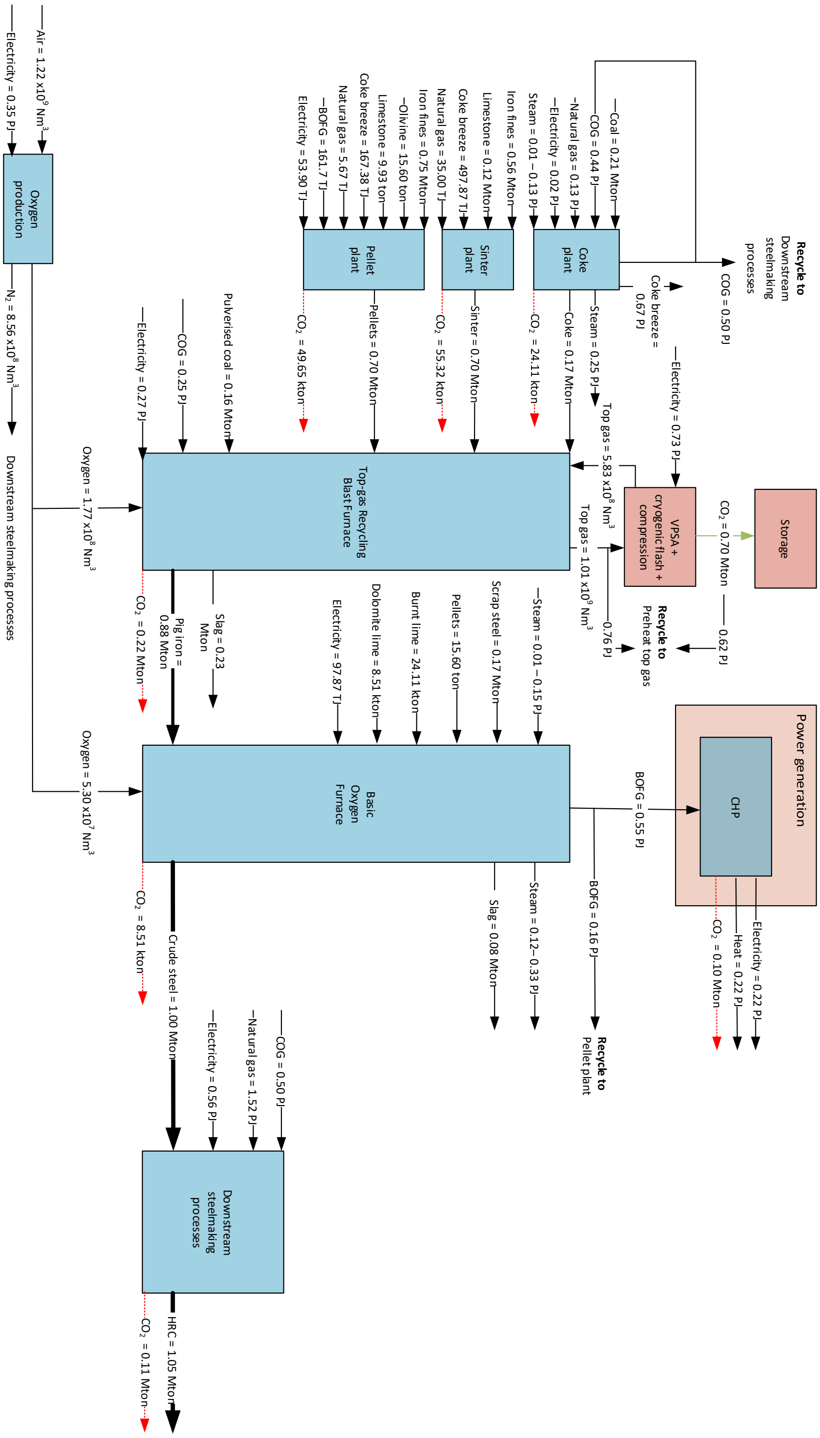

Figure B.2: Flowchart of TGR-BF (version 4) steelmaking route

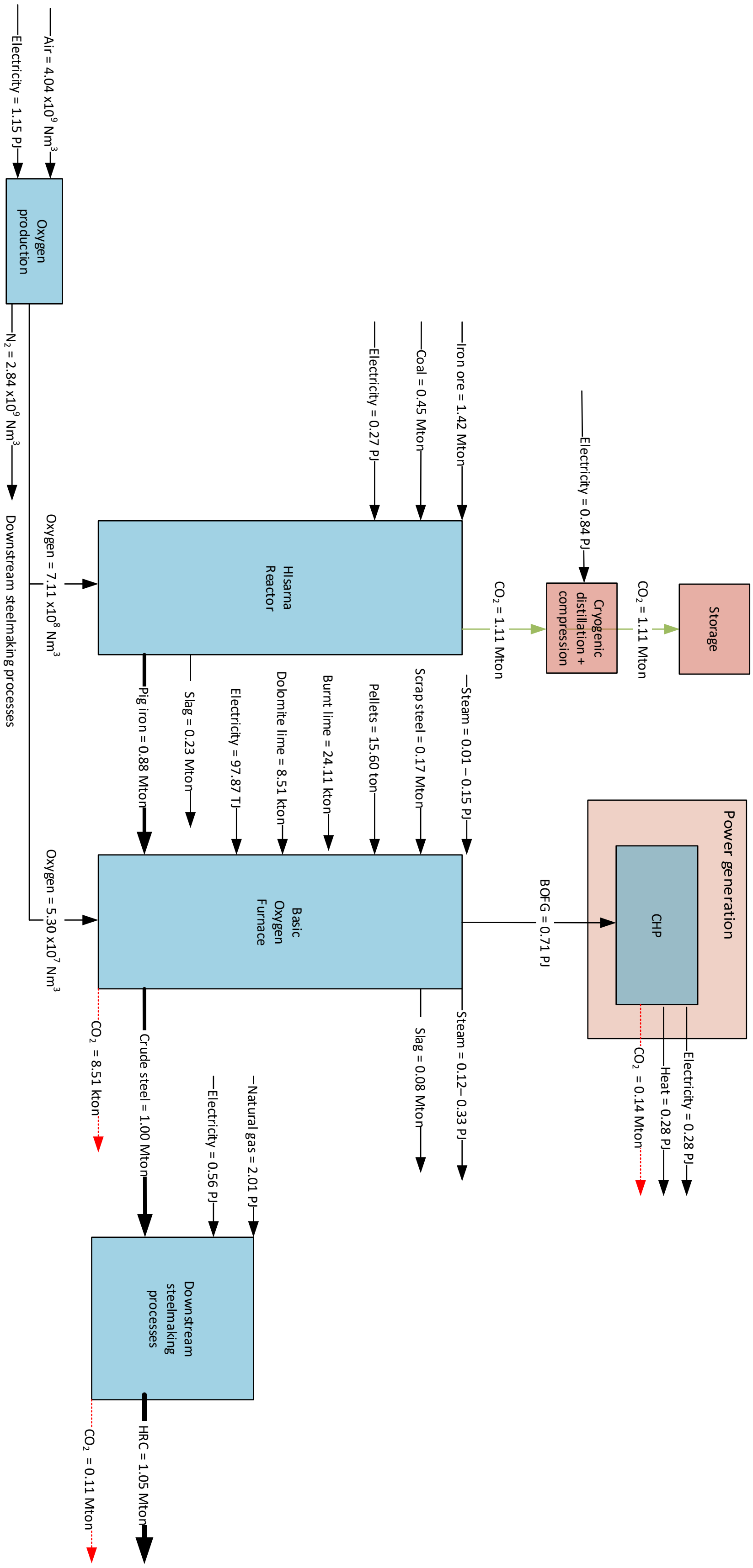

Figure B.3: Flowchart of the HIsarna steelmaking route

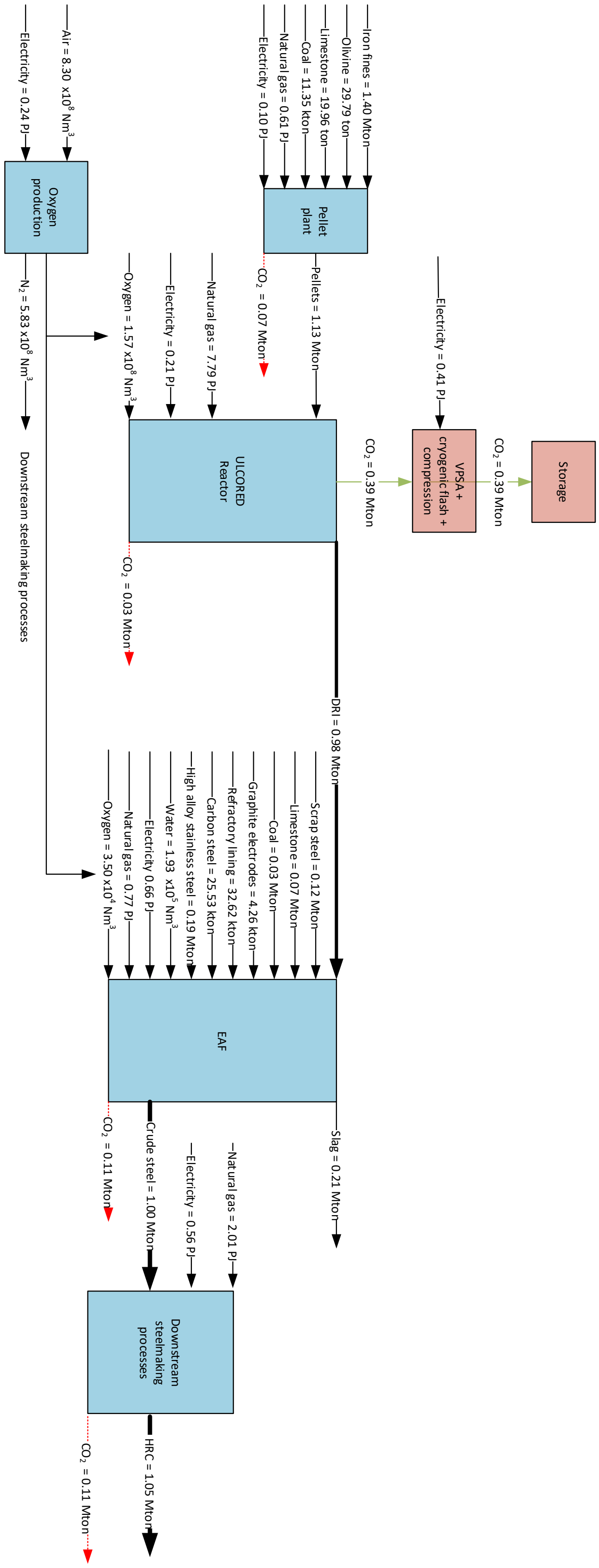

Figure B.4: Flowchart of the natural gas-based ULCORED steelmaking route

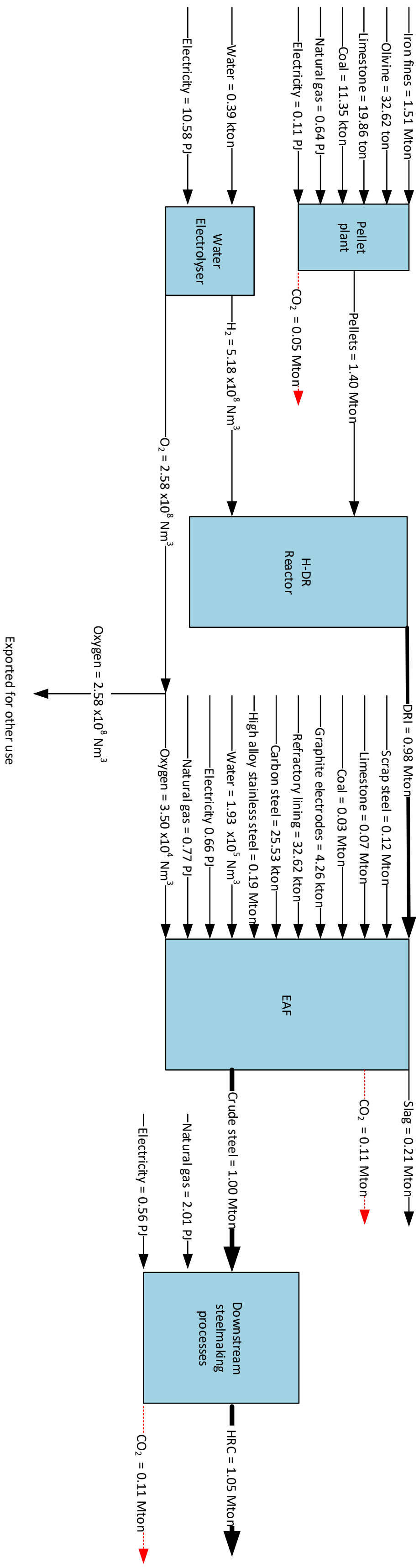

Figure B.5: Flowchart of the H-DR steelmaking route

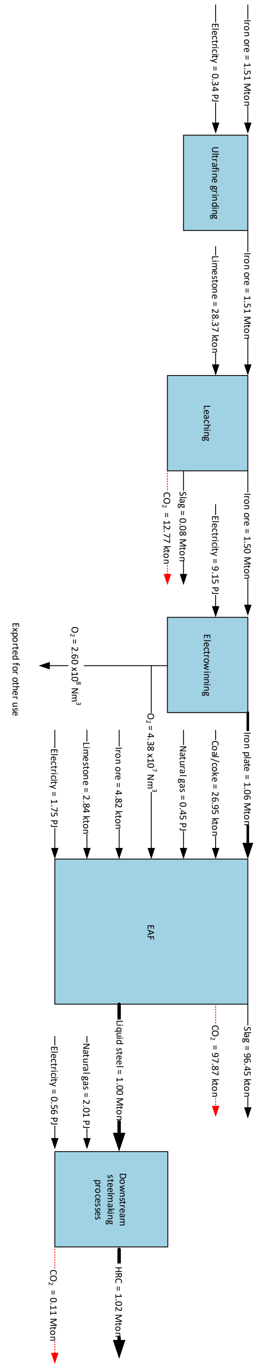

Figure B.6: Flowchart of the ULCOWIN steelmaking route

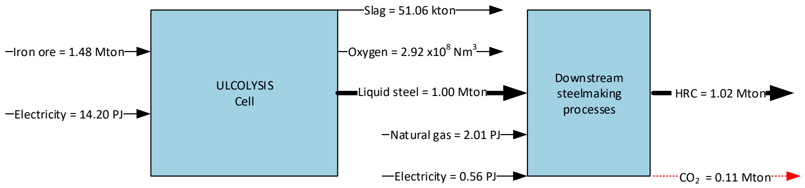

Figure B.7: Flowchart of the ULCOLYSIS steelmaking route

C 2050 SCENARIO ASSUMPTIONS

This section describes more detailed assumptions behind the selected 2050 scenario, primarily based on the Distributed Generation scenario composed by ENTSO-E and ENTSOG.

ELECTRICITY DEMAND

An estimation of the European electricity demand in 2050 is based on the linear extrapolation of the trend in electricity demand between 2030 and 2040 in the DG scenario. This scenario assumed a relative high share of flexible demand, mainly determined by hybrid HPs and EVs. ENTSO-E only provides data on the total electricity demand, the number of EV's, and the number of hybrid HP's per country, hence, additional assumptions are made to derive the flexible and inflexible share in total electricity demand. These assumptions are described in this section.

Hybrid heat pumps

ENTSO-E provides data for the total number of hybrid heat pumps but is absent of data describing the type (e.g. residential, industrial) and their contribution to the electricity demand. The DG scenarios assumes a high share of hybrid HPs in total for the residential and industrial sectors. However, it is logical to assume that the majority of the quantity is in the residential sector due to their smaller capacity. Thus, the average electricity demand per hybrid HP, will broadly represent the residential sector. An estimation of the average annual electricity demand per hybrid HP is derived as follows:

Currently there are around 98 million households in the EU28[1], assuming that the number of households will be the same in 2050, around 35% of these households will have a hybrid HP in 2050. To estimate the electricity demand from hybrid HPs as assumed by ENTSO-E, the total demand of hybrid HPs in the built environment alongside the number of houses with a hybrid HP are used (Table C.1).

Table C.1: Assumptions to calculate electricity demand per hybrid HP in EU28

Demand of hybrid HPs in the built environment [TWh]	3.96
# houses with a hybrid HP[2]	590400
Average yearly demand per hybrid HP [kWh/HP]	**6707**

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[1] `https://ec.europa.eu/eurostat/statistics-explained/index.php/People_in_the_EU_-_statistics_on_household_and_family_structures`

[2] $307.7\text{x}10^3$ (rental) + $10\text{x}10^3$ (new built houses) + $272.7\text{x}10^3$ (non-rental) = 590,400 [38]

Hybrid HP's can provide flexibility by consuming in times when the marginal cost (MC) of producing heat by electricity are lower than the MC of a conventional gas boiler. For example, during times when wind and solar generation levels are high. It is assumed that the maximum hourly potential is derived from total yearly electricity demand of power-to-heat (P2H) divided by hours in a year (8760) as in [41]

Electric vehicles

Currently approximately 300 million cars are on the road in the EU, and assuming that the total number of vehicles remains the same in 2050, approximately 40% can be considered to be EVs based on linear extrapolation between 2030 and 2040 in the DG scenario. Table C.2 displays the assumptions based on [38] used to determine the average electricity demand per EV.

Table C.2: Assumptions to calculate electricity demand per EV in EU28

Average electricity demand per km [kWh/km]	0.148
Average distance per EV per year [km/EV/year]	15427
Average electricity demand per EV [kWh/EV]	2277

In order to determine the contribution EVs can have to flexibility, an initial 'dumb' EV profile is considered in COMPETES, showing a peak in the morning and in the evening[3]. Demand shifting is then applied taking into account optimal shifting of demand from EVs over a day, explained in full in [41].

Flexibility contribution

The share of flexible demand assumed for both hybrid HPs and EVs is displayed in Table C.3 based on liner extrapolation of the DG scenario between 2030 and 2040 until 2050.

Table C.3: Assumptions for the share of flexible demand for hybrid HPs and EVs in 2050

Demand [TWh]	**2018**	**2030**	**2040**	**2050**
EU total	3299	3686	4017	4348
% difference w.r.t. 2018	-	12%	22%	32%
of which inflexible (88%)				3827
of which EV (6%)				278
of which hybrid HP (6%)				243

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[2] `https://www.acea.be/statistics/tag/category/vehicles-in-use`

[3] Consistent with assumptions in: `https://www.ecn.nl/nl/flexnet/index.html`

D FLEXIBILITY MODEL ASSUMPTIONS AND CALCULATIONS

The model to assess the potential of operational flexibility is based on the profitability of different operational scenarios. The profitability is simplified compared to reality to be represented by sales of steel products, CAPEX, OPEX and energy costs. This is displayed in Equation D.1 and the values of the parameters are explained below.

$$Profit = Sales - CAPEX - OPEX - E_{total} \tag{D.1}$$

where:

$Profit$ is the profit achieved by the steel producer [€/ton-HRC]

$Sales$ is the sales price of HRC in Europe [€/ton-HRC]

$CAPEX$ is the capital expenditure [€/ton-HRC]

$OPEX$ is the non-electricity related operating cost [€/ton-HRC]

E_{total} is total cost of electricity [€/ton-HRC]

Ultimately, the cost benefit or penalty of flexible operation is a trade-off between electricity cost savings and increased capital costs of having an oversized electrolyser system. The relation between plant capital cost and capacity can be linked by a capacity power law, as displayed in Equation D.2. n is typically in the range 0.4 to 0.9 depending on the considered plant or equipment [53]. However, according to [18], an electricity-based steelmaking via electrolysis is anticipated to not benefit economically from scaling up capacity, i.e. n is close to 1. Due to the premature technological development, this value still holds great uncertainty. Hence, to determine the $CAPEX$ of oversized systems in the assessment, three n values are used for comparison: 0.5, 0.75 and 1.

$$CAPEX_2 = CAPEX_1 \times \left(\frac{Q_2}{Q_1}\right)^n \tag{D.2}$$

where:

$CAPEX_1$ = base cost [€]

$CAPEX_2$ = scaled up cost [€]

Q_1 = base plant capacity [MW]

Q_2 = scaled up plant capacity [MW]

n = capacity cost factor [-]

Table D.1 displays the assumed cost parameters used for the profit calculations. Given that electricity prices determined by COMPETES are quoted in €$_{2010}$, all values will be converted to this reference[1]

Table D.1: Cost parameters assumed for profit calculation

	Value	**Source**
Steel price (HRC)	€500/ton-HRC	Average HRC steel price between March 2018 and February 2019 in Europe
CAPEX	€88.6/ton-HRC	[18][2].
OPEX	€239.8/ton-HRC	[18]

E_{max} is defined as maximum expenditure on electricity to the point of zero profit. E_{max} is determined by calculating the cost of electricity at the point in which steel production is just at the point of being profitable.[3]. $E_{total} = E_{max}$ when $Profit = 0$, hence this forms Equation 2.1. Because the $CAPEX$ value increases with systems incorporating flexibility, E_{max} will also vary.

$$E_{max} = Sales - CAPEX - OPEX \tag{D.3}$$

Table D.2 displays the calculated values of E_{max} and scaled up $CAPEX$ costs ($CAPEX_2$) for each flexibility scenario with different capacity cost factors.

Table D.2: Calculated values of E_{max} and $CAPEX_2$ for each flexibility scenario with different capacity cost factors

Scenario	**n**	Q_2 **(kW/ton-HRC)**	$CAPEX_2$ **(€/ton-HRC)**	E_{max} **(€/ton-HRC)**	E_{max} **(€/MWh)**
Base	0.5	0.296	88.6	141.6	35.8
	0.75	0.296	88.6	141.6	35.8
	1	0.296	88.6	141.6	35.8
Low flexibility	0.5	0.444	108.5	121.7	30.8
	0.75	0.444	117.7	112.5	28.5
	1.0	0.444	127.6	102.6	26.0
High flexibility	0.5	0.592	125.3	104.9	26.6
	0.75	0.592	143.9	86.3	21.8
	1.0	0.592	165.3	64.9	16.4

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[1] The steel price is converted from €$_{2018}$ 555.5/ton-HRC by a conversion factor of 0.9 to €$_{2010}$ 500/ton-HRC. The $CAPEX$ and $OPEX$ are converted from €$_{2005}$ 82/ton-HRC and €$_{2005}$ 222/ton-HRC, by a conversion factor of 1.08 to €$_{2010}$ 88.6/ton-HRC and €$_{2010}$ 239.8/ton-HRC, respectively.

[3] E_{max} can be converted from €/MWh to €/ton-HRC given that the entire ULCOWIN process has an electricity demand of 3.95 MWh/ton-HRC is the electricity requirements of the entire ULCOWIN process, not solely the electrolysis part.

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