An Integrated High-Grade Waste Heat Network For Carbon Emission Reduction In Industrial Zones

An exploratory case study on integrated waste heat networks

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The global battle to reduce greenhouse gases 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 to reduce carbon emissions. This is generally done by improved technologies, and by reusing existing energy flows. This study is focused on how industrial zones can optimally utilize their available waste heat (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. The research has been performed in four phases. (1) An orienting and descriptive phase, (2) a scenario creation and modeling phase, (3) verification, analyzing, and evaluation of the gained insights, and (4) the discussion and conclusion of the research. Sectors with both large scale demand and supply of WH are likely to be interested in participating in an integrated WH market. As a result, establishing large scale connections prevents large amounts of carbon emissions. Additionally, the financial incentive to invest in these solutions increases due to increasing carbon taxation. Key drivers for carbon reduction are the large scale connections, with a demand profile that exceeds the supply pattern by much. 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 options in the WH market would be interesting, however with the current supply and demand patterns, WH can be utilized almost fully. That means that in the current system flexibility options do not add value. 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.

Keywords: Waste Heat Network, Industrial Symbiosis, Energy Efficiency, Energy Storage, Carbon Emission Reduction, Thermochemical Material

1. The global challenge of increasing energy efficiency

The global battle to reduce greenhouse gases 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). 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. The ETS, a 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 emission levels remain the same the carbon price would increase. According to the Dutch government, the ETS is not performing well enough. Therefore they designed an additional carbon taxation system.

To cope with the increasing pressure to reduce carbon emissions, industrial companies are researching partnerships to create industrial synergies. 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). Successful examples of symbiotic links are bio-based fuel production and district heating. This research focuses on the exchange of high-grade (>200 °C) waste heat to reduce the use of primary energy resources, such as coal and gas. By assessing an industrial zone from a network perspective, supply and demand nodes in the network can be connected to reduce the uptake of primary energy resources. The field of integrated WH networks can be divided into three categories:

- WH recovery and storage;
- High-grade heat transportation networks;
- Industrial heat exchanger networks.

The first category, *Waste heat (WH) recovery* and *storage*, is an enabling technology that reuses heat to supply energy-intensive processes. The heat of industrial processes is captured in a medium, which can consist of a variety of salts, minerals, gases, and fluids. Often referred to as Thermal Energy Storage (TES) medium (Miró, Gasia, & Cabeza, 2016). 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, waste heat boilers (Jouhara et al., 2018). A commonly studied method for heat storage is waste heat absorption into a phase-changing material (PCM) (Deckert, Scholz, Binder, & Hornung, 2014). 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). Currently, research is being done 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. To use this heat, low-pressure steam production is one of the possibilities to extract the heat from the TCM (Adinberg, Zvegilsky, & Epstein, 2010).

The second category 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 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 and offer flexibility options in time. 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, Luo, Wang, & Sauce, 2009) have already shown economic performance and feasibility of flexible heat options, while strategic benefits (lower infrastructure investment) can abate barriers to implement flexible heat networks.

The third category is *industrial heat exchanger networks*. A more theoretical research area that focuses on heat flows and looks into the mathematical optimization methods to optimally dispatch the different supply and demand patterns. Depending on the constraints, MILP or MINLP are dominant methods used to determine the optimal dispatch.

2. Research approach and methods

Macro-environmental factors initiating 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). The regulation will be considered as a given and a time span of 2021 to 2030 will be applied in this research. The price will start at 30 Euro per ton CO_2 in 2021 and increases annually with 10.44 Euro per ton CO_2 (RTLZ, 2020). The developed method is specified on self-proclaimed existing industrial regions. These regions have identified themselves as a demarcated cluster due to their geographical location. Out of the multiple symbiotic options of exchanging by-products and energy flows, this research specifies the exchange of waste heat flows in industrial regions.

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. The state of the art technical systems in WH usage will be created; 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 of a literature review, these findings will serve as input for the second phase: the scenario creation and modeling. By modeling a scenario, a case study on an industrial zone could be performed. A single-objective MILP optimization is used for the minimization of carbon emissions in the industrial zone. Currently, it is still not clear how industrial zones can optimally dispatch the available WH to minimize carbon emissions based on hourly supply and demand patterns. 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. The model will be run in different configurations of the scenario to create insights into (1) operational details of WH network; (2) identify drivers for carbon reduction; (3) test resilience of the WH network; (4) estimate the systems' impact in carbon reduction, and (5) assess trade-offs for infrastructure choices. This research specifically focuses on utilizing high-grade WH, hence district heating networks are excluded due to low-grade heat utilization.

The chosen methods 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 are applied in this research. To analyze the strategic positioning of different sectors in the region, the IAD framework is used. Based on the outcomes of the IAD framework, the incentives of a sector to participate in an integrated WH network is are clear. The conceptual framework of the dynamics of industrial symbiosis (Boons, Spekkink, & Mouzakitis, 2011) is used to identify the mechanisms that apply in the scenario, and complement the strategic positioning by identification of the market dynamics. Together with results from existing literature, these methods will be used to perform a system-level analysis from an outsider's perspective. That 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. For the scenario creation the initial step is to create a topology 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 theoretical, physical, and practical limitations of the network. The scenario will be validated with industry experts. 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. To create this multi-configuration WH network model, several steps are undertaken. The modeling steps displayed in figure 1 will be used as guidance for building the actual model.

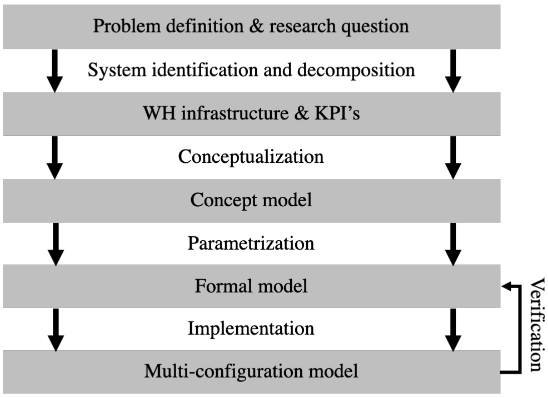

Figure 1 Model building steps.

By running different configurations of the scenarios, it is possible to determine what scenario is sensitive to changing circumstances.

3. Case study: the industrial zone "Metropole Region Amsterdam"

A basic conceptual model of the system is presented in figure 2. A detailed version was used to identify the data requirements, the constraints, and an overview of the potential heat flows in the system.

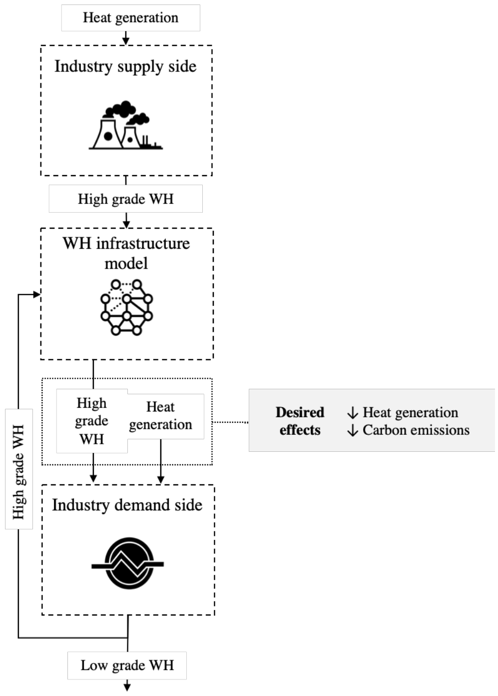

Figure 2. A basic conceptual model of integrated WH network.

Key data for the modeling the system are:

- Hourly heat consumption;
- Hourly WH availability;
- Topology of the network;
- Available infrastructure;
- Heat exchanger losses;
- Transportation losses.

Before the market dynamics and the market layout of WH can be analyzed, a basic topology of the 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 of 7.4% in 2018 (Government of the Netherlands, 2019). Next to that, the regions offer a wide variety of industrial companies that emit a significant share of carbon emissions. The carbon-emitting companies have been categorized into six sectors to analyze the impact of carbon regulation (table 1). In the right column, the likeliness that companies will participate in an integrated WH network is presented.

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

Table 1. The sectors in the MRA

The market dynamics of the integrated WH network have been synthesized into a pyramid structure presented in figure 3. The top-level represents the industry which has the strongest position and incentives to be part of an integrated WH network. These incentives have been identified based on the conceptual framework for IS and are presented in figure 3. The lower the rank in the pyramid, the less prominent the role of the industry will be in the WH network. According to the conceptual framework for IS, the political trigger and large scale are major a drivers for synergies in industrial regions (Boons et al., 2011).

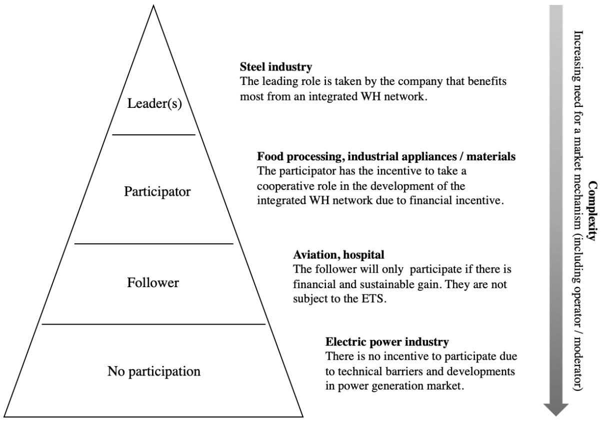

Figure 3 Overview of possible strategic positions based on IAD and IS analysis.

The market dynamics play a large role in the level of complexity of the network. In the MRA, the large scale WH exchange is mainly focused on the leading company. In more fragmented industrial areas this could be more complex. Such areas will benefit from a stable market mechanism that is yet to be established. The monitoring role could be occupied by one of the companies, or by an institutionalized third party.

For each WH connection, there are thermal losses in the system. The overall system efficiency is determined by the theoretical input and the losses. They relate as follows:

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

The technology assessment has resulted in several figures that are used in the model.

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 2 Transportation losses.

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 3 Heat exchanger losses.

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 sources are present in the steel industry. 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. A qualitative assessment is performed to assess the feasibility of making use of WH in each phase. To conduct this research, interviews with nine industry experts were held (steel, electricity, industrial appliances/materials, and food processing). Amongst those were R&D researchers and process technologists. In these interviews, the experts were questioned regarding the technology readiness and fit for purpose of each possible WH phase (flue gas, steam, liquid, and solid). By assigning scores, the results could be visualized in a graph with on the one axis technology readiness opposed to fit for purpose. The experts could choose out of seven scores ranging from very unlikely to very likely. Based on the assessments of industry experts, flue gases and steam have been scored to be a feasible high-grade WH source, while liquids and solids were scored infeasible. The operational restrictions seem to be the highest barrier for WH in solids, while for the WH in liquids, the availability is the restriction.

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 4. The exchange of WH requires transportation, hence it is interesting to determine how the infrastructure is in this region. Traditionally, this is through a piping system, whereas transport by truck, train, or boat concern more novel technology that involves heat storage.

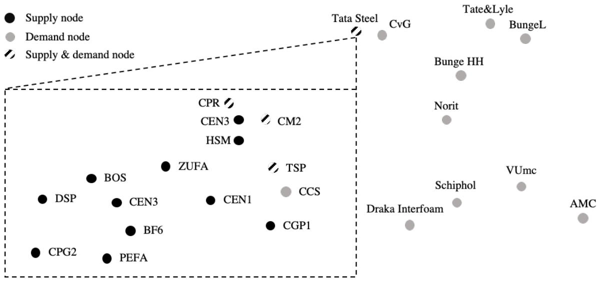

Figure 4. The nodes in the MRA that data was provided for. Else, estimations based on emissions were made if possible.

For none of the nodes, there was data on their available WH, therefore this had to be calculated by using Sankey diagrams, combined with estimations made through discussions with operational experts. By determining the ratio between input and WH output (losses) for each node, the hourly WH availability could be calculated. An overview of the supply and demand quantities is provided in table 2.

Nodes (supply = white, / demand = grey)	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 4 The supply and demand nodes ranked on the quantity.

Different configurations have been created that enable making the 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 for demand nodes varies and is set at a maximum of 3 connections. In the analysis, this is referred to as a level 1, level 2 and level 3. As the number of maximum connections increases, the operational complexity increases due to a higher number of nodes interacting with each other. To test how resilient the system is, three configurations have been created that have limited security of supply. That means that an analysis can be performed to understand the implications of an (un)expected interruption in WH supply. It is expected that in the disrupted configurations (10 to 12) the reduced carbon emissions are affected, and the operations of the demand node will be disrupted. In configuration 10-12, an arbitrary period of 26 days has been eliminated for four nodes. The HSM and CM2 node have 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. 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.

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 5. The configurations that will be run.

As a result of these configurations, the following results are obtained with the single-objective MILP model that minimized carbon emissions. The utilization is based on the match between supply and demand, the heat exchanger losses and transportation losses. The required infrastructure is the combined required infrastructure for all connections in the optimal dispatch. A utilization of 92.0% is maximum due to the heat exchanger losses.

The following function was used to optimize the scenario:

Objective function

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

Where

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

and

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

Constraints

The number of connections for supply nodes

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

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

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

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	125	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 6. An overview of the overall figures for each configuration. The impact of the disrupted supply is measured in carbon emissions reduced.

The scenario was tested in different configurations by varying the freedom (levels) of the system. What can be observed in table 6 from the variation over the total number of allowed connections, 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, which has a similar trend. 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. 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. The increase of carbon reduction stagnates after level 2. As a result, the maximum amount of connections a demand node should take is 2 (level 2) in the MRA. Because a higher number would increase operational complexity because of the increased volatility with 3 connections.

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 increase 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.

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 6).

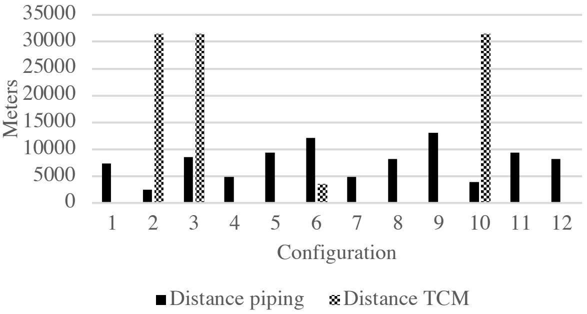

Figure 6 Required infrastructure for the configurations. The TCM distance is measured as a one-way trip.

This result is explained 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.

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 6 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. The optimal dispatch for the disrupted configurations remained the same, hence there was no operational impact on the connections chosen by the model. 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. From an economic perspective, the unexpected WH supply causes a difference. 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 costs of 210 thousand Euro for one year. Although the duration of the disruption was arbitrary, a safety margin should be included for the business case for each connection.

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 7 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 prices.

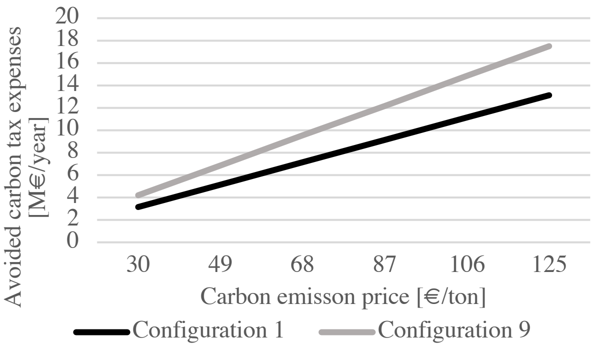

Figure 7. An overview of the range of avoided annual tax expenses for different carbon tax levels. Time horizon: 2021 – 2030.

4. Discussion

A model is a limited representation of reality. Due to the unlimited number of variables that influence the scenario, assumptions had 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 reality. Generally, the most impactful assumptions are the system-level assumptions and technical assumptions.

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.

A limitation caused by using this type of MILP model is the assumption 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. Another assumption was that 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. Apart from configuration 3, which is the most restrained configuration, this assumption was grounded because in all dispatches the utilization was over 82%. In reality the system will unlikely be as limited in configuration 3.

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 technology 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 there, the impact on the overall outcome is therefore limited.

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 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.

In figure 8 the generalized approach to analyze integrated WH networks is presented. The position of this research is placed in the context of existing literature. The methods in the dark box have been applied to the MRA. However, the applicability of the methods is dependent on the data availability-and-provision of the companies within the industrial zone.

Based on the results of this research, it has become apparent that an integrated high-grade WH network will only have a small contribution as a low carbon solution. 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 an increasing trend.

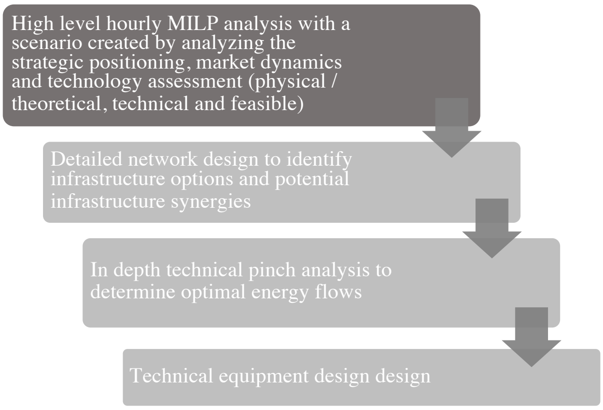

Figure 8. Flow chart of suggested research approach for integrated WH networks in industrial zones in the context of existing literature. The approach used in this research is presented in the dark box. The light boxes are approaches used in the existing literature.

Table 7 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 7 Applicability of the used methods in other industrial zones assessing the potential of high-grade WH utilization.

5. Conclusion and further research

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, an assessment was made on how each sector would be involved in a WH network, with a purpose to reduce carbon emissions. This lead to the conclusion that the steel industry is the most likely sector to be interested in an integrated WH network. Other active participants are the industrial appliances and materials sector, and the food processing industry. The followers, which occupy a less active role in the WH network due to their 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 disrupting market and technical inability to utilize this waste heat on a large-scale.

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. The result was an optimal dispatch for each configuration, with detailed information on the connections and the performance of the overall configuration. This method can be generalized and used for other scenarios.

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.

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 in the MRA 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.

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. A key learning here 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 benefit as compared to more networks with few connections.

Further research can be conducted into the effect of power-to-heat technologies in integrated WH systems. As the oversupply of renewable electricity in peak hours will offer low-cost electricity supply in those peak hours. The power-to-heat efficiency is 100%, hence the technology has much potential to supply industrial processes using steam boilers and simultaneously mitigate the effects of the volatile supply of renewables (International Renewable Energy Agency, 2019). The second proposed research area is an analysis of the market design of integrated WH networks. 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 last suggested research is related to the network design. Additional research in this area might provide extra insights for decision-makers to assess the operational and economic viability of the dispatch.

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