An integrated high-grade waste heat network for carbon emission reduction in industrial zones

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Complex Systems Engineering and Management**

Faculty of Technology, Policy and Management

by

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To be defended in public on October 29th 2020

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TATA STEEL

Preface

Dear reader,

This thesis concludes my master Complex Systems Engineering and Management at the Delft University of Technology. The research has been conducted in cooperation with Tata Steel IJmuiden.

I am glad that I have been provided the opportunity to conduct this research at the Energy Efficiency department of Tata Steel. A team that is dedicated to capturing every possibility to reduce the carbon footprint at the site of Tata Steel IJmuiden. Despite the challenging circumstances during the "COVID-19 crisis", they have inspired, helped, and supported me in writing this thesis. I would like to give a special thanks to ing. Tom van der Velde MBE who has guided me in writing this thesis. He has been very supportive during the process and was always available for a good discussion.

Another special thanks goes out to my supervisors Dr. M.E. Warnier and Dr. ir. G. Korevaar of the Delft University of Technology. They have done an excellent job in challenging me to think critically about every step taken in the process. Through discussions and providing me with constructive criticism, they have helped me to accomplish the outcome that I had hoped for.

Lastly, I would like to thank all other people at Tata Steel and other organizations who have helped me in the process of writing this thesis.

Olaf van Egmond

List of abbreviations

BM	Benchmark
CCS	Carbon capture and storage
CF	Correction factor
EC	European Commission
ETS	European Trading System
GJ	Giga Joules
HAL	Historical activity level
HE	Heat exchanger
IAD	Institutional analysis and development framework
IS	Industrial symbiosis
KJ	Kilo Joules
KPI	Key performance indicator
kton	Kilotons
m	Meters
MILP	Mixed Integer Linear Programming
MRA	Metropole region Amsterdam
PCM	Phase-changing material
PES	Primary energy sources
PJ	Peta Joules
R&D	Research & development
RES	Renewable energy sources
TCM	Thermochemical material
TES	Thermal energy storage
TSIJ	Tata Steel IJmuiden
WH	Waste Heat

Executive summary

The global battle to reduce greenhouse gases (GHG) changes many aspects of how we should think of our energy resources. For a large part, the industry is responsible for worldwide energy consumption. In the Netherlands, this share amounts to 41% of total energy production (Compendium voor de Leefomgeving, 2019). The industry is looking into different methods to lower their energy consumption and reduce carbon emissions. This is generally done by improved technologies, and by reusing existing energy flows.

A research group at Tata Steel IJmuiden (TSIJ) is currently performing research to gain insights into how to reduce CO_2 emissions by using their existing energy flows. They are looking into using their abundantly available waste heat (WH) in such a way that it reduces their CO_2 emissions most efficiently. This study is focused on how industrial zones can optimally utilize their available WH in such a way that carbon emissions are minimized. By creating an optimal dispatch for waste heat in an industrial zone, insights into how the network should be operationalized are gained. It can also lead to industrial synergies due to cooperation between companies in the industrial zone. To provide insights into this research area, the following research question has been created:

How can industrial zones utilize high-grade waste heat networks in such a way that it maximizes carbon reduction?

The research has been performed in four phases. (1) An orienting and descriptive phase, (2) a scenario creation and modeling phase, (3) verification, analysis, and evaluation of the gained insights, and (4) the discussion and conclusion of the research. For phase 1 a literature research was performed and the IAD framework analysis was performed to determine the market dynamics of an integrated WH network. For creating the scenario, interviews were held, data was gathered and literature was used. All steps were taken to create a realistic scenario; run those in different configurations with a single-objective MILP optimization for carbon reduction.

Sectors with both large scale demand and supply of WH are likely to be interested in participating in an integrated WH network. As the impact of establishing large scale connections prevents large amounts of carbon emissions, the financial incentive to invest in these solutions will increase over time. A network is likely to be resilient towards (un)expected disrupted supply, so from an operational perspective, there are limited barriers. Nevertheless, the resilience of a network should be tested more thoroughly before implementing a WH network. Key drivers for carbon reduction are the large quantity connections, where there is a large annual WH exchange and a high utilization factor. Determining the optimal dispatch of an industrial zone will offer a method to account for the volatility of supply and demand. It was expected that flexibility in options

in the WH market would be interesting, however with the current supply and demand patterns, WH can be utilized almost fully. Hence, heat storage in a TCM is unlikely to play a large role in an integrated WH network.

Several considerations remain for the implementation of integrated WH networks. Such as the power-to-heat technology that will likely increase the share of WH supply in industrial zones. Furthermore, a market mechanism has to be established when multiple parties (>2) get involved in the network to increase the feasibility of the deployment of the network.

1
Introduction

The global battle to reduce greenhouse gases (GHG) changes many aspects of how we should think of our energy resources. Since 1995 the global energy consumption has grown on average with 6.6% and it shows no sign of discontinuing this trend. Despite the growing awareness amongst governments, global GHG have reached record heights in 2019 and are unlikely to show a decreasing trend anytime soon (Ritchie & Roser, 2020). Although the COVID-19 pandemic in 2020 has caused a surge in emissions, it is expected that this will not permanently stop this trend. This trend is an alarming notion since an annual reduction of GHG of 7.6% of the 2019 emissions is required to reach the goals of the Paris Agreement (UN Environment Programme, 2019). Therefore, it is a societal challenge to make use of energy resources more efficiently.

The industry is responsible for a large share of worldwide energy consumption. In the Netherlands, this share amounts to 41% of total energy production (Compendium voor de Leefomgeving, 2019). For this reason, the EU introduced the European Trading System (ETS), a capacity market for CO_2 emissions, allowing only companies with the right amount of certificates to emit CO_2. This policy mechanism incentivizes the industry to decrease its emissions, hence accelerating technologies that improve energy efficiency.

A research group at Tata Steel IJmuiden (TSIJ) is currently performing research to gain insights into how to reduce CO_2 emissions. Being the biggest polluter in the Netherlands accounting for 7.4% (12 mton) of the total CO_2 emissions in 2018 (Government of the Netherlands, 2019)(Schwartz, 2019), technological advancement is required to reach their goal of carbon-free steel production in 2050. As part of the program, they are looking into using their abundantly available waste heat (WH) in such a way that it reduces their CO_2 emissions most efficiently. With exhaust temperature that can reach up to 1550 degrees Celsius, it shows high potential for cost-efficiently reducing CO_2 emissions (Miró, Gasia, & Cabeza, 2016). This thesis will be an exploratory research, *'to explore and evaluate an industrial integrated network of WH utilization for carbon reduction'*. More context about the decarbonization plan of TSIJ will be provided in the next paragraph.

The environment around the project is highly complex; the many different stakeholders, the technical, economic, political, and environmental drivers all need to be taken into account. Accordingly, the project touches many aspects of the CoSEM learning goals. It additionally involves an international aspect, being subject to EU legislation and international macro-environment, such as the changing international steel market and increasing demand for carbon-free products.

This thesis consists of four different phases in order to have an analytical approach that answers the main research question, which is formulated in chapter 3. (1) An orienting and descriptive phase where literature and other information sources will be gathered and structured as an input for the next phase. (2) The scenario creation and modeling phase is about building a scenario that matches a real-world situation that functions as an input for the model. The model will be used to analyze the behavior of the WH network. (3) The third phase comprises of verification, analyzing, and evaluation of the gained insights. (4) The last phase covers the discussion and conclusion of the research.

1.1 Tata Steel's decarbonization roadmap

Carbon reduction is part of the long term strategy of TSIJ. TSIJ emits 12 mton CO_2 on an annual basis (2018), and it is their ambition to reduce that with 30% by 2030; 100% by 2050 (Tata Steel, 2020a). Investments in carbon reduction are capital intensive and are mainly driven by macro-environmental factors. National and international carbon taxation, customer demands, and the Paris Climate Agreement cause that the industry is adapting to the new realities. Generally, three levers have been identified for the decarbonization of the plant of TSIJ (figure 1.1). Lever 2 and 3 are in the scope of this thesis. However, lever 1 will be discussed to provide context.

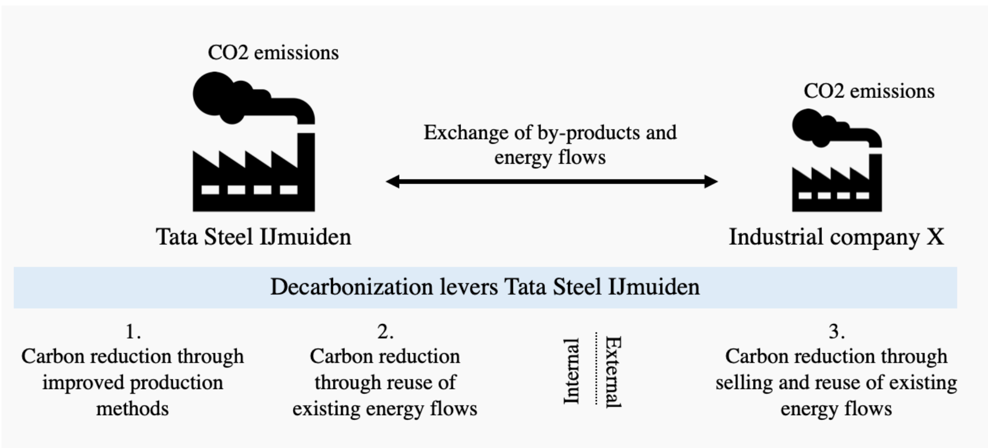

Figure 1.1 Decarbonization levers Tata Steel IJmuiden.

The first lever consists of several projects that are currently done to change the long term operation of the TSIJ plant. The most paramount of those are HIsarna, Athos, and H2ermes. HIsarna is the most carbon-efficient industrial steel production method currently known; patented and operated by Tata Steel. The first pilot plant has been built on the site of TSIJ and has successfully operated for several months. It demonstrated that an even greater reduction in carbon reduction could be realized than expected. HIsarna distinguishes itself compared to the established blast furnaces by taking up pure feeds such as coal and iron ore. Whereas the blast furnaces require energy-consuming pre-treatments to produces cokes gas and sinters (Regoort, 2006). A carbon reduction of 20 – 35% is expected by implementing HIsarna (Tata Steel, 2020b). Project Athos concerns carbon capture and storage, a technology that is considered as a short- to medium-term solution. It comprises capturing and compressing CO_2, which will be transported to- and stored in empty gas reserves in the North Sea. This project demonstrates strong synergies with HIsarna, since HIsarna flue gases contain high concentrations of CO_2 that are ready for immediate storage. Blast furnace flue gases contain lower concentrations of CO_2 and require purification. The last project, H2ermes, has a long horizon and is part of the long term strategy of Tata Steel. Together with partners Nouryon and Port of Amsterdam the development of a 100MW green hydrogen plant at the site of TSIJ is performed. This electrolysis plant will be powered by off-shore wind parks on the coast of IJmuiden. Green hydrogen is an energy carrier that is an enabler for carbon reduction. However, the technology is currently too immature to implement it on large scale.

The second lever is in the scope of this thesis and touches upon industrial symbiosis, a relatively new research area that focuses on reusing by-products and energy flows in industrial areas. Energy flows will be the main focus of this research. Part of the abundantly available WH is currently utilized, however large quantities of unused WH could still be captured and reused. Currently, these investments have not shown high financial performance, but the increasing CO_2 taxation and increased commercial importance change these returns on investments. Hence the interest of the Tata Steel research group to gain knowledge in this field.

WH supply to external industrial companies is an emerging paradigm and fully commits to the principles of industrial symbiosis. This is the third lever for decarbonization. By connecting two industrial companies, synergies can be created; carbon emissions could be reduced on a system level. Nevertheless, this inter-company exchange of energy flows is a complex matter and requires a systematic approach to account for mutual benefits. Interest in this field is due to the potentially higher yields and better matching patterns of demand and supply, hence a more optimal dispatch of heat in the system. Therefore, the research group of Tata Steel has started this research project to look into the possibilities of an integrated WH network.

2

Background & Literature Review

A potential role for WH is reserved in the plan for decarbonizing the industry. By reusing heat, the usage of primary energy will reduce due to the lower residual energy demand, hence increasing energy efficiency. Moreover, the planned increase of carbon taxation will drive investments in this area, such that investing in WH infrastructure is preferred over paying carbon emission taxes (Government of the Netherlands, 2020). To understand how carbon taxes drive carbon clean technologies, the chapter will start with an explanation of the carbon taxation system. Followed by a literature review to establish the current status of this research field. Based on the background and literature review, the scientific and societal relevance will be elaborated on; a knowledge gap will arise.

2.1 Carbon taxation

As stated in the introduction, the main driver for investing in clean, low carbon technologies is the increasing carbon tax. Companies situated in the Netherlands are currently subject to one form of carbon taxation, the ETS. The ETS also concerns two other GHG, nitrous oxide and perfluorocarbons. These are due to the scope of this assignment not considered. This cap and trade system, founded in 2005, is designed so that all installations in the system will not exceed the total emissions cap. This cap is reduced over time, meaning that if demand would remain the same the carbon price would increase. Within this cap, companies receive or buy emission allowances, which can be traded if needed. It is also possible to buy a limited amount of international credits from emissions-saving projects. After each year, a company must submit its credits equaling its emissions (European Union, 2015). The inability to submit these credits leads to high fines and is strategically not interesting. Although the ETS has proven to drive carbon emission down, the system is not perfect yet. The European Commission (EC) has planned several improvements for the ETS towards 2030. The EC will increase the pace of annual reductions with 2.2%, starting from 2021. It will also reinforce the market stability reserve (Council of the EU, 2018), a mechanism that deals with the surpluses of credits caused by economic fluctuations.

Companies that are on the EU carbon leakage list obtain free credits. This list is created for industries of which the risk exists that they move their operation to countries where the carbon taxation is cheap or non-existent. The steel industry is placed on this list and receives free credits based on three factors. The historical activity level (HAL), a benchmark factor (BM), and a correction factor (CF). This benchmark factor compares the performance to the industry and determines whether a company belongs to the top

10% in terms of emission performance. If a company belongs to this category, a larger share of the emissions will be covered by free credits.

$$Free\ carbon\ credits = HAL * BM * CF$$

According to the Dutch government, the ETS is not performing well enough, therefore they designed an additional carbon taxation system. This law is created to further stimulate companies to innovate in low carbon technologies. The CO_2 tax is designed as a tax with a decreasing exempted rate. This entails that the emissions belonging to the category of intended national carbon reductions are taxed. The remaining emissions are exempted; will decrease linearly until 2030 to the corresponding carbon reduction goals (Stibbe, 2020). Tariffs paid for carbon emissions are determined in this law and increase over time. The price level is expected to start at 30 Euro per ton and increases annually with 10.44 Euro until 2030 (RTLZ, 2020). The difference between these tariffs and the price of an ETS credit is the tariff to be paid. Although this law applies to the whole industry, a few exceptions are made. Installations for the greenhouse horticulture, DH networks, and systems have been built for the general living area (e.g. hospitals, airports).

2.2 Literature review

Extensive literature research has been done in the field of WH recovery, storage, and transportation. The following research areas that touch upon this thesis have been identified: (1) WH recovery and storage, (2) Heat transportation networks, (3) Industrial heat exchanger networks, and (4) Industrial symbiosis. In each subsection, the state of the research area, the methods, the challenges, and the relevance will be highlighted.

2.2.1 WH recovery and storage

The first area, *Waste heat (WH) recovery* and *storage*, is an enabling technology that reuses heat to supply energy-intensive processes. It belongs to the passive type of WH recovery technologies (figure 1.1). The heat of for example the steelmaking process is captured in a medium, which can consist of a variety of salts, minerals, gases, and fluids. In literature, this medium is commonly referred to as *Thermal Energy Storage (TES) medium* (Miró et al., 2016). These substances can 'carry' this heat to be able to transport it. In WH recovery it is important to distinguish between *low-grade heat* (under 200ºC) and *high-grade heat* (above 200ºC), the latter being suitable for industrial applications (Ma, Luo, Wang, & Sauce, 2009). In heat storage, there are two types: sensible and latent heat. Latent heat concerns phase changing processes, such as melting or evaporation. Sensible heat involves temperatures changes in materials that maintain their phase.

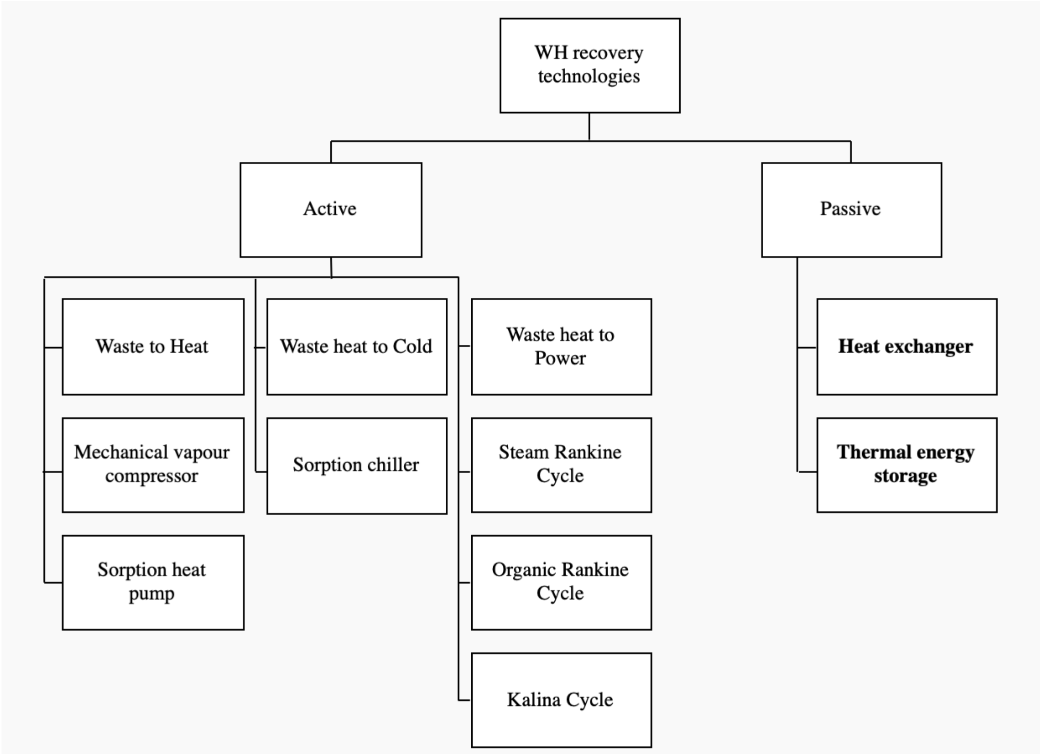

Figure 2.1 A schematic overview of WH recovery technologies (Miró et al., 2016).

There are different methodologies for WH recovery, but the basic principle is capturing and transferring heat into any system that requires heat. High-temperature WH is useful due to a high number of possibilities for application. This leads to better carbon emissions reduction possibilities on a network level. Different technologies are available for the extraction of waste heat, such as recuperators, regenerators, economizers, heat wheels, run around coils, heat pipe exchangers, plate heat exchangers, and waste heat boilers (Jouhara et al., 2018). Depending on the application an appropriate technology can be chosen.

A commonly studied method for heat storage is waste heat absorption into a phase-changing material (PCM) (Deckert, Scholz, Binder, & Hornung, 2014). PCM's transform from liquid to solid to store or release heat energy on a constant temperature level. PCM storage containers have similar esthetics as regular containers. They can store around 16,6MJ per container when charged at 250 °C, carrying 14 tons of Zeolite (the TES medium) as PCM (Krönauer, Lävemann, Brückner, & Hauer, 2015). Charging at higher temperatures could result in even higher energy densities. (Storch & Hauer, 2006) have shown that with a sorptive system the economic potential increases drastically. This is a system that dries the zeolite through a dry hot air input and extracts the heat with a moist cold air inlet. A prerequisite for this is a quasi-continuous supply (>6000h) of waste heat, resulting in lower system costs compared to natural gas. Nevertheless, with these specifications, the industrial exchange of WH is still limited. The low energy density requires a large number of containers to be transported. Currently, the Netherlands Organization for applied scientific research (TNO) is performing research into high energy density heat storage materials. The principal is similar to the application of PCM, however the material used for this application is a thermochemical material (TCM). (Xu, Li, Chao, Yan, & Wang, 2019) describe how a multi-step sorption process with a TCM can lead up to energy densities of 1368 KJ/kg at a charging temperature of 200 degrees Celsius. This equals 19 GJ per container of 14 tons of material. Which is the size of the pilot setup of (Krönauer et al., 2015), and is a factor 10^3 higher compared to storage in a PCM. Low-pressure steam production is one of the possibilities to extract the heat from the TCM (Adinberg, Zvegilsky, & Epstein, 2010).

WH *recovery* technology is in an advanced stage and is already widely applied in industrial contexts. However, advanced applications of high-quality WH *storage* are not yet widely implemented. Research into this field is progressing, with three full-scale pilot experiments performed by (Deckert et al., 2014), (Kaizawa et al., 2008), and (Selvaraj, Thenarasu, Aravind, & Ashok, 2015). The full-scale pilot experiments provide technical insights and show the performance of storage containers in a WH network. The work of (Selvaraj et al., 2015) has also been tested in the context of metal processing and makes it therefore extra relevant. It demonstrates that by capturing heat in a mold during the cooling process of metal casting, at least 6.4% of this currently lost heat could be used for preheating of the next batch. Other research of (Chiu, Meany, & Martin, 2015; Nomura, Oya, Okinaka, & Akiyama, 2010) shows that by coupling heat sources of the steel industry to a chemical plant potentially reduces the energy consumption of the chemical plant by 91% and CO_2 emissions by 82%.

2.2.2 Heat transportation networks

The second research area is the *transportation network*. There are generally two types of heat transportation networks, being a *flexible heat network* and a *continuous heat network*. A *flexible network* means that the captured heat energy is put in a secured tank or container and is transported by either truck, train, or ship. The main reason to implement flexible heat networks is to avoid the high investment costs of infrastructure. Additionally, building physical infrastructure would also cause a strategic risk by being dependent on third parties in the network. A *continuous network* consists of pipes through which a TES medium flows constantly towards its final destination, called the *heat sink* (Miró et al., 2016). *District heating (DH)* is a widely applied and the most known form of a continuous network, supplying waste heat (water) to housing areas through a long network of pipes. Industrial applications of continuous networks vary, consisting of steam and flue gas networks, or transporting heat in solid by-products (Regoort, 2006).

While the continuous heat networks are already widely applied, the state of flexible heat networks is currently immature. With the growing pressure to reduce CO_2 emissions, it becomes gradually more interesting to make use of flexible heat networks.

(Ma et al., 2009) have already shown economic performance and feasibility of flexible heat options, while strategic benefits can lower barriers to implement flexible heat networks. The full-scale pilot experiments of WH storage (Deckert et al., 2014; Kaizawa et al., 2008) are based on a flexible network design. However, a majority of research into WH recovery and storage has been performed into continuous networks. The economic and technical results can be modeled with more certainty due to the convenience of continuous heat flows.

2.2.3 Industrial heat exchanger networks

The third area is *industrial heat exchanger networks*. A more theoretical research area that focuses on heat flows and develops the mathematical optimization methods to optimally dispatch the supply and demand patterns. In industrial heat exchanger systems, different industrial installations can complement each other. By exchanging heat, more optimal use of energy can be achieved. However, flexible heat networks are not widely incorporated in this research area, although it shows high economic potential (Chiu et al., 2015). All researches are done on a numerical scale and are often combined with case studies. Depending on the constraints, MILP or MINLP are dominant methods used to determine the optimal dispatch. MI(N)LP is often used in optimizing distributed energy networks, such as the electricity grid. Other common methods are the pinch analysis, used to couple different physical heat streams optimal with minimum connections (Anantharaman & Gundersen, 2006), and simulation. Through analysis of this literature, it is evident that the goal of your optimization and the applied methods have to be customized to the case study.

2.2.4 Industrial symbiosis

A more holistic research approach is used in the last research area, where industrial regions are considered on a system level. This relatively young research domain is referred to as industrial symbiosis (Neves, Godina, Azevedo, & Matias, 2020). The concept of industrial symbiosis is that a group of firms and their stakeholders interact to achieve symbiotic linkages by revalorizing and exchanging by-products of distinct business entities (Boons & Berends, 2001). Industrial symbiotic regions can be artificial, where a third party coordinates and develops the emergence of these industrial synergies. In other cases, these regions are already existing and the emergence of industrial synergies start more locally. According to (Gibbs & Deutz, 2007) this is more often the case and also relates to the problem of the TSIJ research group. These emerging synergies are generally divided into three phases. (1) Regional efficiency is a phase in which organizations use their relationships for the coordination of industrial synergies out of their own interest. In this exploratory phase, the area is explored for potential links of supply and demand streams of waste energy, physical by-products, and knowledge (Gibbs & Deutz, 2007). (2) Companies start partnerships to create trust by making mutual agreements for industrial synergies (Boons & Berends, 2001). To account for the value of the different by-products, a systematic method has to be developed. By establishing this system to exchange valuable waste streams, it becomes more convenient for a third party to enter the agreement. (3) Symbiotic linkages are established (Boons & Berends, 2001).

Research into industrial symbiosis remains necessary but is it not the purpose to discover new scientific laws. It rather focuses on practicalities that are concerned with creating symbiotic linkages (Yap & Devlin, 2017). Successful examples of industrial synergies can be found in the manufacturing sector such as the chemical, cement, paper, steel, and iron industries. Conventional methods used in this research area are the life-cycle analysis, with a strong focus on the environmental and economic dimensions. The results of this thesis can be exemplary for other industrial zones, because “the knowledge of existing cases of industrial symbiosis can foster new synergies through relationship mimicking (Neves et al., 2020)”. Therefore, this thesis could provide a useful contribution to the research field, resolving a lack of understanding of how industrial zones can optimally use integrated WH networks.

2.3 Scientific and societal relevance

Through the literature review in paragraph 2.2, the status quo of WH recovery, storage, and networks is determined. With a system-level approach, the paradigm of industrial symbiosis has changed the view on the use of by-products and waste streams. With the increasing carbon taxation enforcing the industry to apply the reuse waste streams. This literature review is supported by the situational description of Tata Steel in paragraph 1.1, a call for smarter use of by-products and waste streams. In this thesis, waste energy flows will be the main focus, potentially being a part of a carbon-neutral society.

To realize the exchange of waste energy-flows between potential supply and demand nodes, an infrastructure should be designed that optimally reduces the carbon emissions. Paragraph 2.1.1 and 2.1.2 describe the multiple methods for heat storage and transport, however there is a lack of knowledge about how WH can be utilized to optimally reduce carbon emissions. Generic flexible infrastructure trade-offs for time and distance have been described in the work of (Miró et al., 2016), stating that the maximum distances for truck, train, and boat (flexible networks) are respectively 35km, 200 km, and 3 days. However, a method to determine how to minimize carbon emissions and operate the network is missing. Industrial heat networks often have volatile heat supply and demand patterns; the topology and infrastructure are different for every industrial region. The role of time, distance, available infrastructure, demand- and supply patterns play a big role in choices for new industrial WH infrastructure. These factors and the trade-offs have not been widely studied yet and formulate the following knowledge gap:

Investing in WH infrastructure to lower carbon emissions can be part of the solution of a carbon-neutral industry. Nevertheless, a high-level system approach that incorporates the volatility of supply- and demand is missing. This approach has to determine how WH can be utilized in industrial zones to minimize carbon emissions.

Scientific relevance:

- A novel approach to measure to determine the optimal utilization of WH in industrial zones based on the hourly dynamics of supply and demand.
- There is a lack of thorough understanding of how industrial zones should operationalize integrated WH networks and coordinate regional synergies.

Societal relevance:

- There is a need for increased energy efficiency to prevent carbon emissions, emitted by the use of primary energy resources.
- To provide insights into how heat energy can gain perceived value given the increasing carbon taxation.

3
Research Goal & Method

In this chapter, the main research goals and methods will be discussed. First, the scope of the research project will be defined, followed by the research approach. In the approach, the main research question will be divided into sub-questions. In the final paragraph, the methods will be discussed per sub-question.

3.1 Research goal

The industry is currently facing the challenge to reduce its carbon emissions. This can be achieved by improved production methods and through more efficient use of primary energy resources. In this thesis, a focus will be put on the latter, by connecting potential demand and supply nodes for WH in existing industrial regions. The *main goal of this thesis* is to establish a method that enables determining how to optimally utilize WH to reduce carbon emissions in industrial zones. The method should be applicable in different industrial zones and will generate insights into what connections are the most effective and efficient for carbon reduction. It should also help to identify the trade-offs between costs, infrastructure, and carbon emission reduction.

3.2 Scope

Macro-environmental factors such as carbon regulation are the main driver for investing in energy efficiency. Therefore, this research is limited to policies concerning carbon emissions. The regulations of the carbon taxation system are highly complex, due to the dynamic and interactive behavior with industrial benchmarks and other industrial carbon emitters (European Union, 2015; Government of the Netherlands, 2020). For industrial companies in the Netherlands, a combination of the national carbon tax and the ETS applies starting in 2021. The price level will function as a tariff-based instrument that is effective if the ETS price is below the Dutch price level. The regulation will be considered as a given and a time span of 2021 to 2030 will be applied in this research.

The developed method will specify on self-proclaimed existing industrial regions. These regions have identified themselves as a demarcated cluster due to their geographical location. The idea is that they can work on their mutual economic and environmental ambitions in a more efficient way (van Veen & Amsterdam Economic Board, 2019). The dynamics of this system have been conceptualized in a three-step framework of IS (Boons, Spekkink, & Mouzakitis, 2011). It describes the mechanisms and elements that drive the development of industrial synergies. The framework is displayed in figure 3.1 and will be elaborated on in chapter 4. Out of the multiple options of exchanging by-products and energy flows, this thesis specifies the exchange of waste heat flows in industrial regions; specifically focuses on utilizing high-grade WH. This focus excludes district heating networks, due to their low-grade heat utilization. Research into several technological applications is already in an advanced stage. However, it is still not clear how industrial zones can optimally dispatch the available WH to minimize carbon emissions. Also, the role of flexible heat networks is unclear and it is difficult to make a well-argued choice for the different infrastructural WH options. Therefore, a model will be developed that can optimize the use of WH in industrial zones; additionally can provide insights into the operations of the integrated WH network. Through the use of different CoSEM methods, which will be described in paragraph 3.4, a detailed scenario will be created that represents the real-world situation. This realistic model input will guarantee that the output of the model will be accurate and meets academic standards.

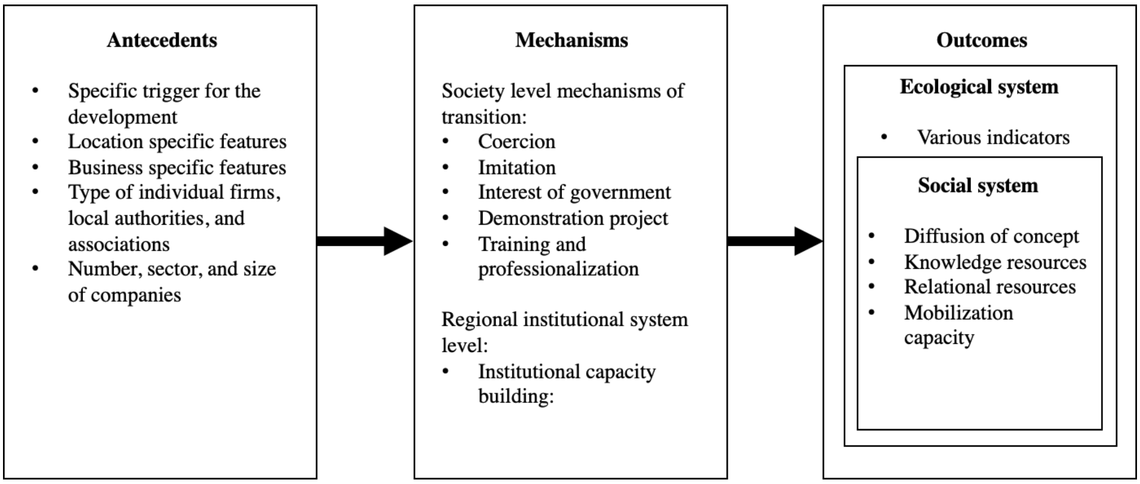

Figure 3.1 Conceptual framework of the dynamics of industrial symbiosis (Boons et al., 2011).

3.3 Research approach

To be value-adding to the academic knowledge base, a combination of two research approaches will be used. The first is an exploratory research approach. In this phase mainly two areas will be explored. It presents an overview of the dynamics of a WH market, the state of the art technical systems in WH usage, and the local industrial playing field will be mapped. In this approach, multiple methods will be used such as the institutional IAD framework, the conceptual framework of the dynamics of IS, and conceptual modeling. Together with results from existing literature, these methods will be used to perform a system-level analysis from an outsider's perspective.

Scenario modeling of a case study will be used as a second research approach. The literature study in chapter 2 shows that MILP is a commonly used method to determine the optimal heat dispatch for industrial regions. This method will be used to solve the different configurations of the scenario using a single-objective minimization for carbon emissions. Through analysis of the results, drivers of environmental and financial effects can be identified; trade-offs between costs, carbon reduction and infrastructure are identified.

In chapter 2 a research gap is identified. This research gap is translated into the following main research question:

How can industrial zones utilize high-grade waste heat networks in such a way that it maximizes carbon reduction?

This main research question is divided into six sub-question that will aggregate the main research question. Each sub-question will represent a step in the research project.

1. *How are WH networks conceptualized and what are the interactions between heat supply and demand nodes?*
2. *What are state of the art WH recovery, storage, and transportation technologies?*
3. *What are the patterns of potential WH sources, heat sinks, and transportation in Metropole Region Amsterdam?*
4. *How can the industrial heat demand- and supply patterns be matched utilizing WH to minimize carbon emissions?*
5. *How resilient is the integrated WH network concerning (un)expected interruptions?*
6. *What are the key drivers of carbon emission reduction in WH networks?*

3.4 Research method

The chosen methods for answering the main research question are based on the paradigm of IS and include methodological aspects of other pure technical research areas. A similar approach to the work of (Chae, Kim, Yoon, & Park, 2010) is used. In their methodology, they make use of accumulated data and interviews with process engineers for technology assessments. They limit their research to stable and conservative energy flows due to the assumption of continuous heat networks. In their model, they use a single objective MILP to minimize the total energy used in the industrial region. Although these methods provide many of the required tools required for this main research question, additional or customized methods will be applied in this thesis. The customized methods enable accounting for the dynamic patterns of demand and supply and analyze the strategic interactions. In this paragraph, the methods used to answer each sub-question will be discussed according to their purpose, strengths, and weaknesses.

1. *How are current WH infrastructures conceptualized and what are the interactions compared to other distributed energy networks?*
   This sub-question relates to the **orienting** part of the research, where the modeled system will be conceptualized and the system interactions are defined. This conceptualization of the system will gain insights into the systems' possibilities for carbon reduction. The conceptual model also provides an overview of essential data,

such as the inputs, outputs, efficiencies, and a quantitative overview of different infrastructure options. A basic system overview that will be conceptualized is provided in figure 3.2.

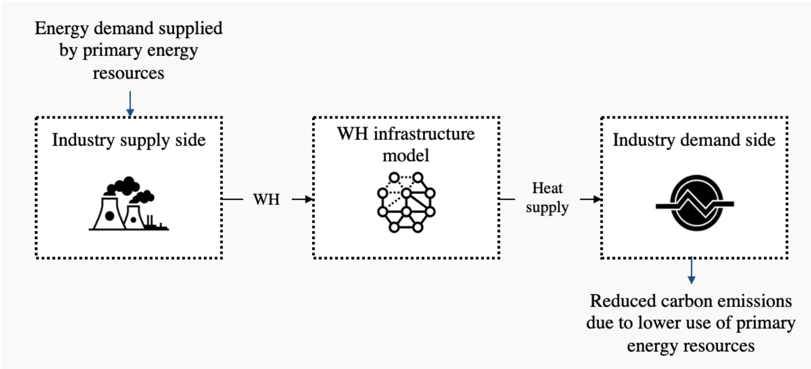

Figure 3.2 A schematic overview of the system.

To understand the strategic interactions in a potential network, the IAD framework (figure 3.3) will be applied to different sectors in the industrial zone. By using this framework it is possible to identify the role of a sector in this system over time. The framework is designed to perform an analysis to understand how institutions operate and change over a period of time, given a policy change. In this case, the carbon policies strongly influence companies in different ways due to its complex nature; could change a firms' strategic position in an industrial region. By using this framework, it is possible to create a general understanding of the strategic interactions between the different sectors in this industrial zone. Nevertheless, the IAD framework shows limitations in this context due to its strong institutional focus. Therefore, elements of the framework for IS dynamics of (Boons et al., 2011) will be used to supplement this framework. The framework provides an opportunity to identify the mechanisms, antecedents, and outcomes of industrial synergies. It is a way to verify the obtained insights from the IAD framework. In the existing literature, the actors in the network are assumed to be there, and data is available for these nodes. However, for this research, an outsider's perspective is used, which means that the companies in the region do not cooperate in the research from the start. This approach enables policy- and decision-makers to identify the actors in the network and assess the potential impact of their involvement.

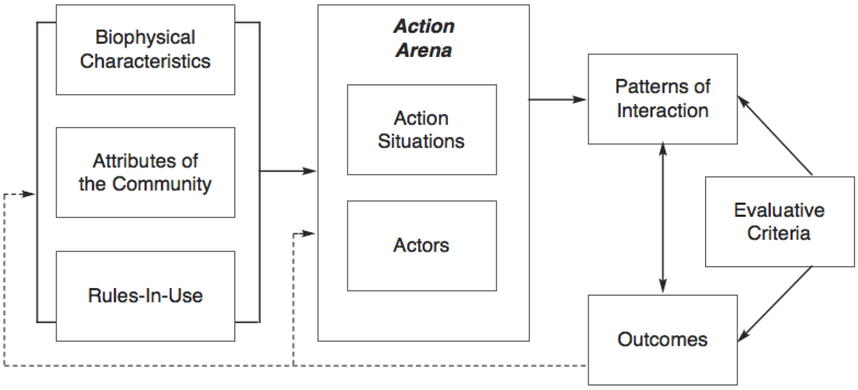

Figure 3.3 IAD framework by Elanor Ostrom (Mcginnis, 2011).

2. *What are state of the art WH recovery, storage, and transportation technologies?*
   This sub-question relates to the **descriptive** phase of the research. State of the art technologies obtained in the literature research will be researched and reviewed. The trade-offs for each technology can be assessed and will be quantified using a combination of quantitative and qualitative assessments. Quantitative data can be assessed on aspects such as efficiency and energy density. Qualitative assessments will be quantified by using quadrants, with industry experts indicating the technology readiness and fit for purpose. The absolute score is not of major importance, however it measures the likeliness that a technology will be suitable in the industrial environment.

3. *What are the patterns of potential WH sources, heat sinks, and transportation in Metropole Region Amsterdam?*
   This sub-question relates to the **scenario creation** phase, which will provide an overview of the scenario's in which the proposed intervention will be modeled. The goal is to create a scenario that matches the reality as closely as possible. For the development of the scenario, principles of the basic design cycle will be applied. The complete modeling cycle will be explained under the next sub-question.

   The initial step is to create an overview of the region and identify the consumption within the industrial network. Quantitative data will be gathered by requesting it through representatives of different stakeholders and by accessing open-source data. Constraints will be listed based on the theoretical, physical, and practical limitations of the network. The scenario will be validated with industry experts.

4. *How can the industrial heat demand- and supply patterns be matched utilizing WH to minimize carbon emissions?*
   This sub-question relates to the **scenario modeling** phase of the research, where all technical and qualitative input will result in key insights for the main research question. The goal is to produce a model that can determine an optimal dispatch

between different demand- and supply patterns in an industrial region, which minimizes carbon emissions.

For the modeling phase, MILP will be used to determine the optimal dispatch of heat demand and supply in each scenario. A single objective function for carbon reduction will be the optimization goal. This is method is widely applied in literature and is a suitable way for modeling distributed energy networks. It is a way to match demand- and supply patterns, while simultaneously complying with the systems' restrictions. In this model, a form of the pinch-analysis will be incorporated, to adhere to the limitations of physical heat exchange networks. This method is usually applied in a chemical context, used as an efficient method to minimize the energy usage of a system. However, this method can be incorporated into the MILP model to simulate the heat flows. The optimal dispatch, carbon reduction, but also operational details will be key outcomes of the model. The quality of the model fully depends on drafting the right constraints. Therefore, this will be considered as one of the core tasks for this sub-question.

To create this WH network model, several steps are undertaken. The modeling steps displayed in figure 3.4 will be used as guidance for building the actual model.

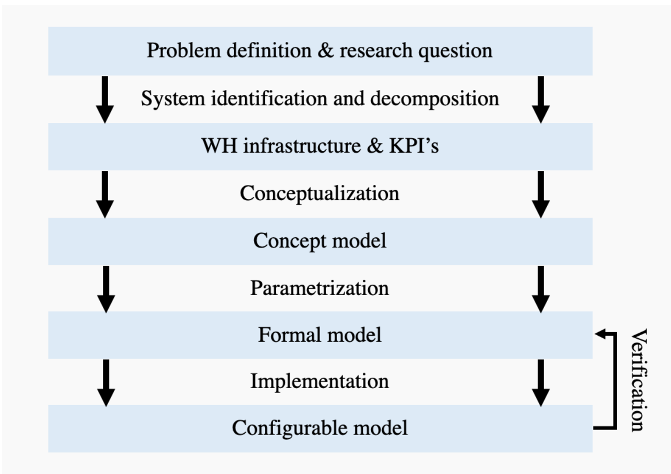

Figure 3.4 Model building steps.

5. *How resilient is the integrated WH network concerning (un)expected interruptions?* This sub-question relates to the **validating** phase. The outcomes will be tested and verified whether they are sensitive to changes in the systems' environment. By performing sensitivity analyses on the different scenarios in the model, it is possible to determine what scenario is sensitive to changing circumstances. A predetermined set of factors will be tested on sensitivity. It will provide initial findings on whether

the system is affected in a major way due to an (un)expected WH supply. This part of the research will be limited to a few configurations and will require further research to conclude on this matter.

6. *What are the key drivers of carbon emission reduction in WH networks?*
This sub-question relates to the **analyzing & evaluating** phase. A reflection on all the performed analyses will be given that will provide insights into what the key drivers of carbon reduction in a WH network are. The main goal of this sub-question is to layout a generalized insights, based on this thesis, for which other industrial regions can use to perform similar analyses. When following this method it should be possible to optimize carbon reduction by implementing the most efficient form of WH infrastructure.

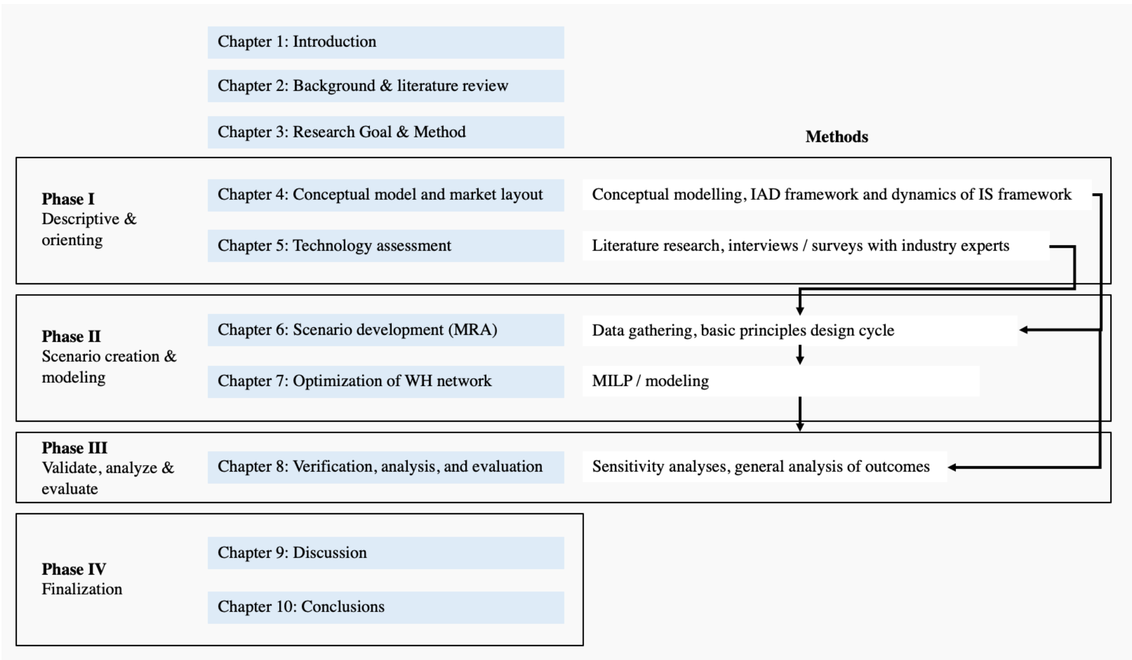

Figure 3.5 Research flow diagram.

4

Conceptual model & market layout

In this chapter, several methodologies will be applied to create an overview of the system to be modeled. The goal is to understand the dynamics of an integrated WH system and how the model could be designed. The first part of the chapter will consist of the meta-model. This high-level representation of the system allows identifying the flows within the system, the system constraints, and the required data to model the system. In the second part of the chapter, an initial list of actors in the system is created. This is required to perform an analysis of the strategic positioning and market dynamics of different sectors within the integrated WH network. The third part of the chapter contains two types of analyses. First, the strategic positioning of each sector in the region is identified by applying the IAD framework. Followed by the use of the basic framework of IS to identify the antecedents and mechanisms of industrial synergies.

4.1 Conceptual model

The conceptual model will function as a graphical representation of the system in which the intervention will be modeled. The conceptual model is a simplification and shows the systems' separate elements and interactions. Each element contains in- and outputs that represent an energy flow that is limited by constraints. These limitations are predominantly due to geographical and technological factors and will be determined through the analysis of literature. A detailed conceptual model of each of the three system elements is presented in figure 4.2. This detailed model provides an overview of the data requirements, the constraints, and gives an overview of the possible heat flows in the system. The industrial process is considered as a black box that requires energy consumption. The next paragraphs will elaborate on the detailed conceptual model.

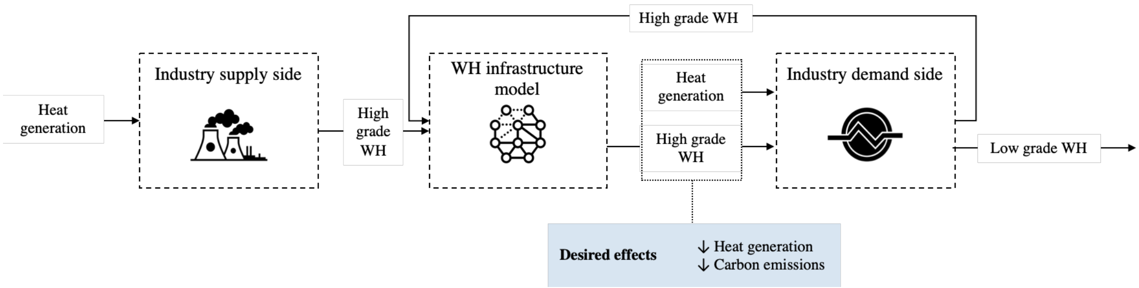

Figure 4.1 A basic conceptual model of integrated WH network.

The *industry supply-side* is the part of the system where heat is produced by consuming primary energy resources. For this study, industrial applications that emit abundantly available high-grade WH are considered. Literature study shows that heat exhausts of these industrial processes generally have four different physical states: flue gases, steam, liquid, and solid-state. Data on these outputs is desirable, however data availability often lacks. In those cases, the primary energy consumption is used with a conversion factor, based on thermodynamic principles. Hourly supply data of WH is supplied to the model.

The *WH infrastructure* is the core of this model. In this arena, the input of the industry supply-side is translated into a viable operation of potential WH exchanges. Only if an option fits the predetermined set of constraints, a solution will be computed. Based on these computations, the model will search for a dispatch of the system that minimizes the carbon emissions in the industrial region. As can be seen in the figure, only flue gas, steam, and liquid can be converted into TCM or operated directly in a continuous network. This is because solid to solid heat transfer cannot be operated at reasonable efficiency. On the other hand, heat containing solids can directly be transported by employing a flexible network. After transport, the energy flows are inserted in a heat exchanger system that fits the specifics of the industry demand-side. In some operations with a TCM container, the heat exchanger is partly operated on the truck itself (Nomura et al., 2010). Through analysis of the behavior of the model, the potential of an integrated WH network can be determined.

The *industry demand-side* is key in realizing carbon emission reduction. Part of the primary energy consumption will be replaced by the use of WH. Although the demand-side is separated from the supply-side in the conceptual model, there is a possibility that the demand-side is at the same company. This internal exchange of heat flows often applies to heavy industries that produce at a large scale. In this case, the model likely shows a preference for a connection between demand and supply at short distances due to lower losses. Industrial processes can have both low- and high-grade WH. For this research, only high-grade WH is considered.

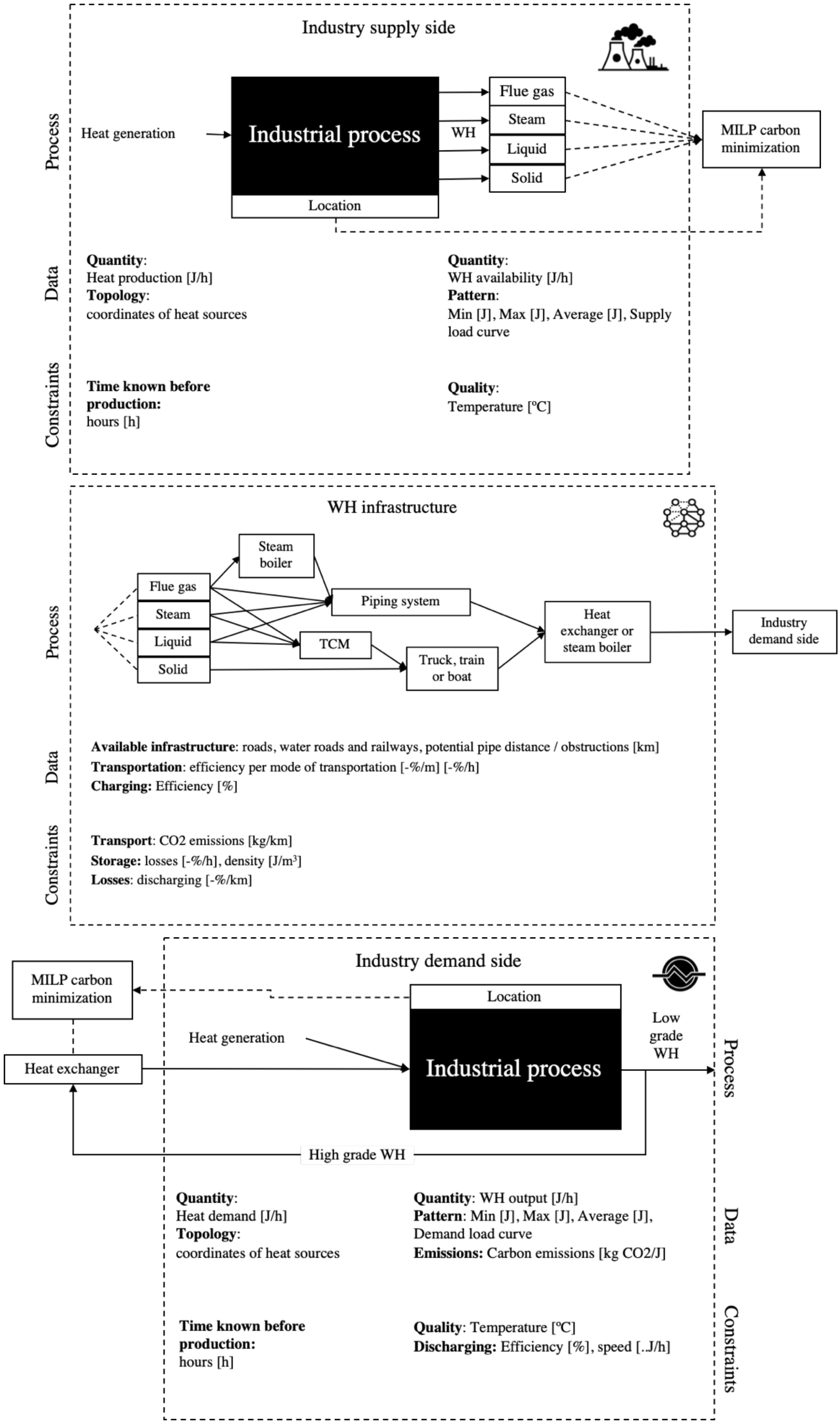

Figure 4.2 Detailed conceptual model showing data requirements and constraints, solid lines represent physical flows, dotted lines represent information flows.

4.2 Identifying potential actors in the integrated WH network

Before the market dynamics and the market layout of a WH can be analyzed, a basic topology of an industrial region is required to determine what the potential roles of actors are. For this thesis, the Metropole Region Amsterdam has been selected. This region is specifically interesting because of the presence of Tata Steel, that due to its extremely high heat demand emit the highest share of carbon emissions in the Netherlands (7.4%). Next to that, the regions offer a wide variety of industrial companies that emit a significant share of carbon emissions. For this thesis companies emitting more than 14 kton on annual basis are considered. This number has been chosen because it allows creating a list of companies that operate in multiple sectors. To identify the carbon emitters, the digital Heat Atlas ("Warmte Atlas") has been used (Netherlands Enterprise Agency, 2020). This atlas is a government website that specifies carbon emissions and the use of primary energy resources of each company over a certain threshold. An overview of the companies that are in this category is presented in table 4.1. The topology of these companies are presented in Appendix A.

Company	Sector	CO_2 emissions [kton/year]
Tata Steel	Steel	6206
Nuon Hemweg	Power generation	4195
Nuon Velsen	Power generation	4054
Nuon IJmond	Power generation	1984
Engie Maxima centrale	Power generation	1233
Afval Energie Bedrijf	Power generation / waste incineration	1169
HVC alkmaar	Power generation / waste incineration	1078
Nuon Diemen	Power generation	944
Schiphol	Aviation	687
Draka Interfoam	Industrial appliances / materials	410
Crown van Gelder	Industrial appliances / materials	143
Tate & Lyle	Food processing	75
Bunge Houthavens	Food processing	68
Albermare catalysts	Industrial appliances / materials	67
Cargill BV	Food processing	65
Norit Nederland	Industrial equipment supplier	38
Academic Medical Centre	Hospital	38
VU-VUmc	Hospital	38
ADM Cocoa BV	Food processing	27
Bunge loderus Crocklaan	Food processing	19
Forbo Flooring	Industrial appliances / materials	14
KLM Engineering & Maintenance	Aviation	13
ENCI	Industrial appliances / materials	14

Table 4.1 List of companies emitting >14kton/year in the MRA on the heat atlas.

4.3 Market layout

The current market for WH is limited and knowledge on the strategic positioning and incentives to participate in such a market are not defined. The plans to increase taxation on CO_2 are likely to incentivize the industry to reduce their carbon emissions. Based on the IAD framework, a policy impact analysis can be made to understand how the operations of institutions change over a period of time. In this analysis, CO_2 must be considered as a common-pool resource. That means that there is a maximum capacity of CO_2 emissions. To prevent a "free riders effect", only actors participating in the system can make use of this common-pool resource. The ETS is based on this rationale and will be supplemented by Dutch CO_2 legislation, which sets a minimum price if ETS prices are too low. By using the IAD framework it is possible to create a meta-theoretical language for the system. Meaning that there is a common language to talk about the integrated WH network, its relations, and its elements. Although the IAD provides a useful approach, the framework of the dynamics of IS (Boons et al., 2011) provides additional insights in the drivers of industrial synergies. Antecedents and mechanisms of this framework will be used as validation of drivers of IS in the IAD framework.

4.3.1 Strategic positioning

Carbon-emitting companies have been categorized into six sectors to analyze the impact of carbon policies (table 4.2). Each company will respond differently to the imposed carbon regulations, however sectors will be subject to similar conditions. In this paragraph, the different components of the IAD framework will be discussed. The strategic position of each sector to *reduce their carbon footprint by using WH* is identified through analysis of the filled out frameworks. Similarities and differences that influence their position will be discussed concerning each component of the framework. The filled-out IAD frameworks can be found in Appendix B.

Sector	***Companies***
Steel	Tata Steel
Aviation	KLM Engineering & Maintenance, Schiphol
Power generation	Vattenfall, Engie, HVC, AEB
Industrial appliances/materials	Crown van Gelder, Tate & Lyle, Albermare catalysts, Cabott (Norit), Draka Interfoam
Food processing	Cargill, ADM Cocoa, Bunge Houthavens, Bunge Loderus Crock, Forbo Flooring
Hospitals	AMC, VU-MC

Table 4.2 The categorized sectors in the MRA

<u>Policy change</u>

The main policy change that the companies are subject to is the Dutch carbon regulation. This stepwise increasing carbon emission tariff will impact many companies. Effectively this means that the price of different primary energy resources will increase. An approximation of this increase is provided in the following formula:

$$Total\ gas\ price = gas\ price\ per\ m^3[€] + CO2\ per\ m^3\ of\ gas\ [kg] *\ CO2\ price\ per\ kg\ \left[\frac{€}{ton}\right] * 10^{-3}$$

In 2021 this corresponds to a cost increase for natural gas use of 12%:

$$Total\ gas\ price\ per\ m^3 =\ 0.34\ [€] + 1.78\ [kg] * 30\ \left[\frac{€}{ton}\right] = €\ 0.39$$

In 2030 this corresponds to a cost increase of 65% when assuming a constant gas price.

<u>Biophysical conditions</u>

The biophysical conditions entail how every industry handles its surroundings, goods, and resources. The different components, interactions, and path dependency are a good measure of how carbon reduction could potentially be realized in the sectors' context. After analyzing the six sectors, a major similarity between the sectors is that WH can potentially reduce their carbon emissions. However, it is unlikely that WH can fully supply industrial processes with heat. This is due to the assumed unpredictability and unreliability of heat supply. High reliability is required because in every sector the primary operation is leading. The level of resilience to disrupted energy supply is therefore low. In most cases this means that a hybrid system is required, that can ramp up and down its heat production. Due to the limited security of supply of WH, the installed capacity should always be able to fully supply the process with energy.

Nevertheless, the IAD analysis highlights multiple differences amongst the different sectors. The *electricity sector* is currently subject to major changes in its energy supply and infrastructure. The growing share of renewable energy sources (RES) already causes a reduction of the use of primary energy resources. This volatile supply can be balanced by the existing production facilities, and in the future will be balanced by technologies incorporated in a smart grid. The *steel industry* distinguishes itself by its enormous heat demand and supply, which potentially provides them with a big role in an integrated WH network. Its proximity to open sea and the river provides a unique possibility in terms of infrastructure. Therefore, the biophysical conditions could be favorable for an integrated WH network. The *food processing industry* often has a continuous heat demand and the processes are often energy-intensive. Typical for this sector is that it needs to commit to high safety standards, such as food-grade hygiene. Their primary operation cannot be polluted due to any of the heat exchanging systems. As a result, these safety standards make the implementation of additional WH systems more complex compared to other sectors. Particular for the *industrial appliances and materials* sector are the rough circumstances, which can occur in all types of heavy industry. If these standards can be met this sector shows the potential to participate in the integrated WH network. Typical for the *aviation industry* is that there is a continuous heat demand for space heating of the airport. Although this is a low-grade heat source, it is incorporated into the list due to its large carbon footprint. Benefits for this industry are the high quality of the rail and road infrastructure around the airport. *Hospitals* characterize themselves as similar to an airport. A low-grade continuous heat source with a significant carbon footprint.

Attributes of community

The attributes of community is a summarizing term that is designated to all social, cultural, and behavioral context that are subject to an action situation. Generally in the industry, there are a few similarities when analyzing the filled-out IAD framework for each sector. In an industrial context, the production of the primary product is often leading. This means that processes prior to the main operation, such as energy supply, have to be reliable. This also means that if a system proves to be resilient, it is more likely to be implemented.

The *electricity sector* is already subject to major change due to the increasing amount of RES, advancing technologies, and the increasing use of electric vehicles. Due to the physical limitations to make use of WH, it is unlikely that there would be an interest in lowering carbon emissions by using WH. The potential to use new low carbon technologies in this sector is more promising. The *steel industry* has another perspective. The Dutch steel industry is dominated by Tata Steel, and as the only actor, they have the opportunity to be pioneering. As the steel industry is currently facing high competition, it is their chance to become unique and set the benchmark in terms of sustainable steel production. Due to the high share of carbon emissions (7.2% of the Netherlands), the steel industry is highly motivated by the government to reduce their contribution to the total emissions. The political pressure and the energy intensity of the process make that the steel industry is pursuing the use of transportable WH intensively. Other significant differences in the usage of WH amongst the sectors is their production scheme. In a pushed supply chain the time and quantity of production are often known, while in pull production the energy demand can be volatile and unpredictable. WH supply is push driven, hence push driven supply chains have an operational benefit over pull driven supply chains. Therefore, the nature of the industrial process seems to be an important aspect.

Rules in use

Each industrial sector is subject to regulation when it comes to health, safety, and the environment. In carbon reduction one of the major similarities between sectors is that they are subject to emission regulation. As soon as a company is marked as a large emitter according to government standards, the company has to participate in the ETS. These laws are in line with the EU directives, and the ETS covers around 45% of total EU emissions (European Comission, 2003). By using the heat atlas, the companies that are subject to the ETS are highlighted. Companies that are currently subject to the ETS will also have to pay the Dutch emissions tariff when this will be put into operation.

The industry in the MRA also shows differences concerning the rules in use. The Vattenfall plant in Velsen and IJmond are rented and operated by Tata Steel to produce electricity from the rest flows of the factory. This changes the dynamics when it comes to governance of the plant because if Tata Steel would decide to use WH in this electricity plant, this is coordinated more easily. Another major differentiation for the electricity sector is that the emissions caused by burning biomass are not subject to carbon regulation. In climate agreements it is argued that biomass is within the short carbon lifecycle, which means that the emissions are compensated for by nature (Milieucentraal, 2019).

Action situation

The action situation is the core of the IAD framework in which actors (institutions or organizations) observe information, select actions, engage in patterns of interaction, and realize outcomes for the interaction. As mentioned before, the action situation is analyzed for carbon reduction by using WH in each of the sectors. Generally, there are little similarities amongst the sectors. Carbon reduction is in all cases rewarded by lower tax expenses and an increased image. However, for one sector this image might be more relevant than others.

Within the action situation, there multiple components make it possible to analyze how a sector positions itself concerning carbon reduction. Eventually, the responsibility for the carbon reduction is located at the top management within the sector-specific companies. Depending on the costs and rewards, available information, the level of control over carbon emissions, the complexity of the sector, and the governance, strategic choices concerning carbon policies are made. When looking at the costs and rewards, the scale is of major influence. Organizations with relatively low emissions are not subject to the ETS, hence they are not incentivized to reduce their carbon emissions as much. A good example of this in the MRA is Bunge, a food processing company with two sites located within the MRA. One of the two, located near Amsterdam is subject to the ETS and is looking for smart solutions to reduce their emissions. While their other locations, situated near Zaanstad is not subject to the ETS and is less likely to invest in these kinds of solutions (Netherlands Enterprise Agency, 2020). Noticeable for large scale organizations is that the rewards do not only consist of reduced carbon tax expenses, but they experience increasing commercial interest in low carbon products from their clients. A good example in the steel industry is the demand for carbon-free packaging materials. Thereafter this client wants to sell the final product eventually as carbon-free. Also, the number of positions seems to be of importance due to increasing governance complexity. In the aviation industry, there are many stakeholders connected to the airport, which all have different sustainability objectives. In order to let this sector make use of WH to reduce its carbon emissions is complex. The steel industry possesses multiple supply and demand nodes, which means that the number of positions is low. This results in relatively less complex stakeholder management for an integrated WH network.

It is important to understand to what level the potential actors in such a network have the mandate to implement WH solutions. Again, this strongly differs per sector. In the *electricity industry,* the responsibility for carbon reduction is mainly located at the people managing the portfolio. The industry's main lever to decrease their emissions is the implementation of more RES into the system. Local operators responsible for the operation of conventional gas and coal-fired power plants are responsible for the optimal operation of these plants. Minor efficiency improvements can still be made , however they do not have the mandate to make large changes into their processes. In the *steel industry,* this mandate seems to be more scattered within the organization. Dedicated teams are working on energy efficiency improvements on the current processes, and people are working on more fundamental solutions by changing the steel making process. Within the organization, the budgets are controlled per separate business unit, which means that there might be a mismatch between the available budget and the projects with the highest impact. Often financial performance is leading for each separate unit.

Generally, in the *food processing and industrial appliances/materials* are oriented towards one production process. In these cases, the mandate of the people responsible for the operational and financial performance of the plant is on the same level as the responsible people for carbon reduction. In this case, there is no mismatch between the level of the hierarchical level of the person responsible for carbon reduction and the investment decision. The food processing industry is a good target to convince and implement WH solutions in terms of governance. A similar governance structure holds for *hospitals and airports*, where heat production is not part of the primary operation. The person responsible for decision-making on sustainability is hierarchically on a similar level as the person that has control and saying over the budget.

Eventually, the governance structure for each specific company determines how likely it is that a choice for WH usage is made. Complexity increases as the level of decision-making increases. In international companies, there might be a sustainability strategy that is not in line with the use of WH for carbon reduction. In the case of more local governance, chances are higher that the boundaries in which you have to work are less limited. Although this might have a major impact on the results, this is not strongly considered in this study, since the research goal is more oriented on the network optimization rather than the actual implementation.

Interactions

Based on the biophysical conditions, the attributes of community, the rules in use, and the action situation the interactions between the industrial sectors in the MRA can be determined. Eventually, these interactions lead to outcomes that are tested and compared to evaluative criteria. These criteria will be discussed in the next sub-paragraph.

An important first conclusion is that within the MRA, based on the strategic positioning, there is a potential demand for WH as a driver for carbon reduction. This is both in the form of batch and continuous and pull and push production. Depending on the circumstances these supply and demand patterns can be matched.

There is also a difference amongst the sectors. In the *electricity sector,* there is a limited effective demand for WH due to technical constraints. Combining this with their already disrupted market due to new technologies, it is unlikely that they have a demand for WH to reduce their carbon emissions. In the aviation and hospital industry, there is a potential demand for WH for space heating, however the efficient use of a cogeneration system makes that the production of heat and electricity together creates an efficiency of 85% (van Beek, 2019). Therefore these industries would initially be less interested in using WH for space heating. However, if this is financially more interesting they would consider it. As a result, this industry relies on the financial performance of the heat supply. The industries that are most interested in the application of WH for carbon reduction are the steel industry, food processing industry, and industrial appliances/materials. For these industries, it is more likely that the financial benefits arise due to the increasing carbon taxes.

Evaluative criteria

The evaluative criteria may be used to test the outcomes of the IAD framework and determine whether they are satisfactory. Generally, there are five evaluative criteria for each potential actor in an integrated WH network. With these parameters the successfulness and feasibility if implementing WH solutions for carbon reduction are determined:

1. Supply: the quality, reliability, and quantity.
2. Efficiency: the use of resources, especially the benefits of economies of scale.
3. Operational fit: also referred to as operational disruption. This is the ability to implement the WH system without disrupting the primary production process. It also entails to what extent the primary operation is resilient to a disrupted supply. Systems that are more resilient to supply fluctuations are more likely to fit in.
4. Financial performance: the financial gains or losses of the implementation. This will be analyzed for multiple scenarios, which in this case that means multiple carbon prices.
5. Technical performance: the system operation, the complexity to implement, the reliability of the system.

Outcomes

The outcomes are the synthesis of the exogenous conditions and the interactions of the action situation. General similarities between the sectors are that in every sector, apart from the *electricity sector*, there is potential for carbon reduction by the use of WH. The electricity sector is excluded (as mentioned before) due to its current technological transformation towards a carbon-free electricity supply. The complexity of the implementation and the reward for making use of such systems is however sector-specific.

The *steel, food processing and industrial appliances/materials sectors* have the highest chance of feasibility due to their operational circumstances. The *hospital and the aviation industry* have a moderate chance of using WH for carbon reduction. This is due to their already efficiently operating cogeneration systems, and in the case of the airport highly dispersed carbon emissions. For each sector, the complexity of implementation is easier for push driven supply chains, rather than the pull driven supply chains where heat demand often is known only short in advance of production. In push is driven supply chains there is a high amount of available information. Moreover, literature study (Deckert et al., 2014) shows that continuous heat supply and demand flows have a better chance of succeeding because of financial performance. However, with a fully integrated WH network, several batch production nodes could form a more constant heat flow when aggregated. Based on the outcomes of the IAD framework analyses, an overview of the willingness to participate in the integrated WH network is indicated per sector (table 4.3).

Sector	*Carbon reduction by using WH*
Steel	Likely
Industrial appliances/materials	Likely
Food processing	Likely
Aviation	Moderate
Hospitals	Moderate
Power generation	Unlikely

Table 4.3 The likeliness that a sector will make use of WH to reduce its carbon emissions based on its strategic positioning.

4.3.2 Market dynamics

From the strategic position of each of the sector, it is possible to analyze how the market dynamics of an integrated WH network will be. In this paragraph, the use and relevance of the framework for IS will be discussed. By indicating which components of the framework for IS are relevant to this region, the behavior of each sector in this region can be analyzed. With these outcomes, it is possible to specify the dynamics of a regionally integrated WH system. As mentioned before, there are different forms in which IS emerges. This can either be an artificially formed industrial region, in which an institutionalized actor takes the lead towards creating synergies. In the other situation, which applies to this region, industrial symbiosis emerges through a specific trigger in which the actor with the highest incentive would likely to be the leading actor (Boons et al., 2011). The applied framework suggests that industrial symbioses can be best conceptualized as a process. In this process, traditionally separated industries move towards connectedness in terms of material, energy, and information flows. In the framework, there is a general distinction between IS mechanisms at a societal level, and at a regional industrial system level. At a societal level IS is promoted through different mechanisms. These mechanisms are based on the diffusion of concepts of IS through (1) coercion, (2) imitation, (3) private interest government, (4) demonstration projects, (5) training and professionalism, and (6) altering boundary conditions. Both demonstration projects (research) and altering the boundary conditions (carbon tax) apply to the WH network in the MRA. The mechanism of industrial WH exchange is currently on the regional industrial level. This is also the central focus of existing literature on IS and is more focused on specific cases than on the diffusion of knowledge. The mechanism that applies here is institutional capacity building. Over time a knowledge base is created, and an agreement for cooperation is formed based on trust. "*An array of practices in which stakeholders, selected to represent different interests, come together for face to face, long-term dialogue to address a policy issue of common concern*" (Innes & Booher, 1999), wherein this case the carbon taxes apply. (Innes & Booher, 1999) also specify that this can lead to *"both tangible and intangible results"*, such as synergies and knowledge increase. For this network, it could result in viable connections of WH supply and demand nodes. Additionally, it could generate insights into what carbon price corresponds to economically viable technologies.

There are several antecedents in the framework for IS that resemble the situation in the MRA. These antecedents function as an incentive to consider symbiotic linkages. The findings from the IAD framework analysis show similarities to antecedents in the framework of IS. These similarities concern the companies that are subject to the ETS, which are triggered to invest in low carbon technologies due to increasing carbon tax. The power generation, steel, appliances / materials and food processing industry apply high amounts of heat for their processes, which is a business-specific feature that leads to specific interest in the use of WH. In terms of scale, it can be seen in table 4.1 that especially in steel and electricity production there is a large interest in WH. However, in the IAD analysis of the electricity sector, it showed technically infeasible to realize significant carbon reduction by using WH in this sector. According to the antecedents in the framework for IS, the political trigger and large scale are drivers for synergies in industrial regions. The steel industry would be the actor taking initiative due to scale because it is most beneficial for them. They potentially can supply large quantities of their waste heat internally and to other companies. Nevertheless, other industrial players that possess WH could be joining forces with the steel industry to conduct this research. Smaller industrial players with only demand have less incentive to be leading in the development of an integrated WH network. They will occupy a follower position in the WH market.

An overarching dilemma for an emerging industrial symbiotic network is the choice for a WH network operator, or whether none is needed. This problem emerges when more than 2 nodes are connected to exchange WH. In case there is a single connection, there is no need for a network moderator and companies can come to a mutual agreement. If synergies are realized on a network level, meaning there are over 2 nodes that can exchange WH multi-directional, there has to be an actor managing the market mechanism. This network operator is responsible for making and safeguarding the rules in the network. In an artificially formed industrial symbiotic park, this role is often automatically provided to the initiator of the park. However, in an emerging symbiotic region, there are multiple possibilities to whom this role is attributed. The initiator, who has the most incentive to create those synergies, could take this role. However, this would strategically be unfavorable for other participants in such a network. In the framework, this referred to as mobilization capacity: "*the structure and means by which knowledge resources and relational resources are formed and mobilized*" (Healey, De Magalhaes, Madanipour, & Pendlebury, 2003).

A key factor for successful synergetic linkages is based on another mechanism described in the framework, which is referred to as relational resources. The embeddedness of actors in a social network determines the level of mutual trust between two industrial companies. Based on this trust they would choose to participate in an integrated WH network. The higher the number of participants, the stronger the relational resources have to be. Since none of the existing parties have ever worked with such a complex exchange of WH, the mutual trust level will likely be low. This results in a relatively low chance that WH will be exchanged by two different firms compared to the internal exchange of WH flows.

Based on these findings, the market dynamics of the integrated WH network have been synthesized into a pyramid structure shown in figure 4.3. The top-level represents the industry which has the strongest position and incentives to be part of an integrated WH network. These incentives are mainly based on the antecedents, which are a trigger for the process of IS. The lower the rank in the pyramid, the less prominent the role of the industry will be in the network. A description of each role will be provided.

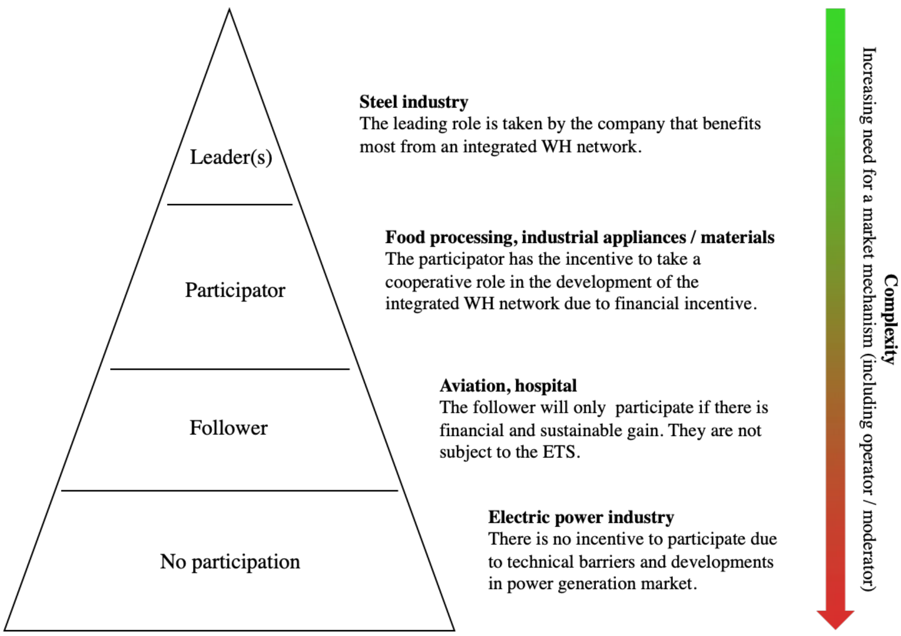

Figure 4.3 Market layout in an integrated WH network based on IAD and IS analysis.

4.4 Assumptions and parametrization

Based on the analysis performed on the strategic positioning and market dynamics, it is possible to set the initial parameter for the MRA. This parameter is the first in a line of lower-level assumptions for the scenario. Although this region will serve as a case study, the studied sectors are unlikely to hold a radically different strategic position in other industrial zones.

Assumption #4.1: The electricity sector will not participate in an integrated WH network.

5

Technology assessment

Based on the market dynamics and strategic positioning of each sector, the high-level system dynamics have been established. Now it is important to test what technology is allowed and suitable in the system. Based on both qualitative and quantitative measures, a technology assessment is made to determine the limits of WH usage. This technology assessment consists of three separate parts: (1) a quantitative technology assessment based on literature, (2) a qualitative technology assessment based on expectations of field experts, and (3) the parametrization of the different technologies. The goal of this chapter is to establish theoretical / physical, technological, and feasibility constraints that will serve as an input for the modeling phase. The analysis is based on the assumption that only high-grade industrial heat sources are of interest.

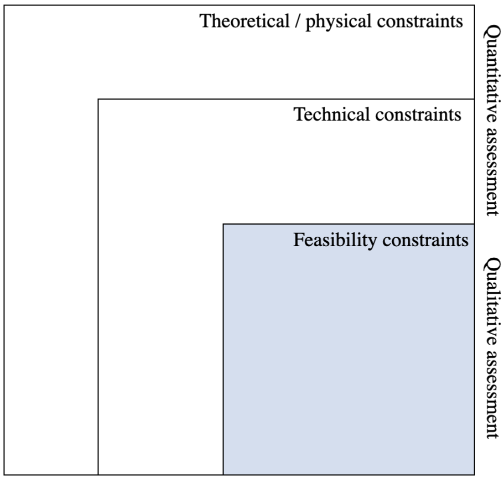

Figure 5.1 Three types of constraints that the WH application has to abide by. Interpreted from (Brückner et al., 2015).

5.1 Quantitative assessment

This section is an important phase as part of the model-building steps. The technological and physical limits will have a strong influence on the behavior and of the model. Setting these values will influence the choices and preferences that result in a constrained optimization problem. To determine what factors influence the behavior of the system, a conceptual supply chain of heat has been created (figure 5.2). This supply chain covers each possible form of WH exchange. The elements of the chain will be discussed on three types of limits: theoretical/physical potential, technical potential, and feasible potential. The first two belong to the quantitative assessment, while the latter will be discussed in the qualitative assessment.

Figure 5.2 The supply chain of WH exchange.

WH potentially comes in four different phases. Those are flue gases, steam, solids, and liquid form. Typically for the MRA is that most of the available high-grade WH are present in the steel industry. As a result, the first two elements in the supply chain will be analyzed primarily from the steel industry's perspective. From a process point of view, each of these phases requires a different extraction method. Therefore it is important to assess how they perform on the theoretical/physical potential and the technical potential separately. The overall system efficiency is determined by the theoretical input and the losses. They relate as follows:

$$Overall\ system\ efficiency = Available\ WH * (1 - HE\ losses - transportation\ losses)$$

Phase WH	*Theoretical / physical potential*	*Technical potential*	*Source*
Flue gases	There is high potential due to the extremely high flue gases present in various steel manufacturing processes, with temperatures up to 800 ºC and high quantities. This results in high exergy values, hence WH reuse of flue gases shows potential.	Flue gases have the technical possibility to be transported over short distances. Another option is a transformation into a heat carrier such as steam or phase-changing materials. Efficiencies are based on the specific transformation but have shown up to 92%	(Miró et al., 2016)
Steam	Steam is often a valuable product and is not excessively available as WH. In cases steam would be available there is a high chance that this will be used in other processes since steam is widely used in most industries for heating purposes and electricity generation. It also does not require a transformation of phase, due to its advantageous properties as a heat carrier. Therefore the heat exchanger step is skipped for this phase in the supply chain.	Steam has proven itself as a suitable heat carrier for industrial purposes. It is often produced to supply different types of processes with heat. Transportation of steam is possible although long-distance transportation causes a pressure and temperature drop, hence a loss of efficiency. Pressure drop and distance are linearly correlated: $1.0*10^{-5}$bar m^{-1}.	(Miró et al., 2016)
Solids	The steel industry is unique for its high-grade WH available in solids. The steel slabs produced in the Basic Oxysteelplant (approximately 1500 ºC) promise high exergies. Both scale and temperature are favorable for WH reuse. Other places where hot solid states occur are in the rolled steel products at approximately 650 ºC.	The extraction of electrical energy from this radiation heat is technically possible at a system efficiency of 7%. This is however not reuse of WH but conversion of energy, and therefore out of scope. Another technical possibility is the deployment of heat pumps, which yields a low-grade heat supply. Due to the low-grade heat supply, this possibility is also out of scope. Other technical possibilities with lower potential also serve options that are out of scope.	(Castillo, 2015)
Liquids	A liquid byproduct of steel production is called slag, at approximately 1500 ºC this liquid is currently cooled in a cooling tower. The product is useful as a base product for the cement industry. In this phase there are	The technology is immature but shows efficiencies up to 65%.	(Barati, Esfahani, & Utigard, 2011) (Anonymous, 2020)

Table 5.1 An overview of the theoretical / physical, and technical potential for different phases containing WH.

Assumption #5.1: WH recovery and usage from solids will be will not be used in the scenario due to the non-available technology to recover it.

Assumption #5.2: WH recovery from slag is currently under development with efficiencies up to 65%. However, due to the scope of this research non-mature recovery technologies are not considered.

Assumption #5.3: Steam is the industry standard for continuous high-temperature heat transport, hence liquids will not be considered for continuous heat networks.

Heat exchangers (HE) play an important role in the supply chain of WH exchange. The most common types of HE are shell and tube exchangers. In these exchangers, two different steams are passing each other in parallel pipes and stay separated by a solid wall. The overall efficiency of the system is partly determined by the losses of the heat exchangers used for a particular process. Heat exchangers exist for liquid and gaseous states; both steam and flue gases belong to the gaseous state. From the conceptual model in figure 4.2, it can be seen that heat exchangers are only required for the following five transformations:

Heat exchanger losses	***Estimated system efficiency***	***Reference***
Flue gas to TCM	95%	(Zeper, 2016)
Flue gas to steam	92%	(Viessmann, 2015)
Steam to TCM	95%	(Zeper, 2016)
TCM to steam 3.5 bar	90%	(Yogev & Kribus, 2014)
TCM to water 80 degrees	90%	(Yogev & Kribus, 2014)

Table 5.2 Heat exchanger losses.

Assumption #5.4: Efficiencies of PCM related case studies will be applied for TCM in this model due to the similar process.

Assumption #5.6: all available WH [GJ] will be used, even though in practice this will not be 100%. The unused energy is incorporated in the overall WH losses.

Assumption #5.7: Efficiencies to TCM have been based on results of research into PCM. However, due to the similarities in processes, this estimated efficiency is assumed similar.

The storage medium is dependent on what the model will choose as the optimal connection between a supply and demand node. This can be a continuous connection with steam of flue gas transport, or a flexible connection by using a TCM. During the transportation of the WH there will be losses due to the heat exchange with the environment. Therefore a loss factor has to be determined to correlate the transportation distance with heat losses. There are different types of TCM's and they have different properties. For each application, a suitable TCM should be selected to match the physical constraints of the material. In figure 5.3 a pressure – temperature diagram displays different temperature ranges of the TCMs.

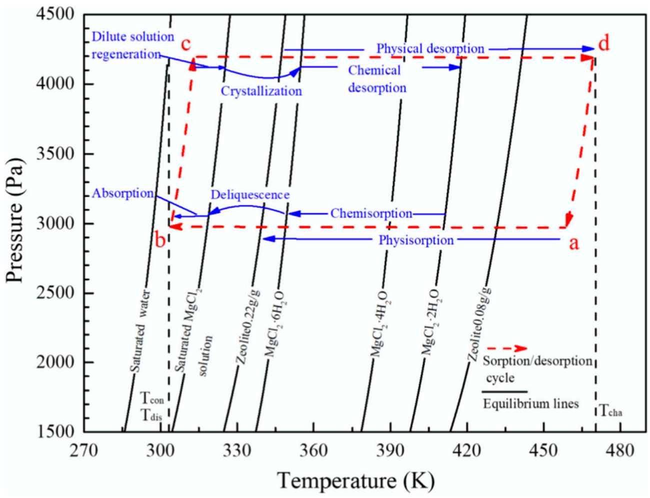

Figure 5.3 P-T diagram of different types of TCMs (Xu et al., 2019).

Assumption #5.8: one storage vessel with TCM weighs 14 tons (Krönauer et al., 2015) and has an energy density of 1368KJ/kg (Xu et al., 2019).

Transportation losses	***Estimated losses***	***Reference***
TCM	Negligible 0% h^{-1} 0% m^{-1}	(Ranjha, Vahedi, & Oztekin, 2019)
Steam	$1.6*10^{-9}$% m^{-1}	(Sanjeev Garg, 2017) & Appendix C
Flue gas	0.025% m^{-1} Based on 1.5m diameter pipe	(Sanjeev Garg, 2017)

Table 5.3 Transportation losses.

Assumption #5.9: Long-distance heat transport will be done in the steam or TCM phase, as the flue gas losses are 100% at a distance of 4000 meters or more.

The benefit of a TCM is that heat can be stored over time without a significant loss. This makes this technology promising and interesting at the same time. Intermittence in production, and thus WH availability, could be mitigated by temporary storage in this system. It shows similarities to electricity storage in a battery that can efficiently store electricity over time. Therefore, it can be a valuable asset to increase the value of WH, not being limited to a time factor. Steam pressure is related to temperature according to the steam saturation curve depicted in figure 5.1, hence a pressure drop over distance results in a temperature drop. At the same time, steam transportation efficiencies are based upon multiple factors, such as the diameter of the pipe, the steam density, the mass flow, and the length of the pipe. There is a linear relationship between pipe length and pressure drop, which means that the losses correspond to the pressure drop over the full length of the pipeline.

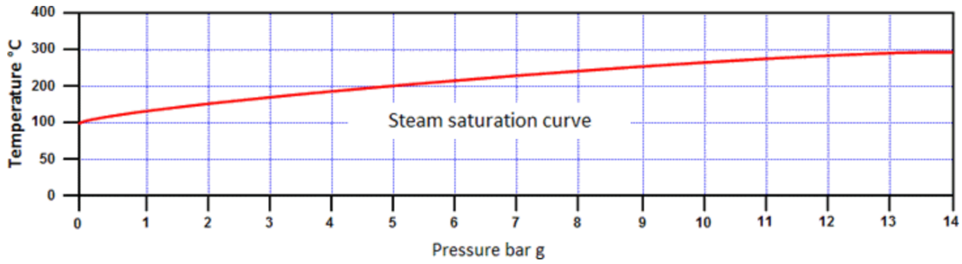

Figure 5.3 Steam saturation curve

Hot flue gases can also be transported, bringing it directly to a heat exchanger for processes that require hot air. In transportation through pipelines, it shows similar behavior to steam. That means that the total energy loss is dependent on the relationship between flow and diameter size of the pipe. Other factors such as insulation will also affect the losses. The larger the diameter, the lower the losses due to the high 'volume' : 'pipe surface' ratio. This effect is explained by the fact that losses only occur with the environment due to the temperature difference inside and outside of the pipe. (Sanjeev Garg, 2017) has researched the transportation losses and based on these results the loss factor has been determined.

Assumption #5.10: The estimated losses for steam are calculated over a temperature drop of 15 bar steam and are considered similar for other steam pressures. Other dimensions that influence the pressure drop are neglected.

Assumption #5.11: The estimated losses for flue gas transportation are based on a 1.5m diameter pipe (Selvaraj et al., 2015).

Assumption #5.12: If steam from flue gas is required, the location of the steam boiler will be at the exhaust pipes.

Assumption #5.13: There are no conductive losses in steam transport due to well-insulated pipes.

After analyzing the supply chain of WH usage, the technical input for the model to determine the overall system efficiency has been established. Together with assumptions made on physical and technical limitations, this will serve as a basis for calculating the optimal dispatch for the distributed energy system.

5.2 Qualitative assessment

The goal of the qualitative assessment is to gain an understanding of how different phases of WH can be valuable to the industry. As mentioned earlier, the technology assessment consists of three types of limits: the theoretical/physical potential, the technical potential, and the feasible potential. In this part of the technology assessment, the feasible potential of different phases of WH will be assessed. To conduct this research, interviews with nine industry experts were held. Amongst those were R&D researchers and process technologists from different industries in the MRA. The questionnaire is presented in Appendix D and a visualization of the scores is presented in Appendix E. In these interviews, the industry experts were questioned regarding the technology readiness and fit for purpose of each of the WH phases (flue gas, steam, liquid, and solid). By assigning scores to the questions, the results could be visualized in a graph with on the one axis technology readiness, and on the other axis fit for purpose. They could choose out of seven scores ranging from very unlikely to very likely. Based on these graphs and notes made during the discussion, other technological limitations have been identified and will be elaborated on in this paragraph. Process technologists / experts of the following sectors have been interviewed:

Sector	***Number of interviews per sector***
Steel	6 (different factory locations/types)
Electricity	1 (gas to power)
Industrial appliances/materials	1
Food processing	1

Table 5.4 Conducted interviews per sector.

In the questionnaire, a score (Appendix E) for each of the phases was obtained for the technology readiness and the fit for purpose of each phase. Within both of these axes, the phases were scored on three different aspects: (1) usage in their own phase, (2) transformation into another heat carrier (e.g. flue gas to steam), and (3) and transmission into a TCM. In case an interviewee was not sure what to score, no score was assigned. Scores were also rated based on the assumption that there is available WH.

Flue gases

Flue gases are a commonly available form of waste heat in the industry. This shows both through the number of process technologists involved with flue gases, as well as the fact that all the sectors in which interviews have been held, flue gases were present in their processes. The overall score shows that there is quite a high potential on both axes for flue gases. From a pure technology readiness perspective, it seems like flue gases in any form of usage will be feasible. Experts in three of the four interviewed industries think that it is possible to incorporate flue gases in their processes. On fit for purpose flue gases also score positively. Again in three of the four sectors, the experts think that WH from flue gases can be fit into their processes. This means that the chances that flue gases are useful in the context of WH exchange are favorable.

The reason for the negative score of respondent number 3 on both the technology assessment and fit for purpose, is that the gases within the specific process of this process technologist require cleaning. This process is performed with cool water, after which no high-grade heat is left in the flue gases. This cleaning process cannot be changed or replaced due to is toxicity, which makes it is technologically and practically not possible. This result emphasizes that it important to assess the feasibility of extracting WH from potentially hot exhaust gases.

<u>Steam</u>
The heat contained in steam is not often available as WH due to its high value. Many industrial heat demanding processes require that in the form of steam and already have an optimized intake of steam. Out of the respondents, two have indicated that they were involved with steam demanding or supplying processes. They indicate that steam in its own form is the most obvious choice both in terms of technology readiness and fit for purpose. Transforming steam as a waste stream into a TCM could be a useful application. However, they have indicated that the temperatures of waste steam are often not high. Hence the TCM cannot be charged to a very high temperature. Although heat transformed into another substance has been scored as very likely on both axes, this was only applicable for processes that require a temperature around 80 degrees Celsius.

Assumption #5.14: Heat transformation from steam to other substances will not be further considered due to the low potential temperatures

<u>Liquid</u>
WH carried in liquids concerned different cases with varying temperatures. In the steel industry, there is liquid slag at a temperature of approximately 1500 degrees Celsius, whereas in the food processing industry there is a WH availability at 80 degrees Celsius. Due to the focus on high-grade heat sources, the results of the food processing industry were only considered for supply purposes.

The results show that the feasibility of using this phase is perceived differently amongst the experts. These outcomes can be explained according to the different operating temperatures and roles of the interviewed people. In the low-grade heat region, a liquid (often water) is a suitable carrier for heat. It is easily transported, cheap, and transmits heat efficiently in a heat exchanger. On the contrary, slag is a high-grade heat source that requires complex technology to recover the heat from the slag. This technology is still in the development phase, which means that there is currently no commercially available technology that can recover this. The negative fit for purpose score has been given by a process technologist, while the positive score has been assigned by an R&D employee. This explains why these outcomes have to be interpreted individually. This underlines assumption 5.2, stating that non-mature WH recovery technologies are out of scope.

Assumption #5.15: Liquids as WH source and heat carrier are not considered due to their unfavorable feasibility in high-grade temperatures.

Solids

WH in solids are relatively unique and is only found in production processes that have a high volume of high-temperature product output. In this case that is the steel industry, where heat can be found in the steel slabs and hot rolled coils of steel. The transformation from WH in solids to TCM is not considered since solid-solids heat exchange is operationally not feasible.

From the results, it became clear that heat recovery from solids state in its own form is infeasible. The arguments provided for this score were the logistic complexity of moving around a product that contains heat for WH recovery purposes. Moreover, this heat is often maintained in the product for the next step in the production process, where it is pre-heated for further processing. The transformation of solid-state WH into another substance has been scored feasible. However, this will result in a low-grade WH flow, which means that it is out of the scope of this research.

Assumption #5.16: WH recovery and usage from solids state is scored infeasible and will therefore not be considered as WH source.

5.3 Technology assessment

The technology assessment has been performed to assess what technology is allowed and suitable for an integrated WH system. Both through literature research and expert interviews the potential technologies have been assessed on their theoretical/physical limits, the technical limits, and the feasibility limits. After these analyses, several assumptions have been made, which will be applied in the scenario and modeling phase of this research.

Out of the four phases of potential WH, steam and flue gases seem to be the most promising states to recover WH from. From a theoretical, technical, and feasibility perspective steam and flue gases have proven to be suitable for the integrated WH network. Therefore, from this point on only those two phases will be considered for the scenario. Hereafter, the heat exchanger efficiencies have been established for the two phases based on literature. These efficiencies serve as input for the modeling phase to establish the overall system efficiency together with the transport losses. For the storage medium, basically three options have been chosen that adhere to the three layers of limits. Transport in steam is the most widely applied and conventional type of heat carrier in the industry, due to its low loss factor over distance and its convenience as a gaseous state. Flue gases seem to be an option for the heavy industry where large quantities of WH have to be transported over a relatively short distance. Due to the high loss factor for transportation this potentially only is a viable option for short-distance transport. Heat storage in a TCM is technically immature, but it shows high potential in different aspects. Not only as a transportation material for heat but also as a storage material to mitigate the volitivity of heat supply and demand. Since this research is focused on the operations of integrated WH exchange in industrial areas, the TCM will be in scope to assess what its potential role will be. Lastly, the TCM has been chosen as a heat carrier instead of PCM due to its higher operating temperature and the negligible losses. Therefore it is a better fit for the analysis of industrial areas that often operate at high temperatures.

6

Scenario development

In this chapter, the scenario that will be modeled is presented. To ensure that the scenario approaches reality, elements of the basic design cycle have been applied. By using this cycle, an iterative process is performed that constantly evaluates the quality of the scenario, which results in an approved design that serves as input for the model. This iterative cycle is performed in a three-step process. The first step is data gathering, where a network of the nodes will be created including their heat supply and demand. In the second part, several scenario choices will be elaborated on, which will be followed by verification with industry experts. After verifying the scenario, adjustments to the scenario have been made according to the feedback. The main goal of the scenario development is creating a set of configurations for the scenario that make it possible to answer the main research question.

6.1 Network and infrastructure

In paragraph 4.2 the choice for the MRA and the basic list of actors has already been elaborated on. A more detailed description of the region will be provided in this paragraph, which is necessary as input for the model. Based on previously obtained results in chapters 4 and 5, choices will be made on what nodes will actively participate in the network. The general conclusion of chapter 4 was that the electricity sector is unlikely to participate in an integrated WH network due to its strategic position. Therefore, these nodes have been removed from the initial list of companies that were based on carbon emissions. All other sectors have a different strategic position within the network. An overview of the remaining nodes and their strategic positioning is presented in table 6.1.

Company	*Sector*	*Potential role*
Tata Steel	Steel	Market initiator/leader
Schiphol	Aviation	Follower
Crown van Gelder (CvG)	Industrial appliances/materials	Participant
Tate & Lyle	Food processing	Participant
Bunge Houthavens	Food processing	Participant
Albermare catalysts	Industrial appliances/materials	Participant
Cargill BV (Soja)	Food processing	Participant
Norit Nederland	Industrial appliances/materials	Participant
Academic Medical Centre	Hospitals	Follower
VU-VUmc	Hospitals	Follower
ADM Cocoa BV	Food processing	Participant
Bunge loderus Crocklaan	Food processing	Participant
ForboFlooring	Industrial appliances/materials	Participant
KLM Engineering & Maintenance	Aviation	Follower
ENCI	Industrial appliances/materials	Participant
Draka Interfoam	Industrial appliances/materials	Participant

Table 6.1 Strategic position per company.

After the identification of these companies, representatives of several companies that are on this list have been contacted. Data on their energy consumption was requested to use that for the modeling phase. Requests were not fulfilled by all firms. In these cases, their consumption has been estimated (if possible) based on their emissions. An overview of the nodes from which consumption data and WH availability has been retrieved or estimated is presented in the network overview in figure 6.1. A distance matrix of the nodes is presented in Appendix F. Based on this overview it was decided that there were sufficient nodes with varying scale and geographical specifications to model the behavior of an integrated WH network.

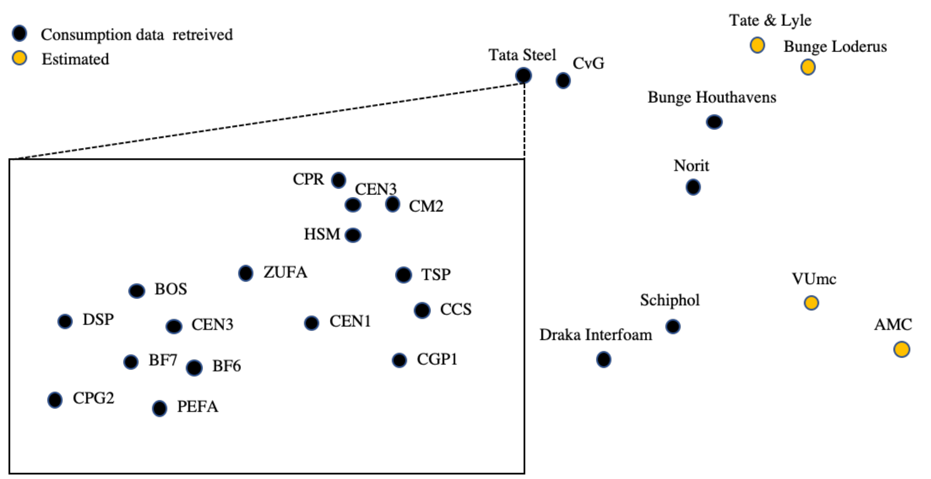

Figure 6.1 The nodes in the MRA that data was provided for and estimates. Estimations are based on emissions.

The exchange of WH requires transportation. Hence it is interesting to determine how the infrastructure looks like in this region. The conceptual model (figure 4.2) describes the four general methods there are to transport WH. The most traditional is through a piping system, whereas transport by truck, train, or boat concerns a novel technology of heat storage in a TCM. In paragraph 5.1 the transport losses have been described, which show that transport losses for gases are relatively high, with a loss of 100% at a distance of 4000 meters. This implies that heat transport through a pipe with flue gases is viable internally at Tata Steel or with Crown van Gelder, since all other nodes have a distance over 4000 meters. The pressure drop for steam over long distances is low, which makes its transportation over long distances viable. However, realizing long-distance piping systems can be a long and complex process. That often has a negative influence on the feasibility of the project. Complexity is created due to the many involved stakeholders and physical obstacles such as cities, roads, and other types of infrastructure. Flexible heat networks don't have this characteristic, because currently existing infrastructure can be used for transportation. In the MRA, there is a difference amongst the nodes in terms of accessibility. An overview of the accessibility for each node is provided in the following table.

Node	***Road***	***Railways***	***Waterways***
Tata steel nodes	○	○	◔
CvG	○	◕	○
Bunge Houthavens	○	◐	○
Tate & Lyle	○	◕	◔
Bunge Loderus Crocklaan	○	◕	◔
Norit	○	◐	◔
AMC	○	◐	●
VUmc	○	◕	●
Schiphol	○	◔	●
Draka Interfoam	○	●	●

Table 6.2 The pie chart indicates the level of accessibility through different types of infrastructure (black is less accessible). Results are based on the availability of roads, the proximity of unloading train stations, or unloading docks for ships.

Based on this table, the outcomes of the model can be evaluated on the operational feasibility. If the model generates outcomes that are infeasible based on the accessibility, additional constraints will be added to force the model to a solution that matches the scenario.

6.2 Heat sources

In this paragraph, the potential heat sources of the WH network will be described. To obtain these data, several data requests (2018 energy consumption data) were done to all the companies that were in the scope of the research. Although data was not received from all the potential nodes, it was beneficial that this research has been conducted in cooperation with Tata Steel. Tata Steel is the largest energy consumer within the network, and also operates at the highest temperatures. Accordingly, they have the largest share of energy consumption and WH availability. The plant is operated by multiple factories that belong to different phases of the steelmaking process. The plant itself enables modeling of an industrial region since it operates as a multitude of different energy-consuming processes. Another beneficial circumstance is the fact that the plant operates both batch and continuous processes. This enables the chance to model how those two can potentially interact with each other, and what trade-offs can be identified based on these results.

For none of the nodes, there was data on the available WH. Therefore, this had to be calculated by using Sankey diagrams[1] combined with estimations made through discussions with operational experts. The results of these estimations can be found in Appendix G. By determining the ratio between input and WH output for each node, the hourly WH availability could be calculated based on hourly consumption data. The WH availability calculations are explained in Appendix H. The potential nodes for WH supply were identified based on two aspects. The node either had to have residual heat in the form of flue gases at high-grade temperature, or a steam surplus. Other forms of WH are out of scope due to temperature levels, physical, theoretical, technical, or feasible limits described in chapter 5. An overview of the potential WH suppliers is provided in table 6.3. Note that the available WH in PJ is based on the consumption data of each node. Temperatures purely serve as an indication of whether the output is a high-grade heat.

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[1] A Sankey diagram is a diagram where the width of the (energy) flows are proportional to their quantity. In this case, it serves as an energy balance to determine what the potential available WH is by identifying the losses.

WH supply node	*Temperature ºC*	*Type*	*Quantity (PJ/year)*
BF6	192	Flue gas	0.18
BOS	150	Steam	0.11
DSP	700	Flue gas	0.11
HSM	550	Flue gas	1.05
TSP	700	Flue gas	0.25
CM2	700	Flue gas	0.14
CPR	400	Flue gas	0.24

Table 6.3 Temperature and quantity of available WH of each supply node.

All of the nodes are located on the terrain of Tata Steel, which concentrates this as a major supply area. This is favorable when looking at the accessibility of the plant, where its overall score is one of the best. Therefore, all transportation options are considered as a feasible option.

The supply pattern is an important factor that influences the operations of the integrated WH network. To visualize the level of supply, the supply load curve of the nodes has been created. The supply curve for the HSM node is presented separately, due to its scale. The load curve is an important graph that helps to determine the potential capacity that can be exchanged. Investment decisions rely on the number of operational hours and the corresponding capacity, especially when it comes to building new pipelines or other types of infrastructure. The steeper the line in the graph is, the more volatile the supply of the node is.

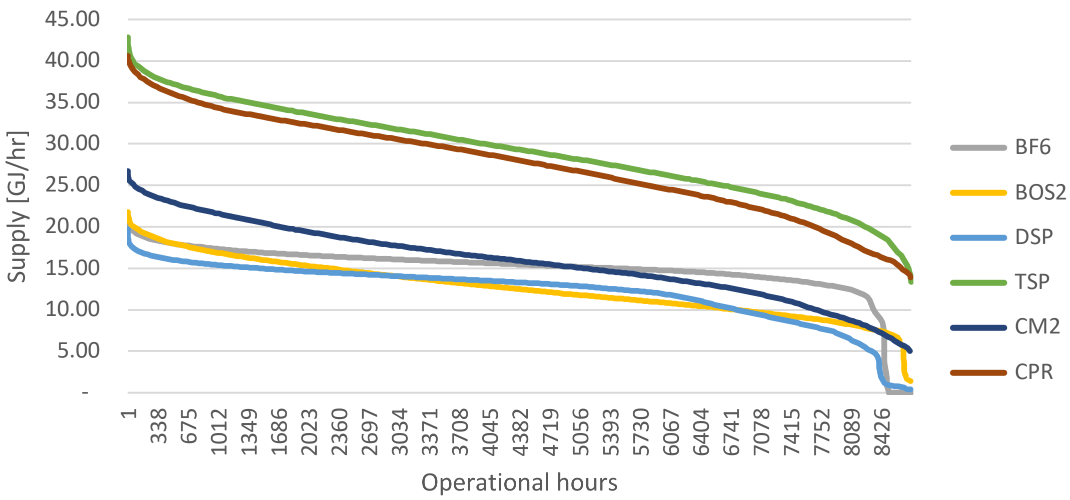


Figure 6.2 The supply curve for the different nodes.

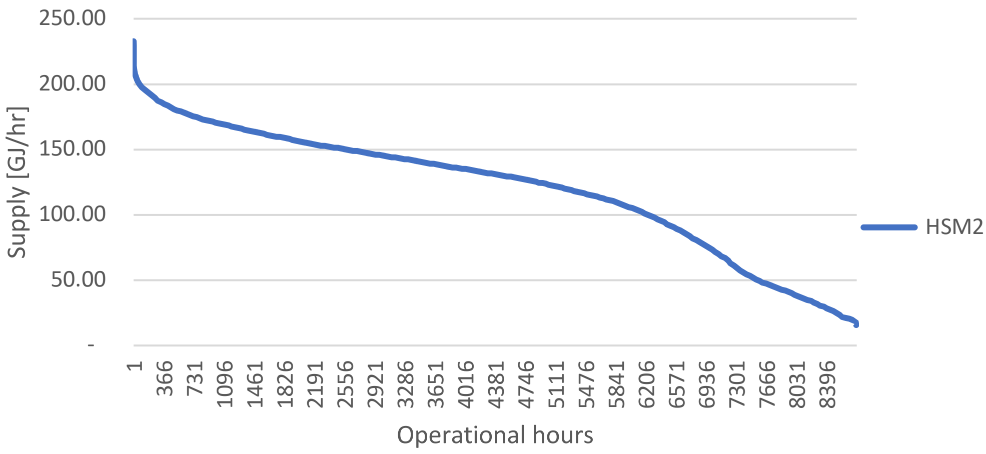


Figure 6.3 The supply curve for the HSM node in a separate graph due to its scale.

6.3 Heat sinks

The heat sinks are the potential demand nodes of the integrated WH system. Based on the assumptions made in chapter 5 and the qualitative assessment in paragraph 5.2, it became apparent that heat in flue gases and heat in steam shows the highest feasibility within the MRA. An overview of the demand nodes has been created and is presented in table 6.4. The quantities are based on the annual hourly consumption profile of the nodes. All the nodes are currently operational (except for the CCS node) and data has been retrieved from 2018. The CCS node is the only node that is currently not operational. This is an installation that will be built in the near future at Tata Steel, which has a stable and high energy demand. Tata Steel has specifically requested to add this node due to its large energy consumption and important role in their future energy system.

WH demand node	*Temperature ºC*	*Type*	*Quantity (PJ/year)*
CPG1	190	*Steam 15 bar*	*0.64*
TSP	*190*	*Steam 15 bar*	*0.46*
CM2	*172*	*Steam 3.5 bar*	*0.18*
CPR	*172*	*Steam 3.5 bar*	*0.06*
CEN1	*190*	*Steam 15 bar*	*0.12*
CEN3	*172*	*Steam 3.5 bar*	*0.03*
ZUFA	*190*	*Steam 15 bar*	*0.07*
CCS	*172*	*Steam 3.5 bar*	*14.6*
Bunge HH	*80*	*Water*	*1.31*
CvG	*190*	*Steam 15 bar*	*19.7*
Draka	*80*	*Water*	*0.30*
Schiphol	*80*	*Water*	*1.53*
Norit (cabot)	*1000*	*Hot air*	*1.80*
VUmc	*80*	*Water*	*0.40*
AMC	*80*	*Water*	*0.40*
Tate & Lyle	*172*	*Steam 3.5*	*1.45*
Bunge Loderus	*80*	*Water*	*0.37*

Table 6.4 Temperature and quantity of heat demand for each demand node.

The WH demand is mainly driven by the CCS and nodes outside the terrain of Tata Steel. In this scenario, 5% of the total WH demand can theoretically be covered by reusing the available WH. However, this is theoretical and does not incorporate possible losses and a mismatch of demand and supply at a specific hour. The actual percentage that can be covered will be determined by the solutions obtained from the model.

The demand load curves of the nodes are presented in figure 6.4, 6.5, and 6.6. Most of the nodes show a relatively stable energy demand, however Norit and CvG have a more volatile demand based on their steep curve. The straight demand curve for Bunge HH is because of the way that they have provided the data. They have provided the monthly consumption data and indicated that their operations are fully continuous for 8300 hours per year. The same holds for the currently non-operational CCS node, where an estimation of the consumption is provided by the Energy Efficiency team of Tata Steel.

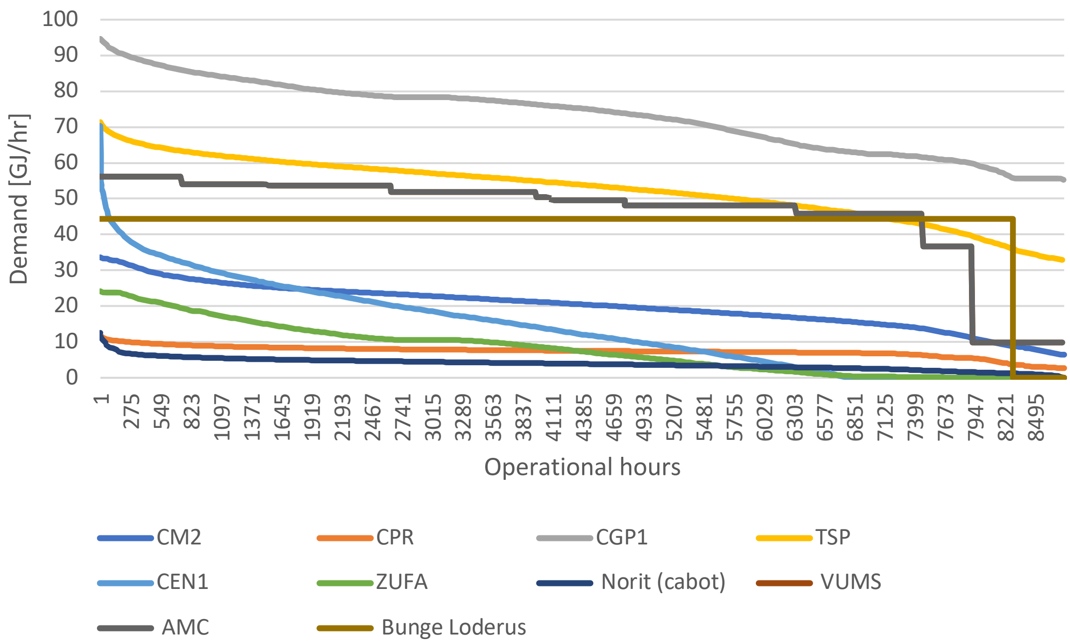


Figure 6.4 The demand load curve of the smaller scale nodes

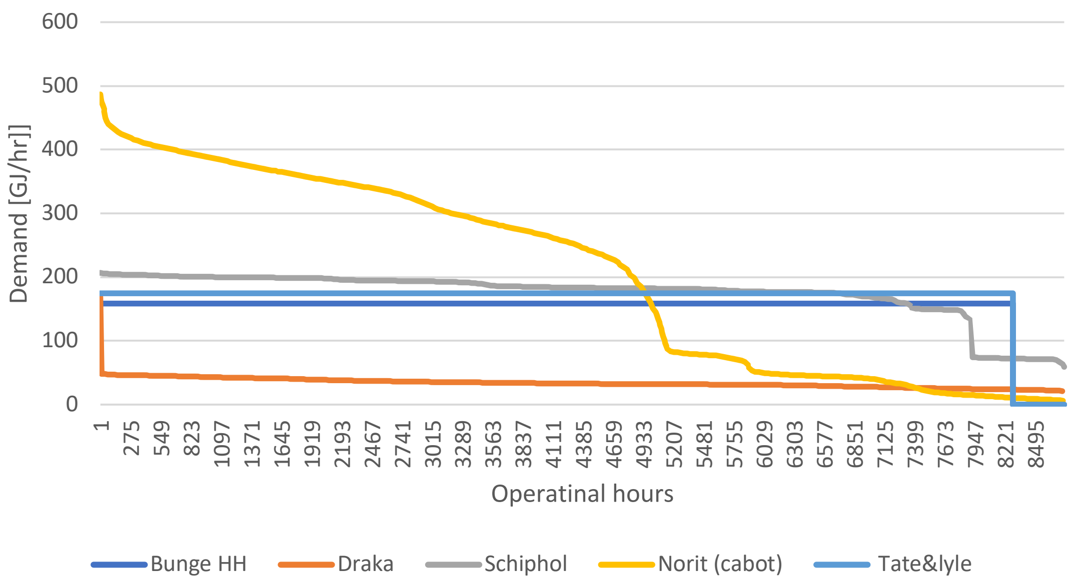


Figure 6.5 The demand load curve of the medium-scale nodes

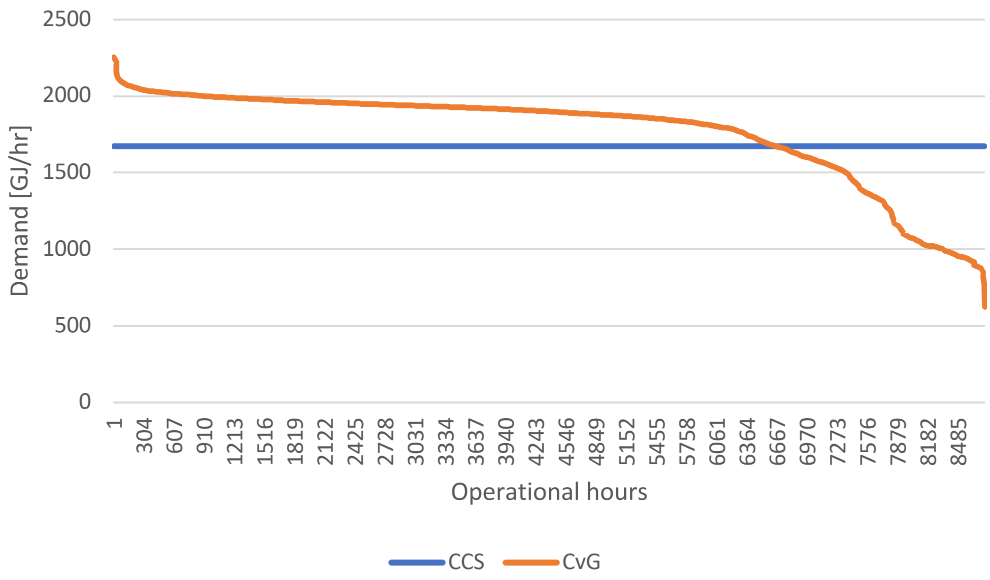


Figure 6.6 The demand load curve of the large scale nodes

6.4 Modeling choices

In this paragraph, several choices concerning the scenario input will be discussed. The way the scenario will be entered into the model determines what types of analyses can be performed. The three main insights that have to be obtained to answer the main research question are (1) how the network should be operationalized, (2) carbon emission reductions, and (3) trade-offs between different energy storage and transportation technologies. For each of those three, an explanation will be provided on how the input will be set so that they can lead to valuable outcomes.

The operations of the integrated WH system are key to understand how WH can be used to lower carbon emissions on a system level. The model will try to find a dispatch with connections between nodes that optimally use this WH. However, there are different options for how to operate a WH network. Each node has several in and outgoing connections after the dispatch will be made. Theoretically, the number of connections can be infinite, however this is practically not desired. This could lead to a complex solution where a small change of input could change the overall dispatch completely. It would also imply that allowing a node to have infinite connections every node can adjust its operations according to the WH dispatch at any time. Although this might lead to better results in the optimization, it not an operationally feasible solution. Therefore, the maximum number of outgoing connections is limited to 1, and the maximum number of incoming connections is 3. This number has been established by verification with industry experts. The exchange of WH will be measured in GJ, after which the exchange profile is obtained. Based on these exchange profiles the analysis of the operations can be performed.

Assumption #6.1: the maximum number of outgoing connections for supply nodes is 1, and the maximum number of incoming connections for demand nodes is a maximum of 3.

The main optimization goal is the minimization of carbon emissions. In the model, this is done by maximizing the amount of carbon emissions reduced over the whole network. However, for each type of WH exchange, there is another type of energy input that is replaced by WH. Therefore, the potential WH exchanged is multiplied by the emission factor of the different types of energy input. An overview of the emissions factors is provided in table 6.5.

Emissions	kg CO_2/GJ	Source
Natural gas	56.1	(van Harmelen & Koch, 2002)
Hot water	60.0	(van Harmelen & Koch, 2002)
Hot air	56.1	(van Harmelen & Koch, 2002)
Steam 3.5 bar	74.8	(IEA ETSAP, 2010)
Steam 15 bar	76.8	(IEA ETSAP, 2010)

Table 6.5 Emission factors.

In an integrated WH network, the situation of every node is unique due to its location, energy intake/supply, and consumption profile. Therefore, many trade-offs influence the choice of what technology will be the most suitable for the connection between two nodes. Flexibility might be valuable to one node, while the security of supply is important to another node. In that case, flexibility could be offered by that storage, while the security of supply is better guaranteed with a pipeline. These are aspects that are difficult to quantify for optimization. Therefore, these aspects will not be part of the input of the model, hence this will not be subject to optimization. To gain insights into the trade-offs without optimizing these aspects, the different configurations of the scenario have to provide the opportunity to gain insights on the following aspects:

- Infrastructure options;
- Maximum carbon reduction;
- Operations of the WH network;
- The resilience of the WH network;
- Key drivers of carbon reduction.

The model has limitations when it comes to inserting different configurations. Once a supply node has supplied its energy to another node, the model is not able to calculate what share of the potential energy is left. This is an option in more advanced (dynamic) modeling. However, the running time and power of the Excel solver do not allow this for this work. For this research, this is not a major limitation because it is expected that a supply stream will be fully consumed. The number and quantity of the demand nodes (see table 6.6) show that the demand-side outweighs the supply-side by much. Therefore it is assumed that each supply node can only supply its energy to one demand node. This assumption will be validated by checking if there is a large percentage of unused available WH in the optimal dispatch.

Nodes (supply/demand)	***Quantity (PJ/year)***
CvG	19.7
CCS	14.7
Norit (cabot)	1.80
Schiphol	1.53
Tate & Lyle	1.45
Bunge HH	1.31
HSM	1.05
CPG1	0.64
TSP	0.46
VUmc	0.40
AMC	0.40
Bunge Loderus	0.37
Draka	0.30
TSP	0.25
CPR	0.24
BF6	0.19
CM2	0.18
CM2	0.14
CEN1	0.12
BOS	0.11
DSP	0.11
ZUFA	0.07
CPR	0.06
Norit	0.05
CEN3	0.03

Table 6.6 The supply and demand nodes ranked on the energy quantity (bleu = demand & white = supply).

Different configurations have been created that enable making the required analyses to answer the main research question. The number of allowed connections for the demand node is set at a minimum of 0, as there are not enough supply nodes to provide every demand node with WH. The maximum number of connections of demand nodes vaires and is set at a maximum of three connections. This is limited due to the increasing operational complexity of the system as the number of connections increases, as well as the time constraint to conduct this research. To test how resilient the system is, three configurations have been created that have limited security of supply. In this case, that means that an analysis can be performed to understand the implications of an unexpected interruption in WH supply. It is expected that in configuration 10 to 12 the reduced carbon emissions are not highly affected, however operations of the demand node can be disrupted due to this. In scenario 10-12, an arbitrary period of 26 days has been eliminated for four nodes. The HSM and CM2 node had an interrupted supply from 1 to 26 April, and the BF6 and CPR from 1 to 26 September.

The total number of connections is limited to the number of supply nodes, which are in total 7. This is varied over 3, 5, and 7 because a lower number of connections will lead to solutions close to suboptimal, while the maximum number of connections might lead to a solution with less suboptimal outcomes but increased overall performance. After the results are generated for a configuration, they will first be validated on their feasibility. This means that supply nodes do not supply more than the maximum available WH that they have, and that the demand nodes do not receive more WH than they consume at each hour.

Configuration	***#connections supply nodes***	***#connections demand nodes***	***Security of supply***	***Total number of connections allowed***
1	*1*	*Min. 0 - max. 1*	*yes*	*3*
2	*1*	*Min. 0 - max. 1*	*yes*	*5*
3	*1*	*Min. 0 - max. 1*	*yes*	*7*
4	*1*	*Min. 0 - max. 2*	*yes*	*3*
5	*1*	*Min. 0 - max. 2*	*yes*	*5*
6	*1*	*Min. 0 - max. 2*	*yes*	*7*
7	*1*	*Min. 0 - max. 3*	*yes*	*3*
8	*1*	*Min. 0 - max. 3*	*yes*	*5*
9	*1*	*Min. 0 - max. 3*	*yes*	*7*
10	*1*	*Min. 0 - max. 1*	*No*	*5*
11	*1*	*Min. 0 - max. 2*	*No*	*5*
12	*1*	*Min. 0 - max. 3*	*No*	*5*

Table 6.7 The configurations that will be run.

Assumption #6.2: to generate a feasible solution, the supply node cannot supply more than its maximum WH availability.

Assumption #6.3: the total received hourly WH for each demand node is lower than their total hourly energy consumption.

Assumption #6.4: Available WH will be consumed in the same hour as availability. This assumption will be verified during the analysis.

7

Determining the optimal dispatch

In this section, the obtained data from the modeling phase will be presented. Several configurations have been modeled to gain insights into the dynamics of this system, as described in paragraph 6.4. First, the optimization approach will be discussed, followed by an overview of the system constraints that have been identified in chapters 4, 5, and 6. The results will be presented in the last part of the chapter.

7.1 Optimization approach

By conceptualizing the model in paragraph 4.1, a clear overview of the data requirements was made; the initial system constraints were identified. After further parametrization in chapters 4 to 6, the formal model could be created.

By targeting maximum carbon reduction in a MILP model (see Appendix H for the objective function, constraints, and other calculations used in the model), it is possible to determine the optimal dispatch of WH amongst the nodes to minimize the carbon emissions on a network level. The model was provided with the overall losses in the system, such as heat exchanger losses and transportation losses. It is expected that suboptimal solutions are likely to be connections with overall high demand compared to supply and low distance between nodes. That would result in high utilization of the WH supply node and relatively low transportation losses. By using the model in different configurations, it is possible to determine differences in both effectiveness and efficiency. Hourly consumption data of 2018 was used if provided. If not provided, the demand of the node was either estimated based on their emissions (Appendix G), or the node was removed from the network if the estimate could not be made. By feeding a node with WH, the decline in consumption could be calculated on an hourly basis. The replaced consumption was either natural gas for hot air purposes or process steam at 3.5 bar of 15 bar. Based on the carbon emissions per GJ consumption, the 'prevented' carbon emissions could be calculated.

7.2 System constraints

The modeled system is subject to many constraints. Amongst those are theoretical, technical, feasible, strategic, and modeling limits, which have been identified in chapters 4, 5, and 6. In this paragraph, an overview of the structural assumptions made for this system is presented.

Structural assumptions made for the system:

Assumption #4.1: The electricity sector will not participate in an integrated WH network.
Assumption #5.1: WH recovery and usage from solids will be will not be used in the scenario due to the non-available technology to recover it.
Assumption #5.2: WH recovery from slag is currently under development with efficiencies up to 65%. However, due to the scope of this research and the technology being non-mature, slag will not be considered as a viable heat source.
Assumption #5.3: Steam is the industry standard for continuous high-temperature heat transport, hence liquids will not be considered for continuous heat networks.
Assumption #5.4: Efficiencies of PCM related case studies will be applied for TCM in this model due to the similar process.
Assumption #5.5: Heat storage will only take place in a TCM. Steam and flue gases will be used for direct purposes. Transportation time for all heat carriers will be neglected due to the negligible expected impact on the results.
Assumption #5.6: all available WH [GJ] will be used, even though in practice this will not be 100%. The unused energy is incorporated in the overall WH losses.
Add Assumption: efficiency assumed to be similar for water
Assumption #5.7: Efficiencies to TCM have been based on results of research into PCM. However, due to the similarities in processes, this estimated efficiency is assumed similar.
Assumption #5.8: one storage vessel with TCM weighs 14 tons (Krönauer et al., 2015) and has an energy density of 1368KJ/kg (Xu et al., 2019).
Assumption #5.9: Long-distance heat transport will be done in the steam or TCM phase, as the flue gas losses are 100% at a distance of 4000 meters or more.
Assumption #5.10: The estimated losses for steam are calculated over a temperature drop of 15 bar steam and are considered similar for other steam pressures. Other dimensions that influence the pressure drop are neglected.
Assumption #5.11: The estimated losses for flue gas transportation are based on a 1.5m diameter pipe (Selvaraj et al., 2015).
Assumption#5.12: If steam from flue gas is required, the location of the steam boiler will be at the exhaust pipes.
Assumption#5.13: There are no conductive losses in steam transport due to well-insulated pipes.
Assumption#5.14: Heat transformation from steam to other substances will not be further considered due to the low potential temperatures
Assumption#5.15: Liquids as WH source and heat carrier are not considered due to their unfavorable feasibility within high-grade temperatures.
Assumption#5.16: WH recovery and usage from solids state is scored infeasible and will therefore not be considered as WH source
Assumption #6.1: the maximum number of outgoing connections for supply nodes is 1, and the maximum number of incoming connections for demand nodes is a maximum of 3.
Assumption #6.2: to generate a feasible solution, the supply node cannot supply more than its maximum WH availability.
Assumption #6.3: the total received hourly WH for each demand node is lower than their total hourly energy consumption.
Assumption #6.4: Available WH will be consumed in the same hour as availability. This assumption will be verified during the analysis.

7.3 Results

An overview of the supply and demand nodes in the MRA is provided in figure 7.1. Within this network, the different configurations will vary over the total connections established, and the total allowed connections for demand nodes. In configuration 10 to 12, there is a disrupted supply.

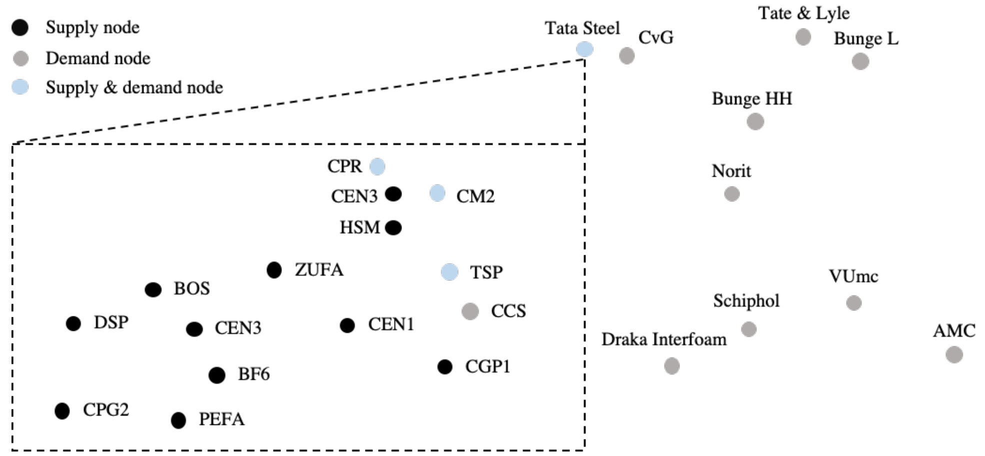


Figure 7.1 All potential demand and supply nodes.

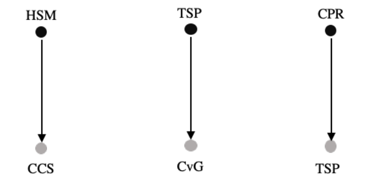
7.3.1 Results of the different configurations

By inserting different configurations into the model, it is possible to identify how the system behaves. The configurations have been categorized into four categories: level 1 level 2, level 3, and the disrupted system. For each of the four, the rationale and hypothesis will be discussed.

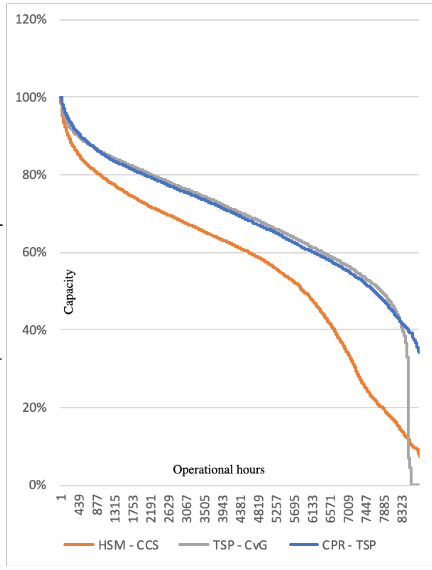
<u>Level 1</u>

In configuration 1-3, a level 1 version of the WH system is modeled. That means that there is only one interaction between two separate nodes. By letting the number of total connections increase, it is expected that the overall carbon emissions will decrease. Next to that, it is expected that the overall utilization of the available WH will decrease with an increasing number of total connections. The utilization is a percental expression of how much of the available WH is received at the demand node; is affected by heat exchanger losses and transportation losses. The model will identify the most efficient connections at first, after which less optimal connections will be added to the set of solutions. This is one of the aspects that will help in understanding how carbon reduction can be maximized and will provide insights for trade-offs. By increasing the number of total connections, it is possible to examine what the added value of an extra connection is. Moreover, it can show if extra connections are causing an increase or decrease in the overall WH utilization, or that it is stable. For each configuration, the required infrastructure is expressed in the length of the pipelines and the single distance in TCM transportation.

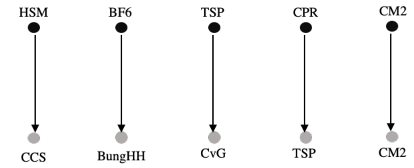
Configuration 1



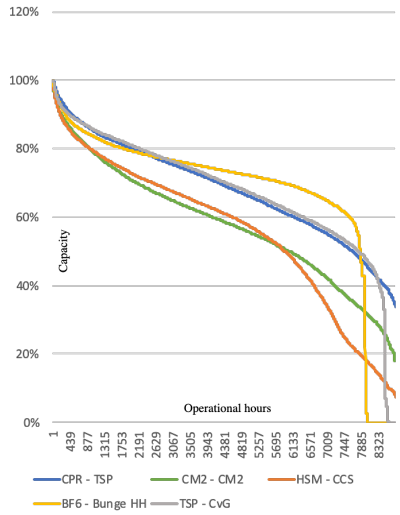
		HSM → CCS	TSP → CvG	CPR → TSP
Per connection	WH Exchanged [PJ/year]	0.96	0.21	0.22
	Utilization [%]	92.0%	82.5%	92.0%
	Max WH exchange capacity [GJ/hour]	214	36	37
Overall	Total WH exchange [PJ/year]	1.4		
	Total CO_2 reduction [kton]	105		
	Distance piping [m]	7300		
	Distance TCM transport [m]	0		
	Overall utilization [%]	90.4%		



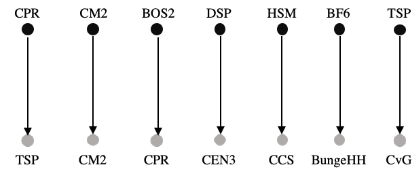
Configuration 2



		HSM → CCS	BF6 → BungHH	TSP → CvG	CPR → TSP	CM2 → CM2
Per connection	WH Exchanged [PJ/year]	0.96	0.11	0.21	0.22	0.12
	Utilization [%]	92.0%	80.6%	82.5%	92.0	88.6%
	Max WH exchange capacity [GJ/hour]	214	18	36	37	24
Overall	Total WH exchange [PJ/year]	1.6				
	Total CO_2 reduction [kton]	120				
	Distance piping [m]	2490				
	Distance TCM transport [m]	31440				
	Overall utilization [%]	89.6%				



Configuration 3



		CPR → TSP	CM2 → CM2	BOS2 → CPR	DSP → CEN3	HSM → CCS	BF6 → BungeHH	TSP → CvG
Per connection	WH Exchanged [PJ/year]	0.22	0.12	0.06	0.03	0.96	0.11	0.21
	Utilization [%]	80.6	57.3	57,3	26.2	92.0	88.6	92.0
	Max WH exchange capacity [GJ/hour]	37	24	12	18	214	18	36
Overall	Total WH exchange [PJ/year]	1.7						
	Total CO_2 reduction [kton]	127						
	Distance piping [m]	8500						
	Distance TCM transport [m]	31440						
	Overall utilization [%]	84.49						

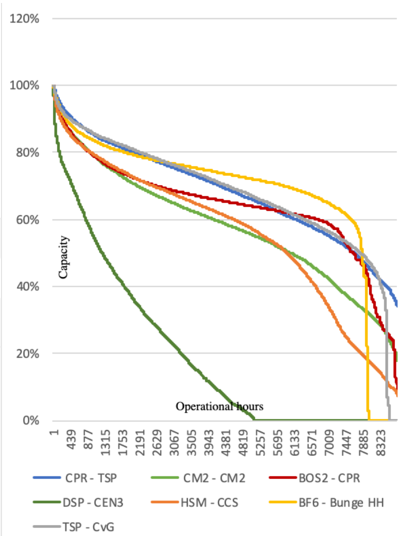
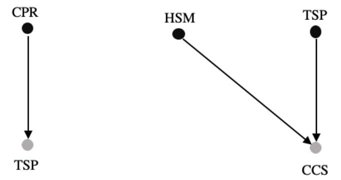


Figure 7.2 The optimal dispatch for configuration 1-3. Data on the separate connections and general data are presented. On the right-hand side, the WH supply curve for each connection is shown.

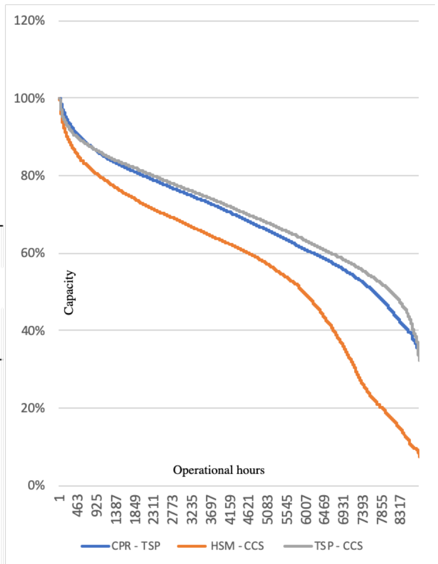
Level 2

In configuration 4-6 a more open version of the system is modeled. Demand nodes are allowed to have a maximum of two incoming connections. That makes the supply of WH more unpredictable and possibly more volatile because the supplied WH is an addition of two separate supply curves. In these cases, it is expected that the overall performance of the system will increase compared to level 1. The supply nodes are allowed to make connections that were not allowed in level 1. These new optional connections might show a higher utilization factor due to a better match in supply and demand patterns; the transportation losses are likely to decrease. Hence, it is expected that the level 2 configurations will show a better performance in carbon reduction and WH utilization.

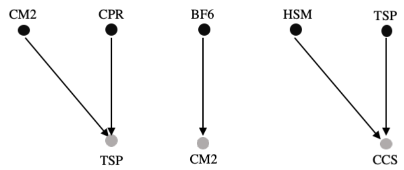
Configuration 4



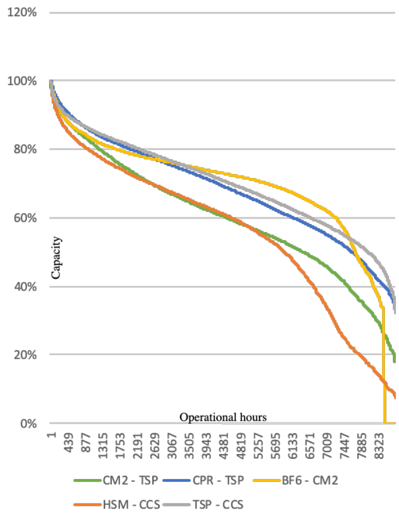
Per connection	WH Exchanged [PJ/year]	0.22	0.96	0.23
	Utilization [%]	92.0%	92.0%	92.0%
	Max WH exchange capacity [GJ/hour]	37	214	39
Overall	Total WH exchange [PJ/year]	1.4		
	Total CO_2 reduction [kton]	106		
	Distance piping [m]	4900		
	Distance TCM transport [m]	0		
	Overall utilization [%]	92.0%		



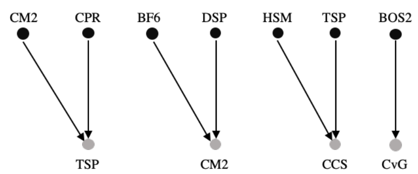
Configuration 5



Per connection	WH Exchanged [PJ/year]	0.13	0.22	0.11	0.96	0.23
	Utilization [%]	92.0	92.0	87.8	92.0	92.0
	Max WH exchange capacity [GJ/hour]	24	37	19	214	40
Overall	Total WH exchange [PJ/year]	1.7				
	Total CO_2 reduction [kton]	125				
	Distance piping [m]	9420				
	Distance TCM transport [m]	0				
	Overall utilization [%]	91.7%				



Configuration 6



Per connection	WH Exchanged [PJ/year]	0.13	0.22	0.11	0.10	0.96	0.23	0.09
	Utilization [%]	87.8	82.8	89.2	92.0	92.0	92.0	92.0
	Max WH exchange capacity [GJ/hour]	25	37	19	18	214	40	19
Overall	Total WH exchange [PJ/year]	1.8						
	Total CO_2 reduction [kton]	139						
	Distance piping [m]	12120						
	Distance TCM transport [m]	3490						
	Overall utilization [%]	91.1%						

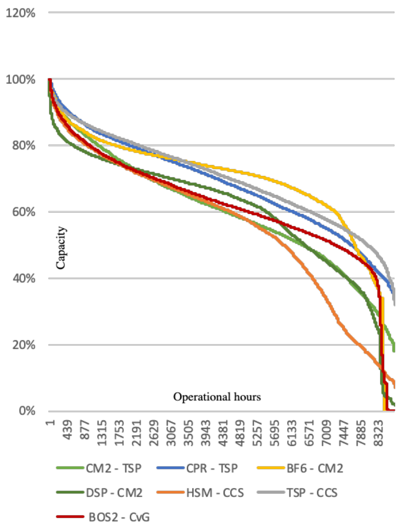
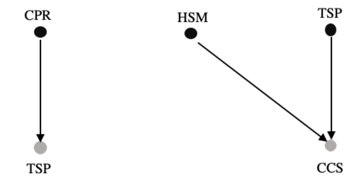


Figure 7.3 The optimal dispatch for configuration 4-6. Data on the separate connections and general data are presented. On the right-hand side, the WH supply curve for each connection is shown.

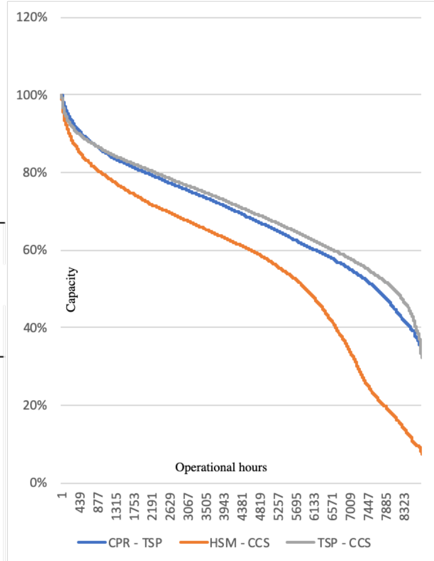
Level 3

By modeling configuration 7-9 and comparing them to the previously modeled configurations, it is possible to provide the insights that are required to answer the main research question. Demand nodes are now allowed to have three incoming connections, which again increases uncertainty in supply and potentially increases the volatility of supply, compared to level 1 and level 2. It is likely that in level 3, WH will be concentrated towards large demand nodes with proximity. Utilization is likely to be higher compared to the level 1 and level 2 system because the model is allowed to make connections that were not allowed in configuration 1-6. It is however interesting by how much the total carbon reduction increases by increasing the openness of the system. Moreover, it can also provide insights on how the required infrastructure changes as the system gains freedom.

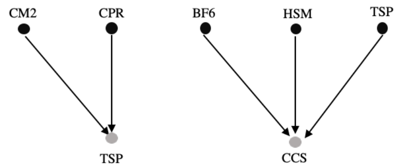
Configuration 7



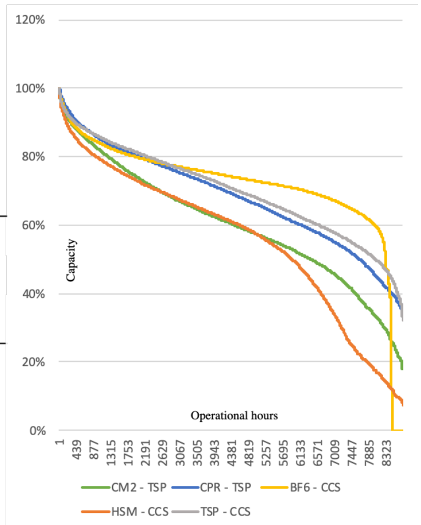
		CPR → TSP	HSM → CCS	TSP → CCS
Per connection	WH Exchanged [PJ/year]	0.22	0.96	0.23
	Utilization [%]	92.0	92.0	92.0
	Max WH exchange capacity [GJ/hour]	37	214	40
Overall	Total WH exchange [PJ/year]	1.4		
	Total CO_2 reduction [kton]	106		
	Distance piping [m]	4900		
	Distance TCM transport [m]	0		
	Overall utilization [%]	92.0%		



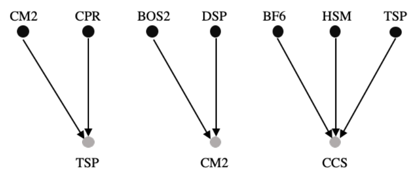
Configuration 8



		CM2 → TSP	CPR → TSP	BF6 → CCS	HSM → CCS	TSP → CCS
Per connection	WH Exchanged [PJ/year]	0.13	0.22	0.12	0.96	0.23
	Utilization [%]	92.0	92.0	92.0	92.0	92.0
	Max WH exchange capacity [GJ/hour]	25	37	20	214	40
Overall	Total WH exchange [PJ/year]	1.7				
	Total CO_2 reduction [kton]	125				
	Distance piping [m]	8150				
	Distance TCM transport [m]	0				
	Overall utilization [%]	92.0%				



Configuration 9



		CM2 → TSP	CPR → TSP	BOS2 → CM2	DSP → CM2	BF6 → CCS	HSM → CCS	TSP → CCS
Per connection	WH Exchanged [PJ/year]	0.13	0.22	0.10	0.10	0.12	0.96	0.23
	Utilization [%]	92.0	88.5	89.2	92.0	92.0	92.0	92.0
	Max WH exchange capacity [GJ/hour]	24.57	37.32	20.03	18.14	19.53	214.13	39.37
Overall	Total WH exchange [PJ/year]	1.9						
	Total CO_2 reduction [kton]	140						
	Distance piping [m]	13100						
	Distance TCM transport [m]	0						
	Overall utilization [%]	91.7%						

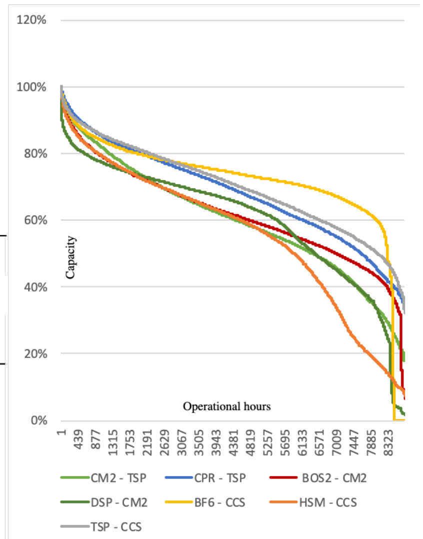
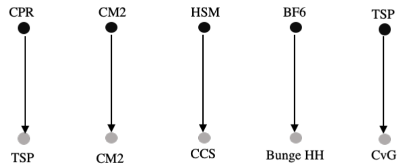


Figure 7.4 The optimal dispatch for configuration 6-9. Data on the separate connections and general data are presented. On the right-hand side, the WH supply curve for each connection is shown.

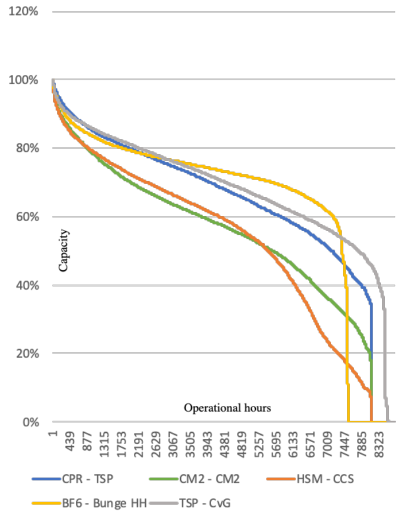
Disrupted supply

To examine the impact of (un)expected disruption in WH supply, configurations 10-12 have been modeled. In all of the three configurations, several days of WH supply were eliminated (put to zero). For all three configurations, this was done from 1 up to 26 April for the HSM and CM2 supply node and from 1 up to 26 September for the BF6 and CPR node. The disrupted supply pattern was modeled in level 2. The total number of connections was varied at 3, 5, and 7. It is expected that in these circumstances, the configurations will show slightly affected utilization and lower overall carbon emission reduction. It also measures how sensitive connections will be to a change in circumstances. This can be compared to configuration 4 to 6 (level 2). It is expected that the connection of the biggest supply node will not change, whilst supply nodes with an average annual WH availability could be subject to a change in case of disrupted supply.

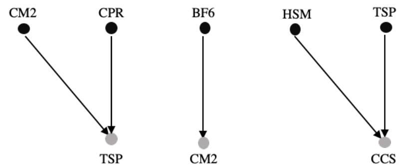
Configuration 10



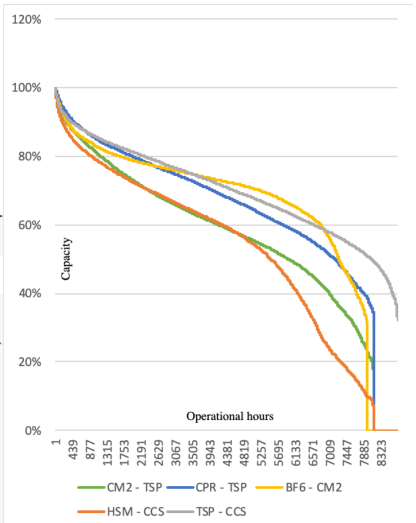
Per connection	WH Exchanged [PJ/year]	0.21	0.11	0.90	0.10	0.21
	Utilization [%]	92.0	88.6	92.0	80.7	82.5
	Max WH exchange capacity [GJ/hour]	37	25	214	18	36
Overall	Total WH exchange [PJ/year]	1.5				
	Total CO_2 reduction [kton]	113				
	Distance piping [m]	3860				
	Distance TCM transport [m]	31440				
	Overall utilization [%]	89.5				



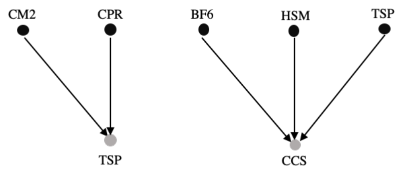
Configuration 11



Per connection	WH Exchanged [PJ/year]	0.12	0.21	0.11	0.91	0.23
	Utilization [%]	92.0	92.0	87.6	92.0	92.0
	Max WH exchange capacity [GJ/hour]	25	37	19	214	39
Overall	Total WH exchange [PJ/year]	1.6				
	Total CO_2 reduction [kton]	118				
	Distance piping [m]	9420				
	Distance TCM transport [m]	0				
	Overall utilization [%]	91.7%				



Configuration 12



Per connection	WH Exchanged [PJ/year]	0.12	0.21	0.11	0.90	0.23
	Utilization [%]	92.0	92.0	92.0	92.0	92.0
	Max WH exchange capacity [GJ/hour]	25	37	19	214	39
Overall	Total WH exchange [PJ/year]	1.6				
	Total CO_2 reduction [kton]	118				
	Distance piping [m]	8150				
	Distance TCM transport [m]	0				
	Overall utilization [%]	92.0%				

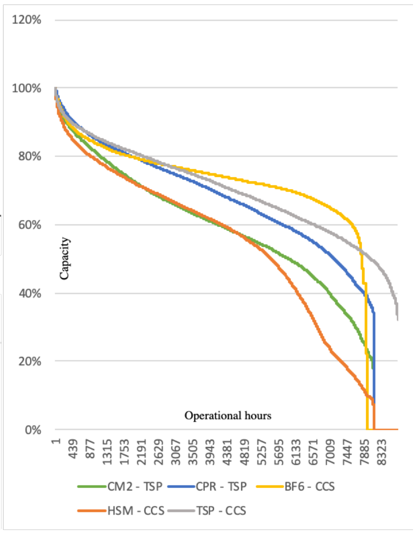


Figure 7.5 The optimal dispatch for configuration 10-12. Data on the separate connections and general data are presented. On the right-hand side, the WH supply curve for each connection is shown.

7.3.2 Configuration comparison

To compare the outcomes of different configurations, an overview is presented in this paragraph. Additional figures will be presented to analyze how each connection can be operated.

Config.	WH exchanged [PJ]	CO_2 reduced [kton]	Overall utilization	Distance piping [m]	Distance TCM [m]	Impact disruption
1	1.4	105	90.4%	7300	0	n.a.
2	1.6	120	89.6%	2490	31440	n.a.
3	1.7	127	84.5%	8500	31440	n.a.
4	1.4	107	92.0%	4900	0	n.a.
5	1.7	1251	91.7%	9420	0	n.a.
6	1.8	139	91.1%	12120	3490	n.a.
7	1.4	107	92.0%	4900	0	n.a.
8	1.7	126	92.0%	9420	0	n.a.
9	1.9	140	91.7%	13100	0	n.a.
10	1.5	113	89.5%	3860	31440	-5.9%
11	1.6	118	91.7%	9420	0	-5.8%
12	1.6	118	92.0%	8150	0	-5.8%

Table 7.1 An overview of the outcomes of the configurations. The impact of the disrupted supply in configuration 10, 11, and 12 is measured in the change of carbon emissions reduced compared to configuration 4, 5, and 6.

To gain further insights into what the most valuable connections in a WH network can be, an overview of the frequency that connections are made is presented in figure 7.6.

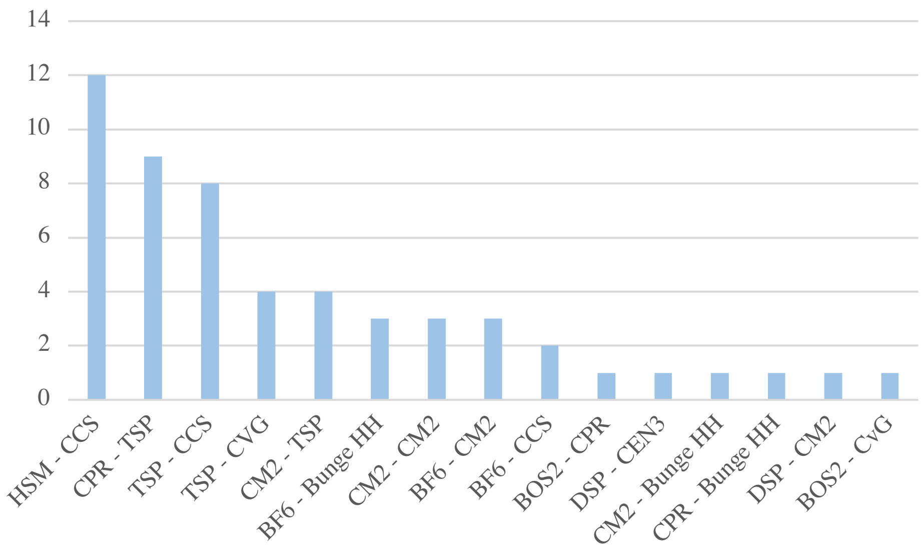


Figure 7.6 The frequency of connections made in the 12 different configurations.

In the following table, the WH exchange curves of the connections with a frequency higher than 1 in figure 7.6 are presented. The load curve has strong implications for the operations of the WH exchange connection.

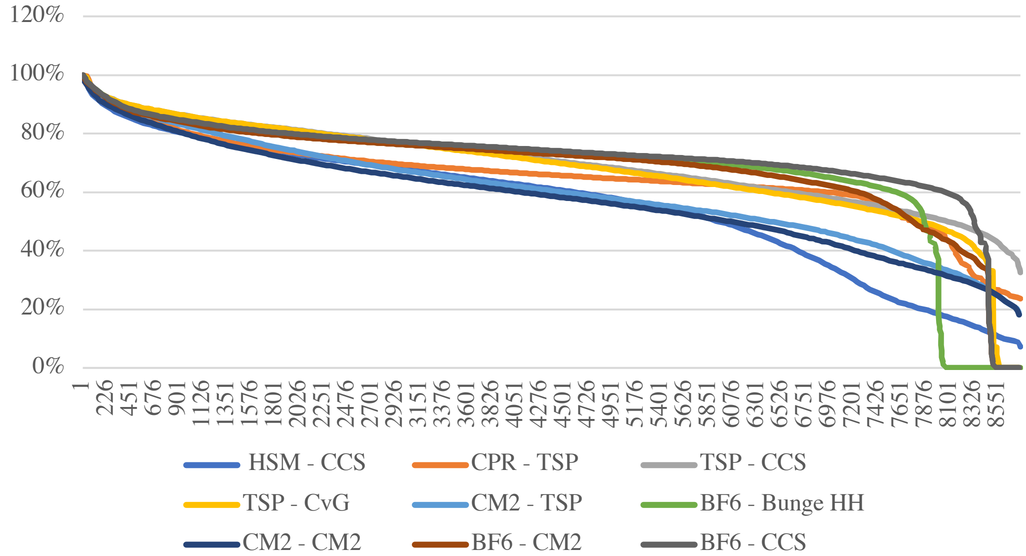


Figure 7.7 WH exchange curves of the connections with frequency >1. The curves are taken for a non-disrupted WH supply.

For all connections within Tata Steel, the steam pipeline has been selected as the optimal transportation method. Connections made from Tata Steel to consumers outside of the plant are transported by truck, train, or boat, using TCM as a heat carrier.

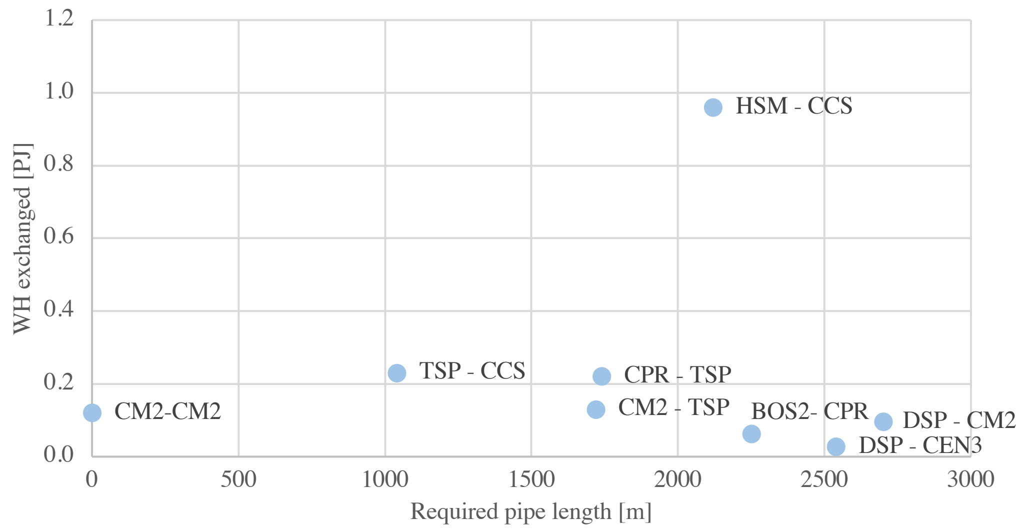


Figure 7.8 The required length of the pipe as opposed to the exchanged WH for all the connections with a frequency >1 for which pipelines have been chosen.

To assess the feasibility of the connections, an overview of the accessibility and required transportation capacity per transportation modus is made. Although it is preferred that the HSM – CCS link is connected by a steam pipe, the figures for flexible transportation is presented for comparison.

Connection	**Distance [m]**	**Accessibility** Truck	Train	Boat	**Required capacity / year (#containers)** Trucks (1)	Trains (50)	Boats (250)
TSP - CvG	3440	○	◕	n.a.	11054	221	n.a.
BF6 – Bunge HH	28000	○	◑	◔	5546	111	22
CM2 – Bunge HH	28000	○	◑	◔	6708	134	27
CPR – Bunge HH	28000	○	◑	◔	11659	233	47
BOS2 - CvG	3940	○	◕	n.a.	4831	97	n.a.
HSM - CCS	2120	○	○	n.a.	46921	938	n.a.

Table 7.2 The accessibility of all flexible connections with a frequency >1. The accessibility is rated based on the lowest accessibility score of the two connected nodes. The required capacity is calculated based on the full utilization of the WH and a storage container that stores 19 GJ.

7.4 Verification

"Without rigor, research is worthless, becomes fiction, and loses its utility"(Morse, Barrett, Mayan, Olson, & Spiers, 2002). Hence, a great amount of attention has to be applied to test the reliability and validity of the research methodologies and the outcomes. In this paragraph, the chosen methods, the application of the methods, and the outcomes by using these methods will be discussed to verify the outcomes that have been presented in paragraph 7.3. Although these outcomes are the main focus of the analysis, the parametrization in chapters 4 to 6 will also be subject to discussion. This is relevant because the constraints have a strong influence on the outcomes of the model. Through discussions with industry experts and testing the hypotheses, the outcomes of the research will be verified on two dimensions: (1) do the outcomes match the initial hypothesis and do they align with logic, and (2) do the outcomes provide the insights that are required to answer the main research question. The research approach, methods, and results were discussed with Tata Steel's energy consultant Ing. T. van der Velde MBE and former program leader of Tata Steel's Energy Efficiency program Drs. ir. G. Jägers.

7.4.1 Initial hypothesis and logic

The configurations were differentiated on the number of allowed connections for the demand nodes, and the total amount of connections made. By increasing the allowed incoming connections for demand nodes, it was generally expected that the overall carbon reduction would increase, but with a stagnating trend. This hypothesis matches the results.

The model first identifies and selects the connections with the highest impact, hence by increasing the number of connections, less impactful connections are added to the set of solutions.

By increasing the number of allowed connections for each demand node, a similar increasing trend is expected for the overall carbon reduction. What is interesting in these cases is the required infrastructure for each configuration. Although the cost factor is left out of the optimization, the efficiencies of the short distance steam pipelines are favored over the long-distance, which is done by TCM transportation. From the perspective of carbon reduction, this makes sense. As the efficiency positively influences the overall carbon reduction.

In the scenario creation phase, the assumption was made that a supply node could make a maximum of one connection. This was based on the hypothesis that once a supply node has made a connection, it is (close to) fully utilized (assumption 6.2). The only configuration where this assumption did not apply is number 3. This was one of the level 1 configurations; this was the most restricted configuration of the system. As the freedom of the system increased in level 2 and level 3, the utilization of these supply nodes went up to almost full utilization. Realistically, a level 1 configuration would not be applied. Therefore, the assumption is well-founded proved.

7.4.2 Insights for the main research question

The last verification step is to test whether the results provide the required insights to answer the main research question. The separate elements of the research question, expressed in sub-questions will be listed and the corresponding data references will be displayed. Based on this overview it is decided that there is sufficient data to perform the analysis.

Required for main RQ	**Data**
Infrastructure options	Technology assessment (Chapter 5)
Maximum carbon reduction	Optimal dispatch (chapter 7.3), overall WH reduction (chapter 7.3)
Operations of WH network	Load curves (chapter 7.3), steam pipes (chapter 7.3), TCM transport (chapter 7.3), distance matrix (Appendix F), accessibility table (table 6.2), frequency of connections (chapter 7.3)
Resilience of the WH network	Configurations 10-12 (disrupted WH supply) (chapter 7.3), load curves (chapter 7.3)
Key drivers carbon reduction	(Analysis of) difference between configurations (chapter 7.3)

Table 7.3

8

Analysis and evaluation

In this section, the analysis of the results will be performed and the main research question will be answered. The analysis is performed per listed required insight, of which an overview is provided in paragraph 6.4. In table 7.3 the data references that directly correspond to these insights are provided. A thorough interpretation of results will be used to discuss and determine their meaning and implications. Next to that, these outcomes will be evaluated based on the initial hypotheses.

8.1 Key drivers of carbon reduction

When reflecting on the main objective of this research, the key drivers of carbon reduction within an integrated WH network are an important measure. For effective carbon reduction, thus a high carbon reduction, several key drivers occupy a big role. The market dynamics play a large role in the level of complexity of the network (chapter 4). In the MRA the large-scale WH exchange is mainly focused on the leading company. In more fragmented industrial areas the governance could be more complex. Such areas will benefit from a stable market mechanism that is yet to be established. Additionally, fragmented industrial areas would require a market operator to manage the dynamics of the WH flows. This role could be occupied by one of the companies, or by an institutionalized third party. To assess the feasibility of an integrated WH system, the market dynamics of an industrial zone should be analyzed.

The scenario was tested in different configurations by varying over the level of freedom (level 1, 2, 3) of the system. What can be observed in figure 8.1 is that in level 1, level 2, and level 3 the overall carbon reduction increases with a stagnating, but an increasing trend. This implies that the added value of an extra connection is lower than those of the first connections. In level 1, this stagnating trend is strong compared to level 2 and level 3, where the stagnation is less and at a similar level. What can be learned in this respect, is that a key driver for carbon reduction are the first made connections within this system. As they occupy approximately the first 105 kton carbon reduction while adding 4 extra nodes to the system delivers a maximum increase of about 36 kton carbon reduction.

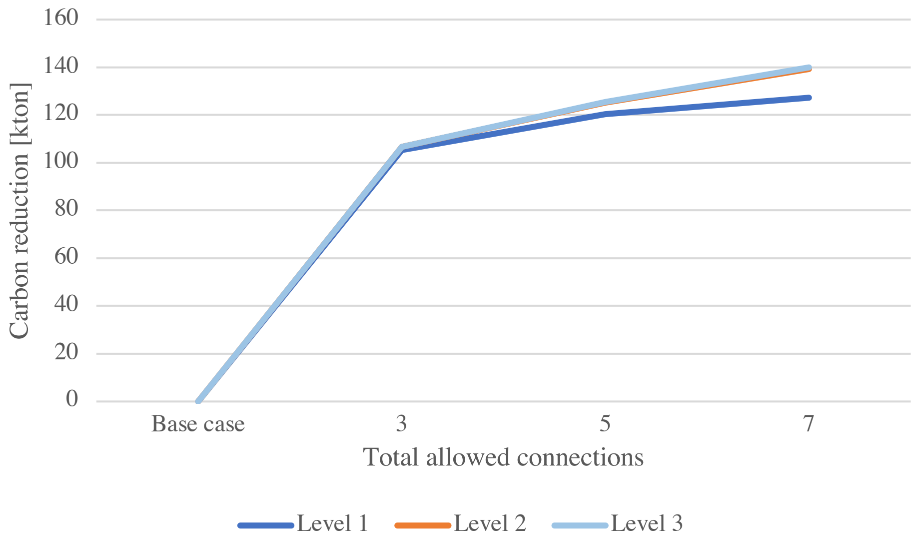


Figure 8.1 Variation over the number of total allowed connections in the system for the different types of systems. Numerical data can be found in Appendix I. (# connections demand node: level 1 = 1, level 2 = 2, and level 3 = 3)

By varying over the maximum number of allowed incoming connections of the demand nodes, it is possible to identify if adding freedom to the system results in a more optimal solution. This analysis is relevant for the operations of the network, due to the increasing volatility of supply as the number of allowed incoming connections increases. What can be observed in figure 8.2 is that there is a difference in carbon reduction between the number of allowed connections. This implies that by increasing the allowed incoming connections, the overall carbon reduction will be higher. This difference becomes increasingly strong as the total number of allowed connections of demand nodes increases. However, after increasing the total number of allowed connections more than 2, the overall performance of the network does not increase significantly. As a result, the maximum amount of connections a demand node should take in this network is 2 (level 2). This has implications for the operation of the network, as the supply of 2 connections is less volatile than a combined supply of 3 connections. To minimize the operational complexity, it is the level 2 system that is likely preferred over the level 3 system for this scenario.

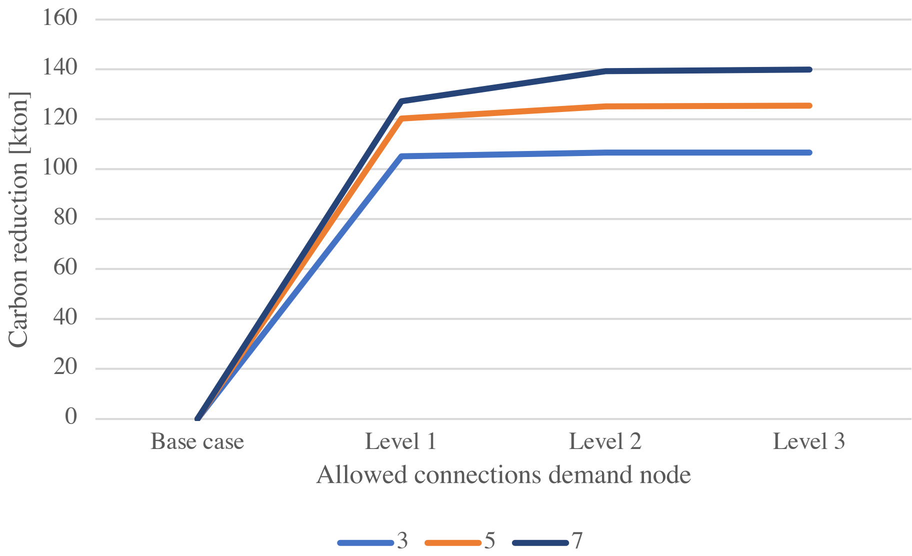


Figure 8.2 The lines are the total allowed connections in the network. On the x-axis, the maximum number of connections for the demand nodes is displayed. Numerical data can be found in Appendix I. (# connections demand node: level 1 = 1, level 2 = 2, and level 3 = 3)

By observing figure 7.6 and 7.8, it becomes apparent that the connections made the most frequent are the ones that have a high overall exchange quantity. They typically have a large heat demand, of which the WH supply can only serve a fraction. Therefore, this connection is efficient and effective in terms of carbon reduction, due to the high utilization factor and large scale. The utilization is high because there is little to no mismatch between supply and demand between these nodes; they are connected by pipelines, which are the most efficient method of heat transportation. Hence, a key driver for carbon reduction is identifying large heat sinks and connecting the WH supply with proximity. In these connections, there is a large overall WH exchange and the utilization will be high.

8.2 Operations of the network

The operations of the industrial WH network play a role in the decision of the deployment of the connection. A dispatch may provide a solution with connections that are complex to operate or seem economically not viable. Operational complexity can increases as the exchange pattern becomes more volatile and unpredictable. An additional layer of complexity is added when this connection is operated by transporting the heat in a TCM. Transportation requires planning and capacity cannot be ramped up or down easily. Therefore, it is interesting to compare the exchange curves of the different connections to assess what a realistic installed capacity would be to operate this connection. This analysis has an impact on the different configurations because it negatively affects the overall carbon reduction of each configuration.

The connection from HSM to CCS has been chosen in every configuration (figure 7.6). This is an impactful connection due to its high utilization and scale. However, the exchange load curve shows that the supply of WH will be relatively volatile compared to the other connections. This means that if installed at maximum capacity (pipe width), this capacity will often be idle. In steam networks, this can cause a pressure drop which is not favorable. This can be solved by installing pipes in parallel so that the capacity can be ramped up and down without causing a significant pressure drop. Although this is technically not a barrier, this increases the costs for the capacity that is required for a smaller part of the WH exchange. The matrix in figure 7.8 shows that the distance opposed to the required pipe length is favorable for the HSM to CCS node. Eventually, the costs of installing a pipeline are mainly influenced by the length of the pipe and less by the diameter. The second most favored connection is the one from CPR to TSP. This connection has been part of the optimal dispatch in 9 configurations, which means that this connection would be likely to be chosen. This connection scores average on the required pipe length as opposed to exchanged WH. Compared to the HSM to CCS connection this WH exchange pattern is more stable, which means that a larger capacity can be installed without risking any pressure drop. For the CPR to TSP connection approximately 60% of the maximum capacity can be installed to operate at least 7000 hours per year, while for the HSM to CCS node this percentage is approximately 35%. This difference is exemplary for all different connections, whereas some connections have a relatively steep exchange load curve, compared to other exchange curves with a more flat exchange curve. To assess what the installed capacity should be, an economic analysis has to be performed for each connection. Whereas the costs comprise of installing the pipelines or installing the TCM installations and operations. While the benefits can be expressed in the avoided carbon taxes. As the carbon prices will increase over time, this should be accounted for when assessing this business case.

There is an additional layer of complexity for exporting WH from one firm to another by TCM transport. Because this transport involves human-driven transportation; knowing the required capacity in advance is an important aspect. Moreover, there is a technical limitation to the energy density, hence large quantities of energy require large quantities of transportation. As can be seen in table 7.2, the required transportation for trucks is high. The number of required trucks for the connections makes that long-distance exchange is economically challenging, as this increases the number of required trucks and drivers. However, for the short distance and lower volume connections, the number decreases drastically. The BOS2 to CvG connection would require 4831 trucks annually. Theoretically, this can be operated by 1 truck over the year, transporting 13 to 14 containers per day. The TSP to CvG connection, which has been in the optimal dispatch of 4 configurations would require approximately 31 trucks per day to transport this amount of WH. This number will be a little bit lower in reality, because the installed capacity will not be 100%. Hence in peak supply hours utilization will be lower.

8.3 Infrastructure options

Amongst the optimal dispatches of the different configurations, there is a significant difference in the required infrastructure. As the configurations gain more freedom, the model shows a clear preference for the pipeline connections (figure 8.3).

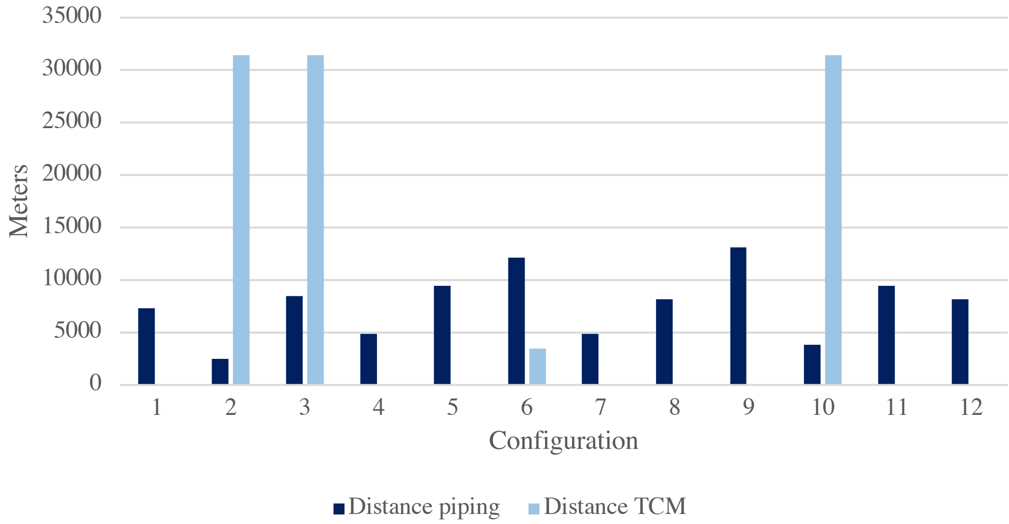


Figure 8.3 Required infrastructure for the configurations. The TCM distance is measured as a one-way trip. Numerical data can be found in Appendix I.

This result is due to the higher efficiency of steam production and lower transportation losses, which result in higher utilization of WH. What also can be observed is that in configuration 1, 4, and 7 there is a relatively limited infrastructure required to establish the connections. While the required infrastructure increases sharply as the total number of connections increases. This trend can be observed by comparing configurations 1 up to 3, 4 up to 6, and 7 up to 9. As a consequence of this increase, it proves that the first three connections add more value per investment in infrastructure. In the situation of a disrupted supply, the optimal dispatch is likely to be similar and does not affect the required infrastructure. For this analysis configuration 2 and 10; 5 and 11; 8 and 12 are compared.

8.4 Resilience of the network

In reality, there is a possibility that the WH supply is disrupted due to planned or unplanned interruptions of supply. To measure this impact, and see what the effect is on the operations, configuration 10 up to 12 have been modeled. The impact is assessed based on the change in carbon reduction, a possible change of optimal dispatch, the utilization, and the required infrastructure. In table 7.1 it is observed that for all three configurations the decrease in carbon reduction is approximately 6%. That means that the impact on the configurations with 3, 5, or 7 connections is similar. When comparing the optimal dispatch of configuration 2 and 10; 5 and 11; 8 and 12, it is observed that the disrupted supply has no impact on the result of the optimal dispatch. This automatically implies that the required infrastructure is the same for these configurations. The utilization could be affected by the disrupted WH supply. In the situation where the supply is interrupted at a moment with high utilization, this negatively affects the overall utilization. When comparing the utilization (table 7.1) of configuration 2 and 10; 5 and 11; 8 and 12, it is observed that in none of the cases there is a significant decrease in utilization.

Based on the impact and the effects on the operations, the integrated WH system seems to be resilient (under these specific circumstances) with a disrupted WH supply as in scenario 10 to 12. Figure 7.7 shows that some of the exchange streams are able to operate every hour of the year. That would imply that the installed capacity of steam boilers at the demand-side can be lower. However, because the WH supply servers only a small fraction of the heat demand, and that in industrial installations a safety margin is always added to the installed capacity, it means that it does not make an impact on the installed capacity of the steam boilers. Therefore, it is not expected that a disrupted WH will negatively affect the operations of an integrated WH system. However, due to the limited number of configurations ran in this research, full-proof has to be tested with a greater variety of interruptions of WH supply.

From an economic perspective, the unexpected WH supply makes an impact. Fewer carbon emissions are reduced, which means that taxes have to be paid for these emissions. When comparing configuration 2 and 10, 7 kton of carbon emissions are not reduced due to the interrupted supply. At a current carbon price of approximately 30 euro per ton, that means that this disruption causes tax expenses of 210 thousand Euro in one year. Although the duration of the disruption was arbitrary, when assessing the business case a safety margin should be included to account for the potential disruption of WH supply.

8.5 Maximum carbon reduction

The goal of this research is to maximize carbon reduction by operating an integrated WH network in an industrial zone. To measure the impact of recovering and reusing heat on a system level, the maximum carbon reduction for this area is a measure to determine how effective this network is. In the most and limited configuration (configuration 1), the overall carbon reduction is 105 kton, whereas the maximum carbon reduction is 140 kton (configuration 9). This corresponds to approximately 0.5% of the emissions in the MRA and accounts for 0.88 – 1.17% of the carbon emissions of only Tata Steel. This figure tells that an integrated WH network is not going to occupy a large role in the transition towards a carbon-neutral industry. However, carbon taxation can be an incentive to invest in this network and technologies. It will be one of the many technologies that will contribute to a carbon-neutral industry. As it is expected that the carbon prices will rise sharply over the coming year, figure 8.4 presents an overview of the avoided tax expenses for different carbon prices with the range of different configurations. Based on these avoided expenses, the companies within the MRA can make an economic analysis of whether investing in this technology is profitable, given the rising tax increases.

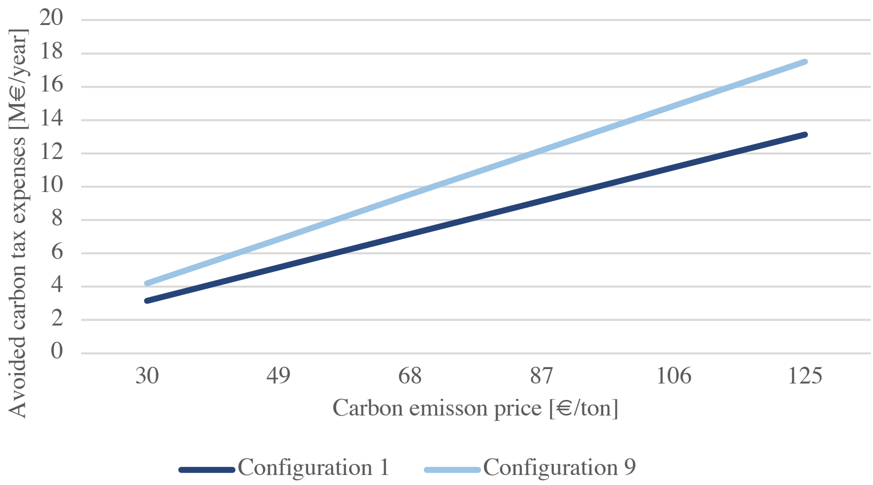


Figure 8.4 An overview of the range of avoided annual tax expenses for different carbon tax levels. Time horizon: 2021 – 2030. Numerical data can be found in Appendix I.

9
Discussion

In this chapter, a reflection will be given on the research. This is done through discussion of the (1) limitations of the research, (2) a generalization of the applied approach and methods to be applicable to other industrial zones, and (3) by placing the outcomes into a high-level perspective of the energy system.

9.1 Limitations

A model is a limited representation of reality. Due to the unlimited number of variables that influence the scenario, assumptions have to be made. The most paramount assumptions will be reflected upon to assess their impact on the outcomes of the research; to determine how the outcomes could be different in real life due to this assumption. Generally, most impactful assumptions are the system-level assumptions and technical assumptions.

9.1.1 System-level assumptions

Through analysis of the strategic positioning and market dynamics in chapter 4, it became apparent that the electric power industry will not participate in the integrated WH network. Hence, based on this analysis, the assumption was created that these nodes were not considered for establishing a potential connection. After analyzing the results, it seems unlikely that the electric power industry would have a dominant role in the WH network. The high impact connections have proven to be positioned within the steel industry, acting as both supply and demand node. The map in Appendix A shows that there are no power generation facilities with proximity to the steel industry, which empowers this statement. That also implies that from an operational perspective these connections would not be favored due to the required TCM transport. As a consequence, the exclusion of the electric power industry has not highly affected the results.

Another limitation of this research is caused by using this type of MILP model. It assumes that the available WH is consumed at the same hour. In reality, the heat has to be transported, and especially in the case of TCM transport, this requires time. Opposed to steam transportation, with high velocities of 25 to 35 m/s (Forbes Marshall, 2020), this could influence the match between supply and demand. It is given that in only in configuration 2, 3, 6, and 10 the optimal dispatch contains connections with TCM transportation. As the model gains more freedom in level 2 and level 3, the required infrastructure for TCM decreases. As the more optimal solutions contain predominantly pipelines, the results of the optimal dispatch will not be highly affected by the delay in transport. An additional argument is that it is likely that the mismatch of supply and demand due to the transportation time is negligible, as the demand is often a magnitude larger than the available supply. Therefore, it is unlikely that the utilization will be negatively affected by the delay of a maximum of one hour.

In the model, the supply node was limited to making only one connection. This assumption was made based on the hypothesis that once a supply connection was made, it would be fully utilized. When assessing the utilization of the made connections, only configuration 3 shows two connections with the utilization of under 60%, which is in line with logic, as this is the most limited configuration that has been modeled. In all other configurations, the utilization was close to the maximum utilization. In reality, the system will not be as limited as in configuration 3, as it will be allowed for the demand nodes to make more than 1 connection. Therefore this assumption does not limit the model to find the optimal solution for all configurations other than 3. On the other side, demand nodes could be only able to make a maximum of three connections. In the analysis it became clear that increasing this number from 2 to 3 did not significantly increase the overall carbon reduction, hence the model was not constrained to measure the maximum impact of the network due to this assumption.

The previous assumptions that are reflected upon all don't negatively affect the outcomes of the research. However, there is a system-level assumption that could negatively affect the overall carbon reduction. In chapter five, the efficiencies of heat exchange and transportation have been described. Based on the available WH, measured in GJ, the demand node receives the available WH minus the losses. However, due to the high temperature (>160 ºC for steam production) required at the demand node, the utilization might be lower in reality than expressed in literature. This residual heat in the lower temperature region still contains energy in terms of GJ, it is however not useful for the demand node anymore. In literature, this low residual heat is already partly accounted for, as the steam boiler efficiency expresses the losses of the incoming energy. Also for the TCM transport, these losses are already partly accounted for, expressed in the heat exchanger loss from flue gas to TCM and TCM to steam or water. However, due to the high-temperature regions, it might be possible that a small fraction of the available WH might not be recovered into the TCM. Although the assumption might negatively affect the overall carbon reduction, it is not expected that this will have a high impact.

9.1.2 Technical assumptions

The technical assumption to consider only TCM for flexible heat networks was done due to the promising characteristics of the technology. The high energy density and the possibility to operate at high-temperature make it a suitable material for the industry. However, using this material brings operational complexity that has not been incorporated into the model and analysis. It is still possible that this technology, which is currently being researched and tested on a lab scale, will not become commercially available. Therefore, the flexible connections made are currently less feasible than the connections made by steam pipelines. As the most optimal configurations show a preference for steam pipelines, the impact on the overall outcome is therefore limited. Nevertheless, in case the model would have preferred a network with a majority of flexible heat connections, this would make it only feasible to realize as soon as the technology is mature and commercially available. This might be applicable in other scenarios and should therefore be considered.

During the verification of the model, it came forward that in the industry the losses for steam transportation are higher than those expressed in literature. Actual losses can go up to 10% for internal use at the Tata Steel plant, while in the model lower losses were assumed of far under 1%, which are the theoretical losses. This difference can be explained due to the theoretical losses being in an isothermal process, while in reality, steam transportation is an adiabatic process. This will have an impact on the results, that will increase the transportation losses. That means that the utilization of each connection with a steam pipe connection will decrease up to 10%, depending on various variables such as the hourly steam flow rate, the pipe diameter, the insulation, and the steam density. Insulation is costly, yet this might be economically interesting with the coming carbon taxes. Therefore the actual losses in newly deployed steam pipelines will be under 10%.

9.2 Generalization

To analyze the potential of an integrated WH network in other industrial zones, the methods and approach can be generalized in such a way that the research can be applied in different contexts. The work can be generalized by highlighting what is learned in the context of integrated WH networks and by comparing that to the existing literature. The paragraph will be concluded with a generalized methodology and elaborate on the applications to analyze the potential of an integrated WH network in other industrial zones.

The generalized approach offers extensive and tangible outcomes, with which policy- and decision-makers can assess the impact of establishing an integrated WH network in industrial zones. The generalized approach complements methodologies used in existing literature, where case studies are also often part of the research. In the optimal dispatch of these case studies, the amount of exchanged WH is given as a result, as in the work of (Ashaibani & Mujtaba, 2007) and (Stijepovic & Linke, 2011). With this approach, the overall impact of a WH network can be analyzed. However, this is limited to the assumption that the supply and demand are constant. In the work of (Kralj & Glaviĉ, 2005) a MINLP model is used, where the utility cost, heat exchanger areas, and selection of matches are optimized simultaneously. This approach is more detailed from a technical perspective, but it is limited to a numerical study; as well as it assumes constant supply and demand patterns.

The approach used in this thesis offers insights from another, more high-level perspective. The research starts from a system perspective, through the analysis of the strategic positioning and market dynamics. This approach complements the current methodologies by taking an outsider's perspective, which means that policy- or decision-makers can assess the potential impact of the integrated WH network before the actors in the industrial zone are participating in the research. While in existing literature an insider's perspective is used, assuming the actors are participating. As a result of the outsider's perspective, the power electricity sector was excluded from this research. Other regions can exclude additional sectors by also taking this perspective. A second complementary methodology is the analysis of the dynamics of WH exchange. By analyzing the supply and demand patterns on an hourly basis for different nodes, the dynamics of the network are taken into account. Whereas these dynamics are neglected in the existing literature. By performing an analysis based on hourly data, high utilization of the WH will be subject to optimization. Lastly, the used approach in this thesis also offers a more realistic result concerning the impact of the dispatch, expressed in carbon emission reduction. The assessment of industrial zones should include the hourly match between supply and demand. If not accounted for, this could lead to outcomes that are overestimating the overall carbon reduction due to an overestimated utilization of the WH. This becomes increasingly important as the number of total connections increases, as the difference between supply and demand levels decreases. This could result in lower utilization of the WH and overestimate the carbon emission reduction.

It is proposed that the generalized approach is performed prior to the more deep and technical analyses performed in current literature. In that way, it provides an approach to policy- and decision-makers to assess the potential of an integrated WH network. The positioning within the context of the current literature is presented in figure 9.1.

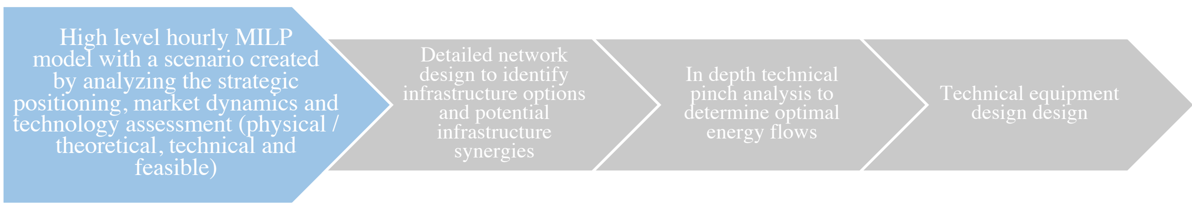


Figure 9.1 Flow chart of suggested research approach for integrated WH networks in industrial zones in the context of existing literature. The approach used in this thesis is presented in the blue box. The grey boxes are approaches used in the existing literature.

Table 9.1 presents how each method can be applied in another context (other industrial zones).

Method	General application
IAD and framework for dynamics of IS	• Identify key actors (high emissions, high WH availability); • Identify the role each sector occupies in the industrial zone and exclude actors that are unlikely to participate; • Identify the incentives to participate for each sector; • Determine the urgency of a market mechanism; • Analyze how policy changes will impact each sector.
Technology assessment	• Determine viable heat sources; • Determine the specifications of relevant technologies; • Determine technology readiness of WH usage in different phases for the industrial zone; • Determine fit for purpose of WH usage in different phases for the industrial zone.
Modeling / MILP	• Analysis of hourly demand and supply patterns to identify the dynamics of WH exchange; • Incorporate the possibility to connect volatile supply and demand of WH; • Determine the carbon emission reduction for a dispatch; • Produce tangible results that are useful to determine the operations of the system (WH exchange curve, utilization).

Table 9.1 Applicability of the used methods in other industrial zones assessing the potential of high-grade WH utilization.

The applicability of the methods is dependent on the data availability-and-provision of the companies within the industrial zone. For the identification of key actors, the "heat atlas" has been used. Although this is available for the Netherlands, other countries might not have this data openly accessible. Moreover, there must be a certain level of cooperation from company representatives. Those can help to find the right consumption- and supply data; provide insights to assess what share of WH can potentially be recovered.

9.3 The impact of WH utilization on the energy system

As the pressure for carbon emission reduction increases due to carbon taxes, the industry is looking for ways to utilize their abundantly available WH efficiently. By analyzing the potential of an integrated WH network, it is possible to determine optimal dispatch for an integrated WH network.

Based on the results of this research, it has become apparent that an integrated high-grade WH network will only have a small contribution towards a carbon-neutral industry. In the MRA the overall carbon reduction corresponded to approximately 0.5% of the industrial carbon emissions. It is also not expected that this share is going to increase significantly over time, as the efficiencies of steam boilers and the TCM storage are already high and do not show improved performance in the short term. Nevertheless, there is still room for expansion in the further future due to developing technologies in the electricity market. The volatile character of solar PV and wind energy will cause temporary oversupplies of electricity. This oversupply could be used for power-to-heat applications and can provide the industry with heat. This can be consumed directly, or it is possible to make use of a TCM to temporarily store the oversupply of heat.

10

Conclusions

In this chapter, the conclusion of the study is presented. The chapter is divided into three parts and starts by answering the research questions. Secondly, the scientific and societal contributions are presented. The chapter is concluded with the potential areas for further research.

10.1 Answering the research questions

The main research question is presented below. This question is divided into six sub-questions which are answered subsequently.

How can industrial zones utilize high-grade waste heat networks in such a way that it maximizes carbon reduction?

Sub-question 1: How are WH networks conceptualized and what are the interactions between heat supply and demand nodes?

Through the identification of the carbon-emitting companies within the MRA, an overview of the potential participants of an integrated WH network was created. Based on the strategic positioning and market dynamics described in chapter 4, an assessment was made on how each sector would be involved in a WH network for carbon reduction. This led to the conclusion that the steel industry is the sector to be interested in an integrated WH network most likely. Other active participants are the industrial appliances and materials sector, and the food processing industry. The general lack of available high-grade WH would mean that they can only consume heat to reduce their carbon emissions. The followers occupy a less active role in the WH network due to the low-grade heat demand. This applies to the aviation and hospital sector. The electricity sector will not participate in the network, due to the already disrupted market and technical inability to utilize WH on large scale. An overview of the market positioning of each sector is provided in figure 10.1.

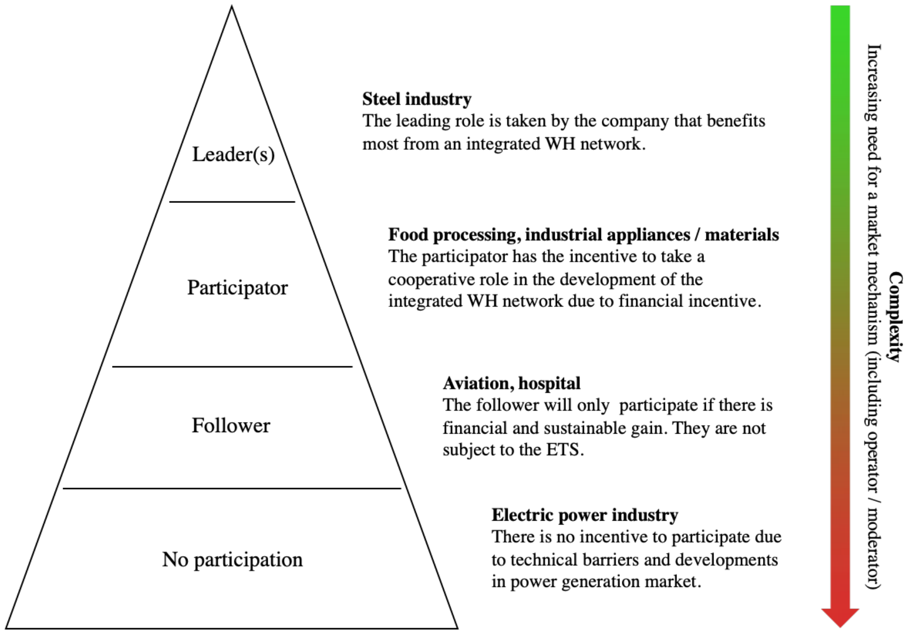


Figure 10.1 The market positioning of each sector.

A conceptualization of the working of this network has been created by conceptual modeling. A high-level overview describes how carbon emissions are reduced in the system (figure 10.2).

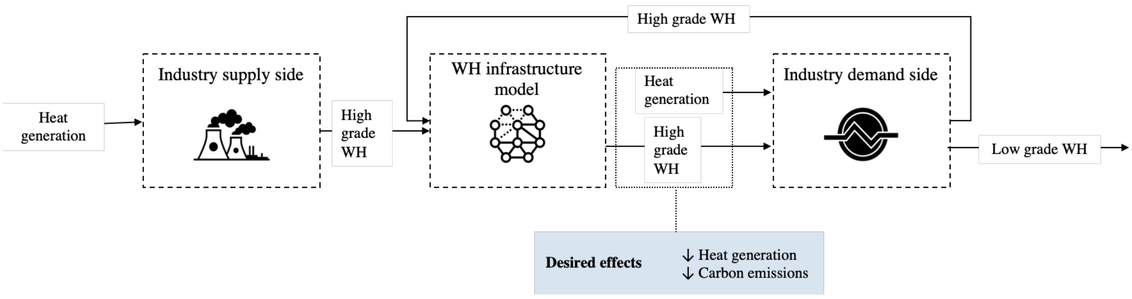


Figure 10.2 The integrated WH network conceptualized.

Sub-question 2: What are the state of the art WH recovery, storage, and transportation technologies?

In this research, a technology assessment was performed to assess the state of the art technologies involved in the integrated WH network. The answer to this sub-question has provided insights for the scenario. This assessment was performed both qualitative and quantitative. The quantitative assessment provided insights into how the process technologists and other experts assess the forms in which WH can be exchanged. This resulted in a clear preference for WH in flue gases and steam. As a result, WH sources in the form of solid and liquids were not considered.

The second part of the technology assessment consisted of a quantitative assessment of the literature. Several key figures were obtained, like the heat exchanger efficiencies and transportation losses. With these figures, the overall losses in the integrated WH network could be calculated.

Sub-question 3: What are the patterns of potential WH sources, heat sinks, and transportation in Metropole Region Amsterdam?
This sub-question related to the data acquisition and creating the scenario of the MRA. Data were received for several nodes. If not received, the supply and demand data was estimated based on the emissions of the company. This is applied to nodes with continuous operation. Companies with discontinues operation and no data provision were not considered as a node in the system. That resulted in the nodes displayed in figure 10.3.

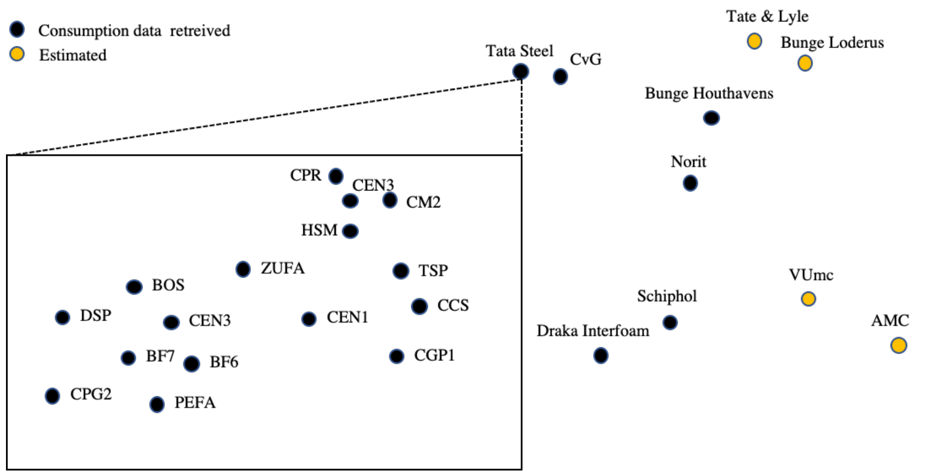


Figure 10.3 The nodes in the MRA that data was provided for. Else estimations based on emissions were made if possible. The geography is relative and does not correspond to the real distance between the nodes.

Hourly available WH was based on estimated losses in the Sankey diagram of Tata Steel. As Tata Steel is the only supplier of high-grade WH in the MRA, this sufficed to obtain an overview of the WH sources. The heat sinks were based on energy consumption and were available on an hourly basis. The different transportation methods were identified in sub-question 2. For each transportation, a loss factor was established. Based on distance and this loss factor, the transportation losses could be calculated. For each potential connection, there was an overall loss factor, which was the available WH minus the heat exchanger- and transportation losses.

Sub-question 4: How can the industrial heat demand- and supply patterns be matched utilizing WH to minimize carbon emissions?
To answer this sub-question, a modeling approach was used. A single objective MILP model was created to maximize carbon reduction in the scenario. The model was used in 12 different configurations, to examine how the scenario would behave to a change in its

environment (different configurations). The result was an optimal dispatch for each configuration, with detailed information on the connections and the performance of the overall configuration. This type of model can be generalized and used for other scenarios. Based on the avoided consumption of primary energy resources by reusing WH, the avoided carbon emissions were calculated.

Sub-question 5: How resilient is the integrated WH network concerning (un)expected interruptions?
In reality, there is a possibility that the supply of WH is disrupted due to unexpected downtime of supply nodes, or planned interruption due to maintenance. By modeling configuration 10 up to 12, it became apparent that these interruptions do not affect the optimal dispatch, operations of the system, and utilization. However, due to the limited number of configurations ran in this research, full-proof has to be tested with a greater variety of interruptions of WH supply.

The major effects were a lower overall carbon reduction, which negatively affects the business case of investing in a connection. By arbitrarily eliminating 104 days of supply from different nodes (each 26 days), the overall carbon reduction was negatively affected with approximately 6% in each configuration, which corresponds to 7 to 8 kton carbon emissions. That would negatively affect the avoided annual tax expenses by 210 to 240 thousand Euro at a carbon price of 30 Euro per ton. Yet again, this disruption is chosen arbitrarily and varies with the duration of disrupted supply.

Sub-question 6: What are the key drivers of carbon emission reduction in WH networks?
The last sub-question is closely related to the main research question and provides insights into how carbon emissions can be reduced efficiently. It was answered by performing an analysis of the obtained results of the optimal dispatch of the different configurations.

A key driver for carbon reduction is that the first connections established by the model outperform the additional connections by much. Even at relatively low carbon tax levels, these connections might be a profitable investment. As the tax level increases, the smaller and relatively less value-adding connections might also prove economic viability. Another identified driver of carbon reduction is allowing the demand nodes in the network to have multiple incoming connections. For the MRA it seemed that at two or more incoming connections the optimal results were obtained. However, in a network with more nodes, this number can be higher. Moreover, a higher number might decrease the required infrastructure investment and should not be excluded. Additional drivers are the size of the heat sink compared to the heat source. As the difference becomes bigger, the chance that high utilization is realized is higher.

Main research question: How can industrial zones utilize high-grade waste heat networks in such a way that it maximizes carbon reduction?
As announced on 'prinsjesdag 2020', the Dutch carbon tax system will be effective starting January 2021 (Loupatty, 2020). Therefore, policy-makers and executives of industrial companies have to assess the potential of integrated WH networks in their industrial zone to be prepared for decision-making. Although the WH network is not going to serve as a major contributor in a carbon-neutral industry, it can contribute to a small extent. It is given that the steam pipelines are preferred by the model. Therefore, investing in steam pipelines is a technically viable solution that can help reducing the carbon emission levels. Heat storage and transportation with a TCM is a more futuristic solution, which might prove useful in a power-to-heat market.

High carbon reduction is mainly realized at the first chosen connections in the optimal dispatch, as they have the highest quantity and utilization. The model prefers short distance WH exchange in steam pipelines, due to higher efficiencies. Allowing the network to make multiple connections will improve the performance of the system and increase overall carbon reduction. There is a significant trade-off between maximizing the carbon reduction (7 connections) and choosing a limited solution (3 or 5 connections) with less carbon reduction. An extension of an initially chosen heat network will not necessarily lead to an optimal dispatch, because the optimal dispatch is only valid for the initially chosen number of connections. As a result, the total number of connections should be a well-considered choice. Moreover, choosing a high number of total connections leads to relatively high investment in infrastructure. The analysis shows that the first connections are the connections that exchange the most WH, hence most carbon emissions are reduced. By increasing the number of connections, less carbon reduction is realized with relatively much infrastructure. Therefore, there is a strong trade-off between carbon reduction as opposed to investment in infrastructure. That implies that before the level of deployment (number of connections) is chosen, the avoided tax expenses should be compared to the costs of different configurations.

The initial hypothesis was that the development of flexible heat network options would increase the potential for carbon reduction and increase the WH utilization. Both in resolving the mismatch between supply and demand using storage, as well as the relatively long distance between the nodes in the network. Nevertheless, the flexibility options for heat distribution have not shown to be favorable over short-distance steam pipe transportation. However, the role of temporary energy storage can become increasingly interesting as the power-to-heat market is developing. This will be discussed further in paragraph 10.3. One of the general learnings is that for large scale carbon reduction, flexible heat networks will occupy a limited role. By prioritizing the connections that have the highest impact, it became clear that a flexible heat option would only become necessary when choosing to make use of all heat sources, a total of 7 connections. It was also observed that the last added connections show relatively low impact compared to the earlier chosen connections. This insight learns us that a very fragmented WH network does not provide much carbon reduction as compared to a network with few connections.

10.2 Scientific and societal contribution

In section 2 a literature review is presented. As a result, a knowledge gap was identified. The knowledge gap addresses three elements that are missing in the existing literature to assess the potential impact of an integrated WH network in industrial zones. (1) An approach to assess the strategic positioning and market dynamics of different sectors in industrial zones. (2) A complementary approach to assess the potential of high-grade WH networks that incorporates the dynamics of WH supply and demand nodes. (3) Insights into how WH utilization can play a role in the transition towards a carbon-neutral industry. The societal contribution comprises a timeline for the MRA to determine the economic and environmental impact of investing in an integrated WH network.

An assessment of the strategic positioning and market dynamics of different sectors for an integrated WH network.

Previous studies have been performed based on the assumption that supply and demand for heat is there. This approach suffices for industrial zones in which the different actors are participating in the research. For an assessment from an outsider's perspective, initiated by local governments or companies, it is important to understand the dynamics of the market. Together with the strategic positioning of the sectors in the industrial zone, the viability of an optimal dispatch can be examined.

A complementary approach to assess the potential of WH networks, based on hourly consumption and supply data, to incorporate the dynamics of WH supply and demand nodes.

In the existing literature, the assumption is used that heat supply and demand are at constant levels. In reality, the supply and demand patterns are volatile and influence the exchange flows of WH. To incorporate the utilization of those systems and determine if flexibility options for heat would offer economic value, the hourly dynamics are modeled in the MILP model. This offers additional insights into the operations of the system and helps assessing the potential for flexible heat options.

Insights into the impact of WH utilization for a carbon-neutral industry.

Integrated WH networks are optimized based on minimum fuel consumption or maximum cost reduction in the existing literature. This study focuses on minimizing the carbon emissions in industrial areas, which provides a tool to measure the impact (overall carbon reduction) of different configurations of the system. Identified key drivers for carbon reduction are a large scale of supply and demand nodes, where the demand exceeds the supply by much. In this way the utilization of the connection is high and WH can be utilized efficiently. Another driver is allowing the system to lead multiple supply nodes to one demand node. As the system was allowed to have multiple connections at the demand nodes, the overall carbon reduction increased.

A timeline for the MRA to determine the economic and environmental impact of investing in an integrated WH network.

In table 8.1 an overview of the avoided carbon tax expenses is presented for the different configurations of the MRA. This is a tangible measure of the order of the size of the economic impact that the integrated WH network can have. It provides companies and local institutions with insights that support policy- and decision-making. Based on this high-level analysis, companies can decide the moment and size of investment in these solutions. Decision-makers can use these outcomes for their sustainability roadmap.

10.3 Future research

This thesis has established progress in the field of integrated high-grade WH networks in industrial zones. However, the used methods raise further questions and directions for future studies. In this paragraph suggestions for further research are provided.

The first study that can be conducted is the effect of power-to-heat technologies in integrated WH systems. As the oversupply of renewable electricity in peak hours will offer a low-cost electricity supply in those peak hours. The power-to-heat efficiency is 100%. The technology also has much potential to supply industrial processes using steam boilers and mitigates the volatile effects of renewables (International Renewable Energy Agency, 2019). With this technology is possible to avoid investment in heat infrastructure, because the electricity grid can be used to produce the heat at the demand node. This will have effects on the dynamics of the WH system, where buffering residual WH in a TCM or PCM can play a more dominant role. The technology can offer a further integration of the WH network and an optimal dispatch can be determined with the MILP model. That can determine where the power-to-heat steam boilers should be installed. The MILP model allows incorporating the hourly supply patterns of the volatile renewable electricity supply.

The second proposed study is an analysis of the market design of an integrated WH network. Traditionally, the value of heat was low due to high capital investment to reuse it. As the carbon prices increase, investing in these technologies might become attractive, hence the value of heat increases. Accounting for the mutual costs and benefits between two or more companies is still based on double or multiple-sided agreements. The likeliness that these agreements are established relies on these negotiations and can easily ricochet. With the potentially growing share of available WH due to power-to-heat technology, the WH network will become more integrated. That requires a set of rules and boundaries that help to establish how the costs and benefits are accounted for by all involved parties.

A third suggested study is related to the network design. In the approach of this thesis, the network design and infrastructure analysis are limited. Additional research in this area might provide extra insights for decision-makers to assess the operational and economic viability of the dispatch. In the optimal dispatch, two connections may share part of the route between the supply and demand nodes. That means that infrastructure can be shared on the common part of the connections. As the network gains more connections, the chance that this situation occurs becomes increasingly likely. Therefore, it is interesting to study how an optimal network design would look like and what potential synergies can offer. It can positively affect the economic viability of the WH network.

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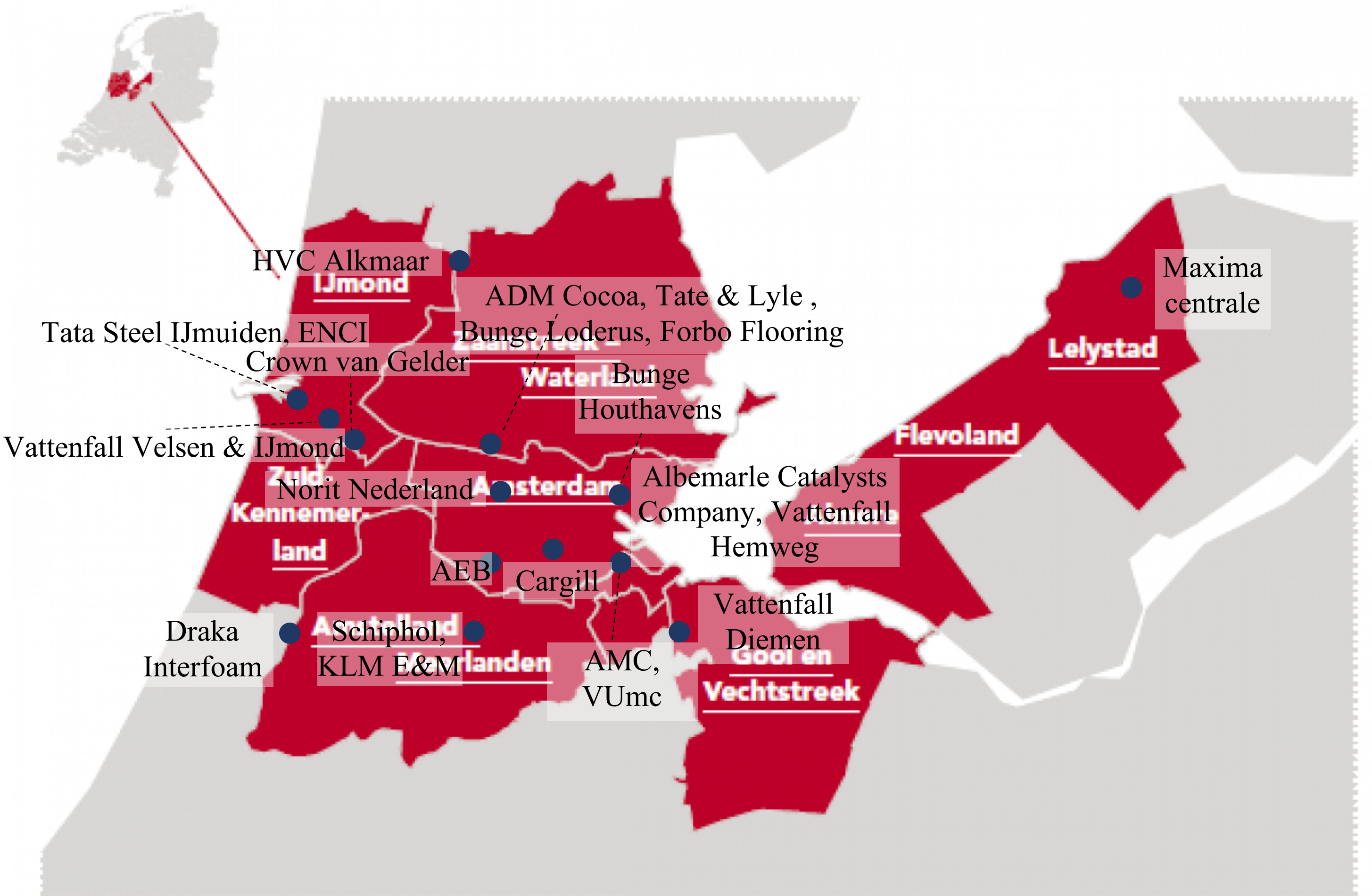
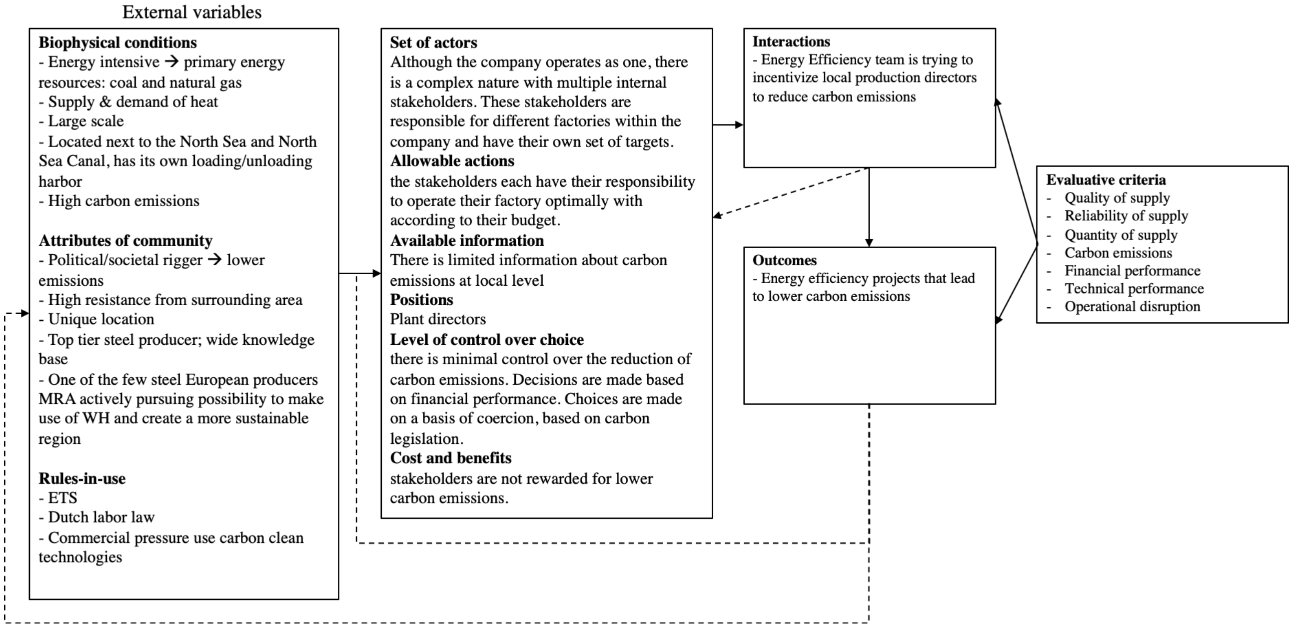


Figure A. MRA topology of companies emitting > 14 kton CO2 in 2015

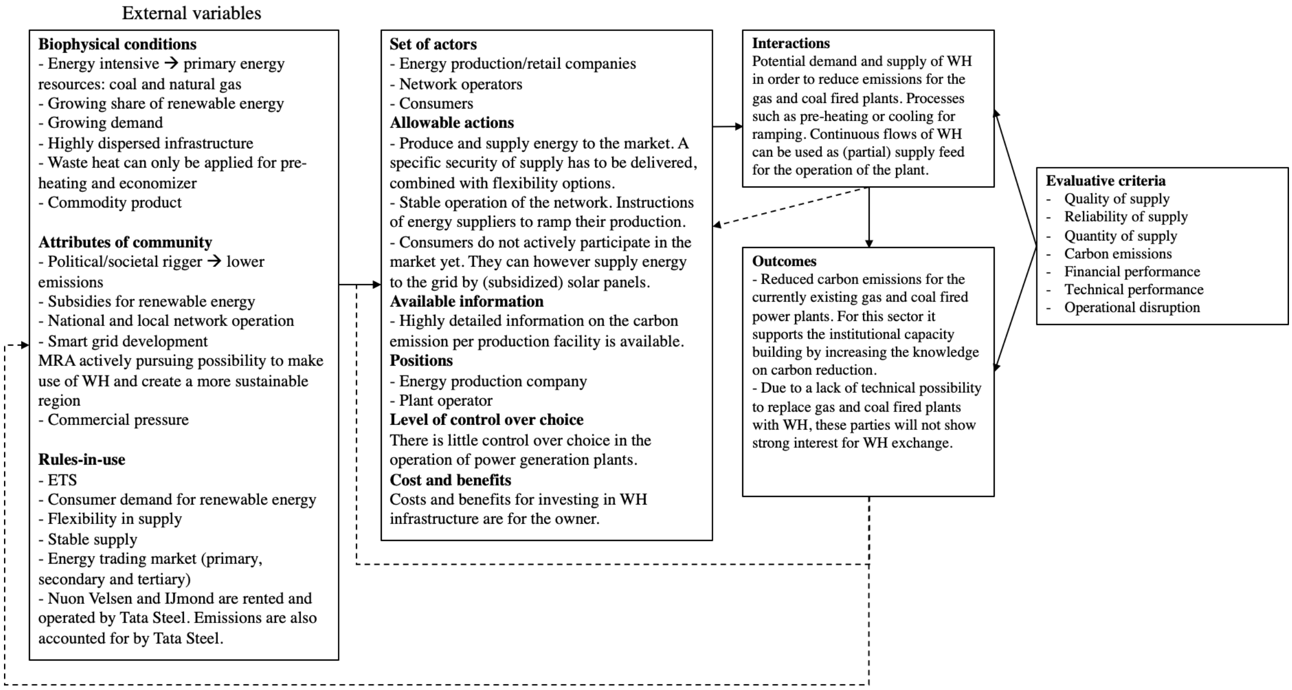
Appendix B

In this Appendix the IAD framework analyses are displayed for the different sectors in the MRA.

Carbon reduction in steel production (Tata Steel)



Carbon reduction in power generation (several Vattenfall plants)



Carbon reduction at an airport (Schiphol, KLM E&M)

External variables

Biophysical conditions
- Many sources that contribute to total emissions
- Large share of emissions due to landing and take-off of airplanes
- Systems have to be highly reliable
- Limited space due to its geography
- Use of WKK

Attributes of community
- Political trigger to lower the emissions in the aviation industry → COVID-19 has amplified this
- Involves many stakeholders
- MRA actively pursuing possibility to make use of WH and create a more sustainable region

Rules-in-use
- ETS
- Strong governmental regulation on operations and carbon emissions.

Set of actors
- Schiphol board
- Flight operators
- Operational support companies (e.g. luggage, maintenance and fueling)

Allowable actions,
- You can only land an airplane if you have a slot
- Flying is limitedly or not allowed during the night
- Airport can make fuel regulation

Available information
- There is little information available

Positions
- Schiphol
- KLM
- People living close
- Government
- Maintenance/operational companies

Level of control over choice
- Low due to very high internation competition
- - first mover disadvantage

Cost and benefits
- Beneficial for the image
- Very constly? Depends on the possible application

Interactions
Potential demand for WH wil most likely be in small batches due to the dispersed operation of the different compoents of the airport. Depends on WKK replacement potential

Outcomes
The exchange of WH will be complex and will require a lot of effort for smaller batches of heat. The division between the

Evaluative criteria
- Quality of supply
- Reliability of supply
- Quantity of supply
- Carbon emissions
- Financial performance
- Technical performance
- Operational disruption

Carbon reduction in food processing

External variables

Biophysical conditions
- Food safety: extremely clean production facility
- Continuous production
- Use of WKK
- Heat required in a lot of food processing

Attributes of community
- Sustainability image of food brands is increasingly important
- MRA actively pursuing possibility to make use of WH and create a more sustainable region

Rules-in-use
- ETS (depend on the scale)
- Food production regulation

Set of actors
Producer
Brands
International management of those brands

Allowable actions
Large contracts
Difficult to change production method

Available information
Often production schemes are available and predictable due to its continuous operation

Positions
Retailer
Food brands

Level of control over choice
There is limited choice due to limited supply possibilities of other heat sources. Process is highly dependend of heat and does not need to be disturbed.

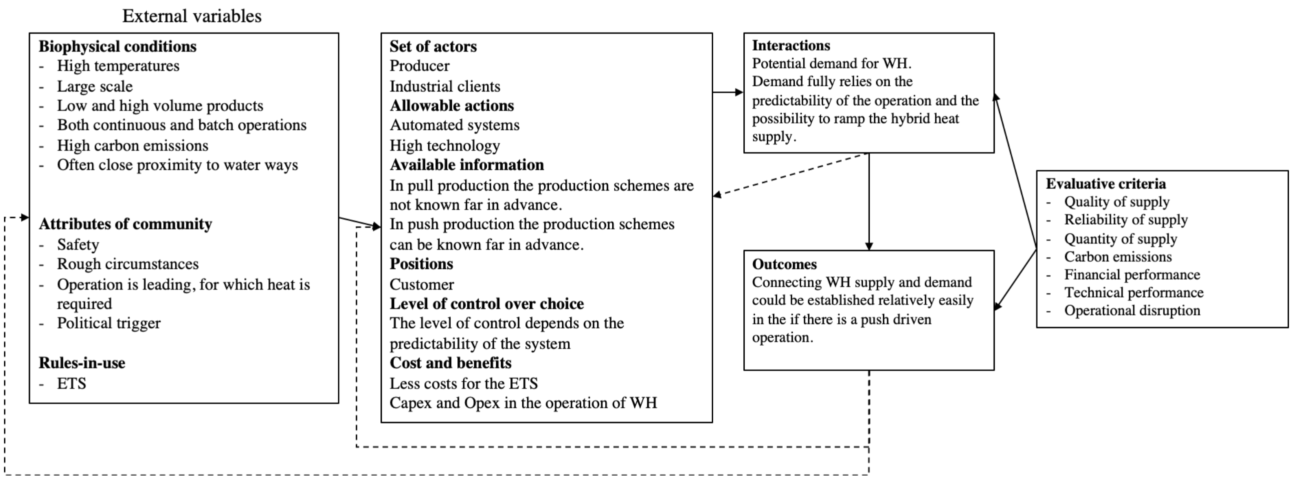
Cost and benefits
A more sustainable image
Lower costs in ETS for future

Interactions
.potential demand for WH

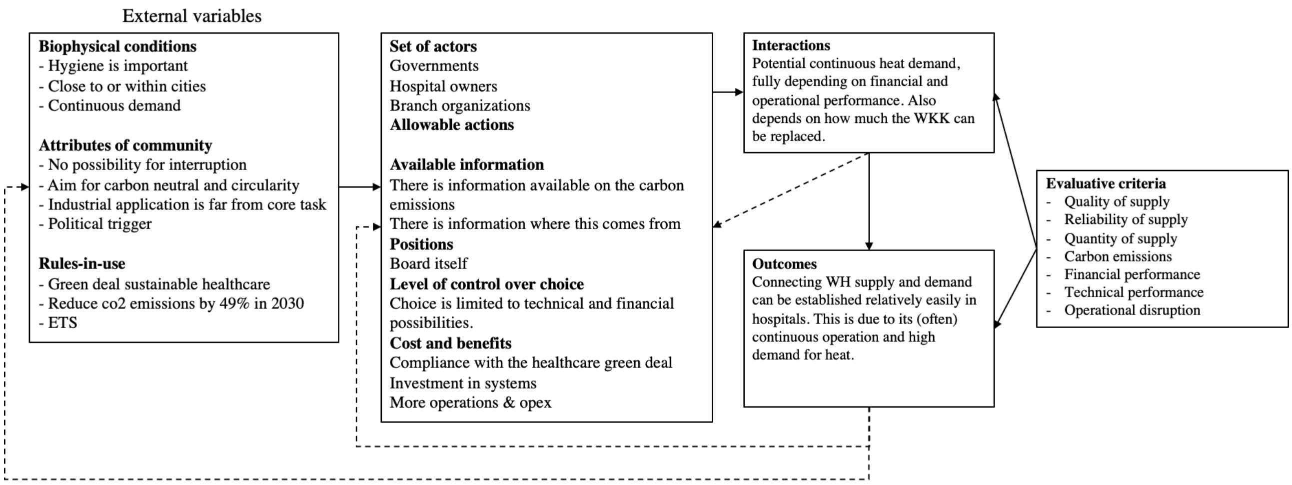
Outcomes
Connecting WH supply and demand can be established relatively easily in the food processing industry. This is due to its (often) continuous operation and high demand for heat.

Evaluative criteria
- Quality of supply
- Reliability of supply
- Quantity of supply
- Carbon emissions
- Financial performance
- Technical performance
- Operational disruption

Carbon reduction in industrial appliances/materials



Carbon reduction in hospitals



Steam transportation losses

Linear correlation steam and pipe length with insulated pipe:

dp = 0.6753 10^6 q^2 l (1 + 91.4/d) / ρ d^5

where

dp = pressure drop (Pa)

q = steam flow rate (kg/h)

l = length of pipe (m)

d = pipe inside diameter (mm)

ρ = steam density (kg/m^3)

Additional calculation to determine the loss as a percentage per meter:

Pressure drop for 1 meter = 1 Pa	Temperature drop of 1 Pa = 3.081*10^-5 ºC
percentage lost per meter based on 15 bar steam (192ºC)	3.081*10^-5 C / 192 = 1.6*10^-9% m

Questionnaire industry experts / process technologists

Procedure

1. Explanation of the context and questions
2. Filling out the form
3. Discussion
4. Consent of the given answers (also via email)
5. Gathered information will be presented anonymously

Purpose of the research

How can industrial zones utilize high-grade waste heat networks in such a way that it maximizes carbon reduction?

Background

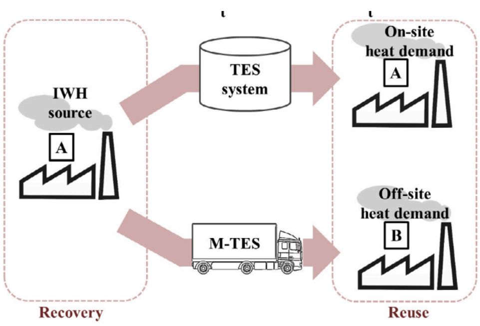


Fig. 2. Schematic of on-site and off-site reuse of IWH.

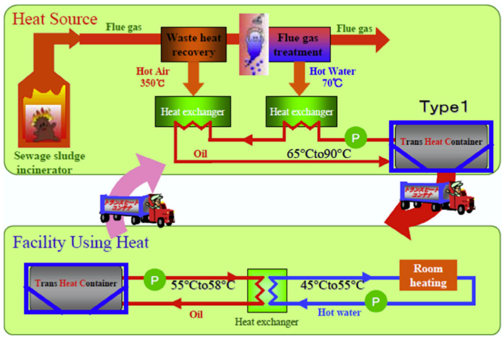
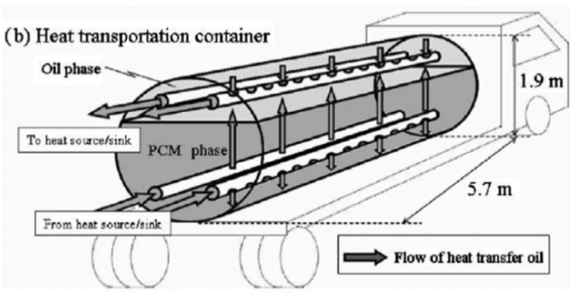
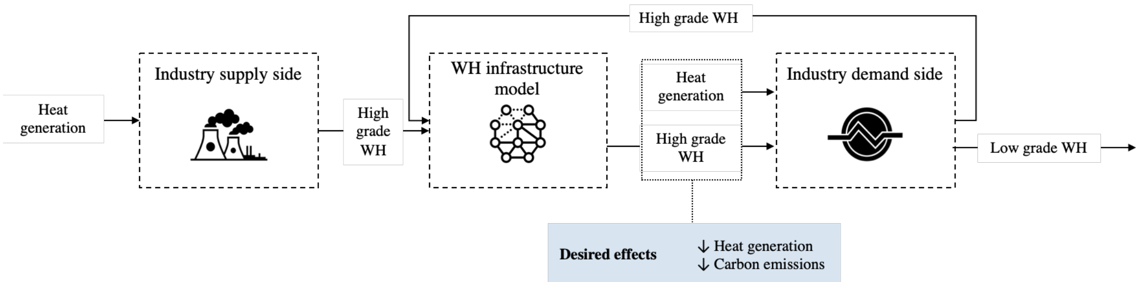


Fig. 16. Flow diagram of the M-TES recovery system proposed by Yabuki and Gabuno [66].



TNO lab experiment with 544KJ/kg latent heat level (equals 7616MJ per 14 ton container) (very high compared to current PCM's. e.g. Zeolite 1.18KJ/kg).



Company:
Department:
Official role:

The waste heat carriers of the processes I am involved with (multiple answers possible):

- ☐ Flue gases
- ☐ Steam
- ☐ Liquids
- ☐ Solids

Technology readiness

Direct use: supply/demand of the waste heat carrier in the context of this company & region (e.g. pipelines):

Very unlikely	Unlikely	A little unlikely	Neutral	A little likely	Likely	Very likely
☐	☐	☐	☐	☐	☐	☐

Notes:

Indirect use: supply/demand of the transformed heat carrier in the context of this company & region. This means transforming the heat into another material (e.g. fluids).

Very unlikely	Unlikely	A little unlikely	Neutral	A little likely	Likely	Very likely
☐	☐	☐	☐	☐	☐	☐

Notes:

Flexible heat transportation in a Phase-changing Material can be applied in the context of this company & region (by train, truck or boat).

Very unlikely	Unlikely	A little unlikely	Neutral	A little likely	Likely	Very likely
☐	☐	☐	☐	☐	☐	☐

Notes:

Fit for purpose

Direct use: supply/demand of the waste heat carrier in the context of this company & region (e.g. pipelines):

Very unlikely	Unlikely	A little unlikely	Neutral	A little likely	Likely	Very likely
☐	☐	☐	☐	☐	☐	☐

Notes:

Indirect use: supply/demand of the transformed heat carrier in the context of this company & region. This means transforming the heat into another material (e.g. fluids).

Very unlikely	Unlikely	A little unlikely	Neutral	A little likely	Likely	Very likely
☐	☐	☐	☐	☐	☐	☐

Notes:

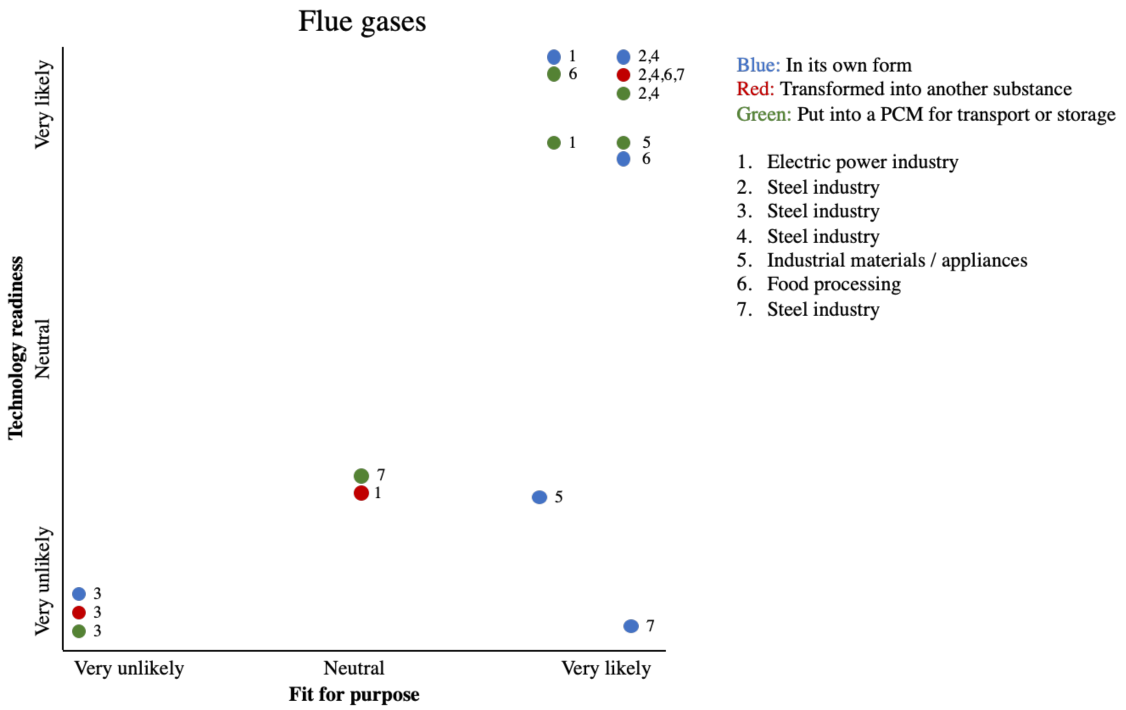
Flexible heat transportation in a Phase-changing Material can be applied in the context of this company & region (by train, truck or boat).

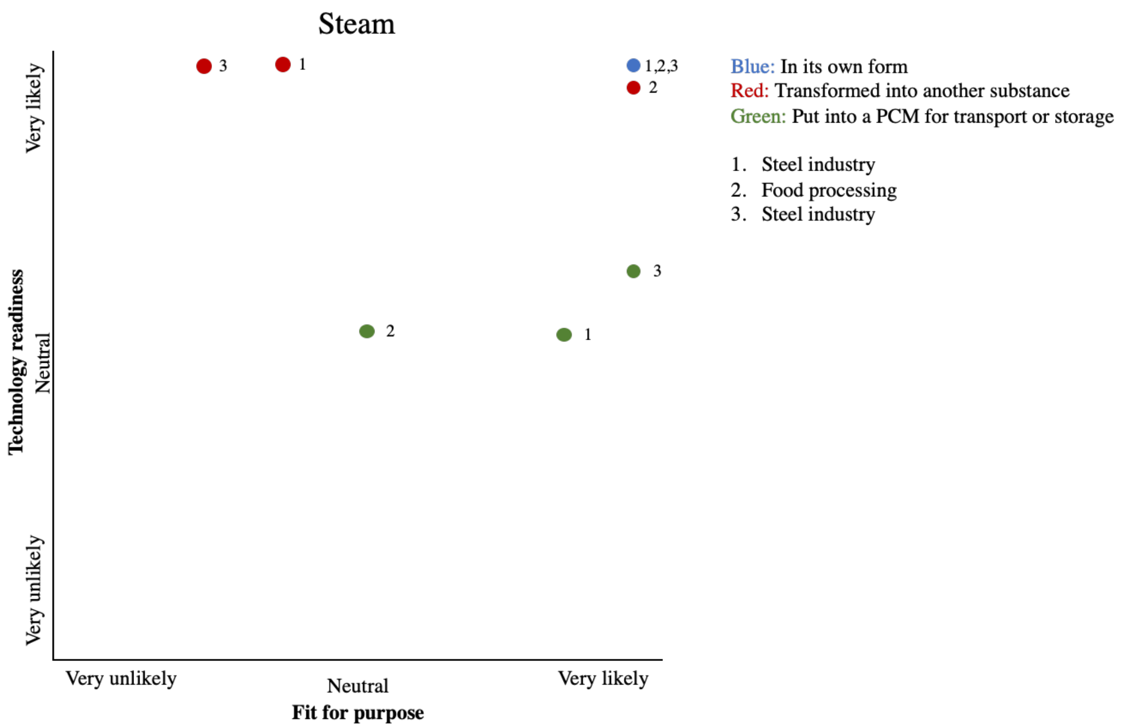
Very unlikely	Unlikely	A little unlikely	Neutral	A little likely	Likely	Very likely
☐	☐	☐	☐	☐	☐	☐

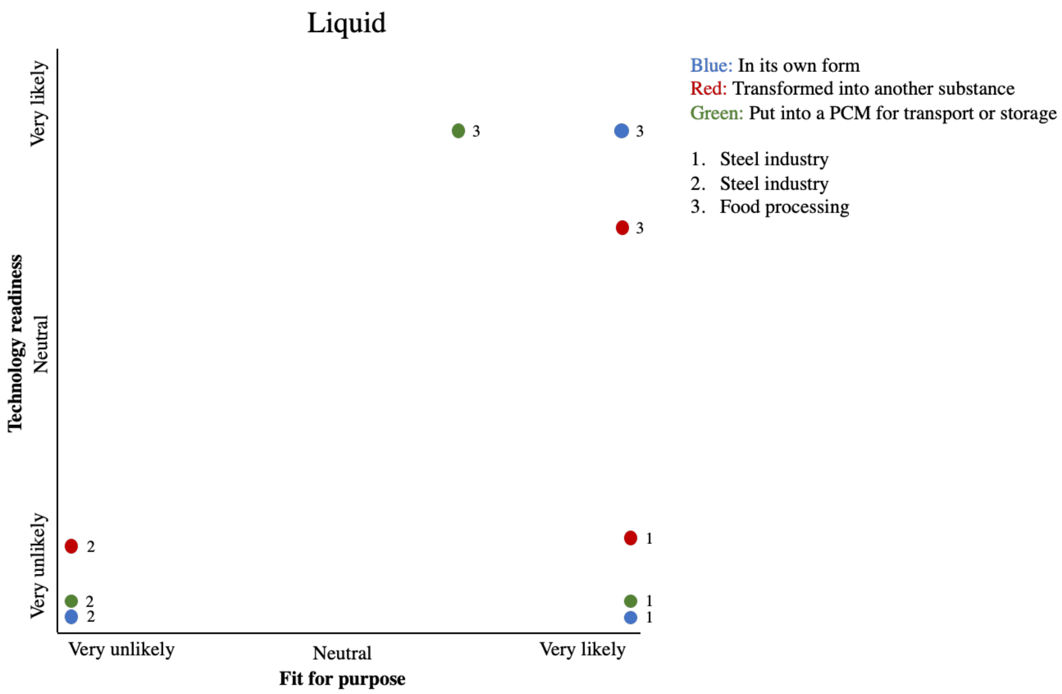
Notes:

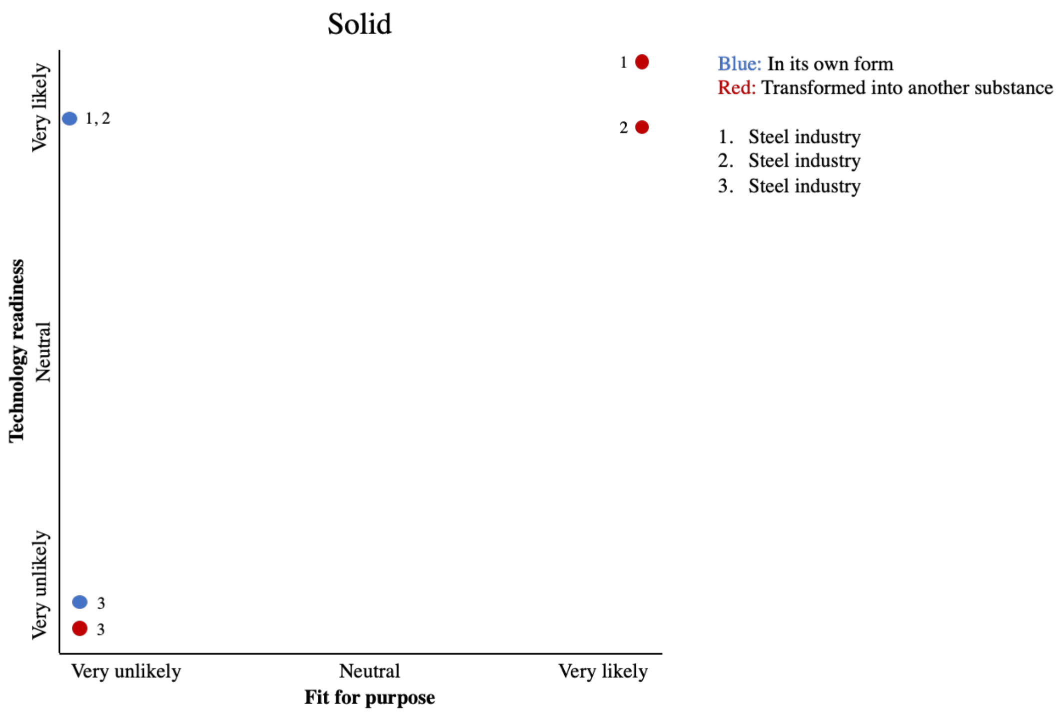
Implementation barriers for this technology (open question)

The graphical representation of the scores given by industry experts in the questionnaire (Appendix D).






Liquid
Technology readiness
Very likely
Neutral
Very unlikely
Fit for purpose
Very unlikely
Neutral
Very likely
3
3
3
2
1
2
2
1
1
Blue: In its own form
Red: Transformed into another substance
Green: Put into a PCM for transport or storage
1. Steel industry
2. Steel industry
3. Food processing


Solid
Technology readiness
Very likely
Neutral
Very unlikely
Fit for purpose
Very unlikely
Neutral
Very likely
1
1, 2
2
3
3
Blue: In its own form
Red: Transformed into another substance
1. Steel industry
2. Steel industry
3. Steel industry

Appendix F

Node		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		CGP1	CGP2	SIFA	PEFA	BF6	BF7	BOS2	DSP	HSM2	TSP	CM2	CPR	CEN1	CEN3	ZUFA	CCS
1	CGP1	0	1920	1020	1650	1430	1570	1440	1650	2020	940	2560	2570	450	2510	1210	100
2	CGP2	1920	0	850	290	550	400	1070	640	2820	2210	3350	3190	1430	3200	1570	2020
3	SIFA	1020	850	0	560	380	450	800	680	2280	1400	2740	2800	630	2700	1070	1120
4	PEFA	1650	290	560	0	340	310	920	540	2620	2000	3200	3010	1200	3000	1280	1750
5	BF6	1430	550	380	340	0	100	600	330	2270	1700	2800	2700	950	2700	1020	1530
6	BF7	1570	400	450	310	100	0	620	300	2300	1700	2900	2800	1050	2700	1130	1670
7	BOS2	1440	1070	800	920	600	620	0	410	1700	1400	2250	2100	1020	2100	510	1540
8	DSP	1650	640	680	540	330	300	410	0	2150	1700	2700	2500	1100	2540	990	1750
9	HSM2	2020	2820	2280	2620	2270	2300	1700	2150	0	1200	550	590	2000	490	1230	2120
10	TSP	940	2210	1400	2000	1700	1700	1400	1700	1200	0	1720	1740	990	1600	800	1040
11	CM2	2560	3350	2740	3200	2800	2900	2250	2700	550	1720	0	370	2540	180	1760	2660
12	CPR	2570	3190	2800	3010	2700	2800	2100	2500	590	1740	370	0	2550	240	1680	2670
13	CEN1	450	1430	630	1200	950	1050	1020	1100	2000	990	2540	2550	0	2460	980	550
14	CEN3	2510	3200	2700	3000	2700	2700	2100	2540	490	1600	180	240	2460	0	1600	2610
15	ZUFA	1210	1570	1070	1280	1020	1130	510	990	1230	800	1760	1680	980	1600	0	1310
16	CCS	8150	2020	1120	1750	1530	1670	1540	1750	2120	1040	2660	2670	550	2610	1310	0
17	Bunge HH	28000	28000	28000	28000	28000	28000	28000	28000	28000	28000	28000	28000	28000	28000	28000	0
18	CvG	2500	4420	3520	4150	3930	4070	3940	4150	4520	3440	5060	5070	2950	5010	3710	0
19	Draka	24000	24000	24000	24000	24000	24000	24000	24000	24000	24000	24000	24000	24000	24000	24000	0
20	Schiphol	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	26000	0
21	Norit (cabot)	19000	19000	19000	19000	19000	19000	19000	19000	19000	19000	19000	19000	19000	19000	19000	0
22	VUMS	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	0
23	AMC	37000	37000	37000	37000	37000	37000	37000	37000	37000	37000	37000	37000	37000	37000	37000	0
24	Tate&lyle	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000	0
25	Cargill	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	22000	0

Table E. Distance matrix in meters

Appendix G

The percentage of available WH was determined based on losses identified in the Sankey Diagram of Tata Steel. The share of recoverable WH was estimated in cooperation with Tata Steel team members of Energy Efficiency: Hans Kiesewetter and ing. Tom van der Velde MBE

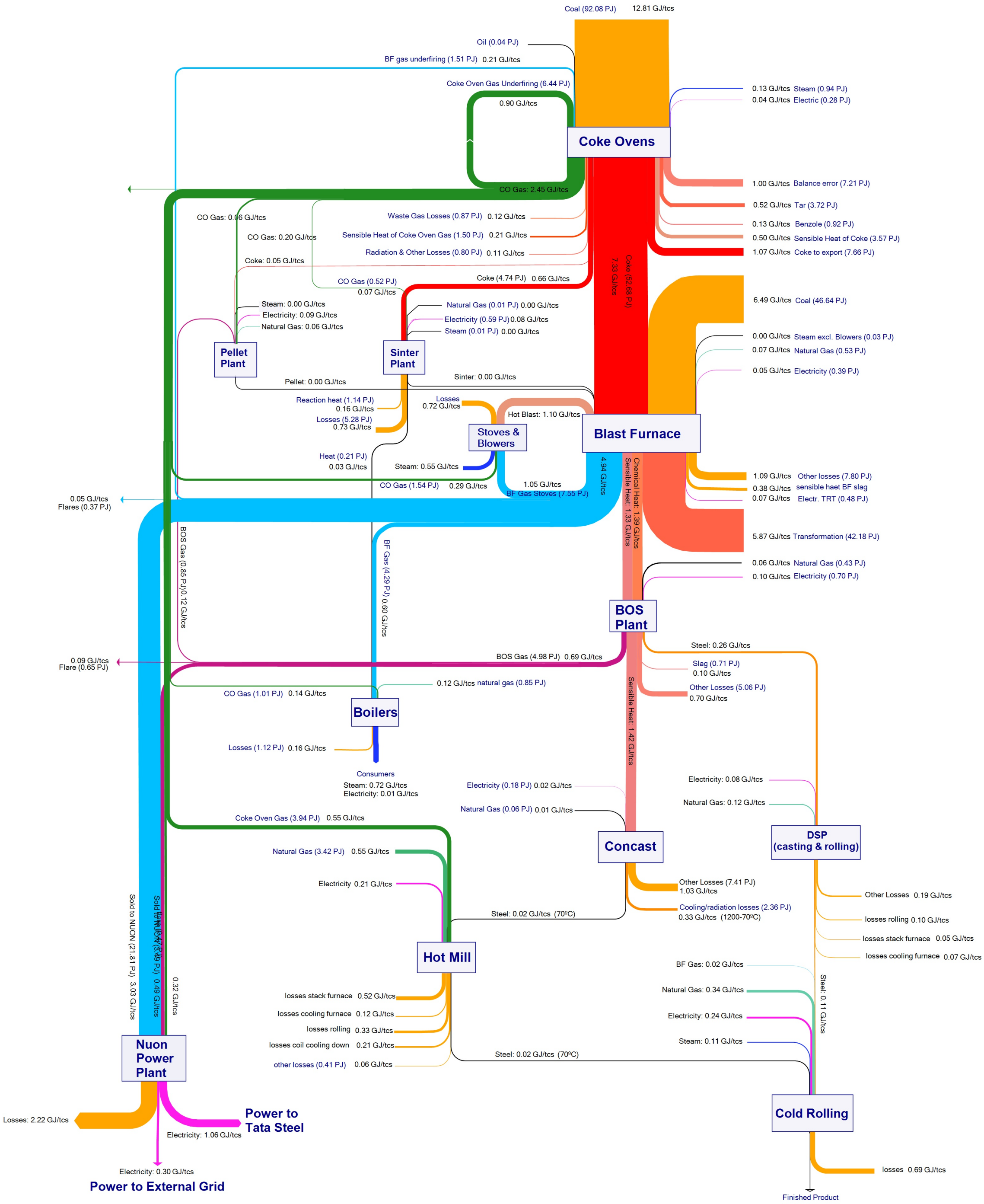


Figure F. Detailed Sankey diagram of the TSIJ plant.

Estimated consumption of nodes

AMC / VUmc

1. Based on annual emissions calculate annual gas consumption
2. Based on use of cogeneration, the use for heat is 60% of total gas consumption.
3. Spread the use similarly to the airport (Schiphol) gas use for space heating.

Cogeneration installation

60% is used for heat

Source: (COGEN Vlaanderen, 2019)

Appendix H

Nodes

1	CGP1
2	CGP2
3	SIFA
4	PEFA
5	BF6
6	BF7
7	BOS2
8	DSP
9	HSM2
10	TSP
11	CM2
12	CPR
13	CEN1
14	CEN3
15	ZUFA
16	CCS
17	Bunge HH
18	CvG
19	Draka
20	Schiphol
21	Norit (cabot)
22	VUMS
23	AMC
24	Tate&lyle
25	Bunge L

Objective function

$$min \sum \sum Lij \cdot Uij : \forall ij \; and \; Uij \; [1,0]$$

Where:

$$L_{ij} = \sum hourly \; WH \; supplied \; node \; i \; to \; j \; * \; emission \; factor \; node \; j \\ = total \; emissions \; reduced \; node \; j \; [kton]$$

and

$$U_{ij} = binary\ decision\ variable\ of\ WH\ supply\ from\ node\ i\ to\ node\ j$$

And

$$i = 5,7,8,9,10,11,12$$

$$j = 1,10,11,13,14,15,16,17,18,19,20,21,22,23,25,25$$

Constraints

The number of connections for supply nodes

$$\sum U_{ij} = 1$$

The number of connections for demand nodes, depending on the scenario

$$\sum U_{ji} \leq 1 \vee 2 \vee 3$$

Other calculations

Assumptions

Emissions	kg CO_2/GJ	Source
Natural gas	56	(Boldrini, 2019)
Cokes gas	48	(Boldrini, 2019)
BF+oxy (mix)	242	(Boldrini, 2019)
electricity	0	
Steam 3.5	75	(IEA ETSAP, 2010)
Steam 15	77	(IEA ETSAP, 2010)

Available WH

$$\text{hourly WH availability node i [GJ]} = \text{primary energy cononsumption [ton or n}m^3\text{]} * \text{energy density} \left[\frac{\text{GJ}}{\text{ton}} \text{or} \frac{\text{GJ}}{\text{n}m^3}\right] * \text{recoverable WH [\%]}$$

Primary energy consumption

$$Energy\ consumption\ [GJ/h] = primary\ energy\ consumption\ \left[\frac{ton\ or\ m^3}{h}\right] * energy\ density\ [\frac{GJ}{ton\ or\ m^3}]$$

Example excel formula:
=('PES Consumption per type'!BZ5*Assumptions!$J$2+'PES Consumption per type'!CQ5*Assumptions!$J$3)

WH exchanged

$$hourly\ WH\ supplied\ node\ i\ to\ j = hourly\ consumptio\ node\ j\ [GJ] * (1 - overall\ loss\ factor)$$

Example Excel formula:
=$C$5-IF($C$5-((1-'Network model'!H$38)*'GJ WH availability total'!H7)<0,$C$5,$C$5-((1-'Network model'!H$38)*'GJ WH availability total'!H7))

Appendix I

	Base case [kton]	3 [kton]	5 [kton]	7 [kton]
Level 1	0	105	120	127
Level 2	0	107	125	139
Level 3	0	107	126	140

Table 8.1. The data corresponding to figure 8.1. The different levels of freedom (vertical) opposed to the maximum number of allowed connections (horizontal) in the dispatch.

	Base case [kton]	Level 1 [kton]	Level 2 [kton]	Level 3 [kton]
3	0	105	107	107
5	0	120	125	126
7	0	127	139	140

Table 8.2. The data corresponding to figure 8.2. The different levels of freedom (horizontal) opposed to the maximum number of allowed connections (horizontal) in the dispatch.

Config.	Distance piping [m]	Distance TCM [m]
1	7300	0
2	2490	31440
3	8500	31440
4	4900	0
5	9420	0
6	12120	3490
7	4900	0
8	8150	0
9	13100	0
10	3860	31440
11	9420	0
12	8150	0

Table 8.3. The data corresponding to figure 8.3.

Carbon price [€/ton]	Configuration 1 [M€]	Configuration 9 [M€]
30	3	4
49	5	7
68	7	10
87	9	12
106	11	15
125	13	18

Table 8.4. The data corresponding to figure 8.4.