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Integrating Data Center Waste Heat into the District Heating Network in Amsterdam

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Thesis report

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Integrating data center waste heat into the district heating network in Amsterdam

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Enjoy the read!

Laura Hattink
August 2020, Amsterdam

Summary

District heating is gaining popularity and can serve as an alternative for the use of natural gas to provide heat to residential areas. District heating systems can make use of heat sources that are often locally distracted and would have otherwise been wasted. Data centers could act as low temperature heat sources by recovering residual heat for district heating purposes. However, integration issues arise on various levels. Most saliently, there is a difficulty in implementing a heat source of low temperature in existing higher temperature networks, the economic viability of integrating new heat sources is challenging and conventional sources are often still very cheap. There is no single right solution for the feasible integration of residual heat from data centers, with every district heating network being unique.

This research aimed to provide insights into how data center waste heat in Amsterdam can be integrated into the district heating network, cumulating in the following main research question:

> *"What are the feasible approaches to integrate waste heat from data centers in the district heating network in Amsterdam?"*

District heating concept

The latest developments of district heating focus on using low temperatures, integrating renewable energy sources, and recovering waste heat. Typically, data center residual heat is wasted into the outside air, but integration into district heating networks creates a solution to recover the data centers' waste heat. Waste heat from data centers is of low temperature, and a heat pump is required to upgrade the temperature to align with the typically higher temperature networks. The efficiency of a heat pump is expressed in its *Coefficient of Performance* (COP) value, which relates to the supply of electricity needed to drive the heat pump's compressor. The heat pump upgrades waste heat for district heating purposes, and the returned chilled water from the evaporator is used for data center cooling. Realizing the utilization of data center waste heat needs to be economically attractive for the data center, the heat provider, and the consumers. Environmental benefits of district heating, in terms of greenhouse gas reductions, are achieved by replacing less efficient heating technologies with a residual heat source.

Comparison of Dutch, Swedish and Danish markets

District heating markets of the Netherlands, Sweden, and Denmark were compared, based on the type of markets (regulated or deregulated), the pricing structures, the degree of market opening, and the ownership structure. Heating plays an important role in Nordic countries, and district heating has a significant position. Although Nordic countries have much in common, the national energy targets, regulations, and price model for district heating are country-specific.

Consumers can be negatively affected by the deregulation of prices, whereas price regulation allows for consumer protection. Too much control can result in an inflexible price setting and might disincentivize market entries and innovations in the system. The degree of market opening, therefore, goes hand-in-hand with price regulations. In the district heating sector, competition on the production side is limited due to the local dependence of the sources. In most countries, district heating suppliers do not compete with each other. Furthermore, there are additional and less apparent factors that play a role in a country's market arrangements, which stem from the policy drivers and ideologies of a country.

System engineering approach

A system engineering approach was developed to find and test opportunities to integrate data center waste heat into the district heating network of Amsterdam. The approach could offer support in the feasibility phase before making development decisions for a district heating network case. The layered network scheme helps to understand the different elements of the system and its interdependencies. The district heating network is deconstructed into the following layers: the physical layer, the technical layer, the economic layer, the institutional layer, and the (external) social and environmental layer (see Figure 0-1). The layers were aligned with four dimensions of energy security, which are: Availability, affordability, accessibility, and acceptability.

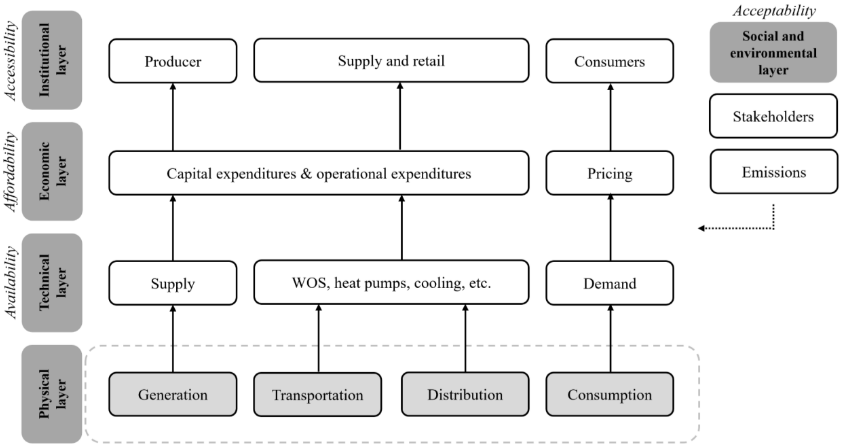

Figure 0-1: Network layered scheme with district heating components.

The network layers were discussed in more detail for the case of integration of data center waste heat in Amsterdam. In terms of the physical network of Amsterdam, there are two main primary heat networks. One is owned by Vattenfall, covering south and east Amsterdam, and the other one is a joint venture between the Waste incinerator company AEB Amsterdam and Vattenfall, named Westpoort Warmte (WPW), covering heat in the Western and Northern parts of the city. The network temperatures in Amsterdam are 115° - 60°C (supply - return) for the primary transport network and 75° - 45°C for the secondary distribution network. Waste heat from data centers is typically 30°C, and therefore needs to be upgraded for integration into the district heating network.

Modeling an area in Amsterdam

The network layered approach that was applied for the case of Amsterdam was used as the starting point for a pilot project ‘Kantorenstrook Amstel III, modeled in the simulation tool EnergyPRO. The tool is used for techno-economic analysis of complex energy systems, such as the district heating system. Data center waste heat integration, under different scenarios in time, was compared to a reference case in which data centers are not integrated. Four Key Performance Indicators supported the analyses of the model: Energy consumption, asset usage, cost of heat and electricity, and CO_2 emissions. For each of the years in time (2020, 2025, and 2030) costs and emissions inputs vary, resulting in different outputs.

When integrating data center waste heat in the area of Kantorenstrook Amstel III, natural gas consumption decreases, whereas electricity consumption increases. This is due to the operation of the heat pumps, as the pumps together cover 73,2 percent of the total heat demand and a large share of the data center’s cooling requirements. In all three years that were studied, overall costs are not only reduced by around 41 percent when integrating data center waste heat, but a CO_2 emission reduction also takes place. The decision to cover a baseload of roughly 1/3rd by using a heat supply of 2,25 MW was verified by modeling two supply variations. Also, a model configuration was applied by making use of air cooling when the ambient temperature is below 17°C. Sensitivity and uncertainty analyses determine the validation of the model: Larger heat pump operation ranges allow for more heat supply and cover more heat demand, but operation range maximization is constrained by the reduction in efficiency and the *full load operating hours* (FLOH) limit. Furthermore, the heat demand profile is uncertain, and an inaccurate prediction of the demand can have a substantial impact on the outcomes.

Both the transport and distribution networks in the Kantorenstrook Amstel III area are owned by Vattenfall, and heat delivery would go through long-term contracts between the data center and Vattenfall. However, Vattenfall would need to receive concession from the municipality to engage a new district heating network and data center integration in the Kantorenstrook area. Such institutional arrangements of heat recovery and delivery in the area were not incorporated in EnergyPRO but must be taken into account too.

Possible future developments

The network layered scheme can help to visualize changes and consequences in each network layer. Physical connectivity between the networks in Amsterdam has been implemented in 2020, and institutional rearrangements might follow soon after. The network could become more open and allow for more third party access, such as to data centers. Opening up the network could work well if economic models create a profitable situation for both the district heating owner and the data center.

Data centers' capacities are growing, which means greater efficiency measures are required. Feeding in waste heat into the district heating network and the development of new cooling technologies can both enhance energy efficiency. The increasing data center heat capacity could drive incentives to optimize cost allocation between the data center and the district heating company. Regardless of what business models would come into place, stability and reliability are critical factors for a feasible integration.

Conclusion and recommendations

The investigation into possible integration opportunities has resulted in a two-step approach: Creating a theoretical understanding of the district heating system for a specific case, and also looking into a practical case study by using a simulation tool. Using the network layered scheme is recommended to find and test opportunities to integrate data center waste heat into the district heating network of Amsterdam. Techno-economic models, such as EnergyPRO, could help in the decision-making process when studying the feasibility of a project, but adoption of the institutional layer is essential to understand the full system. Vattenfall should anticipate the development of new technologies, but also on (often less apparent) institutional rearrangements. Furthermore, system developments require a strong corporation with stakeholders, such as the municipality or the DDA. International case-studies can be studied to gain an understanding of other business models and regulations.

The decision-making and waste heat integration will simply not be ready in a day. Still, a clear vision of the functionality and interdependencies of all system components support steps towards successful integration.

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List of Acronyms

ACM	Authority for Consumers and Markets
AEB	Name of the waste incinerator company in Amsterdam
BENG	Nearly Zero Energy Building (in Dutch: Bijna Energieneutrale Gebouwen)
CHP	Combined Heat and Power
COP	Coefficient of Performance
DDA	Dutch Data center Association
DC	Data center
DH	District heating
EOR	Primary fossil energy efficiency (in Dutch: Equivalent opwekrendement)
ETS	Emissions trading system
FLOH	Full load operating hours
HHV	Higher Heating Value
HTHP	High Temperature Heat Pump
KPI	Key Performance Indicators
LHV	Lower Heating Value
NMDA	Not-More-Than-Otherwise (in Dutch: Niet-Meer-Dan-Anders)
nZEB	Nearly Zero Energy Building
PEF	Primary Energy Factor
PLF (1)	Power Loss Factor
PLF (2)	Part Load Factor
PLR	Part Load Ratio
PUE	Power Usage Effectiveness
TPA	Third party access
WOS	Substation (in Dutch: Warmteoverdrachtstation)
WPW	Westpoort Warmte (joint venture between AEB and Vattenfall)

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1. Introduction

This chapter introduces the topic of data center waste heat integration for district heating networks. Section 1.1 presents the problem statement and the relevance of the research. In Section 1.2, a literature review will be done to identify the knowledge gap. The knowledge gap leads to the main research question, the sub questions, and the research methodology in Section 1.3. The Research Flow Diagram in Section 1.4 visualizes the research approach steps. The outline of this thesis will be described in Section 1.5.

1.1 Problem statement

The Dutch Government has the ambition to make no longer use of natural gas for residential heating in 2050 (Rijksoverheid, 2017). District heating has enjoyed increasing societal attention and can reduce CO_2 emissions and the use of fossil fuels, such as coal, gas, and oil, substantially. The system provides an alternative for the current most common way of heating residential areas, namely by using natural gas. District heating can be best described as a network of pipelines transporting warm water for heating houses that are connected to the system. It can make use of heat sources that are often locally distracted and would have otherwise been wasted in earlier production processes.

In the past, district heating systems mainly utilized heat from Combined Heat and Power (CHP) boilers and wastewater from coal-fired power plants. Nowadays, current sources of heat are much more sustainable and cleaner, such as biomass, industry surpluses, large scale solar collectors, geothermal, aqua-thermal, and residual heat. However, some of those alternatives are still competing with more mature fossil energy sources (Schmidt et al. 2017). Vattenfall wants to make fossil-free living possible within one generation, and new approaches are necessary to reduce carbon emissions.

Low temperature heat sources, such as data centers, could play a key role in reusing residual heat for district heating purposes. However, integration issues arise on the technical level when a low temperature heat source is implemented in existing district heating networks with higher temperatures. Furthermore, the economic viability of waste heat sources is still a challenge because conventional sources are often cheaper and easier to integrate. Approaches depend on many variables, such as the location of the data center(s), the network infrastructure, and heat supply versus demand. The difficulty of this topic lies in the fact that there is not one single right solution for the feasible integration of residual heat from data centers, and every district heating network is unique in terms of implementing possible renewable heat sources.

Integration issues also occur due to the present heat system. In contrast to the more mature gas and electricity system, the district heating system is less developed. The system still runs into technical difficulties related to matching supply temperatures and dealing with losses in the grid. Also, issues related to pricing structures, stakeholders' interests, regulations, etc., are yet to be solved. District heating networks are very complex and involve many factors that influence and affect the system.

1.2 Literature review and knowledge gap

1.2.1 Data centers

Data centers are large consumers of electricity and, therefore, efficient systems are essential. Data centers already use various techniques to reduce the use of energy, and modern data centers are getting close to an ideal *Power Usage Effectiveness (PUE) factor* of 1, indicating the maximum attainable efficiency with no overhead energy (Avgerinou et al., 2017). Now that improvements in the efficiency of the systems are reaching limits, the industry is looking for other opportunities to enhance sustainability. Utilizing waste heat of data centers is a more recent approach to improving the energy efficiency of a datacenter. Wahlroos et al. (2017) conclude that data centers are a reliable heat source, and using waste heat of data centers can be a sustainable practice on technical, economic, and environmental levels.

1.2.2 Integrating

Articles of Wahlroos et al. (2017), Ebrahimi et al. (2014), and Davies et al. (2016) analyze the district heating system from both the data center and network perspective. Heat rejected from data centers is of low quality and, to be useful, heat pumps are used to boost the temperature so that the heat input requirements of the network can be met (Ebrahimi et al., 2014). Wahlroos et al. (2017) conclude that since upgrading the waste heat with heat pumps also consumes electricity, the environmental impact is dependent on the primary energy sources of the power mix and consumption. Davies et al. (2016) point out technical challenges associated with how best to match data centers with district heating networks and how to upgrade the heat, and non-technical challenges, such as readiness, viability, and energy savings comparisons.

1.2.3 Learning from others

Waste heat recovering techniques are developing fast, but according to Werner (2017a), the implementation rates vary per country. Nordic counties have implementation rates over fifty percent, and suitable conditions increase the potential for attracting more data centers, which is contrasting to countries with almost no district heating systems (Werner, 2017a; Wahlroos et al., 2018). The article of Wahlroos et al. (2017) discusses prospects for low temperature district heating networks and points out that implementation rates of low temperature district heating are dependent on heat demand. In countries such as Denmark and Germany, heat demand is lower than in Finland, making overall temperatures in the heat networks lower. This results in a more natural implementation of low temperature heat sources.

Petrovic et al. (2020) have researched the role of data centers in the Danish energy system, and four of the five scenarios studied prove full waste heat utilization, and could contribute from 4% to 27% of Denmark's district heating sources in 2040. The article points out that the results might also be relevant for other (cold climate) countries with a district heating network in place, which is also supported by Dalla Rosa and Christensen (2011).

A case study in Finland by Syri et al. (2015) explores the concept of open district heating by using marginal cost-based pricing. This specific case could be economically attractive to all parties. Liu et al. (2019) did a similar marginal cost pricing study in Zuid-Holland in the Netherlands but concluded that market revenues could not cover fixed costs. Syri et al. (2015) conclude that outcomes depend on fuel prices, taxes, CO_2 prices, and electricity prices, as well as on the scope and geographic location of the study, which is in line with other articles.

1.2.4 Challenges

According to the article by Werner (2017a), there are possibilities for low temperature heat integration, but its viability requires substantial efforts on different levels. Technical issues create challenges, but Wahlroos et al. (2018) also point out the lack of solutions to create economic advantages and the non-transparency of business models. Furthermore, environmental impacts are dependent on the current electricity sources, and this varies in time and per situation. Koronen et al. (2020) state that the world needs more substantial efforts in developing district heating supporting policies, institutional regulations, taxation and subsidies, and a change in market design. Creating awareness is necessary to reach public support for waste heat utilization projects, and decision-makers must be triggered to reuse waste heat from data centers.

1.2.5 Knowledge gap

The reviewed articles discuss technologies and approaches for the integration of data center waste heat in district heating networks. Experiences from more developed countries (mostly Nordic countries) must be explored to prove viability and adaptability for cases in the Netherlands, starting with the big data center hub of Amsterdam. However, one can imagine that ‘copying and pasting’ best practices from other countries will create issues since institutional arrangements (regulations and policies) are not the same. The results of a case study in a specific area or even country can often not be directly applied in or compared to another context due to various factors. Nevertheless, studying multiple cases in different countries would raise the ability to analyze situations and explore what factors influence the system.

When having researched the data center integration in other countries, a comparison to the Netherlands can be made, and a system engineering approach is needed to study the integration of data centers in Amsterdam systematically. Value-adding research would use model simulations for the case of Amsterdam in order to look for opportunities over time and to gain an understanding of the effect of integration of data center waste heat in district heating networks. Viability of integration of data center must be measured by Key Performance Indicators (KPIs), such as consumption, emissions, and costs. Therefore, looking from a multi-level perspective is of great importance.

1.3 Research questions and methodology

1.3.1 Main Research Question

After having explored the knowledge gap, further research on the opportunities for integration of low temperature data center waste heat in district heating networks can be carried out. The main research question is formulated as follows:

> *“What are the feasible approaches to integrate waste heat from data centers in the district heating network in Amsterdam?”*

To give a definite answer to this main research question, sub questions are created and will divide the phases of the research.

1.3.2 Research approach

In this research, the concept of district heating networks and implementation of low temperature waste heat of data centers will be researched on a multi-level perspective, including different levels that influence the system. The objective of this research is to explore how data centers, as an alternative and sustainable heat source, could be integrated into district heating networks in Amsterdam.

The research will follow a *mixed-method approach*, in which the concept of district heating in the Netherlands and other countries is explained, followed by a model and feasibility analysis of the integration of waste heat from data centers. Those two methods will be carried out as follows: A technical approach will help to explore the basic concepts of district heating and country-specific characteristics. This *quantitative approach* only focuses on theory and will not create an extensive solution. Therefore, next, a more *qualitative approach* will help to create an understanding of strategies to integrate data centers in Amsterdam. A model simulation method could provide solutions in time for a specific case in Amsterdam.

1.3.3 Sub-questions

Some steps are followed to provide a clear answer to the main question: A). Exploring the district heating concepts and comparing the situation of the Nordic countries with the Netherlands, B). Defining an approach to integrate data center waste heat for the case of Amsterdam, C). Using a model simulation method to visualize and compare waste heat integration approaches, and D). Analyzing potential future developments that will likely affect the district heating situation in the short- or long-term future. In order to do so, sub questions are formulated as follows:

1. *What is the current situation of district heating in the Netherlands, and how does it differ from district heating markets in Nordic countries?*
2. *What kind of system engineering approach is suitable for defining data center waste heat integration possibilities for the case of Amsterdam?*
3. *What value can be created by data center waste heat integration under different scenarios?*
4. *What are potential future (district heating and data center) developments, and how will these affect district heating in Amsterdam?*

The sub questions are addressed in Chapters 2 to 6 and contribute to an answer to the main research question in Chapter 7. A Research Flow Diagram is set up to visualize the steps of this research (see Section 1.4).

1.3.4 Method

Methods for gathering required information and data per sub question are explained. An explanation is given on what information and data are needed to answer the sub questions, followed by the research method. For literature studies, research databases, such as *Scopus* or *Web of Science*, but also grey literature, will be used. Earlier research and reports of Vattenfall will be consulted too. Interviews will be semi-structured with the advantages that questions can be prepared before the interview, but the conversations will still be open-ended and flexible. Key learnings from earlier interviews could help to improve the next interview.

1. What is the current situation of district heating in the Netherlands, and how does it differ from district heating markets in Nordic countries? (descriptive/analytical)

Technical, economic, environmental, and institutional concepts of district heating will be described, and the current situation of the district heating in the Netherlands will be explored. Next, district heating in the Netherlands will be compared to the district heating market in Nordic countries, based on the institutional arrangements.

Research method: The research method is a literature study on the current district heating situation in the Netherlands and Nordic countries. Research databases will be used by including the search terms 'district heating', 'The Netherlands,' 'case study,' 'best practice,' and '[Nordic countries].'

2. What kind of system engineering approach is suitable for defining data center waste heat integration possibilities for the case of Amsterdam? (implementing)

After exploring the concepts of district heating, a system engineering approach will be set up to systematically explore opportunities for integrating data center waste heat in Amsterdam. The approach will help to understand the feasibility of district heating projects.

Research method: Internal interview(s) will be held to define Key Performance Indicators (KPIs) for district heating projects, and experts will be interviewed to understand the aspects of a complex system approach.

3. What value can be created by data center waste heat integration under different scenarios? (designing)

A software tool for modeling energy projects will be used to model scenarios in which data center waste heat is integrated into the district heating network. The scenarios will be compared to reference cases in which there is no data center integration. Components are varied to measure sensitivity and uncertainty.

Research method: A data analysis will be performed with the software tool *EnergyPRO*. Tutorials, internal expertise, and earlier reports in which EnergyPRO is used, will be consulted to gain an understanding of the tool.

4. What are potential future (district heating and data center) developments, and how will these affect district heating in Amsterdam? (discussing)

Future technology developments and changes in the district heating system and on the data center side create new opportunities and can change integration opportunities. Possible future developments will be discussed.

Research method: Semi-structured interviews with (internal and external) experts will be held to understand the effect of developments for the case of Amsterdam, subsequent to own findings.

1.4 Research approach

A Research Flow Diagram (RFD) visualizes the sequential research steps and shows how one or more research sub questions will be used as input for the following question to, eventually, give an elaborative answer to the main question. The RFD is shown in Figure 1-1 below.

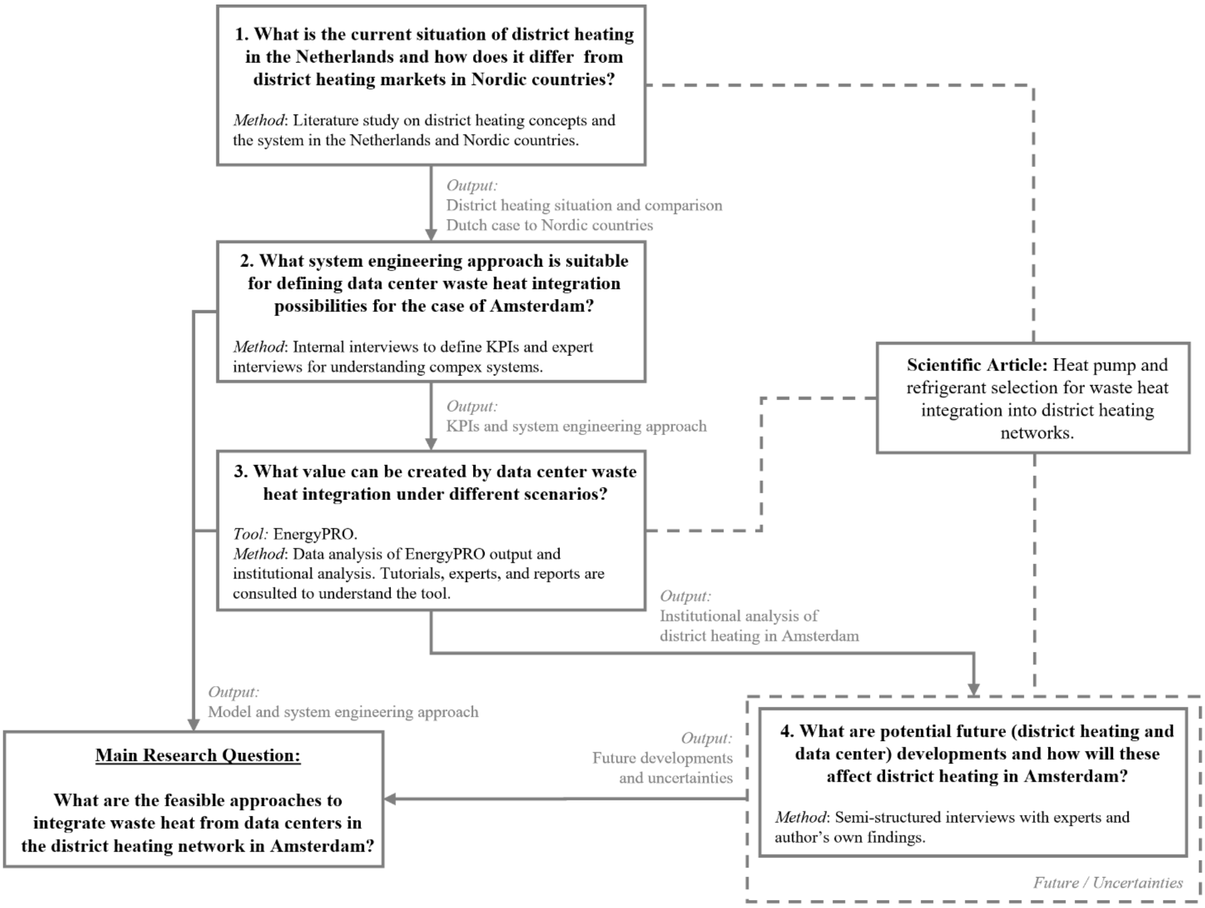

Figure 1-1: Research Flow Diagram with main and sub research questions and outcomes.

As part of the CoSEM master thesis, a scientific article will be written in addition to the main research. The purpose of the article is to study a particular topic of main research in more detail. The article will be about heat pump and refrigerant selection for waste heat integration in district heating networks.

1.5 Thesis outline

This thesis will be outlined as follows: Chapter 2 will provide the reader with an in-depth explanation of district heating concepts and the characteristics of the district heating markets in the Netherlands and Nordic countries. To align the different components of district heating systems, a complex system engineering approach will be introduced and presented in Chapter 3. In Chapter 4, a model will be set up for comparing a data center waste heat integration scenario to a reference case. Model results and institutional arrangements of the case will be analyzed in Chapter 5. Dynamics in the network and future developments will be discussed in Chapter 6. Conclusions and recommendations for further research will be given in Chapter 7, and Chapter 8 will include a reflection on the study.

2. District heating concept

In this chapter, the district heating concept will be explained by investigating the technical, economic, environmental, and institutional concepts. The technical concepts in Section 2.1 include all physical and technical artifacts that comprise the district heating technology. The economic concepts in Section 2.2 entail all cost flows, divided into capital and operational expenditures. The primary fossil energy use and CO_2 emissions associated with electricity and heat consumption are explained in Section 2.3. Institutional concepts in Section 2.4 contain regulatory arrangements, such as the division of ownership and market mechanisms. In Section 2.5, characteristics of the Dutch district heating system will be compared to aspects of the system in two Nordic countries.

2.1 Technical concepts

In the article of Lund et al. (2014, p.1), district heating is described as “a network of pipes connecting the buildings in a neighborhood, town center or a whole city, so that they can be served from centralized plants or a number of distributed heat-producing units.” A district heating system, therefore, provides service over the whole value chain, from generation to consumption.

2.1.1 Physical network

A district heating network can be divided into four main process steps: generation, transportation, distribution, and end-user consumption (visualized in Figure 2-1). Those components are similar to the elements of electricity and gas networks. Besides similarities in the process, also natural monopolistic characteristics, the security of supply, and hourly and seasonal changes in demand are typical for heating, electricity, and gas networks (Wissner, 2014). However, unlike the natural gas and electricity networks, district heating networks are often local or regional systems.

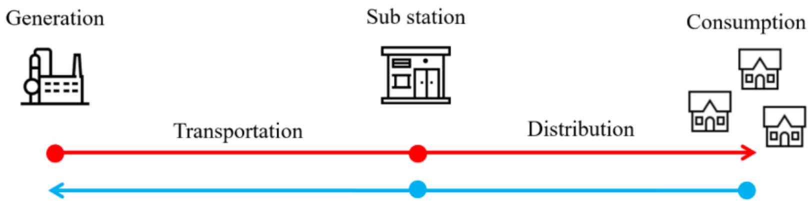

Figure 2-1: Overview of the four main process steps in district heating.

The generation process comprises the production of the heat source or fuel type for district heating. The generated heat is transported from its production site to the location of the heat demand. This is done through pipelines with water as the heat transfer fluid. The transformation network (the primary network) is separated from the distribution network (the secondary network) through a substation (in Dutch: warmte-overdrachtstation (WOS)) that consists of a heat exchanger. The temperature for the transport network is around 115°C for the supply line and 60°C for the return line and for the distribution network it is about 75°C for the supply line and 45°C for the return line.

2.1.2 District heating generations

Developments in the technology of district heating can be divided into different generations (Lund et al., 2014). In the 1880s, the first generation was introduced, using steam as a heat carrier. Nowadays, this technology is considered to be outdated due to high heat losses and safety issues. In the 1930s, a second generation came on the market, using pressurized hot water as a carrier. This was motivated by the utilization of CHP and with the intent to reduce fuel usage. In contrast to the first and second generation, the third generation made use of pre-insulated pipes that were directly put in the ground instead of using pipes in concrete ducts. This third generation makes use of water of temperature below 100°C and is the most commonly existing generation nowadays.

The latest developments of district heating focus on using low temperatures, integrating renewable energy sources, and recovering waste heat. Unlike the first three district heating generations, this fourth generation operates with a supply temperature of 70°C (and lower) and meets the challenge of increasing energy efficiency in buildings by having lower heat losses in the district heating networks. Furthermore, it can operate in smarter energy systems and allows for the integration of new heat sources, such as waste heat from data centers (Schmidt et al., 2017).

Low temperature district heating operates with a supply line below 70°C and a return line below 40°C. The low temperature regimes are only suitable for new, low energy buildings or refurbished buildings. Low temperature district heating networks have lower distribution losses, make it easier to implement heat pumps, and allow for storage possibilities (Sayegh et al., 2019).

2.1.3 Heat pumps

Heat pumps convert low temperatures coming from heat sources into higher temperatures by using a heat transfer medium, called a refrigerant. The most common type of heat pump is the compression heat pump. A basic heat pump consists of four main components (visualized in Figure 2-2): A condenser (heat sink side), an evaporator (heat source side), an expansion valve, and a compressor.

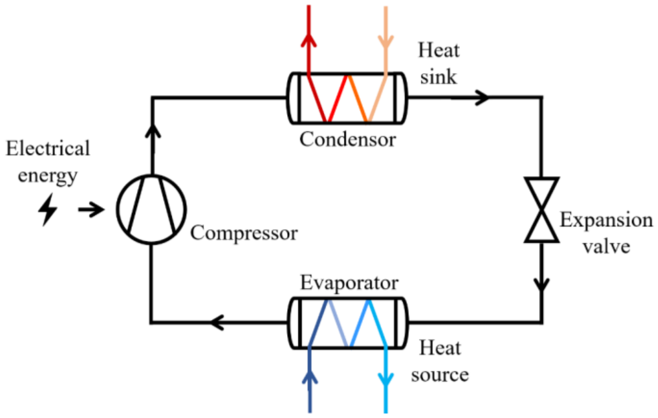

Figure 2-2: Components of a heat pump.

In the evaporator, low temperature heat is absorbed by the (liquid) refrigerant and vaporizes. The vaporized refrigerant enters the compressor in which the pressure and temperature of the vapor increases. It then flows to the condenser at a high temperature. Next, the (liquid) refrigerant flows through the expansion valve, and its pressure and temperature reduce again, after which it returns to the evaporator (Davies et al., 2015).

Coefficient of Performance

The operation of a heat pump requires additional electricity supply to drive the compressor, of which the amount of electricity depends on the *Coefficient of Performance (COP)*. For instance, a heat pump with a COP of 4 requires ¼ portion of electricity to heat ¾ portion of heat (with the same equivalence), meaning that when a data center rejects 90 MW of heat, 30 MW of electricity is necessary to be injected on the side of the compressor. The COP factor is related to the heat temperature in and outflow, given the following formula

$$\mathrm{COP}_{\mathrm{Carnot}} = \frac{T_{Hot}}{T_{Hot} - T_{Cold}} \qquad (1)$$

where $\mathrm{COP}_{\mathrm{Carnot}}$ is the theoretical COP achieved when dividing the high temperature heat T_{Hot} (coming out of the condenser) with the difference in temperature between T_{Hot} and T_{Cold}, where T_{Cold} is the low temperature heat (that flows into the evaporator). However, this formula depicts the Carnot COP, which is the ideal COP but not the actual COP (Zühlsdorf, B. et al., 2019). The actual COP is only a share of the Carnot COP, often with an efficiency between 50 and 60 percent. The COP value depends on multiple factors of which the temperature of the heat source and heat sink are considered the most important factors that influence the COP (Hesaraki et al., 2015). As the temperature difference of the heat source and the heat sink increases, the compressor pressure also increases, and hence the COP decreases. The *Seasonal Performance Factor* (SPF) is used to calculate the mean COP of a heat pump over an entire season. According to interviewee Prof. L. Itard from TU Delft (Appendix A1), it became clear that the Seasonal COP (SCOP) is often used as COP averaged over the whole heating season.

Refrigerants

Besides the COP, the efficiency of a heat pump also depends on the refrigerant used. ASHRAE 34 defines a refrigerant as *"the fluid used for heat transfer in a refrigerating system; the refrigerant absorbs heat and transfers it at a higher temperature and a higher pressure, usually with a phase change."* (ASHRAE, 2019). Refrigerants can be classified according to their chemical composition. There are synthetic refrigerants and natural refrigerants. Each refrigerant has its property (e.g., condensation pressure and critical temperature) and criteria related to safety (toxicity, flammability) and environment (Ozone Depletion Potential (ODP), Global Warming Potential (GWP), etc.). Their property and criteria make them suitable for a particular heat pump application. However, since no refrigerant scores best on all criteria, trade-offs must be made to select the most suitable refrigerant for the heat pump (Interview with prof. C.I. Ferreira, Appendix A4).

2.1.4 Storage

Despite their many advantages, heat pumps have an intermittent character, and their production is somewhat unpredictable, making it difficult to entirely rely on their output for a (flexible) district heating network. Therefore, thermal energy storage is often needed to tackle the challenge of supply/demand fluctuations by storing energy (Sayegh et al., 2019).

Thermal storage in district heating enables higher efficiency to be achieved by securing better supply and demand, thereby playing a vital role in achieving European climate targets. Storage reduces the energy loss created when supply and demand for heat are not in balance. Waste heat recovery from data centers is considered to have an imbalance due to its constant heat supply in contrast to day-night and seasonal demand fluctuations. Storage allows for more flexibility in the network by storing excess energy and cutting off peaks in energy demands (Sayegh et al., 2019). The two main storage types are short-term storage and seasonal storage. Short-term storage is often applied on a daily basis, enabling to cope with the day-night demand fluctuations. In contrast, seasonal storage is commonly used to capture over-supply of energy in summer to serve higher demand in winter. Energy stored in the storage tank can be extracted by heat pumps when demand is high, and the water temperature will be raised to a sufficient temperature (Yumrutas and Ünsal, 2012). Storage could decrease energy losses of the overall system, but storing energy does not work with a hundred percent efficiency. Storage losses depend on various factors, such as (ambient) temperatures, heat transfer, storage volume, and the tank (insulation, conductivity, etc.). Nevertheless, by minimizing storage losses, the advantages of storing energy could outcompete its drawbacks.

2.1.5 Data center as a heat source

Electricity in data centers is used for two primary purposes: To power the IT servers, which are used to store data from computer networks, and for cooling equipment to 'remove' the heat that is generated by the IT servers (Davies et al., 2015). Data centers are big consumers of electricity, and therefore, efficient systems are essential. Typically, data center waste heat is not utilized but wasted into the outside air. Nevertheless, there are various solutions to utilize waste heat, and integrating waste heat recovery into district heating networks is one of those solutions.

The main difficulty of data center waste heat integration in the district heating network lies in the fact that data center waste heat is of low quality, meaning that the heat is typically produced at a temperature of around 30°C, while mid-temperature district heating networks are around 70°C. However, it is possible to upgrade the waste heat with a heat pump. New developments in district heating networks are working towards lower district heating temperatures and heat pump improvements to upgrade low quality waste heat to temperatures suitable for district heating networks (Ebrahimi et al., 2014). This creates opportunities for low quality waste heat utilization from data centers.

Heating and cooling

Data center heat needs to be removed continuously to keep the temperature is below the recommended level. Typically, computer room air conditioners (CRACs) or computer room air handlers (CRAHs) are used as cooling methods, with the heat being rejected to an *electric chiller* (Davies et al., 2015). The chiller removes heat from the data center, which is being circulated through the heat exchanger to supply back chilled water. Air cooling systems require up to 40 percent of the electricity use of a data center, and alternative cooling approaches could reduce energy use for cooling purposes.

The integration of a heat pump to recover waste heat allows for additional cooling and can be combined with the existing cooling method. The heat pump will upgrade waste heat for district heating purposes, and returning chilled water from the evaporator can supply cooling for the data center. Combined configuration of a heat pump on one side and a chiller on the other side has the advantage that they can work independently and simultaneously. The waste heat recovery system acts as an additional source or back up for the standard cooler method and does not affect cooling operation (Davies et al., 2015).

High temperature heat pump (HTHP)

Existing heat pump technologies could upgrade heat of 30°C to the mid temperature of 70°C to supply heat into secondary distribution networks. However, upgrading heat to a higher temperature of 90°C and above would create new possibilities, such as providing over larger distances and integration into more extensive primary transport networks to be able to supply heat to more areas. Realizing this requires bigger temperature lifts and high temperature heat pumps (HTHPs) will be necessary. It becomes clear from the interview with L. Itard (Appendix A1) that upgrading low temperature heat to high temperature results in a very low COP, which is sometimes considered not to be efficient.

The main components of an HTHP are not different from a conventional heat pump. However, for achieving high compressor outlet temperatures, an HTHP operates with a high compressor discharge pressure and temperature. Furthermore, higher temperature lifts require more advanced heat pump configurations to reach high efficiencies (a high COP), and it is likely to use multi-stage compressors or two heat pumps in series. Besides the heat pump configuration, the selection of a suitable refrigerant for the heat pump is critical.

2.2 Economic concepts

To realize the utilization of data center waste heat, it has to be economically attractive for the data center, the heat provider, and the consumers (Wahlroos et al., 2017). An effective price model could incentivize heat providers as well as consumers to efficiently use the system and contribute to energy savings and CO_2 emission reduction.

2.2.1 Cost components

Expenditures can be categorized in capital expenditures (CapEx) and operational expenditures (OpEx). CapEx are (investments) payments to buy or maintain the fixed assets, whereas OpEx are ongoing expenses that are inherent to the operation of the system. The main CapEx costs are connection and distribution costs, whereas the operation & maintenance and costs of heat are part of OpEx (Persson and Werner, 2011). Cost components are depicted in Figure 2-3.

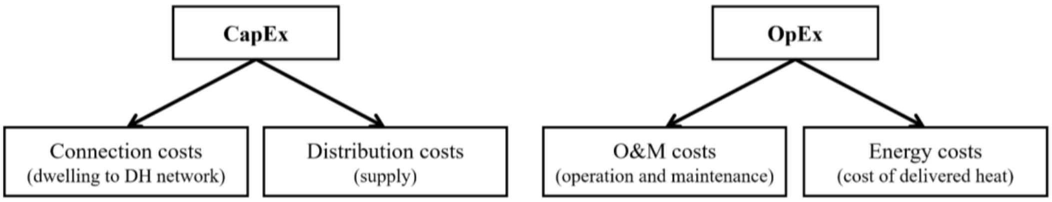

Figure 2-3: Cost components of a district heating network.

The value chain for a heat provider runs from the station where heat is transferred from the producer to the provider and then to the consumer’s building, making the provider responsible for the network and the supply of heat. The two main cost components for a heat provider are, therefore, the connection costs and heat supply (distribution) costs. Distribution costs are depending on the size of the project and the manner of implementation. Implementation in small areas can be economically unattractive while serving larger buildings or high density areas is more attractive. Costs can be relatively low when the network connections are made at the same time as the area is built but would be higher when the network is constructed in an already fully developed area (Rezaie and Rosen, 2012). Other cost components are operation and maintenance (O&M) costs and energy costs. Energy costs correspond to the costs for delivered heat and depend on the heat source. Specific tariff models are in place to determine how costs are covered by heat consumers.

2.2.2 Tariff model

Heat tariffs are used to charge heat consumers for the heat that is provided. Tariffs can be fixed but can also be variable. Often, heat tariffs consist of the following three components for consumers: 1. A fixed connection fee, 2. Fixed standing costs for distribution, and 3. Marginal energy unit costs (Li, 2015).

Financial risk for district heating operators is the large share of capital expenditures. Therefore, heat operators favor tariff models with a large percentage of fixed prices to reduce their risks. However, consumers would always prefer a larger share of variable prices so that upfront payments are minimized, and they pay for their actual use of heat. Furthermore, variable costs can be used as a financial incentive for consumers to save energy use (Verschuur, 2010). This creates a pricing dilemma, and the preferences of both the operators and consumers should be balanced.

2.2.3 Subsidies and taxes

Subsidies and taxes can be applied to give financial incentives and to stimulate the energy transition (Sneum and Sandberg, 2018).

SDE subsidies

In the Netherlands, the *SDE+* subsidy is introduced to stimulate sustainable energy production (PBL, 2020). From September 2020 onwards, the subsidy does not only focus on sustainable energy but also on CO_2 reduction, expanding to the SDE++ subsidy. Several conditions must be met to be granted the SDE++. CO_2 reducing technologies, such as waste heat and large-scale heat pumps, are eligible for the subsidy. This makes it attractive to recover data center waste heat. The SDE++ subsidy can be granted up until 6.000 full load operating hours (FLOH) of the heat pump(s). The following formula

$$\text{FLOH} = \frac{\text{Heat supplied by HPs (MWh)}}{\text{Max. heat supply by HPs (MW)}} \tag{2}$$

applies to determine the full load operating hours of one or more installed heat pumps. It is most advantageous to run the heat pump(s) as many hours as possible up until the limit of 6.000 FLOH.

Energy taxation

The Dutch energy taxation consists of three publicly available components: Energy tax, tax on sustainable energy, and VAT (Dutch government, n.a.; Rijksoverheid, n.a.).

1. Energy Tax (in Dutch: Energiebelasting) is a tax on electricity and natural gas. Dutch gas taxes are increasing over the years, and electricity taxes are decreasing. Those measurements are taken to make a switch from natural gas to (more sustainable) electric options more attractive.
2. Sustainable Energy Surcharge (in Dutch: Opslag Duurzame Energie (ODE)) is introduced in 2013 to stimulate investments in renewable energy production. ODE levies cover the SDE subsidies and are collected via annual energy bills.
3. Value added tax (VAT) (in Dutch: BTW), which is set on 21 percent.

2.2.4 Cost analysis

Typically, the marginal cost of waste heat is cheaper than most primary heat sources, making waste heat integration an attractive solution (Wahlroos et al., 2017). Irrespective of which financial indicator is used for decision-making. However, not only the costs for heat, but also investment costs, operational costs, and revenues, must be combined to allow for feasibility studies of implementing (new) district heating networks and sources. One way of doing this is by using *Levelized cost of heat* (LCOH) measurements. LCOH is the discounted sum of expenses, income, and energy calculated over the full lifetime of a project or technology. It indicates the costs of supplying heat (Sneum and Sandberg, 2018). Decision-making based on cost components can also be done through analyses of other financial indicators such as the Net Present Value (NPV) and the Return on Investments (ROI).

2.3 Environmental concepts

Besides possible financial incentives to move a more sustainable district heating network, also environmental benefits could be imposed. Environmental benefits of district heating in terms of greenhouse gas reductions are achieved by replacing less efficient heating technologies with a central system and by using cleaner energy forms for heating and cooling, e.g., waste heat.

2.3.1 Primary fossil energy use and CO_2 emissions

The level of emission reductions depends on a network's characteristics (Rezaie and Rosen, 2012). Different energy sources for district heating have their share and CO_2 emissions associated. For the carbon content for fossil fuels, the IPCC values are globally accepted as default and can be easily applied. However, there is no such default for electricity (Harmsen and Graus, 2013). Electricity, just like heat, is a secondary energy source generated by the conversion of primary sources. A country's electricity and heat production are not coming from one single primary source, but rather from multiple sources.

The mix of energy sources is different for every country, and therefore, also the primary fossil energy use and CO_2 emissions associated with electricity and heat consumption are different.

- The primary fossil energy use of a country is expressed in the *Primary Energy Factor* (PEF), indicating how much primary fossil energy is used to generate a unit of heat (RVO, 2019). The more renewable energy there is in a country's energy mix, the lower the PEF will be.
- A standard method to calculate CO_2 emissions is the *integral method*, calculating the average CO_2 intensity of a power mix by using the share of each fuel (RVO, 2019). However, it becomes more complicated when including plants that produce not only electricity but also heat: CHP plants typically produce heat that is fed into the district heating network and electricity that is fed into the national grid. When producing heat in a CHP plant, heat production typically leads to reduced electricity production (Harmelink, 2017). The *Power Loss Factor* (PLF) makes it possible to compare CO_2 intensities irrespective of heat generation. Typically, the PLF is between 0,15 and 0,20 (Graus & Worrell, 2011).

2.3.2 Carbon emission price instruments

Besides taxes and subsidies, two additional price instruments can be used to increase the market momentum for renewable energy and reduce carbon emissions: *Guarantee of Origin* and *carbon pricing*:

Guarantee of Origin

Sustainable electricity supply to drive the heat pump would characterize the waste heat from data centers as ‘sustainable heat’. However, this requires both the data center and the energy company, with the heat pump in belonging, to use renewable energy sources. Since the power mix in the Netherlands is far for 100% green, both parties rely on a regulatory instrument, the Guarantee of Origin (GO). A GO is a green label that ensures that one MWh of electricity is produced from renewable sources. Electricity can be labeled as ‘green’ when a sufficient number of GOs is bought (Directive 2001/77/EC).

Carbon pricing

Carbon pricing is an instrument used to create a financial incentive to drive investments in cleaner energy options. Various price instruments can be used to price carbon, depending on a country’s environmental and economic circumstances. There are two main types of carbon pricing:

- *Emissions trading systems* (ETS) allow industries with low emissions to sell their extra allowance to the ones that emit more, thereby determining a market price for CO_2 emissions with a cap to ensure reduced emissions. The EU ETS price is set on 22 euro/tonne CO_2 (PBL, 2019).
- *Carbon taxing* works with a pre-defined tax rate on CO_2 emissions or the carbon content of fossil fuels. ETS works with a market price and required emission reductions, while carbon taxing works with a pre-defined carbon price but without required levels of emissions reduction (CE Delft, 2018).

For both ETS and carbon taxing, the World Bank has set the minimal price range needed in 2020 to be consistent with achieving the Paris Agreement targets between 40 and 80 USD per tonne CO_2e (World Bank Group, 2019).

2.4 Institutional concepts

Each countries’ district heating system is unique, e.g., in terms of network temperatures, cost components, energy mix, and subsidies, and taxes. Those factors, which characterize and distinguish district heating systems, are closely related to the institutional components that are inherent to the regulations and policies of a country.

2.4.1 EU heating policies

Fifty percent of the EU’s annual energy consumption is devoted to buildings’ and industries’ heating and cooling, and renewable energy accounts only for 18 percent of the heat and cooling consumption. The EU Commission states that this sector must substantially reduce its energy consumption and cut its fossil fuel use. The EU’s strategy includes increasing renewable energy use by boosting energy efficiency in buildings and by the integration of electricity and district heating systems, and encourage waste heat recovery (EC, 2016). Three directives set energy targets: the Renewable Energy Directive, the Energy Efficiency Directive, and the Energy Performance of Buildings Directive (Council Directive 2012/27/EU); EC, 2019; Directive 2010/31/EU):

- Renewable Energy Directive sets rules for the EU to achieve its renewable energy sources target of 32 percent for 2030. Previously, the goal was established on 20 percent renewables by 2020. In the national renewable energy action plans, EU countries set out how they plan to meet the targets.

- Energy Efficiency Directive has the main EU target of energy efficiency of at least 32.5 percent, meaning; a maximum of 1128 Mtoe of primary energy and 846 Mtoe of final energy. Countries should take measures to implement efficient district heating.
- Energy Performance of Buildings Directive (EPBD) requires all new buildings to be a ‘nearly Zero Energy Building’ (nZEB) (in Dutch: Bijna Energie Neutral Gebouw (BENG)) as of December 31st, 2020, to promote improvements in the energy performance of buildings. In short, an nZEB is a building with very high energy performance, requiring a very low amount of energy (~zero), and with a substantial energy share coming from local and renewable sources (Directive 2010/31/EU).

All of the abovementioned directives encourage EU countries to use more sustainable heating options.

2.4.2 Network regulation and tariff

In contrast to the electricity and gas sector, in the district heating sector, there is often no competition amongst suppliers since heating networks are not connected. Consumers can, therefore, not choose which supplier network they are connected to (Wissner, 2014). Due to this monopolistic nature, price elasticity is limited in district heating markets, and development is minimized (Klein, 1999).

There are two types of district heating markets: Regulated and deregulated markets. In a regulated market, district heating companies cannot compete with other heating solutions by changing their prices. A cost-plus pricing method is commonly used in a regulated market, where the price is calculated as the sum of the costs to cover production, plus a profit for the district heating company. Cost-plus pricing is simple and easy to administrate, but price components are often based on historical data, creating possible uncertainties. Furthermore, subsidization is often needed to make district heating competitive in its market (Li, 2015).

In a deregulated market, marginal-cost pricing applies. The market price is determined by heat supply and demand matches. The district heating price is based on the marginal costs for the supplier, which motivates to reduce costs. However, the monopolistic nature of district heating systems makes it impossible to create optimal price allocations. A market in which marginal-cost pricing applies is more complicated than a market with cost-based pricing but allows for better price prediction (Li, 2015).

2.4.3 Degree of market opening

Several possible scenarios can be identified for the degree of market opening in a district heating market. The degrees of market opening in order of increased competition are as follows: wheeling, single buyer, TPA, wholesale market competition, and competition in the retail market (displayed in Figure 2-4).

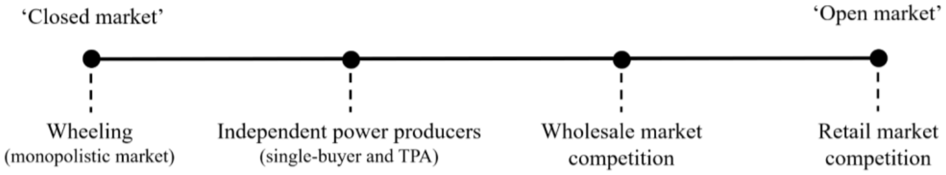

Figure 2-4: Different degrees of market opening from closed to open market.

Wheeling can be considered as a market without any competition. One party, a *monopoly,* is responsible for production, transportation, as well as distribution. Consumers of the networks cannot switch to another party.

Permitting other producers to participate in the district heating network allows for competition in the market. Furthermore, it creates more flexibility in the system, and strategic decisions can be made (Klein, 1999). This means that more waste heat and renewable energy sources could be used, imposing environmental benefits. However, third party access (TPA) might not bring benefits in a situation where a network already comprises a large share of renewable heat or waste heat (Patronen et al., 2017). Furthermore, TPA requires substantial changes in terms of regulations and ownership throughout the whole value chain. If such decomposition results in cost increases in the network, district heating could lose its competitiveness.

Two forms of TPA are *negotiated* TPA and *regulated* TPA. Negotiated TPA refers to the situation where network owners negotiate about network access with (third party) heat producers. In contrast, regulated TPA implies that the network owner is obliged to allow full access to the network (Söderholm & Wårell, 2011). With negotiated TPA, conditions for access to the system are determined afterward instead of in advance, which is the case for regulated TPA. Another form is the *single buyer* market that allows multiple producers to be in one market. Producers sell to one power purchasing company, which sells it to a distribution company or is responsible for the distribution itself (Correljé and De Vries, 2008). It is not very different from negotiated TPA, but in a single buyer market, the new supplier does not sell to the final consumer, but the single buyer does (Söderholm & Wårell, 2011). All three forms include a producer market but not a retail market.

Removing the single buyer would create a *wholesale market* in which there is wholesale competition between producers. The final step of increasing competition would be to create competition in the retail market, which is how the Dutch electricity market operates. For district heating, full network access in the case of competition in the retail market is unrealistic due to its local and isolated characteristics.

2.4.4 Ownership

Ownership of a district heating network can be public, private, or a public-private combination. Public ownership was found to be a solution for the policy dilemma of (unregulated) natural monopolies. Public ownership imposes secure forms of regulation and is common in the absence of a financial incentive, which could be beneficial for achieving non-financial goals (Depoorter, 1999). However, public ownership lacks incentives to reduce costs and is, therefore, not economically efficient and innovative (Correljé and De Vries, 2008). Opposed to public ownership, private ownership does operate more efficiently with lower costs and introduces a form of price competition, which could result in higher consumer prices. Also, private ownership requires a form of regulation to ensure the security of supply. A public-private combination could benefit from the advantages of the two separate ownership models. For instance, the public owner could function as a price controller for private owners that try to maximize profits.

2.5 The Netherlands and Nordic countries

A detailed explanation of the district heating concepts allows for a proper comparison of different district heating markets. Typically, much more than other European countries, heating plays an important role in Nordic countries, and district heating has a significant position. Nordic countries usually use high shares of local renewable energy sources for district heating. Norway has a large share of hydropower resources, in Finland and Sweden biomass is used, and Denmark uses its gas resources. District heating markets in the Nordics are also characterized as more liberal and open, where consumers have stronger positions. Furthermore, their national energy targets are ambitious, and cutting CO_2 emissions and using clean energy is actively promoted by implementing high taxes for fossil fuels (Patronen et al., 2017).

Nordic countries' district heating systems have much in common, but national energy targets, regulations, and price models are country-specific. In this section, the district heating situation in the Netherlands, Sweden, and Denmark are described. Sweden and Denmark are selected because of their matured but different heat markets. Furthermore, Sweden and Denmark are found the most interesting to be explained because Vattenfall is actively operating in those countries.

2.5.1 The Netherlands

District heating represents a small portion of the Dutch heat market, and about five percent of the population is connected to district heating networks (PwC, 2015). District heating networks are owned by energy supply companies, municipalities, small firms, and housing associations. Some large companies (of which Vattenfall is one of them) are dominating heat generation and also manage the supply of heat. However, the Ministry of Economic Affairs pledged for open networks in the Netherlands where consumers can choose between suppliers.

Yet, the district heating market is regulated, and consumers cannot switch from networks. Therefore, the Dutch Heat Act protects consumers that are unable to switch heat suppliers against being charged too high prices. Protection is done by setting a price cap according to the Not-More-Than-Otherwise (in Dutch: Niet-Meer-Dan-Anders (NMDA) principle that is based on the cost of the individual gas-boiler alternative.

Incentives for district heating are also driven by the governmental decision to stop natural gas production in Groningen (Oxford energy, 2019). The Dutch government wants to introduce a minimum price for carbon emissions. This measure is linked to the EU ETS, and the minimum carbon price is set on €12.30 per tonne CO_2 in 2020 (Ramstein et al., 2019; Government.nl, 2019).

The *nearly Zero Energy Building (nZEB)* standard describes how the country is going to comply with the Energy Directives, as described earlier. The energy performances of those BENG requirements are determined by three individual components: 1. The maximum energy needs (in kWh per m^2 per year), 2. The maximum primary fossil energy use (also in kWh per m^2 per year), and 3. The minimum amount of energy from renewable sources (50%) (RVO, n.a.).

At first, residual heat from the industry did not count towards reaching the 50 percent minimum for renewable energy. However, in January 2019, a revision on the classification of residual heat was done, and the Dutch Ministry reports that residual heat will, in some cases, count as renewable energy. Data center waste heat was thereby classified as a renewable energy source (DDA, 2019). However, as opposed to situations in countries such as Sweden, Dutch data centers offer their residual heat free of charge.

2.5.2 Sweden

Initially, Swedish municipalities were dominating the district heating networks in Sweden. This can be explained by the fact that they could deal with long-term financial deals, as municipal taxes could finance the systems, and risks were minimized (Werner 2017a). Deregulation of the electricity market in 1996 has led to ownership changes, and currently, over two hundred district heating companies are operating in Sweden. Although municipality or state-owned energy companies run most of them, the significant share in district heating volume is provided by larger private companies, including Fortum Värme, E.ON, and also Vattenfall (Patronen et al., 2017; Åberg et al., 2016; Magnusson, 2016).

The regulatory changes in 1996 caused the removal of the original non-profit municipal pricing and led to an increase in market-based pricing (versus cost-based pricing), resulting in an unforeseen price increase in the early 2000s (Åberg et al., 2016; Werner 2017b). Price increases induced the need for national pricing principles and district heating legislations. In 2013, a price agreement called 'Prisdialogen' was set between district heating companies and consumers. This agreement provides fair price principles and requires price forecasts for the following two years. Furthermore, the Swedish District Heating Act imposes standards required for companies on price transparency. Those schemes are successful in Sweden, and it requires no price regulation of district heating companies (Patronen et al., 2017).

In Sweden, district heating operators can negotiate TPA access, and when they can prove that TPA would damage the network, they can refuse TPA. There are some examples of open district heating networks where supermarkets and datacenters are selling excess heat to district heating companies at market prices (Brange, 2016).

Carbon pricing is higher in Sweden than in the rest of Europe and stimulates the utilization of district heating. Swedish carbon pricing is based on ETS, energy taxes, and carbon taxes and are higher than stated in the EU Energy tax directives. The energy tax has been there since the 1930s, while the carbon tax was first introduced in 1991. With a carbon tax of $127,- per tonne CO_2, Sweden is one of the few countries worldwide with a carbon tax high above the carbon price ranges for achieving the Paris Agreement goals (Ramstein et al., 2019). Carbon taxation is also the reason for prioritizing other heat supplies over CHP plants since it neglects the CHP heat recovery and taxes the heat output (Werner, 2017a).

In contrast to the case in the Netherlands, in Sweden, mandatory connection to a network is not obliged. This means that district heat is competing with other heat supply sources. However, other incentives, such as quality and environmental impacts, drive consumers to connect to a network, and district heating is currently the market leader in Sweden with a share of 55 percent (Werner, 2017a; Lygnerud, 2018).

Swedish district heating companies are investing in the interconnection between networks in cities and towns. This encourages collaborations, and it is usual practice in Sweden to utilize residual heat in district heating networks. In the last decade, annual waste heat utilization accounted for 9 percent of the total heat production in Sweden (Lygnerud, 2018). Suppliers are incentivized to engage because of the revenues from the heat that would otherwise have been lost.

Best practice – Fortum Värme

In Sweden, energy company Fortum Värme has opened the district heating network to any party that wants to feed in residual heat (Fortum Värme, 2015). A pilot project example is data center Bahnhof Pionen in Stockholm that went from conventional cooling equipment to two heat pumps in series for cooling purposes. The data center is connected to the district heating network and sells its excess heat. This is done through an hourly market price rate at which Fortum Värme purchases heat. The price is depending on the outdoor temperature, the demand, and the available capacity.

2.5.3 Denmark

Already during the 1920s, collective district heating networks were developed with waste heat from local electricity productions (Grohnheit and Mortensen, 2013). In Denmark, district heating also has a market share of more than 60 percent for space and water heating (Chittum and Ostergaard, 2014). Whereas the district heating network in Sweden is deregulated, the Danish network is regulated in a way that consumers are obligated to connect to a network, and consumers will still need to pay the subscription fee when disconnecting (Söderholm & Wårrel, 2011).

In contrast to the case in the Netherlands, where end-user tariffs are regulated, in Denmark, the profits made by district heating operators are capped (PwC, 2015). The cost-plus principle is applied on a non-profit basis where consumers are charged to cover the exact costs for the operators (Söderholm & Wårrel, 2011; Burger et al., 2019). Denmark has full price transparency, with heat tariffs set annually, and voluntary benchmarking of prices has been introduced by the Danish Energy Regulatory Authority (DERA) to support this.

District heating is municipality-owned, but most are cooperatively-owned by municipalities, utilities, and consumers, in several combinations (Grohnheit and Mortensen, 2013). Regardless of the ownership structure, third parties can sell their heat to the heat suppliers. TPA is common in Denmark, probably due to the maturity of the network, where infrastructures have already been repaid. Network operators can buy from different heat suppliers, which increases competition.

With a carbon tax of $26,- per tonne CO_2, Denmark is just above the carbon price ranges for achieving the Paris Agreement goals (Ramstein et al., 2019). Due to the Supply Act of 1976, many power plants have been converted to CHP, so Danish electricity is largely cogenerated with heat. It is therefore arguable whether the carbon taxes have a significant effect in Denmark because decarbonizing could result in reduced revenues for district heating operations (Chittum and Ostergaard, 2014)

The Danish success factor related to heat is due to the active role in the identification of resources (Chittum and Ostergaard, 2014). More than half of the heat in Denmark is coming from renewable sources, and biomass in particular, whereas 9 percent is coming from waste combustion. Residual heat is used when there is a business case, i.e., when it proves financial viability, and local decision-makers have control over approving such projects.

2.5.4 Comparing district heating markets

Institutional design in terms of regulations, pricing structure, degree of market opening, third party access, and ownership are described for the Netherlands, Sweden, and Denmark. Table 2-1 outlines an overview of those institutional characteristics per country. Knowledge about district heating markets in other countries may help to explore regulatory alternatives and to assess what certain market choices would mean for the case of the Netherlands.

When having explored the characteristics of heat regulations in the Netherlands, Sweden, and Denmark, it becomes clear that the level of regulation influences the market on different aspects. Deregulation of prices can negatively affect consumers, whereas price regulation allows for consumer protection. However, when imposing standards like Sweden has done by implementing price agreements and the Swedish District Heating Act, pricing can become more transparent. Too much regulation can result in an inflexible price setting and might disincentives market entries and innovations in the system. The degree of market opening, therefore, goes hand-in-hand with price regulations.

In the district heating sector, competition on the production side is limited due to the local dependence of the sources. Competition in supply only works when there is competition in production, and suppliers can independently purchase heat. Therefore, in most countries, district heating suppliers do not compete with each other (PwC, 2015). However, competition can exist in the heat sector (e.g., district heating versus heating by using natural gas). Consumers know that district heating owners act in a competitive market, and satisfying consumers is necessary to stay competitive. Consumers can, therefore, demand certain heat quality, security, efficiency, and price transparency (Lygnerud, 2018). This can be seen in Denmark, where third party access and the competitive nature of district heating is supported by price transparency and even voluntary benchmarking of prices. Whether or not the district heating market is regulated (Denmark) or deregulated (Sweden), price agreements to support price transparency have provided fruitful outcomes.

	Netherlands	**Sweden**	**Denmark**
Regulation	Regulated	Deregulated	Regulated
Pricing structure	Fixed price based on gas price, and variable consumption price. A price cap is based on the No-More-Than-Otherwise principle.	No price regulation. Swedish District Heating Act imposes standards required for companies on price transparency	The cost-plus principle is applied, and profits are capped. Heat tariffs are set annually.
TPA	Negotiated access for heat producers but not for suppliers	TPA is on the agenda, and district heating operators can negotiate access	TPA is common, and access is guaranteed
Ownership	Owned by energy supply companies, municipalities, small firms, and housing associations.	Was owned by municipalities but is now public-private ownership combination.	Municipality owned, but most are cooperatively-owned by consumers, municipalities, utilities, etc.

Table 2-1: Regulatory characteristics of the Netherlands, Sweden, and Denmark.

Besides the regulatory characteristics to determine market arrangements for countries, also less apparent factors play a role in how a market model is functioning. This has to do with the policy drivers and ideologies of a country that comprise ethical ideas and decisions of how a country should be run. Interviewee Prof. A. Correljé (Appendix A2) says that the ideology of a country is rooted in the norms, values, and ideas of a country’s culture over many years. Ideologies could be social, political, environmental, etc. An excellent example of where ideologies foster district heating developments is happening in Denmark, where the tradition of societal cooperation and local empowerment supports district heating initiatives through power-sharing and local decision-making (Chittum and Ostergaard, 2014). Collaboration between parties can create opportunities as risks can be dispersed but the functionality of cooperation might only work when a country's ideologies support it (Magnusson, 2016).

2.6 Conclusion on district heating concepts

Understanding the concepts of district heating is important to gain insight into the district heating situation in the Netherlands but also other countries. District heating includes not only technical concepts but also economic, environmental, and institutional concepts. The latest developments of district heating focus on using low temperatures, integrating renewable energy sources, and recovering waste heat. Data center waste heat can be recovered and upgraded by a heat pump to a certain temperature level so that it can be integrated into the district heating network. The economic viability of such integration depends on the corresponding capital and operational expenditures, as well as taxes and subsidies. Related to the environmental concept, the primary fossil energy use and the associated emissions are depending on a country's power mix. Besides a country's energy sources for district heating, countries are also characterized by institutional concepts such as network regulations and the degree of market opening.

A description of institutional arrangements made it possible to compare the Dutch district heating market with other countries. First of all, from the comparison with Sweden and Denmark, it became clear that level of regulation influences the market on different aspects, e.g. the degree of market opening is closely connected to price regulations. In Sweden, there is no regulation on pricing, whereas in Denmark, profits are capped, and the cost-plus principle is applied. Furthermore, competition between district heating networks is limited due to geographic dependencies, but competition in the heat market induces enhancements to satisfy consumers. Besides the apparent drivers of district heating markets, also a country's policies and ideologies influence district heating integration.

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3 System Engineering Approach

In this chapter, the process of designing a district heating project will be systematically defined by using the concepts of district heating that were described in Chapter 2. In Section 3.1, the development process of a district heating project will be outlined, after which its complexity will be explained in Section 3.2. A clear approach is required to understand all components and their interaction. The district heating concepts are used as input for the system engineering approach in Section 3.3. This approach not only helps to understand a district heating network in general but can also be applied to a specific case. In Section 3.4, the approach will be used to gain clear insights into data center integration into the network of Amsterdam. Limitations to the system engineering approach will be explored in Section 3.5.

3.1 System engineering context

3.1.1 Development phases

The development of a district heating network comprises of many process actions that could be categorized in the phases of 1. Heat mapping, 2. Feasibility, 3. Development, 4. Commercialization, 5. Construction, and 6. Operation. During the heat mapping phase, an identification of a potential heat network is made. In the feasibility phase, identified opportunities become conceptual and are studied. Next, when the opportunities are feasible, concept development turns the initial idea into an approved business case. Next, the focus becomes market-oriented, contracts are negotiated, and stakeholders are convinced. When everything is settled, the process moves to the construction and operation phases.

In the feasibility phase, an analysis is done to ascertain the likelihood of a successful project outcome. All relevant concepts are taken into account when assessing feasible solutions, including technical, economic, and institutional concepts, as well as stakeholders. Feasibility studies on a complex system such as a district heating system can become very comprehensive, and a clear approach is necessary to understand and link all relevant concepts. Therefore, a system engineering approach is developed to support this phase. A visualization of development phases and the integration of the system engineering approach is given in Figure 3-1.

3.1.2 Purpose of the approach

The ultimate purpose of the development of a system engineering approach for this report is to find and test opportunities to integrate data center waste heat into the district heating network of Amsterdam. The many concepts of a district heating network or any other network are difficult to understand in an isolated manner. Therefore, a network layered scheme will help to create a clear understanding of the aspects as a whole, in one network. The approach could offer support in the feasibility phase before making development decisions for a district heating network case.

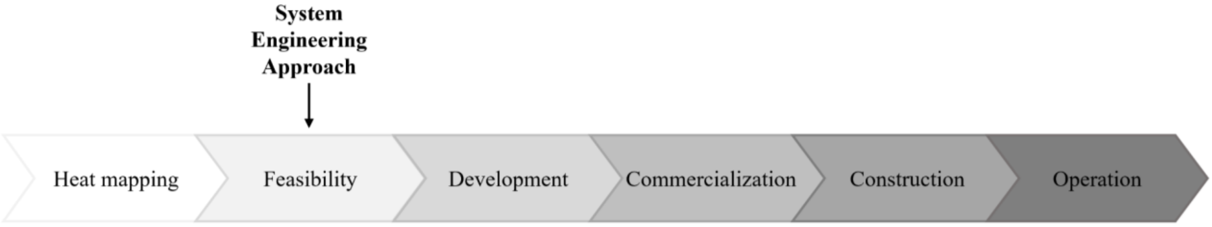

Figure 3-1: District heating development phases and system engineering approach integration.

3.2 Complex system

3.2.1 Deconstruction into layers

Designing large scale systems such as energy systems but also transport systems, water management systems, and information systems, all require multi-level perspectives (Koppenjan and Groenwegen, 2005; Herder et al., 2008). Comprehension of the different perspectives can be better understood by some sort of categorization. A commonly used approach is developed by APERC, in which four dimensions of energy security complexity are addressed: Availability, affordability, accessibility, and acceptability (APERC, 2007). In this research, those four A's are translated to district heating system concepts as theoretically explained in Chapter 2:

- Availability corresponds to the technical concepts.
- Affordability to the economic concepts.
- Accessibility to the institutional concepts.
- Acceptability is related to social and environmental concepts.

The different concepts can be better understood by deconstructing a system into different levels, which are referred to as *layers*. The layers are connected and therefore depend on each other, meaning that the system can simply not be understood by studying the layers in isolation (Herder et al., 2008). Furthermore, each layer consists of multiple components that are also connected.

3.2.2 Complexity factors

A network on itself can be complex, but *interdependencies*, *objectives and constraints*, and the *development* of systems are factors that add up to the complexity.

<u>Layer and component interdependencies</u>

Layers are connected and interdependent, but also components within layers are connected to each other and to components in other layers, resulting in a high dependency across all layers. Therefore, it is likely that if one component in the network is not functioning as it is supposed to, the whole system will not function as supposed. The more interdependences there are in a network, the more complex a network will be. In Section 3.3, the network's layers and interdependencies become apparent.

<u>System objectives and constraints</u>

Systems have objectives and constraints that can be transformed in requirements to be fulfilled. The more objectives and constraints there are, the more complex the system becomes, and the more difficult it will be to come to the best solution. Dealing with conflicting objectives is often inevitable in a complex system where constraints create a particular design space, and multiple stakeholders all have their wishes and demands. Trade-offs will often have to be made to reach certain optimality (Herder et al., 2008; De Bruijn & Herder, 2009). Setting Key Performance Indicators (KPIs) can help to measure progress towards achieving objectives.

<u>Network development</u>

Another complexity is the dynamic nature of networks. A network changes over time, deliberately or non-deliberately (De Bruijn & Herder, 2009). Components within the network can follow dynamic patterns, and complexity increases when dynamic patterns do not align. Possible changes in the network requires the need to explore and understand future developments within a system.

3.3 Network layers

As explained in the previous section, the district heating system is deconstructed into layers, originating from the four A’s and corresponding to the theoretical concepts from Chapter 2: The technical layer, economic layer, institutional layer, and the social and environmental layer. Components in each of those layers are corresponding to the physical components of a district heating network, which form a fundamental physical layer. Figure 3-2 displays the network layers and their interaction. Each layer is described below and discussed in detail for the district heating in Amsterdam in Section 3.4.

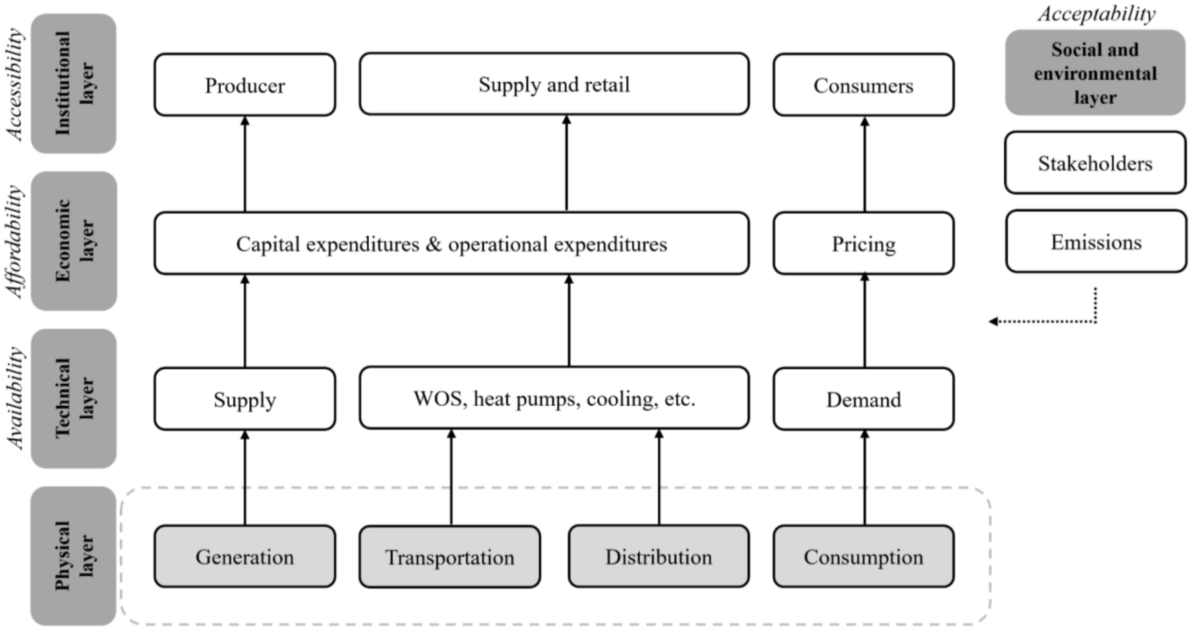

Figure 3-2: Network layered scheme with district heating components.

3.3.1 Physical layer

The physical layer is the fundamental layer of the district heating network and consists of generation, transportation (primary network), distribution (secondary network), and, eventually, consumption. In contrast to the electricity network, for district heating networks, interconnections between production and distribution are stronger (Söderholm & Wårrel, 2011). Transportation of heat over long distances is not feasible due to transportation losses. Therefore, district heating networks remain local or regional, in contrast to the nation-wide electricity and gas networks (PwC, 2015). There are limited possibilities to change the basic design of the physical layer (Herder et al., 2008).

3.3.2 Technical layer

The technical layer of a district heating network is much more detailed than the physical layer. It consists of two highly interconnected components on both sides of the chain; the heat supply component on one end and heat demand on the other end. Due to the dynamics in heat demand and heat supply, it is sometimes difficult to match those two, and other heat sources can be integrated to create more flexibility. When heat supply and demand are estimated, the next task is to select the components that interact between supply and demand (Ajah et al., 2007). Specification of temperature ranges of the network is required (corresponding to the COP) to make decisions on the implementation of the heat upgrading unit, i.e., the heat pump. Additionally, heat exchangers, boilers, and storage tanks might be necessary to enhance the functionality of the network. The technical layer refers to the *availability* of the heat source and network to provide heat when demanded.

3.3.3 Economic layer

Apart from the technical layer, the economic layer is also studied and takes into account capital and operational expenditures as well as pricing components for end users. Every system includes both capital and operational expenditures, and the ratio between those expenditures can differ. Costs for generated heat depend on the operating hours and the production unit, and every heat source has its associated costs. Expenses are covered by consumers of the network, in which tariffs can be (partly) fixed or variable and often depend on the type of consumer. Arrangements in the institutional layer (e.g., ownership of network components, rules, etc.) can affect the economic layer. Expenditures directly relate to the *affordability* of the network, and too high expenditures could indicate difficulties in the realization of a network.

3.3.4 Institutional layer

The institutional layer is different from the technical and economic layer in a way that it includes components that cannot be given a value. According to Koppenjan and Groenwegen (2005, p. 245), “Institutions take care of accountability, distributions and create common orientations and values, which constrain and shape the behavior of parties involved, thus improving the efficient functioning of the system and its outcomes.” The institutional layer includes regulations and policies that influence the producer, the supply and retail, and the consumers. Through ownership, the type of regulation, the degree of market opening, and the pricing structure, the institutional layer places requirements and constraints upon other layers in the system. Institutional arrangements can (or cannot) enhance the *accessibility* of the district heating system and the integration of new heat sources in the network.

3.3.5 Social and environmental layer

The social and environmental concepts are described as an external layer that impacts the other layers. Two most evident components related to the *acceptability* of a network are stakeholders that play a role in the system, and the environmental impact of the system, described in terms of emissions.

Stakeholders

In a complex system, multiple stakeholders are involved. A stakeholder could be anyone who is involved in the network or affected by it. When designing a complex network, stakeholder engagement will inevitably be part of the coordination process and enhances acceptability. Poor stakeholder engagement can result in negative consequences, such as the act of free-riding, when stakeholders use the system for their benefit without contributing to the required actions (Koppenjan and Groenwegen, 2005). Producers, suppliers, retailers, and consumers are directly involved in the institutional layer components, where arrangements regulate the relations between stakeholders (Koppenjan and Groenwegen, 2005). Other stakeholders, such as governmental institutions, policymakers, and market authorities, are involved in different layers across the network.

Emissions

Dutch district heating suppliers are obliged to provide information on four sustainability factors: 1) CO_2 emissions per unit of delivered heat, 2) primary fossil energy use per unit of delivered heat, 3) share of renewable energy sources, and 4) share of waste heat (RVO, 2019). The environmental impact depends on network characteristics and the energy source. Different energy sources for district heating have their share, and CO_2 emissions associated, and uniform calculation methods are necessary to compare those. Environmental benefits in terms of CO_2 emissions reduction can be achieved by integrating cleaner energy sources and can result in increased acceptability.

3.4 District heating in Amsterdam

The network layers are discussed in more detail for the case of integrating data center waste heat in Amsterdam. This gives an understanding of components that must be taken into account when studying the feasibility of a district heating project in terms of availability, affordability, accessibility, and acceptability. Information and data within this section support the set-up of a (pilot) project for an area in Amsterdam, as is done for the Kantorenstrook Amstel III area in Chapter 4.

3.4.1 Physical layer

Today, the primary source of heat in the Netherlands is waste heat from power plants or heat from CHP units. However, this contribution is expected to decrease due to the increase in waste incinerators use. Natural gas will, therefore, be replaced by biomass/biogas (Niessink and Rösler, 2015). In Amsterdam, two main facilities feed heat into the high temperature transport line and are responsible for the largest share of heat in the city: Vattenfall's Diemen CCGT CHP plant in Diemen is supplying the network in the Southern and Eastern part of Amsterdam with natural gas as its primary energy source. AEB Amsterdam is providing the network in the Western and Northern parts with waste as a primary energy source. In Figure 3-3 (left), a map of the heat network of Amsterdam is shown.

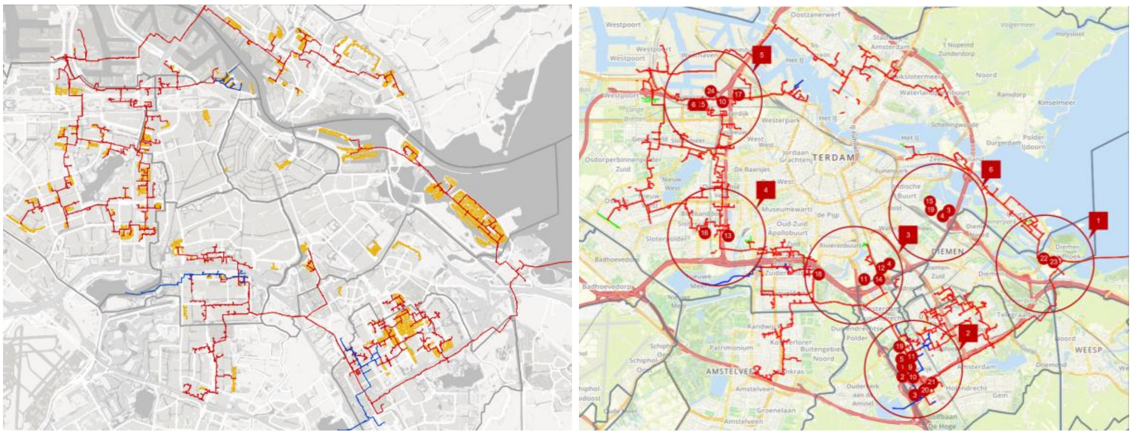

Figure 3-3: District heating network of Amsterdam (left) and data center clusters (right).

Data center opportunities

From the 34 data centers in Amsterdam owned by 20 data center businesses (RVO, 2018), Vattenfall has identified 24 data centers close to the physical district heating network of Amsterdam in six clusters (see Figure 3-3 (right)). Each data center is categorized based on its integration potential for the district heating network of Vattenfall (Vattenfall Heat NL, 2020a). Three interesting categories are:

- DC integration to connect directly to an area in the development
- DC integration to meet growth and CO_2-roadmap
- DC integration to help remove hydraulic restrictions

3.4.2 Technical layer

Integrating waste heat from data centers in Amsterdam provides a suitable additional heat source that could lower the primary energy use and reduce emissions by providing heat at a fairly constant rate. Figure 3-4 shows the components within the technical layer. There are four main categories to integrate data center waste heat into a district heating network: In the primary (transport) supply line, in the primary (transport) return line, in the secondary (distribution) supply line, and the secondary (distribution) return line. Generally, low temperature industrial waste heat from the data center flows through a heat pump in which the temperature is raised to a required temperature level for the supply into one of the four network lines. Feasibility of each category for a particular project in Amsterdam (or elsewhere) depends on characteristics of the network and components. A primary heat source can cover the remaining heat demand and could function as a backup. The WOS exchanges heat from the primary network to the secondary network.

The network temperatures in Amsterdam are 115° - 60°C for the primary transport network (supply-return) and 75° - 45°C for the secondary distribution network. Waste heat from data centers is typical of a temperature of 30°C, and heat needs to be upgraded to supply into the district heating network. When supplying data center waste heat into the secondary supply line, the COP will be around 4. Supplying into the primary network requires a higher temperature lift and the need for HTHPs or advanced heat pump configurations.

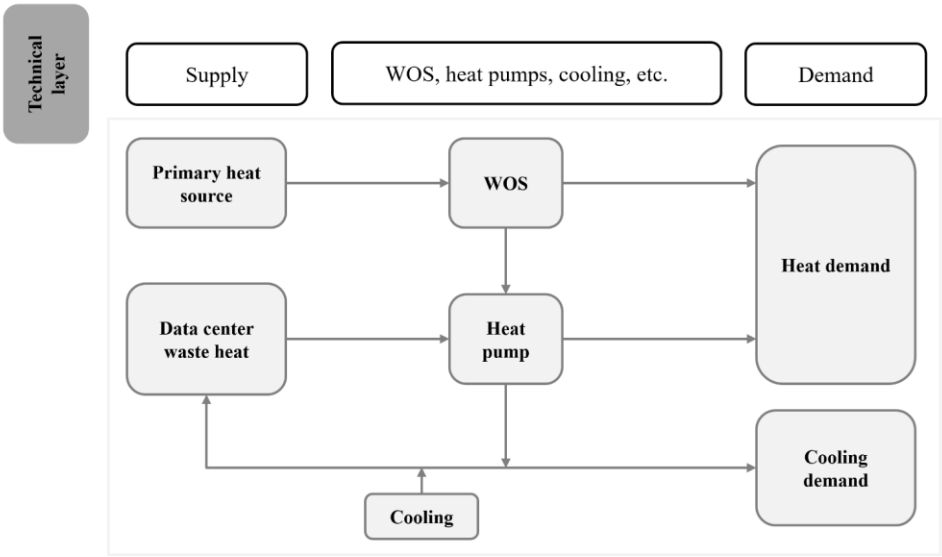

Figure 3-4: Components within the technical layer of a district heating system.

3.4.3 Economic layer

The economic layer includes capital and operational expenditures (CapEx and OpEx) and a pricing component for end-users. CapEx consist of connection costs and distribution costs, which are covered by a one-time fee for the connection and fixed tariffs for distribution of heat for space heating and tap water. OpEx include operation & maintenance costs and energy costs. O&M costs for the metering installation are covering by a fixed annual tariff, and energy costs are covered by a price per unit for delivered heat. Figure 3-5 shows all cost and pricing components within the economic layer.

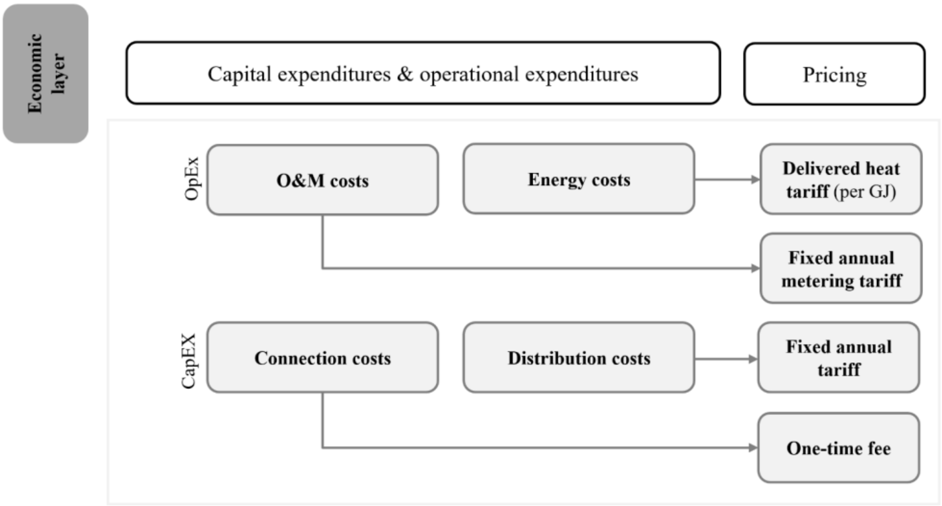

Figure 3-5: Components within the economic layer of a district heating system.

<u>Consumer tariffs</u>

In the Netherlands, the maximum tariffs of district heating for small consumers (max. connection 100 kW) is set by the Dutch consumer and market authority (ACM). District heating tariff decision requires that the average cost of heat from district heating is less than consuming natural gas would have cost (the NMDA principle). Table 3-1 lists all tariffs set by the ACM for 2020 (ACM, 2019). Vattenfall's tariff of delivered heat is below the maximum of the ACM (€25.90 per GJ). In contrast to the annually fixed tariffs for delivered heat for small consumers, medium and large consumers' tariffs and prices are set quarterly, and different contract terms apply.

	Price (€ incl. VAT)
One-time connection fee	€4.510,73
Additional connection fee (when > 25 meter)	€180,74 (per add. meter)
Fixed space heating and tap water tariff	€469,17 (annually)
Fixed metering tariff	€26,63 (annually)
Tariff of delivered heat	€26,06 (per GJ)

Table 3-1: Prices for 2020 set by the ACM (ACM, 2019).

<u>Energy costs</u>

Energy costs for production depend on the operating hours and the production unit. Dispatching production units with the lowest marginal prices results in cost minimization. In Figure 3-6 and Figure 3-7, the prices for natural gas and electricity from 2007 until 2030 are projected based on realities and predictions retrieved from the Dutch Environmental Assessment Agency (PBL, 2019). Also related to costs for energy, there are taxes on electricity and natural gas. The Dutch government wants to encourage sustainable energy use, and this is done by gradually increasing the tax on natural gas and decreasing the tax on electricity.

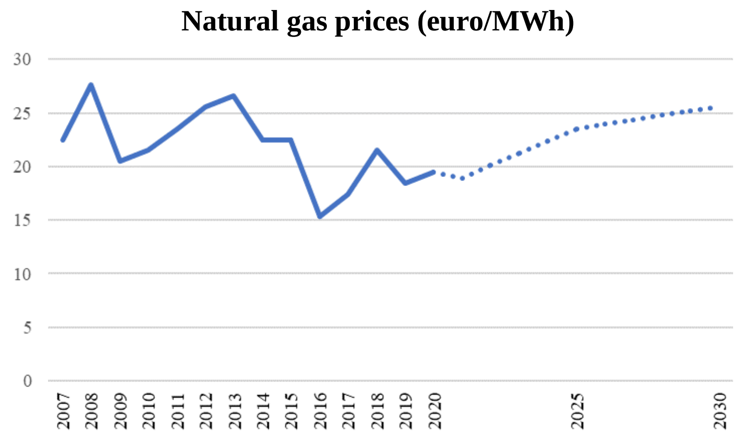

Figure 3-6: Natural gas prices in euro/MWh based on realities and predictions (PBL, 2019).

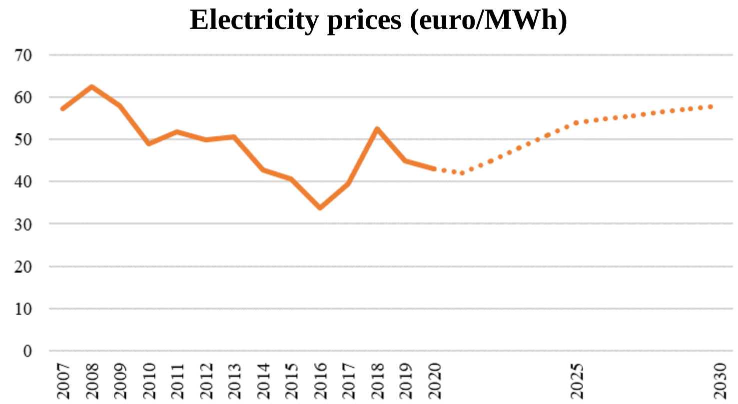

Figure 3-7: Electricity prices in euro/MWh based on realities and predictions (PBL, 2019).

Data center waste heat integration

In the Netherlands, waste heat from data centers is offered for free. However, as explained in the technical layer, waste heat is of low temperature and needs to be upgraded by heat pumps. Heat pumps use electricity to upgrade the heat temperature, of which the amount of electricity required depends on the COP. When dispatching the production unit with the lowest marginal costs, the costs for electricity used by the heat pump will be compared to the costs for the primary energy source in the network, e.g., natural gas. Evident is that the net marginal costs for data center waste heat integration are lower than the costs for natural gas. This margin is required to earn back investment costs, making integration of data center waste heat affordable.

3.4.4 Institutional layer

As explained earlier in Section 2.4, district heating networks are often characterized by regulated tariffs and by long-term contracts between producers and suppliers. Furthermore, heat suppliers often own and operate the distribution (and/or transmission) networks, which is also the case for Vattenfall in Amsterdam.

In Amsterdam, there are two main primary heat networks: One network is owned by Vattenfall and is covering south and east Amsterdam (approximately 2/3rd of the connections in Amsterdam). The other network is a joint venture between the waste incinerator company *AEB Amsterdam* and Vattenfall, named *Westpoort Warmte (WPW)*, covering heat in the Western and Northern parts of the city (approximately 1/3rd of the connections) (RMA, 2018). WPW was established in 1999 to use heat from waste incineration to provide to utilities in the Port of Amsterdam. Nowadays, the network has expanded and caused a shift towards heat demand for householders. Vattenfall is the heat supplier of Amsterdam and owns and operates the transmission and distribution networks. To enhance future-proof district heating networks in Amsterdam, Vattenfall has built a pipeline connection between the two existing networks in Amsterdam. This connection, called the *Amsterdam South Connection*, integrates the two district heating networks to enhance growth and allows for approximately 25.000 new household-equivalents to be connected to the network in five years (Vattenfall Group, 2020). Besides the connection, a buffer is installed to store heat and deliver when demand is high during colder days.

There are many different types of consumers, and Vattenfall categorized consumers into three main groups (small, medium, large consumers) according to their energy consumption. Small consumers include households and small business consumers (in Dutch: kleinzakelijke afnemers). Medium consumers are consuming until 4,977 GJ per year and are mostly self-employed business owners (in Dutch: ZZP'ers) and small-medium enterprises (SMEs). Large consumers have an annual consumption of more than 4,977 GJ and comprise large businesses (in Dutch: grootzakelijke afnemers). Besides consumer categories based on consumption, consumers can also be classified in different types, e.g., households, companies, utility buildings, industry. According to interviewee A. Correljé (Appendix A2), each consumer type has different characteristics in terms of heat demand profile, which are essential to identify to understand heat patterns.

Consumers consume heat according to their needs. They pay for most of the costs of the system, and therefore, they demand reliability supply of heat. Small consumers do not have a freedom of choice between the suppliers due to the monopolistic nature of the network.

Data center waste heat integration

When integrating data center waste heat in the district heating network of Amsterdam, new arrangements will have to be made. A market party, such as Vattenfall, could start a project of data center integration in a network area when the municipality of Amsterdam has given a *concession*, meaning the license to exploit under certain agreements (in terms of supply, connection, tariffs, etc.) (RMA, 2019).

Waste heat from data centers is offered for free, and by delivering heat for district heating, data centers simultaneously receive cold water to cool their equipment. However, this is a continuous process, and the data center demands reliability from the heat suppliers, meaning a constant heat take up. Long-term contracts between the data center and Vattenfall set out the terms of services and the security of supply. In Figure 3-8, the main components within the institutional layer are shown.

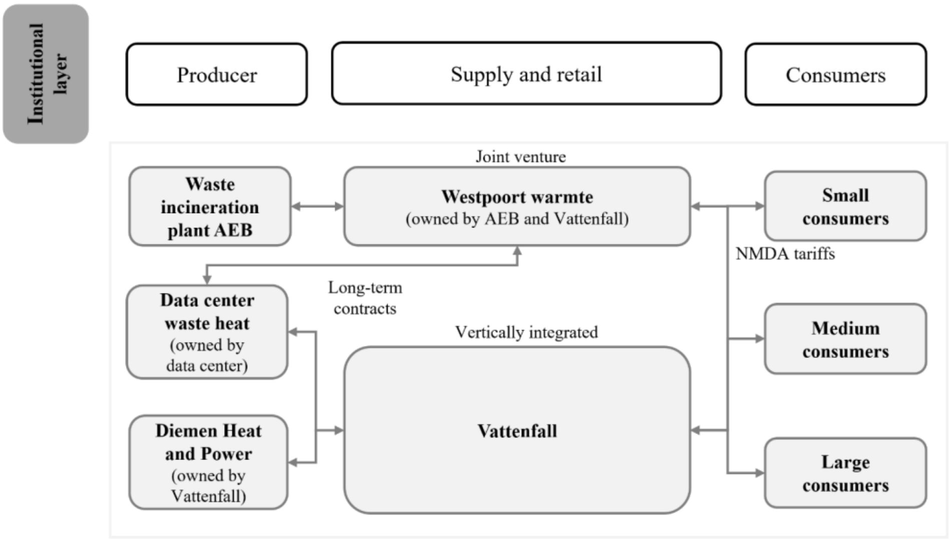

Figure 3-8: Components within the institutional layer of a district heating system.

3.4.5 Stakeholders

Besides the stakeholders that are directly involved in the institutional layer of the network, other stakeholders transcend their stake over the whole network. Those stakeholders are the Dutch Ministry of Economic Affairs, the *Rijksdienst voor Ondernemend Nederland* (RVO) (in English: Netherlands Enterprise Agency), the Municipality of Amsterdam, and the Authority for Consumers and Markets (ACM):

- The Dutch Ministry of Economic Affairs and Climate Policy has the ambition to replace natural gas by other sources of heat to make a transition towards a low-carbon energy economy. The Ministry is the governmental entity for the Dutch district heating market.
- The Rijksdienst voor Ondernemend Nederland (RVO) is part of the Dutch Ministry of Economic Affairs and Climate Policy and stimulates sustainable enterprises. The RVO handles subsidies for sustainable heat projects. The Warmteatlas is published by the RVO to display heat potential in the Netherlands (RVO, 2018).
- The Municipality of Amsterdam is involved in planning and realizing of district heating networks in Amsterdam and is a shareholder (50%) of the WPW network. The municipality has control over the district heating network in Amsterdam in a way that they are responsible for giving concessions. The municipality has the goal of moving to a natural gas-free city by 2040.
- The Dutch Authority for Consumers and Markets (ACM) is the regulatory body in the field of energy market regulations. The ACM sets maximum tariffs for heat (NMDA) The ACM is also responsible for the regulation of the system operators in the Netherlands.
- Dutch Data center Association (DDA) is the trade organization of data centers in the Netherlands. The DDA supports the data centers' business and is actively looking for energy efficiency opportunities.

3.4.6 Carbon dioxide emissions

The emission factor for gas is globally accepted and is set on 56.4 kg CO_2/GJ (LHV), equal to 182.9 kg CO_2 /MWh (HHV) (given in Table 3-2). For electricity, there is no such globally accepted default because CO_2 emissions are depending on the power mix. In the Netherlands, emissions factors for electricity are obtained by the Climate and Energy Outlook (PBL, 2019). The emission factor in 2020 is

300 kg CO_2/MWh and predicted to be 90 kg CO_2/MWh in 2030 (see Appendix C1), which is below the emission limit (in Dutch: 'emissieplafond') of 120 kg CO_2/MWh in 2030 (PBL, 2018).

Definition	*Factor*	*Unit*
Emission factor natural gas	*56.4 (LHV)*[1]	*tonne CO_2/TJ*
Emission factor natural gas	*182.9 (HHV)*[2]	*kg CO_2/MWh*
Emission factor of electricity	*395.0*[3]	*kg CO_2/MWh*
Efficiency primary fossil (EOR)	*78*[4]	*% (in 2018)*
Efficiency gas-fired systems	*87 (HHV)*[5]	*%*
Power loss factor (PLF)	*0.18*	*MWh_e / MWh_t*

Table 3-2: Emission factors, efficiencies, and power loss factor.

Case-specific CO_2-intensity (south and east Amsterdam)

For the case of the Southern and Eastern parts of Amsterdam, 98% of the heat for district heating is produced by CHPs, and 2% was generated with gas-fired heating systems in 2019 (see Appendix B1) (Vattenfall, 2020).

CHP plant: For the CO_2-intensity calculation for CHPs, the Primary Energy Factor (PEF) of the Dutch power mix is needed. In the Netherlands, the concept of *Equivalent Opwek-rendement* (EOR) is more commonly used, referring to the reciprocal of the PEF (PEF=1/EOR). The Power Loss Factor (PLF) is divided by the EOR to determine how much fossil fuel input is needed elsewhere to compensate for the loss in electricity production (caused by the production of heat). The more renewable energy there is in the Dutch power mix, the higher the EOR will be. In 2020, the EOR was 78% (PBL, 2019) (Appendix C2). The PLF is determined to be 0.18. The CO_2 emission factor to be used for CO_2-intensity calculation is the factor of the fuel that was used in the CHP to generate heat, which is natural gas in this case.

Gas-fired heating systems: To calculate the CO_2-intensity for gas-fired heating systems, the emission factor of natural gas is divided by the efficiency of a gas-fired heating system, which is 87% (ACM, 2020).

The CO_2-intensity for heat in south and east Amsterdam in 2020 is calculated by summing up the CO_2-intensity shares of both sources, using factors from Table 3-2 (RVO, 2019). The same calculation is made for other years in time (see Appendix C3). Assumed is that just like in 2019, the share is still 98% CHP and 2% gas-fired heating systems in 2020:

$$CO_2\text{-intensity} = \frac{182.9 * 0.18}{78\%} * 98\% + \frac{182.9}{87\%} * 2\% = 45{,}6 \text{ kg } CO_2/\text{MWh (produced heat)}$$

Data center waste heat integration

Emissions savings when integration data center waste heat depends on what heat source is replaced by data center heat. When CHP is taken as a reference case, CO_2 emissions will likely increase when

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[1] Retrieved from (RVO,2020)

[2] HHV/LHV for natural gas is 1,11 (RVO, 2019)

[3] See also appendix C1 (PBL, 2019)

[4] See also appendix C2 (PBL, 2019)

[5] Retrieved from (ACM, 2020)

implementing the heat pump system, while emissions will decrease with gas-fired heating systems as reference. CO_2 emissions are not allocated to the direct use of industrial waste heat, but emissions are allocated to the electricity that is needed to upgrade the heat.

3.5 Limitations

Networks will always have certain limitations to be dealt with. It is important to take those limitations into account in an early design stage and also when modeling the system. Three limitations are described in theory below and will be referred to when analyzing modeling results in Chapter 5.

3.5.1 Degree of complexity

As explained in Section 3.2, the degree of complexity of a system depends on complexity factors: Layer and component interdependencies, objectives and constraints, and developments. Up to a certain level, those aspects are manageable but complexity can reach a limit at which the system suffers from over-specification, it becomes hard to understand the patterns of dependencies, and the system becomes unmanageable (De Bruijn & Herder, 2009).

3.5.2 Chaos and unpredictability

Due to the dynamic aspect of a complex system, it will seldom be in an equilibrium state but will instead be balancing between its equilibrium and some point of non-equilibrium, or between *order* and *chaos*. Maintaining order is necessary, but changes to the system are very likely to occur, and dealing with chaos can, therefore, not be avoided (Choi et al., 2001). Networks are not only subject to changes in the technical layer, but also in the institutional layer and economic layer. Flexibility in the approach is required to ensure that when changes occur, the approach will still hold and function as intended (Herder et al., 2008).

Predicting a system’s behavior is difficult, and according to Choi et al. (2001, p. 356) “In a complex system, it is often true that the only way to predict how the system will behave in the future is to wait literally for the future to unfold.” However, future changes are not necessarily random, and patterns of system behavior can be discovered to make predictions up to a certain level.

3.5.3 Optimality

Another limitation of the system engineering approach for a district heating system is reaching its optimality. When all system components can be optimized independently, reaching an optimum is likely. However, since layers and components within layers are interdependent, many *local* optima exist, but there will not be a single best optimal state. This is the case since local optima are conflicting and contribute to the system in different ways (Choi et al., 2001).

3.6 Conclusion on system engineering approach

Large scale and complex systems can be better understood by deconstructing the system into different layers. The network layered system engineering approach supports the understanding of the interaction and dependencies between the technical, economic, institutional, and social and environmental concepts that are described earlier. Applying the approach on a city scale enhances the discovery of where in the network integration is feasible in terms of the four A’s. Data center integration opportunities in Amsterdam are identified, and waste heat could be integrated into the primary transport line or in the secondary distribution line, which is depending on the characteristics of the network, technical components, and the data center.

The system engineering approach is also suitable for discovering changes to the network and necessary activities to safeguard functionalities, e.g., matching heat demand and supply after data center integration. It became evident that data center integration requires new arrangements to be made in the institutional layer, also affecting the other layers, e.g., the division of costs. The network layers in Amsterdam can be used as the starting point for a pilot project in a specific area.

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4 Modeling

In the previous chapter, a system engineering approach is set up to understand the network layers and components, their functions, and interdependencies in general and for more in detail for Amsterdam. The system engineering approach can serve as the basis for developing a data center integration design for a specific project in Amsterdam. In this chapter, a data center waste heat integration project called *Kantorenstrook Amstel III* will be modeled in EnergyPRO, introduced in Section 4.1. The model description will be given in Section 4.2, and the model input will be listed in Section 4.3. The simulation will be explained in Section 4.4. and the Key Performance Indicators (KPIs) for the analysis will be defined in Section 4.5.

4.1 Model approach

4.1.1 Simulation model in EnergyPRO

A simulation model in the EnergyPRO tool is built for a specific case study in Amsterdam. According to Lund et al. (2017, p.4), “In simulation models the purpose is to analyse and compare options and/or scenarios that differ in relation to various key parameters such as costs, emissions, energy supply, and others.”. EnergyPRO is a simulation tool from the Danisch company EMD International that is used for techno-economic analysis of energy systems such as district heating systems (EMD International, n.a.). Figure 4-1 shows the graphical layout of the software tool. Input parameters are production units, fuel sources, demand (heating, cooling, electricity) costs components, emissions, etc. EnergyPRO is an input/output modeling tool, meaning that running the program multiple times under the same input values will not give different outputs.

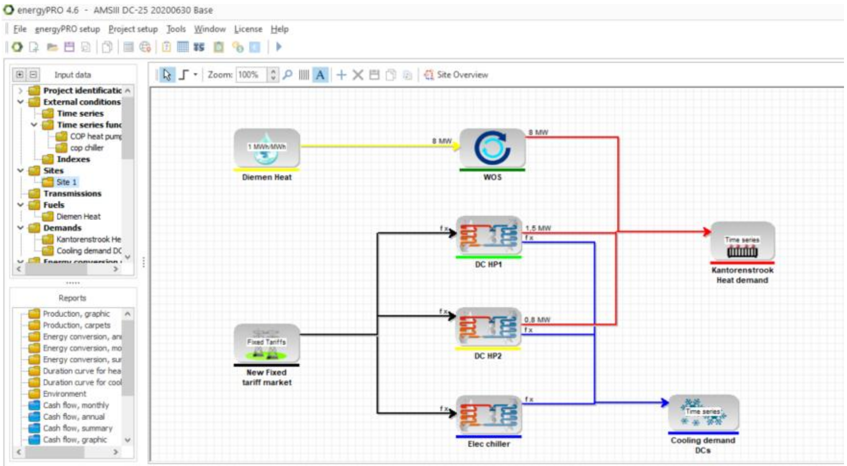

Figure 4-1: Graphical layout of the software tool EnergyPRO.

4.1.2 Model objective and constraints

EnergyPRO is an economic optimization tool following the set operational (prioritization) strategy in the model. The objective of the model is to optimize the allocation of heat demand among production, based on cost minimization by dispatching the unit with the lowest marginal costs. The modeling purpose is to analyze different scenarios of data center waste heat integration in a specific area in Amsterdam. Simulation of the district heating network is used to predict the system’s performance to support decision-making for a particular project.

Referring back to the system engineering approach in Chapter 3, the model set-up and main input parameters are within the technical layer, and the output parameters of this cost optimization model are within the economic layer. Models like EnergyPRO require technical inputs and are quantitative and analytical, as opposed to models that require regulatory or actor input, which are more qualitative and politically directed (De Bruijn & Herder, 2009). It is essential to understand that a different model could have different inputs and outputs. For each scenario that is modeled in this chapter, regulations and actors are unchanged and in line with the current situation in Amsterdam. Therefore, using an analytical model with technical inputs (and varieties) is more logical than using regulatory inputs. Would one be interested in how a system is influenced by its regulations, e.g., when comparing cases of different countries, then another model would be more suitable.

4.1.3 Modeling steps

The modeling approach is sub-divided into five steps, as visualized in Figure 4-2: The case-specific site is identified, and the scenarios that are going to be analyzed are explained. The required data is collected, and assumptions are drawn, serving as input for the EnergyPRO model. For both scenarios, simulations are done, and hourly production is allocated based on the lowest hourly marginal costs of the available production units. The quantitative output is analyzed by using four KPIs.

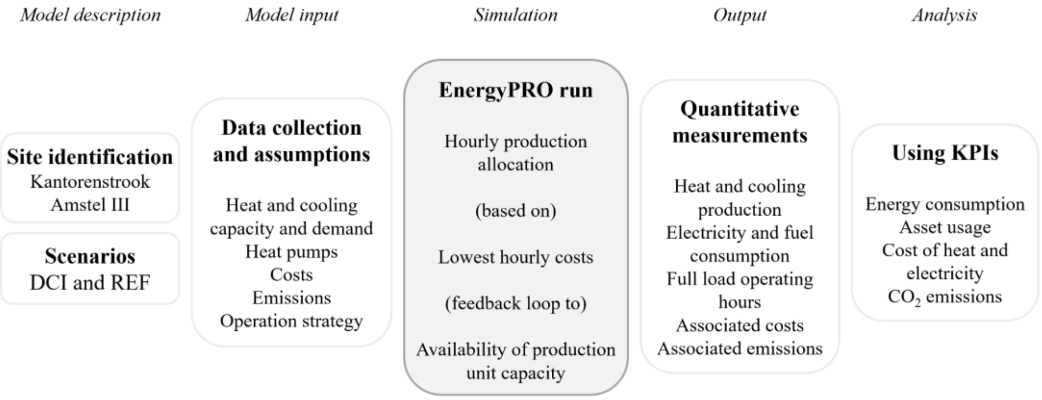

Figure 4-2: Conceptual diagram of modeling steps.

4.2 Model description

4.2.1 Site identification

A district heating network area in Amsterdam called ‘Kantorenstrook Amstel III’ is simulated to measure the effect of data center waste heat integration under different scenarios in time compared to a reference scenario without data center integration.

Amstel III is a large area in Amsterdam South East, between the Johan Cruijff Arena and the Amsterdam UMC (see Appendix D1). Amstel III consists of a business area and an area with offices. The area with offices (Kantorenstrook Amstel III) will change into a lively area where around 5,000 homes will be built in the upcoming years. Closely located to the area is AM7, a data center from Equinix with a capacity of 10MW. Waste heat from Equinix AM7 can directly be coupled to the area in development, which is one of the categories for potential data center integration (see Section 3.4). Equinix AM7 is of a relatively short distance to the area (see Appendix D2).

4.2.2 Scenarios

Data center waste heat integration under different scenarios in time is compared to a reference case in which data centers are not integrated (shown in Table 4-1). In this chapter, ‘DCI’ will be used to refer to the data center integration scenario, and ‘REF’ will be used to refer to the reference scenario. For each of the three years in time (2020, 2025, and 2030), Diemen Heat and electricity costs and emissions inputs are varying, resulting in different outputs to be analyzed.

	DCI scenario	REF scenario
Year 2020	DCI-20	REF-20
Year 2025	DCI-25	REF-25
Year 2030	DCI-30	REF-30

Table 4-1: Overview of different scenarios (reference and DC integration) over time.

<u>Data center integration scenario (DCI)</u>

For the DCI scenario, part of the heat demand in the area will be covered with waste heat from data center Equinix AM7, which will be upgraded by heat pumps and fed into the secondary distribution network. The other part of the demand is covered with heat from the primary network in Amsterdam South East, produced by the Diemen Heat Plant (a CHP), and distributed to the secondary network via the WOS. The DCI scenario is visualized in Figure 4-3.

<u>Reference scenario (REF)</u>

In the REF scenarios, the current situation is taken in which there is no data center waste heat integration in the district heating network in the Amstel III area. Without data center waste heat integration, heat demand is fully covered by the Diemen Heat Plant.

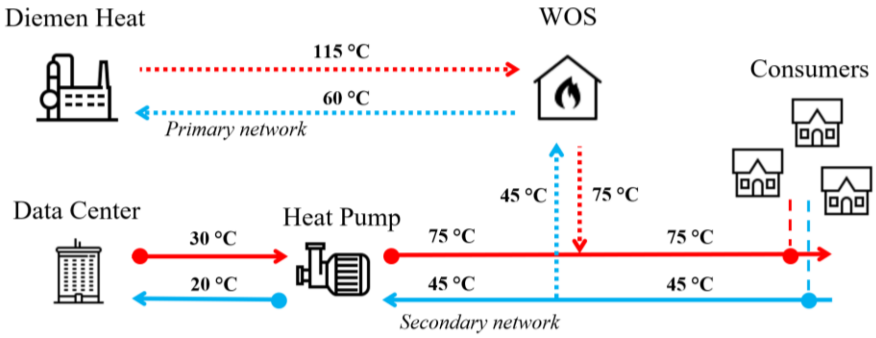

Figure 4-3: Graphical representation of DCI scenario.

4.3 Model input

Technical, economic, and environmental data are collected and will be inserted as an input variable in the EnergyPRO simulation. Data and other assumptions are listed in Table 4-2 below and are further explained (and numbered as data collection items 1 to 11).

Data collection items	Inputs
Heat demand (incl. losses)	17.719,15 MWh per year
Maximum heat demand	7,75 MW
Maximum heat supply HPs	2,25 MW (1,5 MW + 0,75 MW)

COP HP	4,0
Operational range HPs	75-100% of maximum
Minimum operational hours	2 hours
Cooling demand	1,6875 MW
COP Chiller	5,0

Table 4-2: Data collection and assumption items as input for the model scenarios.

1. Heat demand: The heat demand of locations 1 to 9 in Appendix D2 is determined. The annual heat demand profile for the different consumption types are calculated. The consumption types in the selected areas are retail, office, community/education, residential apartments, rows, and affordable rental units. The total heat demand, including losses, is 17.719,15 MWh per year with a maximum heat demand of 7,75 MW (see Appendix D3 for detailed calculation). A demand profile curve is shown in Figure 4-4.

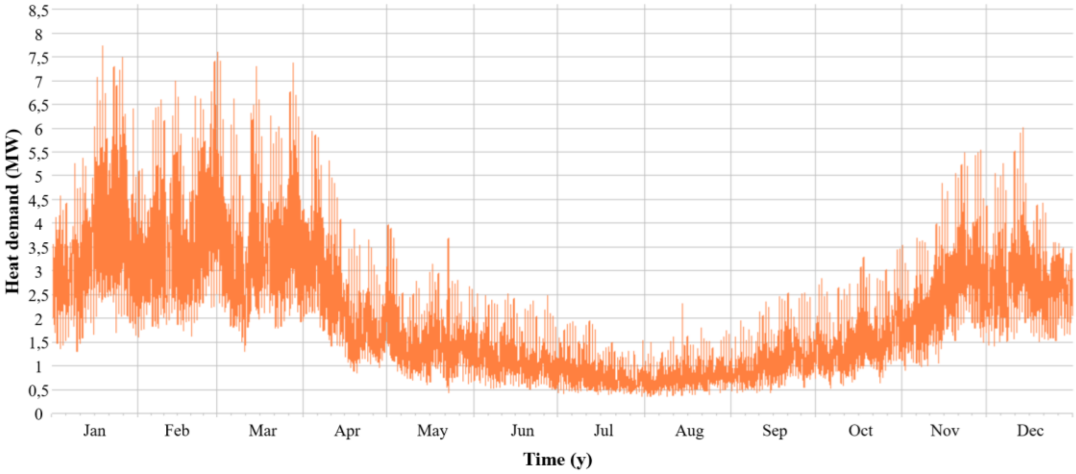

Figure 4-4: Annual heat demand profile curve (fixed over the years).

2. Heat capacity: A maximum of 2,25MW heat supply from AM7 (after being upgraded by heat pumps) is implemented. Diemen Heat heat supply is set at 8,0MW, thus being able to cover the full heat demand in Kantorenstrook Amstel III in case of the reference scenarios.

3. Heat pumps: Two heat pumps are supplying the 2,25MW heat from AM7: One with a capacity of 1,5MW (HP1) and the other one with 0,75MW supply (HP2). According to the COP formula, the Carnot COP would be $COP_{Carnot} = (75+273,15)/((75+273,15)-(27+273,15)) = 7,25$, which would result in an actual COP of 4,0 with 55 percent efficiency. A heat pump is losing its efficiency when partly operating or when being turned on/off many times. Therefore, the heat pumps will only run when they can cover a minimum of 75 percent of their maximum supply, and the operation period shall minimum be 2 hours.

4. Cooling demand: In return for the heat supply, heat pumps can simultaneously deliver cooling back to the data center. When heat supply from the heat pumps is 2,25MW, the heat pump cooling supply can reach $2,25-(2,25/COP) = 1,6875MW$. Therefore, the cooling demand of data center AM7 is considered to be equal to 1,6875.

5. Cooling capacity: The heat pumps can provide 100 percent cooling (1,6875MW) when running at their maximum. However, when a heat pump does not run at full potential, the resulting cooling demand is covered by a chiller. The chiller's COP is assumed to be 5,0.

6. Electricity: Electricity is consumed by the heat pumps and the chiller. The amount of electricity used per MW heat or cooling depends on the COP values of the energy units.

7. Revenues: The heat demand and tariffs are assumed to be the same over time for both the reference scenarios and the data center integration scenario (17.719,15MW annually). Therefore, revenues will be the same for all cases and are excluded from the calculations.

8. Expenditures heat and electricity: The costs for heat and electricity are retrieved from the natural gas and electricity price trends in Figure 3-6 and Figure 3-7. In Table 4-3, the price for natural gas and electricity are given for the years 2020, 2025, and 2030. The other cost components explained earlier are not incorporated in the simulation.

9. CO_2 emissions allocated to heat and electricity: Just like the costs for heat and electricity, the CO_2 intensity is also developing over time. In Table 4-3, the CO_2 emissions for Diemen Heat and electricity are given for the years 2020, 2025, and 2030. Appendix C1 and C3 show the electricity and Diemen Heat emission factors projections and predictions from 2010 to 2030.

	Natural gas prices (euro/MWh)	**Electricity prices (euro/MWh)**	**CO_2 emissions Diemen Heat (kg CO_2/MWh)**	**CO_2 emissions electricity (kg CO_2/MWh)**
Year 2020	€19,40	€43,00	45,6	300,0
Year 2025	€23,50	€54,00	33,3	210,0
Year 2030	€25,60	€58,00	21,2	90,0

Table 4-3: Prices and CO_2 emissions development allocated to energy sources in 2020, 2025, 2030.

Ambient temperature: For the model configuration where free cooling will be added, a yearly temperature trend will be used. The outside temperature is retrieved from the annual hourly temperature at Schiphol in 2018 (KNMI, 2019). This is considered a ‘standard’ year without odd temperature deviations.

4.4 Simulation

The operation strategy of the simulation in EnergyPRO is to minimize Net Production Costs (NPC), considering running the production units by determining the lowest cost for covering the demand. Thus, the simulation tool allocates production units at each hour of the year (2020, 2025, and 2030) based on the lowest hourly marginal costs. Those marginal costs correspond to the price of generating one unit of heat (in MWh), which is entirely based upon the expenditures set up manually as cost allocation.

For the REF scenario, the cost for one unit of heat coming from Diemen Heat corresponds to the natural gas price. For the DCI scenario, heat can either come from the Diemen Heat Plant or the data center. The costs for data center waste heat corresponds to the price of electricity. However, upgrading one unit of heat only requires 1/4th of a unit of electricity. Therefore, when integrating data center heat supply into the network, in this case, a priority will be given to the waste heat, and Diemen Heat will cover the remaining demand. The maximum of 2,25MW of waste heat covers 1/3rd of the maximum demand of 7,75 MW.

4.5 Key Performance Indicators

Analyses of the output in Chapter 5 will be based on Key Performance Indicators (KPIs) to measure system objectives. Four KPIs are considered to be the most important indicators to be analyzed when modeling data center waste heat integration (Interview with Vattenfall Heat engineering manager M. Hierl (Appendix A3)): 1. Energy consumption, 2. Asset usage, 3. Cost of heat and electricity, 4. CO_2 emissions.

4.5.1 Energy consumption

The objective is to reduce electricity and natural gas consumption. It is, however, unlikely that both electricity and natural gas consumption are decreasing when integrating data center waste heat. A priority is to reduce natural gas consumption to meet the ambition of becoming independent of natural gas in 2050. An increase in electricity consumption might be unavoidable, but still, the goal is to reduce consumption.

4.5.2 Asset usage

The objective is to maximize asset usage, meaning a maximization of the data center heat share of the total delivered heat at consumers. Covering full demand with data center waste heat sounds like a logical solution when economically advantageous. However, besides the security of supply issues, the boundary of 6.000 full load operating hours (FLOH) to receive SDE++ subsidies is constraining this maximization (earlier explained in Section 2.2).

4.5.3 Costs for heat and electricity

This KPI is in line with the objective of the EnergyPRO model: The aim is to minimize the total costs for heat and electricity. The EnergyPRO model is based on cost minimization by dispatching the unit with the lowest marginal costs. For the DCI scenario, supplying heat from the data center is prioritized over the Diemen Heat Plant when electricity price for one MW of heat (taking into account the COP) is lower than the Diemen Heat price for one MW of heat. However, prices are changing over the years, so optimization could vary too.

4.5.4 CO_2 emissions

The objective is to reduce CO_2 emissions. Prioritizing dispatching the unit with the lowest emissions sounds best but might not be in line with meeting natural gas reduction targets and cost optimization. CO_2 intensities are changing over the years, so emissions will do so as well. Both emissions and CO_2 are primarily related to energy consumption and asset usage.

4.6 Conclusion on modeling

The simulation tool EnergyPRO is used to analyze the feasibility of data center waste heat integration in the Kantorenstrook Amstel III area. EnergyPRO optimizes the allocation of heat demand among production units, based on cost minimization. Four KPIs that are considered the most important indicators are 1. Energy consumption, 2. Asset usage, 3. Cost of heat and electricity, 4. CO_2 emissions. When integrating data center waste heat, the aim is to reduce electricity and natural gas consumption while maximizing the data center heat share of the total demanded heat. However, this must be aligned with the minimization of the total costs for heat and electricity, which is the model objective. Furthermore, the aim is to minimize the corresponding CO_2 emissions. Prices and emissions per generated unit are developing over time.

The total heat demand (incl. losses) of 17.719,15 MWh of Kantorenstrook Amstel III can be covered by waste heat from the data center and heat from the Diemen Heat plant. A maximum of 2,25 MW can be supplied by the data center, covering the baseload of 1/3rd of the maximum heat demand of the area. Two heat pumps are used to upgrade the data center’s heat and simultaneously deliver cooling back to the data center.

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5 Results

In this chapter, the results of the base DCI and REF model scenarios will be analyzed in Section 5.1, and verification of the heat supply decision will be done in Section 5.2. An additional model configuration with free cooling will be analyzed in Section 5.3. To validate the model, sensitivity and uncertainty analyses will be done in Section 5.4. Insights in model results and sensitivity and uncertainty of the model will influence choices in the decision-making process. The regulatory arrangements are not included in the simulation and will be analyzed separately in Section 5.5. From the analysis results, a network layer for the Kantorenstrook case will be developed.

5.1 Model analysis

For the DCI and REF scenario, Table 5-1 shows the outputs of heat and cooling production, electricity and fuel consumption, and the full load operating hours (FLOH) for each production unit. Independently of the year simulated, energy conversion results are equal for each year because the heat demand and cooling demand, production units, and energy input values are kept the same. Data analysis is done by using the KPIs described earlier. The first two (technical) KPIs are analyzed based on the energy conversion outputs for the DCI and REF scenarios, as given in Table 5-1. The economic and environmental KPIs are analyzed with cost and emissions output, which is varying over the years and shown in Table 5-2, Table 5-3, and Table 5-4.

Year 2020, 2025, 2030		DCI scenario		REF scenario	
Heat demand	Kantorenstrook AMSIII	17.719,1		17.719,1	
Cooling demand	Data center	14.782,5		14.782,5	
Heat production (MWh/year)	Diemen Heat	4.749,5	26,8%	17.719,1	100,0%
	Data center HP1	8.703,2	49,1%	-	-
	Data center HP2	4.266,5	24,1%	-	-
	Electric chiller	0,0	0,0%	0,0	0,0%
	Total	17.719,1	100,0%	17.719,1	100,0%
Cooling productions (MWh/year)	Diemen Heat	0,0	0,0%	0,0	0,0%
	Data center HP1	6.527,4	44,2%	-	-
	Data center HP2	3.200,1	21,6%	-	-
	Electric chiller	5.055,0	34,2%	14.782,5	100,0%
	Total	14.782,5	100,0%	14.782,5	100,0%
Electricity consumed by energy units (MWh/year)	Data center HP1	2.175,8			
	Data center HP2	1.066,7		-	
	Electric chiller	1.011,0		2.956,5	
	Total	4.253,5		2.956.5	
Fuels (MWh/year)	Diemen Heat	4.749,5		17.719,1	
	Total	4.749,5		17.719,1	
Full load operating hours: (hours/year)	Diemen Heat	594		2.215	
	Data center HP1	5.802		-	
	Data center HP2	5.689		-	
	Electric chiller	2.996		8.760	

Table 5-1: Energy conversion outputs for DCI and REF scenarios (equal for 2020, 2025, and 2030).

5.1.1 Energy consumption

Heat and cooling production are, respectively, 17.719,1 MW and 14.782,5 MW. Energy consumption is split up in fuel consumption for heating and electricity consumption for both heating and cooling (listed in Table 5-1). In terms of fuel consumption, in the REF scenario, the full 17.719,1 MW of heat demand is covered by the Diemen Heat Plant (using natural gas). When integrating data center waste heat, only 4.749,5 MW heat remains to be covered by the Diemen Heat Plant, and 12.969,6 MW of heat is coming from the data center (upgraded by the heat pumps). Despite this fuel consumption decrease when integrating data center waste heat, the total amount of electricity consumption increases from 2.956,5 MW for the REF scenario to 4.253,5MW for the DCI scenario. This is due to the heat pumps in operation, which use 0,25MW of electricity for every MW of heat produced. However, although the total amount of electricity consumption increases, the electricity consumed by the chiller is less in the DCI scenario (1.011,0 MW) compared to the REF scenario (2.965,5 MW) due to cooling supply covered by the heat pumps. To sum up, we see a 73,2 percent decrease in natural gas consumption for the DCI scenario (4.749,5 MW) compared to the REF scenario (17.719,1 MW), whereas the increase in electricity consumption from 2.965,5 MW to 4.253,5 MW is 43,9 percent (see Figure 5-1 (left)).

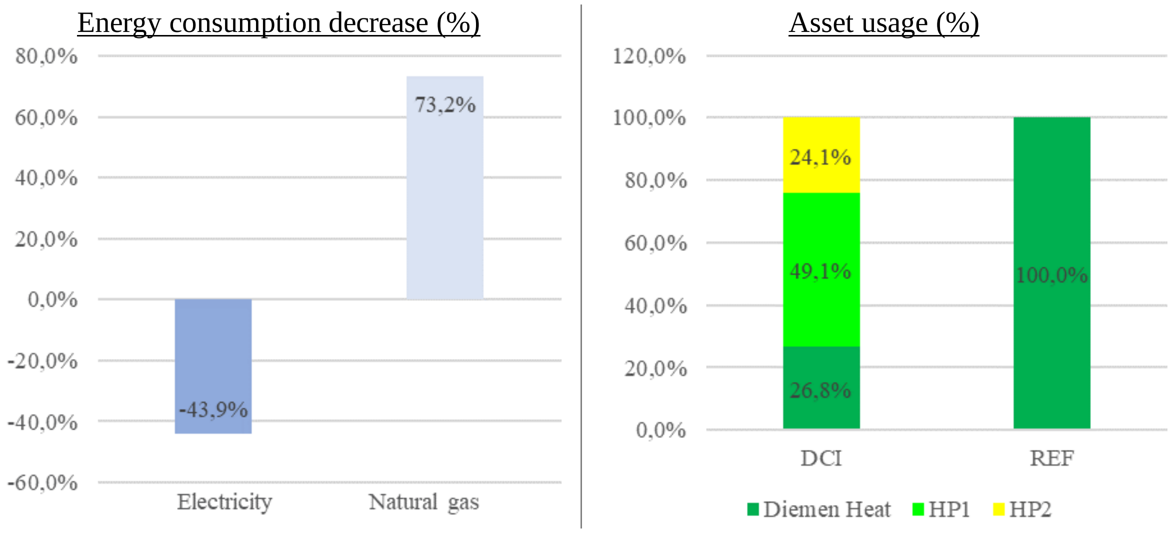

Figure 5-1: Energy consumption decrease graph (left) and asset usage graph (right) (DCI and REF).

5.1.2 Asset usage

In the REF scenario, 100 percent of the heat is produced by the Diemen Heat Plant, and 100 percent of cooling is provided by the chiller. When implementing the DCI scenario, 49,1 plus 24,1 percent of heat will be supplied by heat pumps 1 and 2, respectively, covering 73,2 percent of total heat production (see Figure 5-1 (right)). In return, the heat pumps cover 65,8 percent of cooling demand. Formula 2 (given in Section 2.2) is used to determine the combined FLOH of the heat pumps, which is 5.764h. This result is satisfactory since it is a significant number and below the max. of 6.000h for SDE++.

Figure 5-2 displays the annual load duration curve for the DCI scenario. The curve gives insight into the load division per hour of the year, where the area under the curve represents the total heat demand units. The curve is plotted in the order of decreasing magnitude, meaning that the highest load hour is shown on the left (the maximum of 7,75 MW of heat demand), whereas the smallest load hour is shown on the far right. It must be mentioned that the area composition under the curve in Figure 5-2 is a little 'spikey' due to the assumption that the pumps will only be turned on for an operation minimum of two hours.

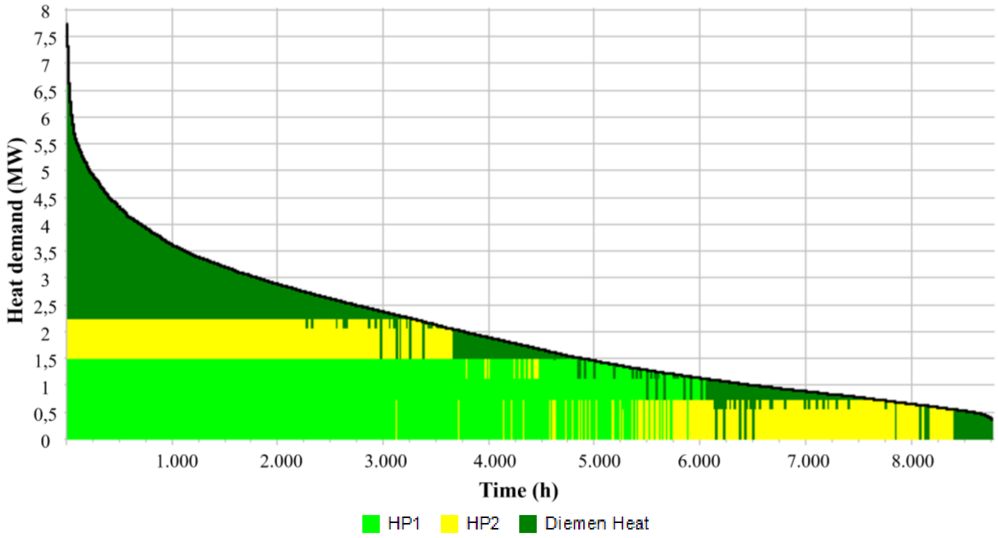

Figure 5-2: Load duration curve for DCI base scenario.

The decrease in natural gas consumption and the increase in electricity consumption when the data center covers 73,2 percent of heat production, can only be reflected upon by assessing the associated costs and emissions. In contrast to the above two KPIs, costs and emissions of heat and electricity are impacted by time-dependent input variables and vary over the years. Therefore, output for 2020, 2025, and 2030 differs in terms of costs and emissions (see Table 5-2, Table 5-3, and Table 5-4).

Year 2020		**DCI scenario**		**REF scenario**	
Costs district heating (euros/year)	Diemen Heat	€92.140	*(4.749,5MWh*€19,40)*	€343.752	*(17.719,1MWh*€19,40)*
	Heat pump 1	€93.559	*(2.175,8MWh*€43,00)*	-	-
	Heat pump 2	€45.868	*(1.066,7MWh*€43,00)*	-	-
	Total costs DH	€231.568		€343.752	
Costs data center (euros/year)	Electric chiller	€43.473	*(1.011,0MWh*€43,00)*	€127.130	*(2.956,5MWh*€43,00)*
	Total costs DC	€43.473		€127.130	
	Total costs	**€275.041**		**€470.881**	
Emissions (tonne CO_2/year)	Power	1.276		887	
	Diemen Heat	217		808	
	Total	1.493		1.695	

Table 5-2: Economic and environmental outputs DCI and REF scenarios for the year 2020.

Year 2025		**DCI scenario**		**REF scenario**	
Costs district heating (euros/year)	Diemen Heat	€111.613	*(4.749,5MWh*€23,50)*	€416.400	*(17.719,1MWh*€23,50)*
	Heat pump 1	€117.493	*(2.175,8MWh*€54,00)*	-	-
	Heat pump 2	€57.602	*(1.066,7MWh*€54,00)*	-	-
	Total costs DH	€286.708		€416.400	
Costs data center (euros/year)	Electric chiller	€54.594	*(1.011,0MWh*€54,00)*	€159.651	*(2.956,5MWh*€54,00)*
	Total costs DC	€54.594		€159.651	
	Total costs	**€341.302**		**€576.051**	
Emissions (tonne CO_2/year)	Power	893		621	
	Diemen Heat	158		590	
	Total	1.051		1.211	

Table 5-3: Economic and environmental outputs DCI and REF scenarios for the year 2025.

Year 2030		DCI scenario		REF scenario	
Costs district heating (euros/year)	Diemen Heat	€121.587	*(4.749,5MWh*€25,60)*	€453.610	*(17.719,1MWh*€25,60)*
	Heat pump 1	€126.196	*(2.175,8MWh*€58,00)*	-	-
	Heat pump 2	€61.869	*(1.066,7MWh*€56,00)*	-	-
	Total costs DH	€309.652		€453.610	
Costs data center (euros/year)	Electric chiller	€58.638	*(1.011,0MWh*€56,00)*	€171.477	*(2.956,5MWh*€56,00)*
	Total costs DC	€58.638		€171.477	
	Total costs	**€368.290**		**€625.087**	
Emissions (tonne CO_2/year)	Power	383		266	
	Diemen Heat	101		376	
	Total	484		642	

Table 5-4: Economic and environmental outputs DCI and REF scenarios for the year 2030.

5.1.3 Costs for heat and electricity

Costs are divided into the costs on the district heating (DH) side and costs on the data center (DC) side. The Diemen Heat source coupled to the natural gas price, whereas the heat pumps and the electric chiller are coupled to the electricity price. When analyzing the costs for heat and electricity, we must refer back to the price development in Table 4-3 (in Chapter 4). Over the years, natural gas prices and electricity prices are increasing, resulting in total costs increase over time for both the DCI and REF scenarios (see Figure 5-3 (left)). In 2020, overall cost reduction when implementing the DCI scenario is €195.840,-, whereas in 2025 and 2030, the reduction is €234.749,- and €256.797,-, respectively. Percentage-wise, the decrease in costs when integrating data center waste heat is equal in each of those years in time, around 41 percent. This is explicable since both natural gas prices and electricity prices are increasing with comparable growth rates over the years.

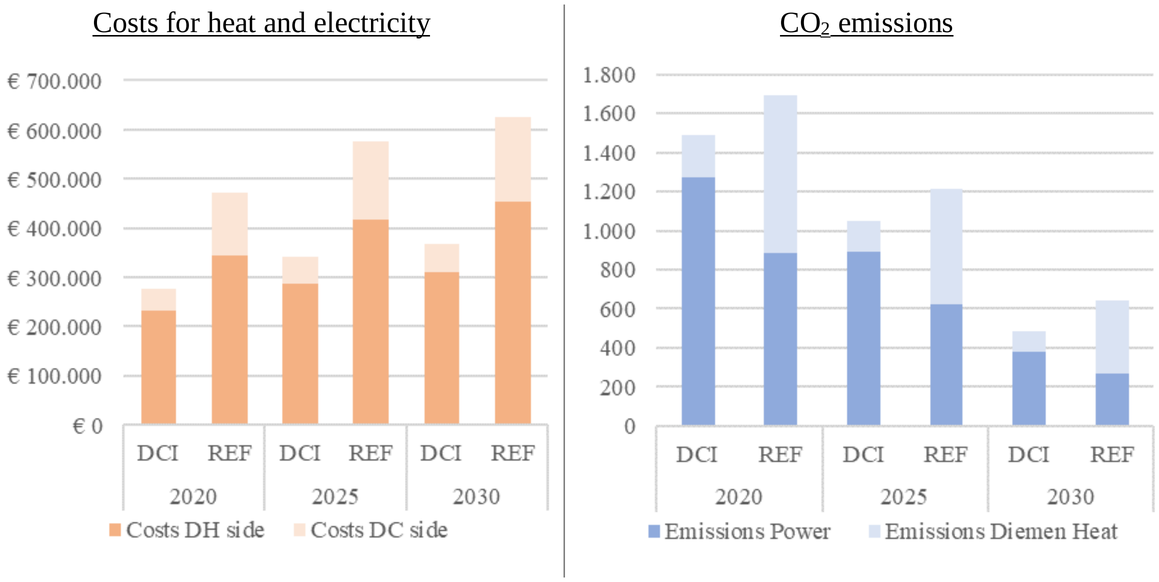

Figure 5-3: Costs for heat and electricity (left) and CO_2 emissions graph (right) (DCI and REF).

Zooming in on cost allocation to see where the 41 percent decrease in costs is coming from, we see that in each year, the cost for district heating is reduced by around 32 percent, whereas the costs for the data center are reduced by about 66 percent. This means that when costs are allocated to the owners, the data center's owner would be taking more advantage of the integration than the district heating network owner. However, one notice must be made: Logically, the costs for the heat pumps are allocated to the district heating side because the primary purpose of the heat pump is to deliver heat for district heating.

However, in return, a heat pump provides cooling, meaning that the operational time and maintenance costs for a chiller are reduced. Therefore, it seems to be a fair deal to allocate part of the heat pump costs to the datacenter's expenses.

5.1.4 CO_2 emissions

For each of the years in time, the CO_2 emissions are decreasing when integrating data center waste heat compared to the REF scenario (see Figure 5-3 (right)). For a CO_2 emission comparison between 2020, 2025, and 2030, we refer back to the emission intensity development Table 4-3. Over the years, both CO_2 emissions for Diemen Heat (natural gas) and electricity (Dutch power mix) are decreasing in time, resulting in 484 kg CO_2 in 2030 for the DCI scenario compared to 1.493 kg CO_2 in 2020. CO_2 emissions for electricity are decreasing faster over time compared to natural gas. The electricity share is higher in the DCI scenario than in the REF scenario, making the emissions reduction bigger for the DCI scenario.

The decrease in natural gas consumption and increase in electricity consumption, when the data center waste heat is covering a substantial heat demand share, results in both a reduction of costs and CO_2 emissions for all the years analyzed. However, changing the data center heat supply input might result in more positive (or negative) outputs. This must first be verified to draw a firmer conclusion on project feasibility.

5.2 Model verification: Heat supply

One factor in decision-making for data center integration projects is the amount of heat supplied by the heat pumps. In Section 4.3, the heat supply coming from the data center was decided to be 2,25MW to cover a baseload of 1/3rd of the maximum demand of 7,75 MW. However, this decision-making factor is critical and must, therefore, be verified by changing the amount of supply: Instead of working with a supply of 2,25 MW for the data center, the model will be run with a supply of 1,5 MW and 3,0 MW[6]. The minimum operation is kept at 75 percent of a heat pump's capacity, and the heat demand is also remained the same. The results are listed in Appendix E1. Only model outputs from the year 2025 are analyzed.

5.2.1 Energy consumption

When integrating data center waste heat with a capacity of 1,5 MW, we see that the natural gas consumption is decreasing with 59,3 percent, and electricity consumption is increasing with 53,3 percent (see Figure 5-4 (top-left). For the capacity of 3,0MW, natural gas consumption is decreasing with 78,4 percent, and electricity consumption is increasing with 26,1 percent. The same trade-off is occurring in terms of heat and electricity consumption: More heat and cooling production from data centers means that less heat is needed from the Diemen Heat Plant (natural gas), but running the heat pumps more frequently requires more electricity.

5.2.2 Asset usage

In Figure 5-4 (top-right), the data center waste heat share is visualized. A comparison must be made between the FLOHs of the heat pump in the DCI scenarios. Running the heat pumps as much as possible

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[6] For the 1,5 MW supply: HP1 = 1,0 MW and HP2 = 0,5 MW (max.). For the 3,0 MW supply: HP1 = 2,0 and HP2 = 1,0 MW.

sounds best, but since the SDE++ subsidy only covers 6.000 FLOH for heat pumps, it would be most advantageous to run both heat pumps with a maximum of 6.000 hours. Therefore, in terms of FLOH, a capacity of 2,25 MW would be the best solution (FLOH of 5.764h) compared to 1,5 MW with a FLOH of 7.002h (exceeding the maximum), and the case 3,0 MW with a FLOH of 4.632h (far below 6.000h).

5.2.3 Costs for heat and electricity

In terms of costs, the total cost reduction (DCI compared to REF) would be €190.090,- for the case with 1,5 MW capacity, €217.526,- with 2,25 MW capacity, and €251.516,- when installing 3,0 MW capacity (see Figure 5-4 (bottom-left)). Percentage-wise, the cost decrease for 2,25 MW capacity is the highest, with 40,8 percent, compared to 36,4 percent decrease (for 1,5 MW) and 40,0 percent (for 3,0 MW).

5.2.4 CO_2 emissions

In terms of emissions, supplying 2,25MW heat results in a decline in emissions of 160 tonnes CO_2, versus a decline of 129 tonnes CO_2 for the case of 1,5 MW, and a decline of 171 tonnes CO_2 for the case of 3,0 MW (Figure 5-4 (bottom-right)).

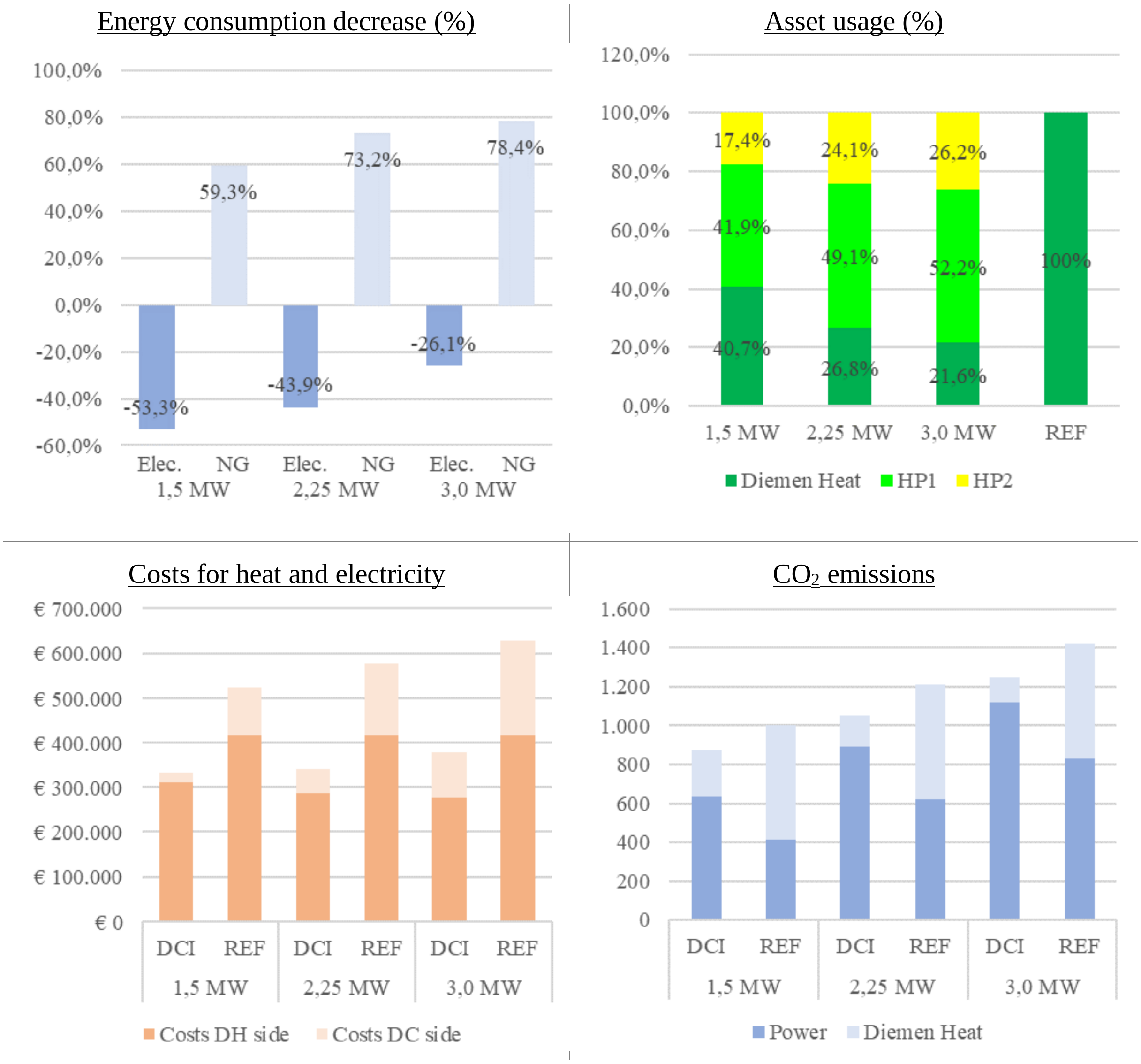

Figure 5-4: Energy consumption decrease (top-left), asset usage (top-right), costs for heat and electricity (bottom-left), and CO_2 emissions graph (bottom-right) for three heat supply variations.

The analysis of the results verifies that, as initially expected, a heat supply of 2,25 MW would be most feasible in this case: the FLOH hours are the closest to 6.000h and not exceeding, it has the largest costs reduction and a significant decline in emissions. For the model configuration and sensitivity and uncertainty in the next sections, we continue with the heat supply decision-making factor of 2,25 MW.

5.3Model configuration: Free cooling

The implementation of efficient cooling systems for data centers is a way to reduce energy use and costs. An advanced technology is the *airside free cooling* technology (referred to as 'air cooling'), used to cool a data center more efficiently than by using conventional technologies such as chillers (Daraghmeh & Wang, 2017). Air cooling is commonly used in mild and colder climate areas and takes advantage of outside air used when the ambient temperature is below a certain degree.

In the base scenarios, the heat pumps could provide 100 percent cooling (1,6875MW) when running at their maximum capacity. When a heat pump does not run at full potential, the resulting cooling demand is covered by a chiller. A model variation is applied where air cooling is added as a cooling source. The efficiency of air cooling is assumed to be very high (the COP is set at 20,0), whereas the chiller's COP is 5,0. Whether cooling is covered by the air cooling technology or the chiller, is depending on the outside temperature.

The study of Oró et al. (2015) provides air cooling operation hours for various locations, amongst which is Amsterdam, with air cooling for approximately 6.600h per year. Using the REF scenario, the air cooling technology would run for 6.548h per year (correlating to 6.600h) when the temperature boundary is set at 17°C. Therefore, assumed is that when the ambient temperature is below 17°C, the air cooler can cover the cooling requirements, whereas the chiller will be run when temperatures are above 17°C (see Figure 5-5 for the annual temperature curve). Note that running the air cooler is more favorable due to higher COP efficiencies. The results of the model configuration effect are listed in Appendix E2.

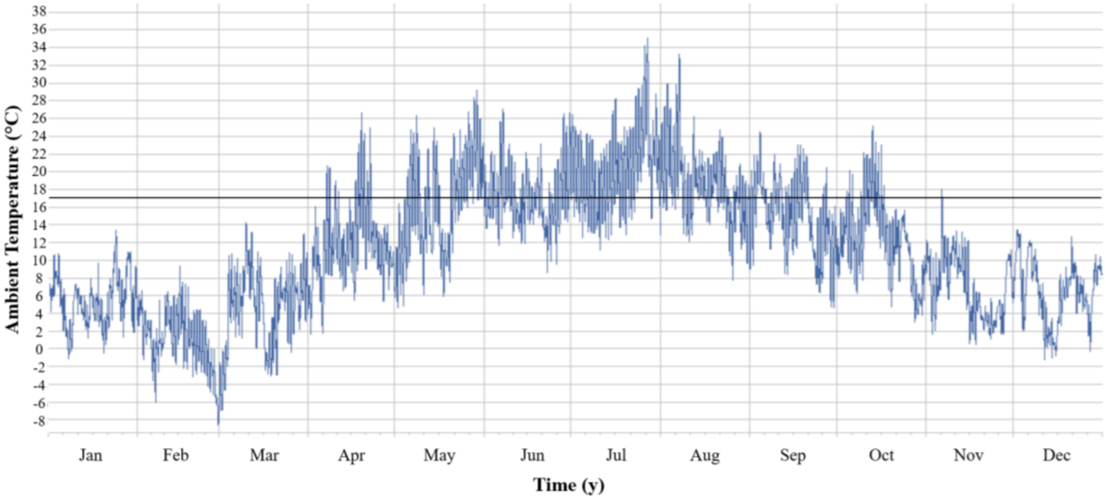

Figure 5-5: Annual hourly temperature model input with a 17°C temperature line.

When using air cooling when the temperature is below 17°C, we see that the electric chiller will only run 25,3 percent (2.215h) of the time, while air cooling covers a significant share of 74,7 percent

(6.548h). Electricity consumption decreases when implementing air cooling in the DCI scenario, compared to the base DCI scenario (from 4.253,5MW to 3.846,1MW). This is due to the high efficiency of the cooling technology. Figure 5-6 shows the cooling demand curve for the DCI scenario with air cooling (left) and the base DCI scenario (right).

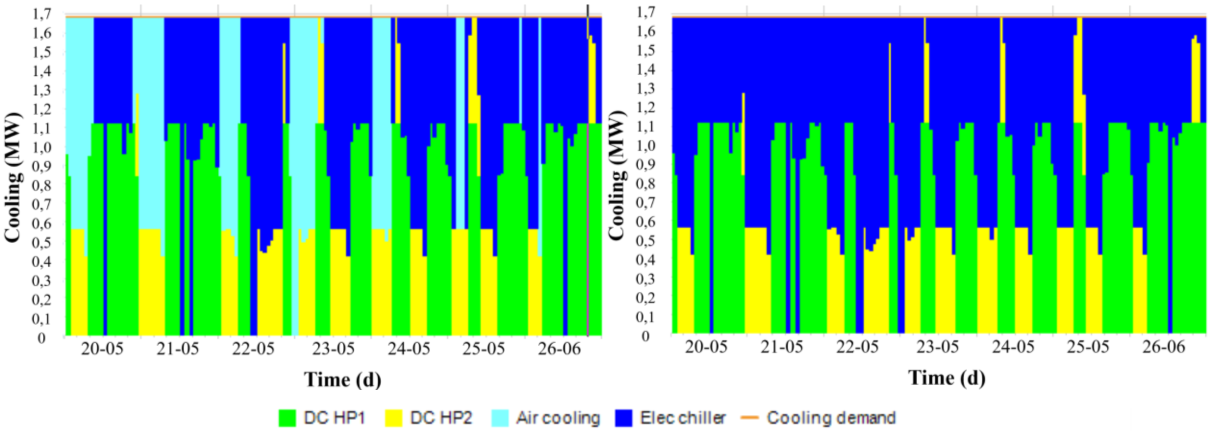

Figure 5-6: Cooling demand curves DCI scenarios with (left) and without (right) air cooling.

The same patterns can be found in the cost and emissions. Compared to the base scenarios, when using air cooling the costs for both the DCI and REF scenario is decreasing. Costs savings for the DCI scenarios with versus without air cooling are €21.997,- (€319.305,- versus €341.302,-). In terms of CO_2 emissions, we see a decrease when using air cooling.

For simplicity reasons, assumed is that the air cooler and chiller cannot run at the same time, and the temperature point of 17°C determines which turns on to cover the (remaining) cooling demand. In reality, the determination is more detailed and would require more information on the data center characteristics and thermodynamics.

Using air cooling for data center cooling purposes is becoming more popular since energy efficiency is high on the agenda. However, not all data centers apply air cooling, and the type, use, and share of air cooling vary per data center. Since air cooling is still an insecure factor in the model, it is not included in the sensitivity and uncertainty analysis. Only the heat pumps and the chiller are included for the purpose of cooling.

5.4Sensitivity and uncertainty of the model

5.4.1 Purpose

Uncertainty and sensitivity analyses are carried out to determine the *validation* of the model. Each of the analyses has its purpose:

- Sensitivity analysis is done to measure the effect of changes in the model to understand what this could mean for decision-making (Pärssinen et al., 2019). In this model, the operation range of the heat pumps is varied to understand the effect of heat pump operation on the output.
- Uncertainty analysis is done by varying the (uncertain) input variables of the model to determine changes in the output. In this model, the heat demand curve is adjusted to determine the effect of

changes to the curve. The result of a change in input is compared to the DCI and REF base scenarios. The sensitivity and uncertainty analyses are applied to the year 2025 only.

5.4.2 Sensitivity: Operation range HPs

For the base DCI scenario, the operation range was set on 75-100%, meaning that heat pump 1 could supply in the range of 1,125 MW to 1,5 MW and heat pump 2 from 0,5625 MW to 0,75 MW. To measure the sensitivity of operation ranges, an analysis is done by changing the original range to 70-100% and also to 80-100%.

Compared to the 73,2 percent of heat supply from the heat pumps for the range of 75-100%, the range of 70-100% has a share of 74,4 percent, and the range of 80-100% has a heat pump share of 71,9 percent (see results in Appendix E3). A variation in this factor can easily be explained, based on Figure 5-7, which shows heat consumption graphs for a particular date (17th of May, 00h-17h). We can see a variation in heat source operation. For instance, between 13h and 17h, the 70-100% range graph (left) is running HP1 to cover the demand, whereas in the 80-100% range graph (right), HP1 is turned off, HP2 is being run, and Diemen Heat covers the remaining demand.

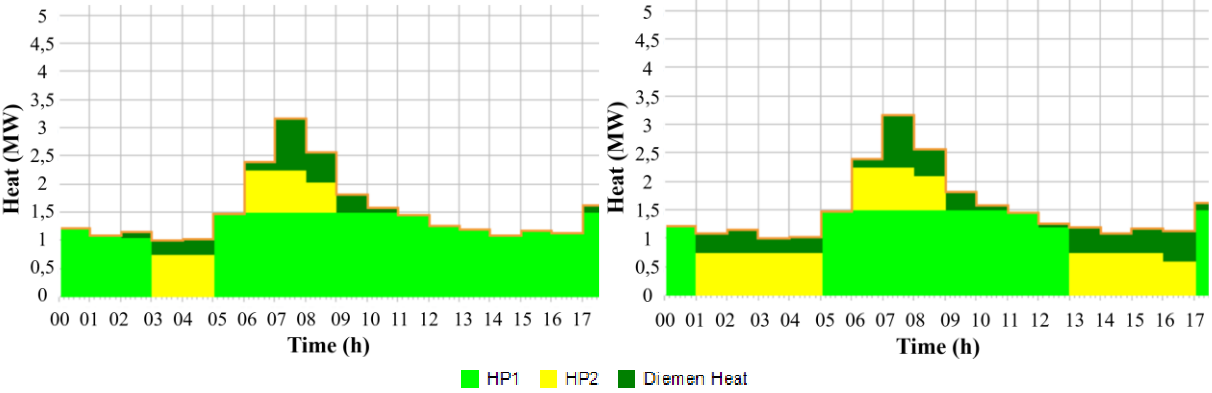

Figure 5-7: Heat consumption graphs for the 70-100% range (left) and 80-100% range (right).

Thus, a bigger operating range allows for more heat supply and logically covers more heat demand. However, two factors constrain enlarging the operation range: 1. Partial operation reduces the heat pumps' efficiencies, and 2. heat pump operation is limited to 6000 hours for SDE++ subsidies.

1. Loss in heat pump efficiency

Loss in efficiency or *performance degradation* is occurring when heat pumps do not run at their full potential. This loss is expressed by the part-load factor (PLF[7]), which is determined by the part-load ratio (PLR), e.g., the range of 75-100%. Since the relationship between PLR and PLF is almost linear between PLR values of 40 to 100%, the following formula

$$PLF = 1 - C_d\,(1 - PLR) \qquad (3)$$

is used (Reddy et al., 2016) (see Figure 5-8). The degradation coefficient C_d is typically between 0.15 and 0.25. For a PLR of below 40%, the PLF is decreasing faster (with a logarithmic trend). The loss in heat pump efficiency would be expressed in a reduced COP. However, it is not included in the

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[7] Note that the part-load factor is not the same as the power loss factor (both in abbreviated form 'PLF')

EnergyPRO model since only minor losses occur in the ranges that are used: When the heat pumps would operate at a minimum of 75%, the PLF is only 0,95 (with C_d = 0,2). In this case, the sensitivity is relatively low. However, larger operation ranges would have induced more efficiency losses.

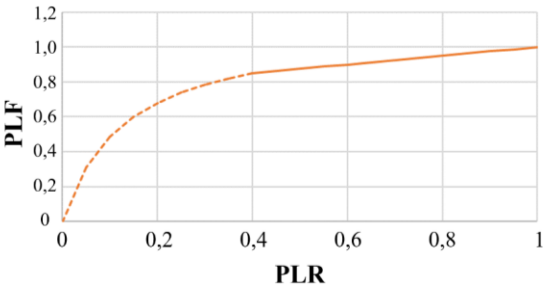

Figure 5-8: The relationship between PLR and PLF ratios.

2. <u>Limited operation hours</u>

Besides three ranges that were already analyzed (with lower range values of 70, 75, and 80 percent), other varieties are measured to determine FLOH maximization up until the SDE++ limit of 6.000h. Increasing the heat pumps' operation ranges results in higher asset usage and more run time (see Table 5-5). The outputs show that the operation range from 60-100% would achieve a FLOH of 5.958h. Up until the range of ~55-100%, the FLOH limit will not be exceeded, and the asset usage KPI is not (negatively) affected by the change in input. Heat supply does not significantly increase when enlarging the operation range, and therefore, the model is not considered hugely sensitive to a change in operating range.

Ranges	**Heat supply HPs (MWh/year)**	**Asset usage HPs (%)**	**FLOH HP1 (h/year)**	**FLOH HP2 (h/year)**	**Combined FLOH (h/year)**
55-100%	13.617,7	76,9	6.601	4.955	6.052
60-100%	13.405,8	75,7	6.385	5.211	5.958
65-100%	13.326,1	75,2	6.185	5.397	5.923
70-100%	13.189,7	74,4	6.001	5.585	5.862
75-100%	12.969,7	73,2	5.802	5.689	5.764
80-100%	12.733,4	71,9	5.606	5.767	5.659

Table 5-5: Calculation for full load hours per operation range for the DCI scenarios.

5.4.3 Uncertainty: Heat demand curve

Besides the choices of heat supply amount and operation hours that are part of decision-making, some model input variables are uncertain and can only be predicted in the best way possible. The most significant uncertainty that must be addressed is the heat demand profile. As described in Section 4.3, the hourly demand curve is based on Kantorenstrook Amstel III area developments and benchmarked data per building type. To determine how the demand profile affects the model output, a different demand curve with an equal heat demand of 17.719,15 MWh as the base scenario is analyzed. The new demand curve is based on an annual heat demand profile of another area (IJburg) in Amsterdam (Vattenfall Heat NL, 2020c). In Figure 5-9, the base demand curve (same as Figure 4-4) is projected (left) in comparison to the new curve (right). Some differences are observed: The maximum heat demand of the new curve is lower (5,86 MW compared to 7,75 MW), whereas the minimum heat demand is higher. Also, the curve looks less 'spikey,' showing fewer fluctuations. Running the EnergyPRO model with this new demand curve results in different model outputs (see Appendix E4).

In the new demand curve scenario, the heat pumps cover more heat demand. Asset usage is 78,0 percent (compared to 73,2 percent in the base DCI scenario), resulting in larger natural gas reduction, although more electricity will be consumed. Both costs and CO_2 emissions are slightly lower in the case of the new heat demand curve. More remarkable is the increased FLOH of 6.141h (compared to 5.764h), which is exceeding the maximum of 6.000h. Seemingly, variation in the demand profile curve could substantially influence the model output. Therefore, proper investigation of the predicted demand profile of the project’s area is necessary to tackle the risk of making ill-considered choices in decision-making.

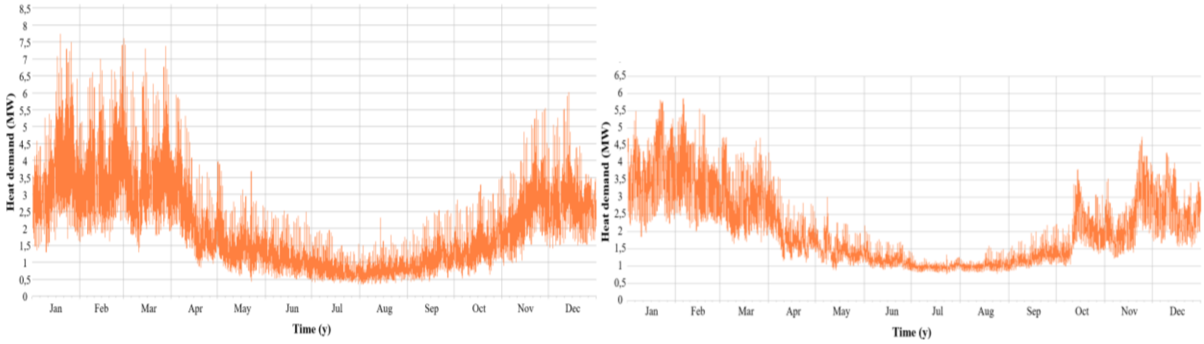

Figure 5-9: Base demand curve DCI scenario (left) and new demand curve (right).

5.5Institutional analysis

The model simulation in EnergyPRO is techno-economic, and input and output variables are within the technical, economic, and environmental layers. Institutional arrangements of heat recovery and delivery in the Kantorenstrook Amstel III area do not directly affect the model but must be taken into account too. Therefore, this layer is analyzed and discussed separately. A complete understanding of all layers that influence the system is necessary for decision-making. Figure 5-10 shows the network layer components for Kantorenstrook Amstel III DCI scenario with its input parameters.

5.5.1 Ownership of the network

As described in Chapter 3, the Kantorenstrook Amstel III area is located in south and east Amsterdam. This network is privately owned by Vattenfall and is therefore of monopolistic nature. In the REF scenarios, the Diemen Heat and Power plant is delivering heat through the primary transport network. When integration data center waste heat (DCI scenarios), waste heat will be fed into the secondary distribution network. Vattenfall owns both the transport and distribution networks in this area, and heat delivery would go through long-term contracts between the data center and Vattenfall.

5.5.2 Consumer types

Heat demand is depending on the demand profile of the area, which is projected by taking into account the building stock and type of buildings (see the interview with H. Otten, Appendix A5). To make an accurate prediction on the demand profile, the type of consumers can be classified based on the developed building types. Almost 3/4th of the consumers consist of households, and roughly 1/4th are office buildings. Understanding the newly developed area is important to avoid uncertainty in the demand curve, as investigated during the uncertainty analysis.

Energy costs for heat and electricity consumption are covered by a particular tariff for delivered heat. Although Vattenfall is the owner of the network and has financial control, the ACM protects consumers against high tariffs. Small consumers have NMDA contracts with Vattenfall, and medium and large consumers work through long-term agreements.

5.5.3 Business model

When integrating data center waste heat in the Southern and Eastern areas of Amsterdam, the monopolistic nature of the network tends towards a more open network where multiple producers are generating heat. However, a characteristic of an open market is that the heat producers actually sell their heat. This is so far not the case data centers in the Netherlands, which are represented by the Dutch Datacenter Association, and offer waste heat for free to support the energy transition actively (DDA, 2017). Thus, the data center does not charge Vattenfall for waste heat.

5.5.4 Concession

As addressed in the interview with H. Otten (see Appendix A5), depending on the ownership of the network, the municipality can decide to take a supporting role and give concession or take full control and engage the network. Since Vattenfall is the owner of the network in south and east Amsterdam, the municipality has no right to exploit in this network. However, Vattenfall would need to receive concession from the municipality to engage a new district heating network and start a data center integration project in the Kantorenstrook area. This does give the municipality some control. If the municipality agrees, then Vattenfall would have the exclusive right to operate in the area. Fortunately, the municipality of Amsterdam is pushing towards the use of data center waste heat as a district heating source in Amsterdam (see the interview with E. Barentsen in Appendix A7).

5.6Conclusion on results

When integrating data center waste heat in the area of Kantorenstrook Amstel III, fuel consumption (natural gas) decreases, whereas electricity consumption increases due to the heat pump usage. The heat pumps together cover 73,2 percent of the total heat demand and a large share of the data center’s cooling requirements. Furthermore, in all three years that are studied, the total costs decrease with around 41 percent when integrating data center waste heat (compared to the reference scenario) as well as a resulting decrease in emissions.

The initial decision to use 2,25MW of heat supply from the data center is verified by testing two supply variations: Considering the four KPIs, using 1,5 MW would exceed the maximum FLOH for which a subsidy applies, and 3,0 MW supply would not be as effective. Implementation of air cooling technologies is an efficient way of reducing the data center’s energy use and costs and would cover cooling requirements for approximately 3/4th of the year when implemented (in Amsterdam) when the ambient temperature is below 17°C degrees. A sensitivity and uncertainty analysis is done to understand the effects of input changes on the model output: Bigger heat pump operation ranges allow for more heat supply and covers more heat demand. However, operating range maximization is constrained by a reduction in efficiency and the FLOH limit. The uncertainty of the heat demand profile and the change in output for a comparable heat demand curve can have a substantial impact on decision-making.

Alongside the techno-economic model, the institutional components are analyzed. Ownership structures, consumer types, a particular business model, and the influence of stakeholders are part of the system and are case-specific. The system engineering approach helps to understand the dynamics of the technical, economic, environmental, and institutional components of this specific case. However, an aspect of a district heating network's complexity is its dynamics: In every layer, changes or *developments* will occur in the short- or long-term future. Those developments are discussed in the next chapter.

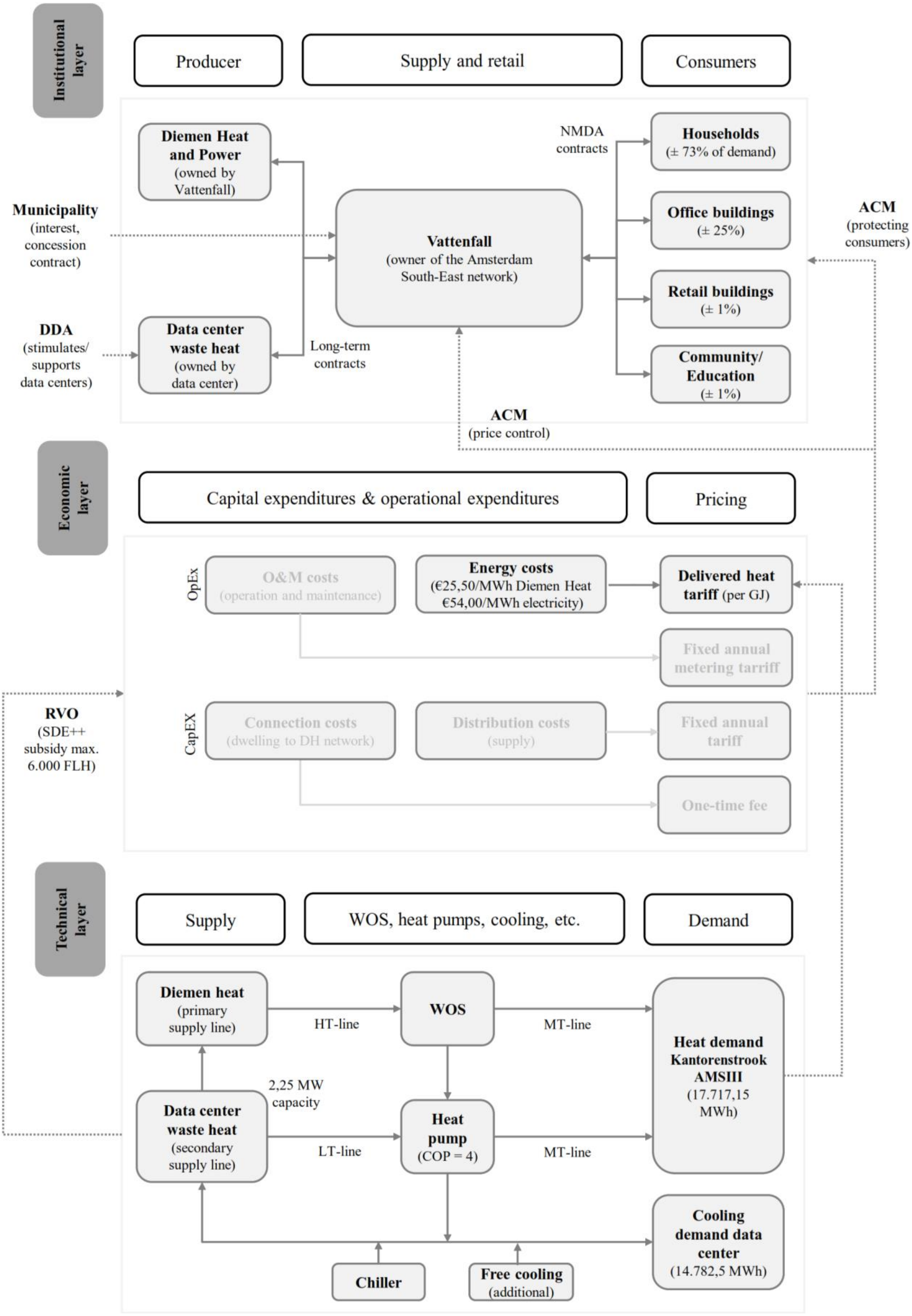

Figure 5-10: Network layer components for Kantorenstrook Amstel III data center integration.

6 Discussion and future developments

The results of the study were analyzed in Chapter 5, but changing dynamics in the complex system creates the necessity to discuss the results further and explore future developments that could impact the district heating system. In Section 6.1, changes in the network of Amsterdam will be presented, based on institutional arrangements and temperature regimes. After having discussed possible changes in the institutional and technical layer, future market and price models will be explored in Section 6.2. Lastly, developments on the data center side that might influence the system will be discussed in Section 6.3.

6.1An integrated network

The district heating network in Amsterdam is split up into two parts: The Southern and Eastern parts of Amsterdam and the Western and Northern parts. In previous chapters, a data center waste heat integration scenario in the Kantorenstrook area was studied in which heat integration takes place in the district heating network in the Southern and Eastern areas. However, when data center waste heat would be integrated into other parts of the network of Amsterdam, the system's components would change. The main differences in terms of 1) network ownership and arrangements, and 2) temperature regimes, are discussed:

6.1.1 Network ownership and arrangements

The district heating network in south and east Amsterdam is original of monopolistic nature, where private owner Vattenfall produces and supplies heat. Whereas Vattenfall is a single player in the South East network of Amsterdam, integrating data center waste heat in the joint venture network WPW would have required other arrangements. In this Northern and Eastern area of Amsterdam, the municipality is not involved in the physical aspects of the network. However, it is financially and institutionally involved since the municipality is the shareholder of AEB, and waste heat recovery is an important instrument for reaching sustainability targets in Amsterdam (Gemeente Amsterdam, 2020).

The Amsterdam South Connection, which is built in 2020 to improve connectivity and heat distribution from one part of Amsterdam to the other, has created a physical connection between the two networks. Still, on an institutional level, both networks are not connected, and each has its own ownership structure and arrangements. Complete integration of both networks with technical, economic, and institutional agreements would create new opportunities for parties such as data centers to integrate into the network.

6.1.2 Temperature regimes

The supply temperature for the case of Kantorenstrook Amstel III is 75°C degrees and belongs to the *mid-temperature regime* (Gemeente Amsterdam, 2020). In the model simulation, the heat was supplied into the secondary (distribution) supply line connected to a newly built area (visualized earlier in Figure 4-3). In Section 3.4, three categories for data center integration opportunities were described. Besides the potential for data center waste heat integration directly into an area in development such as the Kantorenstrook Amstel III area, integration on a larger scale to meet growth and CO_2 targets could also be applied in Amsterdam. In the area of Westpoort, data center waste heat could potentially be fed into the primary (transport) supply line. However, the supply line has a *high temperature regime* and is approximately 90°C in summer and 115°C in winter. Feeding low temperature heat into this line requires the use of more advanced high temperature heat pumps (HTHPs) that can cover larger temperature lifts to integrate data center waste heat into the primary district heating network.

The main components of an HTHP are not different from a conventional heat pump. However, integration in the high temperature regime requires high temperature lifts and more advanced heat pump configurations and necessary. Therefore, larger upfront investments are needed, and there is more risk. Besides financial risks, bigger integration projects also have physical risks in the sense that failure in the network could have substantial consequences. Therefore, clear institutional arrangements are crucial for large-scale integration projects.

Although the application of HTHPs is relatively new, it could increase connectivity of the district heating network when being implemented in the primary supply line of Amsterdam. This allows heat to flow over longer distances to supply waste heat to other areas in Amsterdam and increase the share of sustainable district heating sources. Figure 6-1 shows a possible strategy, introduced by the municipality of Amsterdam, to expand the high temperature network to allow for better connectivity (Gemeente Amsterdam, 2019). This is a projection of what the high temperature network could look like in 2040. Despite the expansion opportunities, losses in the heat grid will always limit the distance of heat transport, and therefore, networks will remain to have a local or regional character, and 'loose ends' are unavoidable.

Figure 6-1: Projection of HT networks in Amsterdam in 2040 (Gemeente Amsterdam, 2019).

6.2Market and price models

Robust market and price models are key to move from the current monopolistic nature of the network to a more open network where multiple producers operate on the market. Two developments that are likely to happen in the future will change the Dutch district heating network: Opening up the network to allow third party access and a dynamic pricing structure.

6.2.1 Opening up: Third party access

Forming an integrated market by restructuring the institutional and physical layers, as described above, will create opportunities to open up the market. The municipality of Amsterdam wants to create possibilities for third parties to integrate into the district heating network of Amsterdam (Gemeente Amsterdam, 2020). In the next few years, the institutional layer, with two separate heat networks in Amsterdam and no third party access, could become an integrated network where the integration of data center waste heat and TPA are introduced (see Figure 6-2).

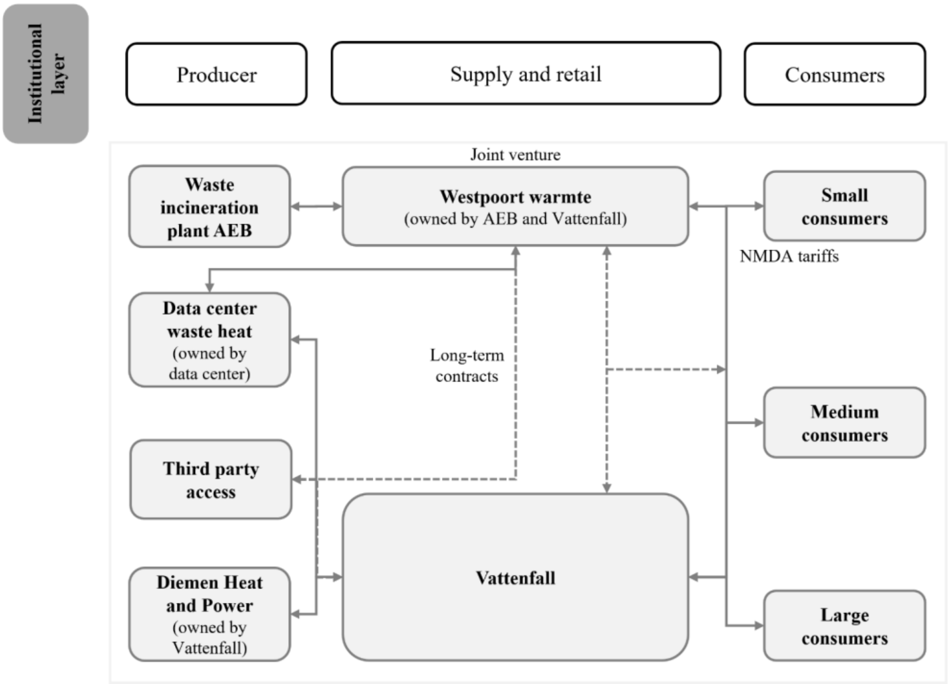

Figure 6-2: Components within the institutional layer of the network in Amsterdam.

An open network allows for more competition and would lead to increased cost-efficiency. A new market model could come into the place where production and supply are not connected anymore, and various producers can enter the heat market of Amsterdam. However, the effectiveness of third party access is depending on the size of the network and might only work for large-scale networks. TPA has proven its effect in large city-wide networks in Sweden and Denmark. However, currently, in contrast to those cities, the network of Amsterdam is still relatively small and loosely connected. Would third party access be implemented soon, over-capacity of the network might become a risk. Therefore, network integration seems to be a necessary step before opening up for third party access.

Having more production sources would lead to a more flexible network and makes it easier to optimize the allocation of heat sources. The consequences of opening up the network on the production side but remain to have a monopolistic supply side, introduce the need for (price) regulations. Most probably, heat producers would apply tariffs per consumption of heat, whereas the operator of the network would apply fixed tariffs.

6.2.2 Dynamic pricing

Going one step further in opening up the network for the third party is the possibility to change the fixed price model to a dynamic one where supply and demand are matched. A dynamic pricing structure enhances optimization in the network but substantially increases the complexity of the network in all layers: All market parties, including end-users, must have access to relevant information about the market, e.g., production, consumption, externalities, etc.

Dynamic pricing requires strict institutional arrangements, such as:

- New forms of consumer protection, which is currently still accomplished by NMDA agreements.
- The prevention of over- or under-compensation for heat producers and operators.
- Instruments to foster the energy transition (reduction of emissions, clean sources, taxes, supporting regulations, etc.).

Although fully open networks and dynamic pricing could be promising in a more mature Dutch district heating market, a single buyer model would be a logical first step in Amsterdam. WPW and Vattenfall would be the buyers of heat from multiple producers, and contractual agreements support the security of supply. With the integration of the two HT networks in Amsterdam, it is possible that WPW and Vattenfall will soon form one single buyer of public-private ownership instead of being two separate buyers, each with their regulations.

6.2.3 Limitations on learning from best practices

What is new for the Dutch district heating system is sometimes common practice in other countries such as Sweden, where the district heating system is more developed. We could learn from institutional concepts within the existing district heating system in Sweden, where parties are incentivized to engage in heat supply, and we could learn from best practices such as the model of Fortum Värme with dynamic pricing structures. However, no country is the same, and fundamental arrangements, regulations, and norms and values that are rooted in the Dutch heat system would make it impossible to copy the Swedish model fully. Even if the possibility would be there, success is not guaranteed due to those fundamental differences between countries.

6.3Future data center developments

Besides the technical, economic, and institutional developments in the district heating system that might be occurring in the future, developments on the side of the data center might also influence the system. Although such developments are outside the district heating system boundaries, they do affect the system (positively or negatively) and can be predicted. Investigation such developments is important to avoid unforeseeable risks.

6.3.1 Data center heat capacity growth

According to H. Otten (see the interview in Appendix A5), IT chips will become smarter and more efficient. Along similar lines, E. Barentsen (see the interview in Appendix A7) argues that server rooms can be arranged more efficiently to allow more servers per area. Furthermore, the expansion of data centers will be significant, and therefore, the total waste heat potential from data centers will increase.

The municipality of Amsterdam has studied data center developments in different scenarios, and all scenarios indicate the growth of heat capacity. The DDA assumes that 90 percent of the data centers in Amsterdam are technically ‘ready’ to recover waste heat for district heating purposes (Gemeente Amsterdam, 2019). From an economic point of view, data centers play an important role in Amsterdam, and the goal is to maintain the data center hub in Amsterdam.

The data center heat capacity growth requires the efficient use of energy and recovery of waste heat. However, utilizing this waste heat is only feasible when the data center is closely located to the heat network. Therefore, for waste heat utilization, growing data center capacity should go hand in hand with developments in the district heating network in Amsterdam. Expansion of the high temperature network and HTHP technologies create opportunities to integrate the growing capacity of data centers in the district heating network.

6.3.2 Business model recreation

Business models for data center waste heat integration are currently not well defined. Delivering energy is not a data center's core business, data center owners lack knowledge, and it is often considered a risky investment. In the current most common business model, the district heating company owns the network and the heat pump, and would get waste heat for free, in return for cooling for the data centers. However, Vattenfall Heat program manager C. Jonis (see Appendix A6) reasons that when a data center would receive cooling, it would save electricity and maintenance costs for running less its chillers. It can, therefore, be argued that data centers would have to pay a fee for the received cooling amount, corresponding to savings on chiller costs.

The increasing data center heat capacity could drive incentives to optimize cost allocation between the data center and the district heating company. A new business model could come into the place where the data center owns the heat pump and receives money for heat, comparable to the structure in Sweden. This would mean that heat recovery is part of the data center's business, and it requires a full understanding of the market. The data center owner and district heating company must work together, and must both understand the entire system; thus, all components and associated risks.

This new business model can seem to work only when a *win-win* situation is created. If the data center owner would invest in waste heat utilization, the sales coming from selling heat to the district heating party must cover the investment expenditures. From the perspective of the district heating operator, e.g., Vattenfall, waste heat from the data center must be cheaper than the costs for the replaced heat to be an attractive business. Erik Barentsen, a senior policymaker at the Dutch Data center Association, believes that for now, waste heat will be delivered for free, and the district heating owner will stay responsible for the connection and operation of the heat pump.

Regarding the energy efficiency of the data center, operating a heat pump requires electricity, which would drive up the PUE. However, electricity consumption for other cooling equipment is reduced, and parts of the electricity use of the heat pump are, in fact, allocated to the district heating side.

6.3.3 Stability and reliability

In data center waste heat integration projects such as Kantorenstrook Amstel III, the data center is not the main heat source. The Diemen Plant will function as a stable back up system that supplies heat when demand is too high to be fully covered by the data center, or in the possible case of malfunctioning. When in the (near) future data center waste heat integration has proven its success, it could become the main heat source, and integration in the high temperature network might become common practice. From the interview with H. Otten (see Appendix A5), it became clear that the data center integration business case in Amsterdam could be developed for 40+ years because data centers are bound to their location, and business will not stop. However, not only the business itself but also the supply of waste heat must be stable and reliable.

6.3.4 Heating and cooling

A data center’s waste heat production is larger when more cooling is required, which is the case during the summer. However, heat demand is less in summer and more in winter. Storage could tackle this mismatch and balance heat supply and demand by storing waste heat when supply is high and/or demand is low.

Data center’s cooling demand could be covered by heat pump operation. However, developments and enforcements to become more energy-efficient might induce a shift from cooling by heat pumps and chillers towards using free cooling or liquid cooling technologies. On the data center’s side, free cooling would make the use of heat pumps less required, which would be a risk for the district heating system. Erik Barentsen confirms that liquid cooling, through small pipes or in the form of emerged cooling, can increase the data center’s temperature and can create higher efficiencies (see Appendix A7).

6.4Conclusion on future developments

Changes in each component of the district heating system require to understand possible future developments, and a network layered scheme can help to visualize such changes and consequences. Physical connectivity between the networks in Amsterdam has been implemented in 2020, and institutional rearrangements might follow soon. The network could become more open and allow for third party access. This can work well if economic models create a profitable situation for both the district heating owner and the heat source owner, i.e., the data center.

Growing data center capacity requires efficiency measures. Besides new cooling technologies, feeding waste heat into the district heating network can play a significant role in a data center’s energy efficiency. The increasing data center heat capacity could drive incentives to optimize cost allocation between the data center and the district heating company. However, regardless of what business models would come into place, the system must be stable and reliable.

7 Conclusions and recommendations

7.1 Conclusions

To give an adequate answer to the main research question, the sub questions are answered first:

1. *What is the current situation of district heating in the Netherlands, and how does it differ from district heating markets in Nordic countries?*

To understand the current district heating situation in the Netherlands, but also other countries, district heating concepts must first be understood. District heating can reduce CO_2 emissions and serves as an alternative for the use of natural gas to provide heat to residential areas. One of the latest district heating developments is to make use of locally distracted heat that would have otherwise been wasted, such as residual heat from data centers. Data centers could act as low temperature heat sources by recovering residual heat for district heating purposes. Besides the technical and environmental aspects, the feasibility of data center waste heat integration also depends on the economic viability and whether institutions are set-up to support its integration.

In the Netherlands, district heating systems provide heat to about five percent of the population, although growing popularity is driven by the governmental decision to stop natural gas production. Large energy companies, such as Vattenfall, but also municipalities, are the main owners of the network. The market is regulated, and consumers cannot switch from network owners. Therefore, the Dutch Heat Act protects consumers against inflated prices. One of the recent district heating developments is the recovery of data center waste heat. As of January 2019, data center waste heat is classified as a renewable energy source and could become an attractive source to achieve the country’s sustainable energy targets. Dutch data centers’ waste heat is provided free of charge, which could offer economic benefits to the integration.

In Nordic countries, district heating systems have a more significant and mature market position. Whereas the market in the Netherlands is regulated, the Swedish district heating market is deregulated, and utilizing residual heat is supported by their price models. In contrast to the Dutch situation, where end-user tariffs are regulated, in Denmark, the profits made by district heating operators are capped. Whether or not the district heating market is regulated (Denmark) or deregulated (Sweden), regulations to support price transparency have provided fruitful outcomes. To move to a more developed district heating market in the Netherlands, we could learn from Nordic best practices, such as more open and competitive networks, profit capping, benchmarking prices, cooperative ownership, purchasing residual waste heat, and actively looking for new resources. However, a country’s policy drivers and ideologies influence decision-making, meaning some changes cannot be simply and immediately introduced.

2. *What kind of system engineering approach is suitable for defining data center waste heat integration possibilities for the case of Amsterdam?*

After exploring the district heating concept, it becomes clear that due to interdependencies, district heating system components cannot be studied in isolation. The network layered system engineering approach supports the connection of all components and to understand their interactions. The network layered scheme divides the system into the technical, economic, institutional, social, and environmental layer, corresponding to the four A’s of energy security (availability, affordability, accessibility, and acceptability). Applying the system engineering approach on a city-scale, for the case of Amsterdam, helps to discover data center integration opportunities.

In Amsterdam, two main facilities feed heat into the primary transport network and are responsible for the largest share of heat in the city. Waste heat from data centers is typical of a temperature of 30°C, and heat needs to be upgraded to supply into the primary transport or secondary distribution network. When integrating data center waste heat in the district heating network of Amsterdam, new arrangements will have to be made to support secure supply. Data center waste heat is currently offered for free in the Netherlands, but contractual agreements are needed to ensure reliability. The network layered approach for the case of Amsterdam can be used as a starting point for assessing data center integration scenarios.

3. *What value can be created by data center waste heat integration under different scenarios?*

The feasibility of a data center integration pilot project in the Kantorenstrook Amstel III area is analyzed for the years of 2020, 2025, and 2030, using the simulation tool EnergyPRO. The tool optimizes the allocation of heat demand among production units based on cost minimization. Four Key Performance Indicators were defined to address the value creation by integrating data center waste heat into the district heating network: Energy consumption, asset usage, costs for heat and electricity, and emissions.

The heat demand of 17.719,15 MWh is covered by waste heat from the data center and heat from the Diemen Heat Plant. Two heat pumps with a COP of 4 are used to upgrade the data center’s heat and simultaneously deliver cooling back to the data center. When integrating data center waste heat in the pilot area, fuel consumption (natural gas) decreases, whereas electricity consumption increases due to the heat pump usage. The heat pumps together cover 73,2 percent of the total heat demand and a large share of the data center’s cooling requirements. Furthermore, in all three years that are studied, total costs will decrease by around 41 percent when integrating data center waste heat (compared to the reference scenario), as well as a resulting decrease in emissions. The initial decision to use 2,25MW of heat supply from the data center is verified by testing two supply variations. Furthermore, a sensitivity and uncertainty analysis is done to understand the effects of input changes on the model output. Larger heat pump operation ranges allow for more heat supply and cover more heat demand, but the full load operating hours (FLOH) constrain the maximization. Uncertainty of the heat demand profile and the change in output for a comparable heat demand curve can have a substantial impact on decision-making. Thus, a thorough assessment to predict the demand profile is necessary to avoid risks in later phases.

The model supports the determination of the value that can be created by integrating data center waste heat. However, proper institutional arrangements need to be in place for its successful integration. Ownership structures, consumer types, a specific business model, and the influence of stakeholders are part of the system and characterize the system. The system engineering approach helps to understand the dynamics of the technical, economic, and institutional components of the district heating network. Still, the system’s dynamics require an understanding of possible future developments that could occur, and the effect this will have on the system.

4. *What are potential future (district heating and data center) developments, and how will these affect district heating in Amsterdam?*

The connection between the two networks in Amsterdam, through the Amsterdam South Connection, was built in 2020 to improve connectivity and heat distribution from one part of Amsterdam to the other. Physical connection enhances waste heat integration on a larger scale through the primary transport network. Such developments require similar rearrangements to follow on the institutional level. A more open and integrated network in Amsterdam could create new opportunities for other heat production parties and requires robust market and price models. An open network, where production and supply are disconnected, and third parties can sell their heat, would lead to an increase in cost efficiency. The next step would be to use a dynamic price model where supply and demand meet, and the market is optimized.

Developments could also occur on the data center side, as heat potential is increasing with their capacity growth, and so the efficient use of energy is required. A business model where the data center owns the heat pump could be implemented, and could create a cost-efficient situation for both the data center and district heating owners. In the (near) future, when data center waste heat integration is a proven business, it may become a primary heat source. However, a stable and reliable business (thus heat supply) is vital to match supply and demand all-time. The data center’s cooling demand could be partly covered by the heat pump operation. However, developments and enforcements to become more energy-efficient might induce a shift from cooling by heat pumps and chillers towards using free cooling and liquid cooling technologies. New cooling technologies would lessen the requirements for cooling from heat pumps.

This research aimed to gain insights into solutions for successfully integrating data center waste heat in the district heating network in Amsterdam. The main research question was defined as follows:

> *“What are the feasible approaches to integrate waste heat from data centers in the district heating network in Amsterdam?”*

In this thesis, data center waste heat potential in Amsterdam was studied. Developments in the physical network and the classification of data center heat as a renewable energy source, ask for an investigation to feasible integration approaches. A two-step approach has resulted from this study: Creating a theoretical understanding of the district heating system for a specific case, and looking into the practical case study by the use of a simulation tool, such as EnergyPRO.

Data center waste heat can be integrated into the high temperature transport network on a larger scale to support growth and meet CO_2 targets, or in the mid temperature distribution network, directly to an area in development. Related to availability of heat supply, network connections require the data center to be close to the district heating network, due to losses in the grid when covering longer distances. The recently constructed connection of the physical networks in Amsterdam can create opportunities for expansion and incorporation of waste heat from data centers, working towards a greener network. Simulation models such as EnergyPRO can support decision-making for a particular integration scenario. The modeled pilot project in the Kantorenstrook Amstel III area has shown feasible outcomes in terms of reduction of natural gas and associated CO_2 emissions and costs. Data center waste heat is offered for free in the Netherlands, supporting the affordability of integration.

However, the institutional component also influences the system, and accessibility can be enhanced by certain future network developments: An open network with allowance for third parties can further increase cost-efficiency. Other institutional rearrangements such as market-based pricing or corporative ownership have proven and fruitful outcomes in the Nordics and might be sufficient for application in the Dutch case. We can learn from more mature district heating markets in countries such as Sweden and Denmark. Still, we must not forget the unique character of a particular network, making each situation different from another. Policy drivers that impose regulations influencing the decision-making and waste heat integration cannot be simply and immediately introduced. Furthermore, interests and concerns from various stakeholders also affect the system. Actions, such as stakeholder engagement and price-transparency, will enhance its acceptability. Nevertheless, a clear vision of the functionality and interdependencies of all system components support steps towards successful integration.

7.2Recommendations

Recommendations to Vattenfall are given, in order to successfully integrate data center waste heat in the district heating network in Amsterdam:

- Using the network layered approach is of value to find and test opportunities to integrate data center waste heat into the district heating network of Amsterdam. Such a system engineering approach creates a clear and holistic understanding of the network layers by visualizing the interdependencies. Having no clear overview of interdependencies between and within the system’s layers makes certain decisions unsubstantiated.
- Modeling an integration case in EnergyPRO or a similar simulation tool is vital when studying a project’s feasibility. Not only will outcomes under certain input variables become visible, but also new insights can be gained for making critical decisions, e.g., how much supply the data center should deliver in the most optimal situation. Furthermore, robustness of the model must be understood by uncertainty and sensitivity analyses. Such a tool could serve as a starting point for a feasibility study, but other tools must be used alongside the tool to enhance decision-making.
- When making plans for new integration projects, taking into account technical components and corresponding costs does not complete a full feasibility study. Changes in the system influence all system layers, so the incorporation of the institutional layer components is also a necessary task. A change in the institutional layer will affect other layers, whether changes are introduced by new developments, such as the Amsterdam South Connection, or imposed by governmental bodies. Intangible reasons why new projects cannot get off the ground are often caused by less apparent institutional regulations. Therefore, all layer interdependencies need to be understood.
- Expansion of the physical network of Amsterdam creates opportunities for data centers waste heat to be integrated into the MT networks but also in the more extensive HT networks to cover more demand. For Vattenfall, anticipating the development of new technologies such as high temperature heat pumps, but also institutional re-arrangements such as third party access is important to maintaining the role of a leading party in the district heating market.
- Developments that will likely change the heating system in Amsterdam ask for strong corporation between Vattenfall and other stakeholders, such as the municipality and the DDA. Waste heat is currently offered free of charge, but increasing popularity of data center integration might require new price models and deals or contracts between involved parties.
- To gain more insights from other business models, international case-studies can be studied. Those can either be from countries with similar institutional arrangements to compare what works and what does not in a (slightly) different context, or from countries with other and sometimes more mature market structures (such as Denmark and Sweden) to understand possible developments.

8 Reflection

This chapter reflects upon the study that is presented in this thesis (Section 8.1) and the district heating system in general (Section 8.2). Furthermore, in Section 8.3, the scientific and social relevance of the study will be discussed. Lastly, recommendations for future research in the area of this topic will be given in Section 8.4.

8.1Reflection on the study

The creation of a network layered scheme has supported the understanding of the different layers that influence the district heating system. Incorporating the technical layer is crucial for an engineering project, the economic layer defines the feasibility of the business case, and the institutional layer is necessary to understand the playing field of the system. The generic scheme was used to create a detailed visualization for a case-specific district heating situation in Amsterdam. Using such a network layered scheme for a complex, unpredictable, and dynamic system will require the revision of components from time to time. Using the system engineering approach *supports* network insights but is not a 'blueprint' that guarantees a full understanding of the system. Furthermore, the scheme only visualizes the theoretical part of the district heating system, and will not itself create solutions for integration.

To explore solutions for integrating data center waste heat, a model was created in the EnergyPRO. KPIs have supported a structured analysis of the results of data center integration, in comparison to the reference case. The robustness of the model was discussed through uncertainty and feasibility analyses. Further validation of the results can be done by using similar software tools (with a different math algorithm) and comparing model outputs. Obviously, full validation of the model can only be retrieved after implementation. The model is techno-economic and institutional arrangements were analyzed separately. Using a more qualitative tool that involves regulatory and societal input parameters will yield other outcomes.

During the thesis, the scope of the research has become smaller, and the level of detail has become larger: The study flows from a national scale towards a specific area. It develops a particular system engineering approach for implementation, and uses EnergyPRO to simulate this system. Choices made throughout the study resulted in the exclusion of other related topics. These topics are left for future research.

8.2Reflection on the district heating system

Various district heating applications in the Netherlands and elsewhere have proven it to be a successful technology for residential and commercial heating requirements. However, certain difficulties in the district heating system introduce the necessity to reflect upon the system in general.

8.2.1 Comparisons to other energy markets

Amongst the literature, district heating in the Netherlands is not only compared to other countries' markets but is also often compared to energy infrastructures of electricity and gas. Electricity, gas, and heat infrastructures are usually represented as comparable markets due to their network similarities, such as the process steps from generation to consumption, and the security of supply. Despite system similarities, many aspects make district heating less comparable to the electricity and gas systems.

Concerning the physical network, many components such as exact supply and return temperatures, distances to be covered, and construction of new pipelines are still up for discussion in the district heating system. In contrast, for the more mature electricity and gas systems, standards (e.g., natural gas extraction, voltages, frequencies, etc.) are formed and complied with, and the network is already in place. Furthermore, transport losses in the heating network are more significant compared to the other energy infrastructures, and high sunk costs make accessibility to new entries more difficult.

Letting loose of analyzing the district heating network as if it is closely related to the electricity and gas networks opens up a way to (re-)design institutional arrangements, such as a change in ownership structure or getting rid of using natural gas as the reference for the heating price. The infrastructure could be designed separately from existing energy infrastructures and more like a fully privately-owned sector where heat is seen as a basic needs, and no competition is existing (more similar to the water utility sector).

8.2.2 Other heat systems

Besides district heating technologies, there are other heating alternatives for the replacement of natural gas utilization. Two alternatives for large-scale applications in the urban area are ‘all-electric’ and the utilization of green gas (biogas or biomethane). All electric is a solution where heat is produced with electricity and heat pumps to heat rooms and tap water. Green gas is made from sustainable raw materials and can replace the unsustainable natural gas source. Each alternative has its costs and related CO_2 emissions, and the most suitable option is dependent on various factors, such as building density and insulation, existing infrastructure, as well as economic and environmental advantages, etc.

Opportunities for sustainable heat utilization in different areas are examined by the municipality, together with network operators, energy companies, housing associations, and homeowners. Every area is unique and requires a specific investigation for the best solution. It is therefore not apparent whether district heating is the best alternative for natural gas, and so the potential of other solutions must be examined too.

8.2.3 Social acceptance

Another concept that is often not included in literature is the social acceptance of district heating systems. In Section 2.5, the aspects ‘norms, values, and ideas’ that are rooted in society’s systems are addressed. Decisions about network developments and arrangements can foster social acceptance, but can also cause disagreement rather than consensus. The effect of certain decisions on the institutional layer, such as ownership and price regulations, must reflect societal perceptions.

Successful integration of district heating networks requires the support of citizens, and this can be enhanced by the transparency and involvement of residents in a project within the concerned area of development. Citizens and (new) consumers can be given a role in the decision-making process throughout project implementation. This will build trust and enhances the *acceptance* of the system. The

Dutch district heating system could not only learn from institutional arrangements and best practices in the Nordic countries, but also from social initiatives and actions to empower citizens.

8.3 Scientific and societal relevance

As introduced in the first chapter, research is being done on technologies and approaches for data center waste heat integration. Alongside studying feasibility in theory, we could learn from real-life examples in countries with more mature networks. However, simply following other countries alone will not work due to differences between the systems, in particular, the less obvious institutional factors. Understanding interdependencies between a country's institutional arrangements and the technical and economic components of the district heating system is necessary. This study affirms that a system engineering approach supports decision-making in such a complex environment.

In this thesis, EnergyPRO is used to model a specific data center integration case. The simulation tool is suitable for modeling complex energy systems such as district heating networks. Not only does EnergyPRO provide clear results based on input parameters, but the model could also give new insights into the system, e.g., what effect changes in the model would have. EnergyPRO is considered useful for various decision-making aspects, but it does not take into account institutional designs, and these must be analyzed separately.

District heating in the Netherlands is gaining attention because it provides an alternative to the use of natural gas and reduces CO_2 emissions. The Dutch Government has targeted completely ceasing natural gas for residential heating by 2050, and Vattenfall actively joins this goal and wants to make fossil-free living possible within one generation. Recovering waste heat from data centers enables sustainability and the furthering of a green city image. Data center waste heat integration in the Netherlands is still in its infancy, and yet, important system decisions are to be made. Developments in district heating and data center businesses are likely to enhance integration. Actively looking for projects and solutions could place Vattenfall at the forefront of the Dutch energy companies making use of data center waste heat.

8.4 Future research

Following on from the reflections of this study, and the considerations of the district heating systems, topics on future research regarding district heating and data center waste heat integration are provided below:

- Applying the methodology in another context: The system engineering approach that is applied in this study could be utilized in district heating networks of other cities, both in the Netherlands or abroad. Insights into other structures could be useful for understanding the system.
- Using a different simulation tool: In addition to EnergyPRO there might be other suitable tools for creating a similar district heating model. Using other tools to compare output and results could enhance the validation of the model and may provide new insights.
- Looking from the opposite perspective: Successful integration of data center waste heat integration into the district heating network is two-fold, and an interesting study would be to research feasible approaches from the data center's perspective. This would elucidate more developments from the data center's perspective.

- Incorporating the ‘social’ component: One component that is not explicitly included in the study but is reflected upon above is the social element. Elaborate research could be undertaken into social support, barriers to waste heat integration or district heating in general. Comparing integration incentives for different countries on the basis of social drivers could also be studied.
- Implementing other heat sources: Alongside data centers, other heat sources such as aqua thermal, geothermal, biomass, etc. could also be integrated into the district heating network of Amsterdam.
- Benchmarking to other network infrastructures: The heat infrastructure is often compared to the electricity and gas infrastructures. New insights could be gained when comparing to other infrastructures such as the privately-owned (drinking) water infrastructure when competition is non-existent.

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Appendixes

A: Interviews

1. Heat Pump COP

Interviewee: Laure Itard, TU Delft professor
Date: April 2, 2020
Purpose: Validation of heat pump specifications and calculations

1. *Heat pump technology*

There are two methods to calculate the COP value. It's simple thermodynamics, so you could prove that both ways would lead to the same outcome. A heat pump consists of a low temperature (evaporator) side and high temperature (condenser) site. Furthermore, a compressor uses electricity to drive the heat pump. To produce heat, you have two inputs; electricity for the compressor and heat from the heat source. The Carnot process is the ideal heat pump process, indicated by the COP_{Carnot} (or COP_{ideal}). This ideal COP can be achieved by dividing the high temperature by the difference between the high and low temperatures. With thermodynamics, you can prove that this value can also be obtained by dividing the amount of heat rejected from the condenser by the capacity going into the compressor.

2. *Carnot factor*

Ideally, the two methods should have the same outcome. However, in practice, you see that the heat pump is not running with 100% efficiency. The Carnot factor (η_c) reflects this. This factor is specified by heat pump manufacturers for different capacities and temperature ranges. The factor can also be determined when the amount of heat from the condenser, the electrical capacity that is used, and the temperatures are known.

However, the COP is varying because both the ambient temperature and the heat demand are not constant. This is the reason that, in practice, we often use the SCOP, which is the seasonal COP, averaged over the whole heating season. Heat pumps are developed for certain temperature ranges and capacities, and they influence the behavior of a heat pump. For instance, in very cold winters, a heat pump might not perform as you would expect.

3. *Temperature levels for COP*

In the case of data center waste heat integration on the distribution network, the temperature on the condenser side must be 70 degrees, and on the evaporator side, you are dealing with a temperature of 20 degrees. However, since the evaporators and condensers are heat exchangers and therefore not 100% efficient, to achieve a range of 50 degrees in practice, the theoretical temperature range must be somewhat bigger. This difference is reflected in the Carnot factor. The factor depends on the design of the heat pump, the performance/efficiency of the compressor, and the performance of the evaporator and condenser (the heat exchange components). High performance results in lower temperature changes in the cycle, resulting in a higher Carnot factor.

There is no reason for using other variables such as the heat going into the evaporator (30 degrees) or using mean temperature.

4. *Heat pump configurations*

From a low temperature source (i.e., a data center), upgrading to high temperatures results in a very low COP and is therefore not efficient. There are examples of configurations in series or parallel, but this requires calculations. E.g., when placing heat pumps in series, the COP is decreasing. However, in some cases, it has advantages.

2. Regulations

Interviewee: Aad Correljé, TU Delft professor

Date: April 6, 2020; May 4, 2020

Purpose: Understanding regulatory concepts of district heating markets in different countries.

Regulations

1. *Gas and electricity markets are different*

There is not one single approach to compare countries' district heating networks. Comparing one-by-one is not easy and not useful because there are so many (significant) differences. It is better than to look at the basic principles that each country has in its legislation and in the way they treat heat. Throughout the EU, electricity and gas networks work the same in every country because of the EU Directive, but this is not the case for heat. Klein (1999) explains in his article the fundamentals of gas and electricity networks and design variables.

2. *Unbundling and single-buyer*

In the case of gas and electricity, we see unbundling happening, meaning; competing elements in the system. For heat, there are limited possibilities for competitiveness. It is, however, possible, but it means that the current system should change to a system where there are multiple heat providers connected based on long-term contracts, coordination, and security of supply. Towards a single-buyer model: Heat providers offer heat via long-term contracts in competition with each other, and the heat company (e.g., Vattenfall) determines who supplies and when. Then the tariffs/fee structures and conditions become important.

3. *Comparing district heating in countries*

For each country, district heating is implemented differently. Choices made in terms of grid management, access to competition, contracts for heat providers and consumers, owners of the grid (collective, municipal, etc.) are different in every country. When having understood those differences for a market variable, the causes and effects of different structures can be identified.

4. *Cause and effects*

Differences between countries can be based on maturity, growth, or the size of the networks. For instance, bigger networks across cities mean that there is more potential for new market entry. For some countries, a certain degree of market opening works, while in other countries you see the tendency towards less or more competition. Question is then why a particular market structure works or not. Is this because of the principles of a country or technical impossibilities? When the origins of markets are clear, you could determine if and how a particular market structure in Denmark or Sweden could be applied in the Netherlands.

5. *Different concepts*

There are technical, economic, and political concepts. Policies are often the starting point, after which the technical and economic dependencies are explored. Besides policies, also ideologies are playing a role based on norms and values. Think about emissions, water protection, civil rights and equality, private initiatives, and other issues that could be of high or low importance for a country. These play an important role in a country's decisions. The basic policy principles are determining a country's regulations, whether this is on a national level (more like the gas and electricity markets) or on a regional level, which is still often the case for heat networks nowadays.

Institutional

6. *Understanding a heat network*

To understand the district heating network, it is important to describe them in detail. What is the capacity, temperature range, need for storage, volumes, and other technical concepts. The same can be done for economic characteristics. Next, the institutional arrangements can be shown to display ownership structures, dependencies between parties, different contracts, and coordination in the techno-economic system.

7. *Data center integration*

When integrating data center waste heat, arrangements, and institutional conditions are of high importance. Think about contracts, risks, fixed/variable costs, etc. Then, for the case of Amsterdam, there is a difference between integrating into Westpoort Warmte versus the stand-alone Diemen plants. The Diemen plants (CHP), with their must-run characteristics, also rely on the dynamics of the electricity market (power versus heat). A new institutional may be unavoidable.

8. *Consumers*

It is important to understand the types of consumers so they can be distinguishable between different heat patterns. For households, you see day-night patterns, whereas offices have weekdays-weekend patterns. Different types can be: Households, small businesses (e.g., shops), large businesses (e.g., offices), utilities (e.g., schools, hospitals, etc.), and industries. Different types of connections have different arrangements. Some are more predictable, and long-term contracts can be formed, whereas others can be somewhat unpredictable but reply to the NMDA principles (households).

9. *Subsidies and taxes*

Subsidies and taxes can be part of the institutional layer (rules of the game), but you could also see them in the economic layer, as part of the where they are part of revenues or expenses. Some subsidies are connected to investments, while others are connected to produced heat (CapEx or OpEx). This is depending on the subsidy structure. The question is: How would data center integration be connected to subsidies and who would receive those subsidies?

3. Key Performance Indicators

Interviewee: Martin Hierl, Vattenfall

Date: March 26, 2020; April 24, 2020; May 8, 2020

Purpose: Defining Key Performance Indicators (KPIs) and other indicators for the district heating case of Amsterdam

1. *Key performance indicators*

When modeling data center waste heat integration scenarios and reference scenarios for comparisons, four Key Performance Indicators (KPIs) are developed and will be used for model analyses.

Key Performance Indicators		
Energy consumption	The modeler wants to minimize electricity and natural gas consumption.	Technical
Asset usage	The modeler wants to maximize asset usage. Asset usage is the data center heat share of the total delivered heat at consumers (expressed in %).	Technical
Cost of heat and electricity	The modeler wants to minimize the cost of heat and electricity.	Economic
CO_2 emissions	The modeler wants to minimize the CO_2 emissions of heat and electricity.	Environmental

2. *Other indicators*

Other (quantitative and qualitative) indicators are included and will incorporated too.

Other indicators		
COP	The modeler wants to maximize heat pump efficiency, COP.	Technical
Heat pump operation	The modeler wants to maximize heat pump operations to 6.000 full load hours.	Technical
Supply flexibility	The modeler wants to run the plant with the lowest price of heat.	Technical/ Economic
SDE subsidies	The modeler wants to apply for SDE subsidies.	Economic/ Environmental
BENG	The modeler wants to comply with BENG regulations.	Environmental/ Regulatory

4. Refrigerants

Interviewee: Carlos Infante Ferreira, TU Delft professor
Date: April 29, 2020
Purpose: Insights into refrigerant developments and criteria for refrigerant selection.

1. *HFCs HCFCs, and CFC phase-out, and HFOs and HCFOs as replacing refrigerants.*

We can see a declining trend when it comes to allowed values of GWP until 2030, but the limit for GWP is 750 (limit is, however, depending on the application). This means that there is not per se a total phase-out of those refrigerants, but you will see that many are not complying with the limit and are therefore phased-out.

HFOs and HCFOs have similar characteristics compared to HFCs, HCFCs, and CFC, such as non-flammability and low toxicity but are better degradable, and therefore, they have a lower GWP. However, they can form TFAHs (which can also be found in the Tefal pans). The composition of HFOs in the atmosphere, you create TFAs, and when considering large amounts, this could be a problem in the future. So in 93' HFOs and HCFOs where suitable solutions for replacing refrigerants with high GWP and ODP, but now we see other environmental factors that could play a role in the future.

Despite the high GWP and ODP of some synthetic refrigerants, we see that they are still pushed in the market due to the lobbying efforts of refrigerant producers (chemical companies). They, of course, need to earn back their earlier investments. Carlos Infante Ferreira sees that even HCFOs such as R1233zd(E) with an ODP above 0 still appear in studies nowadays.

2. *Natural refrigerants.*

Natural refrigerants are complying with ODP and GWP generally and are therefore typically more suitable. Carlos Infante Ferreira would prioritize the choice of natural refrigerants over synthetic refrigerants. However, they do have disadvantages. Some are flammable, and some are toxic. However, the negative impact of those criteria is dependent on the application and might be minimal for industrial applications. Vattenfall could s flammability, but this is different. The question is also what the company's (Vattenfall) considerations are regarding the safety levels.

Ammonia → Ammonia is commonly used in big installations (MW ranges), but is toxic (500 parts per million). So you don't want this in residential areas. However, for industrial applications, this can still be suitable as long as you comply with regulations. Ammonia's price per delivered heat is very cheap, but the installations are more expensive.

Water → When using water, you need to work with lower pressures, so big volumes and big installations. There are examples of products on the market with water as a refrigerant (at very specific conditions), but it is not common.

Carbon dioxide → In the Nordics CO_2 is a commonly used refrigerant (e.g., in supermarkets), and you see examples in the Netherlands too. However, the constant evaporator temperature versus the supercritical compressor temperature on the other side of the heat pump creates challenges. Heat sink and sources with the same refrigerant are therefore hard to combine.

3. *Research NVKL and TU Delft*

The NVKL looks at the socially responsible impacts of refrigerants, so the environmental criteria but also safety criteria. The NVKL and TU Delft have developed a matrix in which refrigerants with a GWP below 750 (also used in the EU car industry) are compared based on their efficiency (COP) and costs (euro/MWh). The study is using design approaches from Zühlsdorf, B. et al. (2019). The amount of working fluid that you need depends on the refrigerant and application. The study takes into account the investment level, the quantification of emissions, and the amount of working fluid.

4. *Economic considerations*

Despite the environmental and safety criteria impacts of refrigerant selection, there are often economic considerations that can restrict choices. You want the price per MWh delivered to be as low as possible. I.e., an HFO could cost much more per kilogram than, for instance, ammonia.

Producers in Japan and Korea often still use HFC R32. It is flammable, has a GWP of 800, and is not efficient but the advantage of R32 is its cheap investment costs. Even though many other refrigerants are more suitable, this refrigerant is used because of economic considerations.

5. *Leakage and flammable refrigerants*

Annual leakage of a heat pump system is ~7%. Only ammonia installations are fully closed. For flammable refrigerants, the system will become more expensive due to their compressors, so generally, investment levels are higher for flammable refrigerants. Also, you want to take measures to minimize the amount of flammable refrigerants to prevent high concentrations.

5. System engineering approach

Interviewee: Hans Otten (former senior consultant at Greenvis)

Date: May 8, 2020

Purpose: Understanding how to go from data center integration concept to business case.

1. *Identifying opportunities, qualification, selection, and a concrete plan*

Data centers produce waste heat, are tied to their location due to the network infrastructure, and they want to grow. However, expanding is only possible when waste heat is 'organized' and equipment is efficiently used. More sustainable and efficient cooling is necessary to get a license to expand. One way is to receive cooling in turn for waste heat. For identifying opportunities for data center integration includes three main aspects: The location of the data center, the heat capacity, and the area type for integration (e.g., built environment, industrial area, etc.).

When qualifying the area of integration, you determine the building stock and types. Newly built buildings are ideal because they are more efficient (better insulation) and, therefore, suitable for lower temperature waste heat sources such as data center heat. You can also look from the other side; to connect close to a high temperature network, which can always serve as a backup. This creates different opportunities.

You pre-qualify the consumer groups in the area (housing corporations, municipal properties, large buildings) based on the heat capacity available and their demand. When having determined the potential consumers, the heat capacity and demand can be coupled.

The municipality joins the table when you have identified the data center, selected the opportunities, the area, and created a business case. Strategies and visions must be aligned.

2. *Technical, economic, social, governance.*

Whether you use GIS or EnergyPRO or another similar tool, they all have the same purpose, which is determining the techno-economic layer. Besides 'technical' and 'economic' components, two other components would be 'social' and 'governance'. The municipality is part of the governance layer. Typically, the municipality has full control. A municipality can act in different ways, from the supporting role for the initiative (of Vattenfall) and giving permits to roll out the project (concession), to taking the role of the developer with the ambition to control the heat network.

3. *Data center potential and future developments*

Data centers have high reliability and certainty: Business cases can be developed for 40+ years because data centers won't move from location, will only deliver more heat over time, and it is a continuous business. Data centers are important and play a big role in Amsterdam. Other sources might have less potential in terms of lifetime and secure supply.

The future will bring smarter chips that release less heat. Data centers will expand, and percentage-wise waste heat potential will increase. With the use of heat pumps, data centers can receive cooling in return and can decrease the running time of costly and 'dirty' chillers. However, in terms of reliability, a data center must act just like a hospital (no risk can be taken), and investing in new technologies can be considered too risky.

4. *Paying for waste heat*

District heating in the Netherlands is not like in Sweden, for instance, where the data center receives money for heat supply. When municipalities own the infrastructure, the market is regulated, and waste heat can be offered. In Amsterdam, the whole chain is owned by Vattenfall, so price structures are different, and lock-in effects might be the result. Nevertheless, there are municipal heat companies in the Netherlands (e.g., Eindhoven and Roosendaal).

6. Arrangements in Amsterdam and Swedish model

Interviewee: Caryl Jonis (Vattenfall)

Date: May 8, 2020, June 16, 2020

Purpose: Understanding data center waste heat integration in Amsterdam and insights into the Swedish model.

Integration in Amsterdam

1. *Data center waste heat integration solutions*

Vattenfall explores two basic technical concepts of data center waste heat integration: Integration in newly developed areas and integration to induce growth and meet sustainability targets. The first type mainly corresponds to a local solution in the mid temperature regime, whereas the second type is a more central and larger-scale solution often in the high temperature regime, where the solution can be seen as a large scale heat source for the grid.

Data center integration in Amsterdam is new, and we must learn from best practices in countries such as Sweden. Starting on a small scale and explore opportunities would be a suitable first step, e.g., such as the case in the Kantorenstrook Amstel III area. Data center waste heat integration could be rolled out in the Kantorenstrook Amstel III area because this area will transform from a monotonous office area to a lively work and residential recreation, which makes it easier to build the physical architecture and connect the data center and heat pump(s). Vattenfall would own this network and is responsible for the operation, although Vattenfall first needs concession from the municipality to develop in this area.

2. *Mid temperature and high temperature regime*

The Kantorenstrook Amstel III mid temperature integration is a neighborhood-scale project and an attractive solution for making an area most sustainable. The Diemen Heat Plant could then still serve for back up heat production. On the other hand, large amounts of data center waste heat would be attractive for integration in the high temperature regime. The grid can then be seen as a heat sink.

In the future, we will possibly see MT and HT networks alongside each other. Temperature ranges might become somewhat lower due to better technologies and insulation. For instance, the current HT network is designed and constructed to supply heat even when the outside temperature is -10°C. The question arises whether this is still necessary with increasingly milder winter and better-insulated homes and offices. Even when the temperature of the HT network declines, we will be making use of HT networks due to the long distances to cover (against heat losses in the pipelines).

3. *Large scale project example Amsterdam*

Datacenter Westpoort (owned by the Caransa Group) is an example of a large scale project opportunity. The waste heat of this data center would be fed into the transport line. Whereas Kantorenstrook Amstel III would be connected to the South East network, the data center Westpoort would be connected to the WPW network. Besides the larger scale of the project compared to the Kantorenstrook Amstel III project, also the different ownership structure results in a large decision-making trajectory: Vattenfall, the owner of the data center, and the municipality are involved in the decision.

The Swedish model

1. *Ownership*

In Sweden, the heat producer (the data center) invests in the construction of the network, pipe installations, heat pumps, cooling systems, etc. and the provider (e.g., Fortum Värme) only invest in the delivery pipeline. The heat pump is then part of the cooling system of the data center. The heat provider would buy heat from the data center.

When integration data center waste heat in the Netherlands, Vattenfall would own the network and the heat pump and would receive residual heat at 'the door' of the data center. However, in return, Vattenfall's heat pump delivers cooling to the data center, and the data center saves energy on running its electric chiller and additional costs for maintenance. We could expect that a particular business model would be in the place where Vattenfall puts a price on the cooling.

2. *Open network*

Consumers in Sweden were unsatisfied that they could not switch from heat provider. Sweden has opened up the district heating market (on the heat producers' side first) to see how the market would develop. It is called an 'open network'. Anyone who has heat left can ask a heating company to make an offer to buy the heat. Heat companies are then obliged to make an offer. The open network works well, and there is no need to open up the market on the supply side to allow multiple suppliers on one heating network. Open networks are common practice in Sweden.

3. *Business model*

In Sweden, there is no price regulation. This seems to work due to transparency in the open network, but also because, in Sweden, energy companies use price models based on hourly marginal costs. For instance, the example of energy company Fortum Värme, that purchases excess heat at a price reflecting its alternative heat production costs spread over several types of contracts.

In contrast to Sweden, where the market is pro-active, in the Netherlands, many parties seem to have 'cold water fear' and do not want to take the risk of changing the current situation.

7. Future developments in data centers

Interviewee: Erik Barentsen

Date: June 25, 2020

Purpose: Insights into future developments in the data center business.

1. *Data center waste heat in Amsterdam*

In 2017, data centers initiated offering residual heat for free. However, data center waste heat was initially not complying with BENG as sustainable heat source and initiatives were started to include data center waste heat as industrial waste heat. Currently, data center waste heat complies with the BENG regulations.

In Amsterdam, Vattenfall (with existing physical networks) but also other companies see opportunities in new business cases. Operators are looking for sustainable district heating sources, and data center's waste heat could be a potential source. The network must, however, be closely connected to the data center. The technical challenge of integrating data center waste heat is upgrading the low temperature heat to a suitable temperature level. The economic challenges lie in the fact that natural gas prices remain low and are competing with new district heating sources. Governmental parties are pushing energy transition, setting the goal to move away from natural gas.

2. *Heating and cooling*

Free air cooling, using outside air to cool data centers, is a cooling technology. About 75 to 80 percent of the year, data centers can be cooled by using this free air cooling method. However, in hot summer days, adiabatic cooling technologies are used. During those days, data centers produce heat while there is no demand for heat on the consumer side. Heat needs to be removed in any case and will be wasted into the outside air.

Connecting to the district heating will not only deliver heat to the network but will also provide cooling for the data centers. The data center saves electricity use and costs for cooling.

3. *Business case*

For now, waste heat will be delivered for free. The owner of the district heating network is (financially) responsible for the connection and operation. However, continuity of data center operation is key, and agreements for proper heat trading need to be made. However, dedicated contract structures between data centers and district heating owners are not realized yet.

Residual heat is delivered with 'best efforts,', and full guarantees of stable heat delivery are risky to make. Therefore, a data center would not be the only heat source in a network. Other stable sources are needed to cover possible peak demand and to act as back-up systems.

Data centers in the Netherlands will probably not be incorporating the business of energy delivery in the near future. However, a possible development could occur when hydrogen is becoming an important energy source, and if data centers are capable of generating their energy with hydrogen pipes. This would create a shift in the business case, and energy production would be a part of the data centers' activity.

4. *Role of Municipality*

The municipality has the exclusive right to decide who is going to supply heat in a certain area (by giving concessions). The municipality of Amsterdam is pushing towards the use of the data center hub and corresponding waste heat potential in Amsterdam, whereas in other cities, other sources might have more potential. However, feeding in heat can only work when the physical network is actually there or can be implemented.

5. *Development trends*

We see two trends:

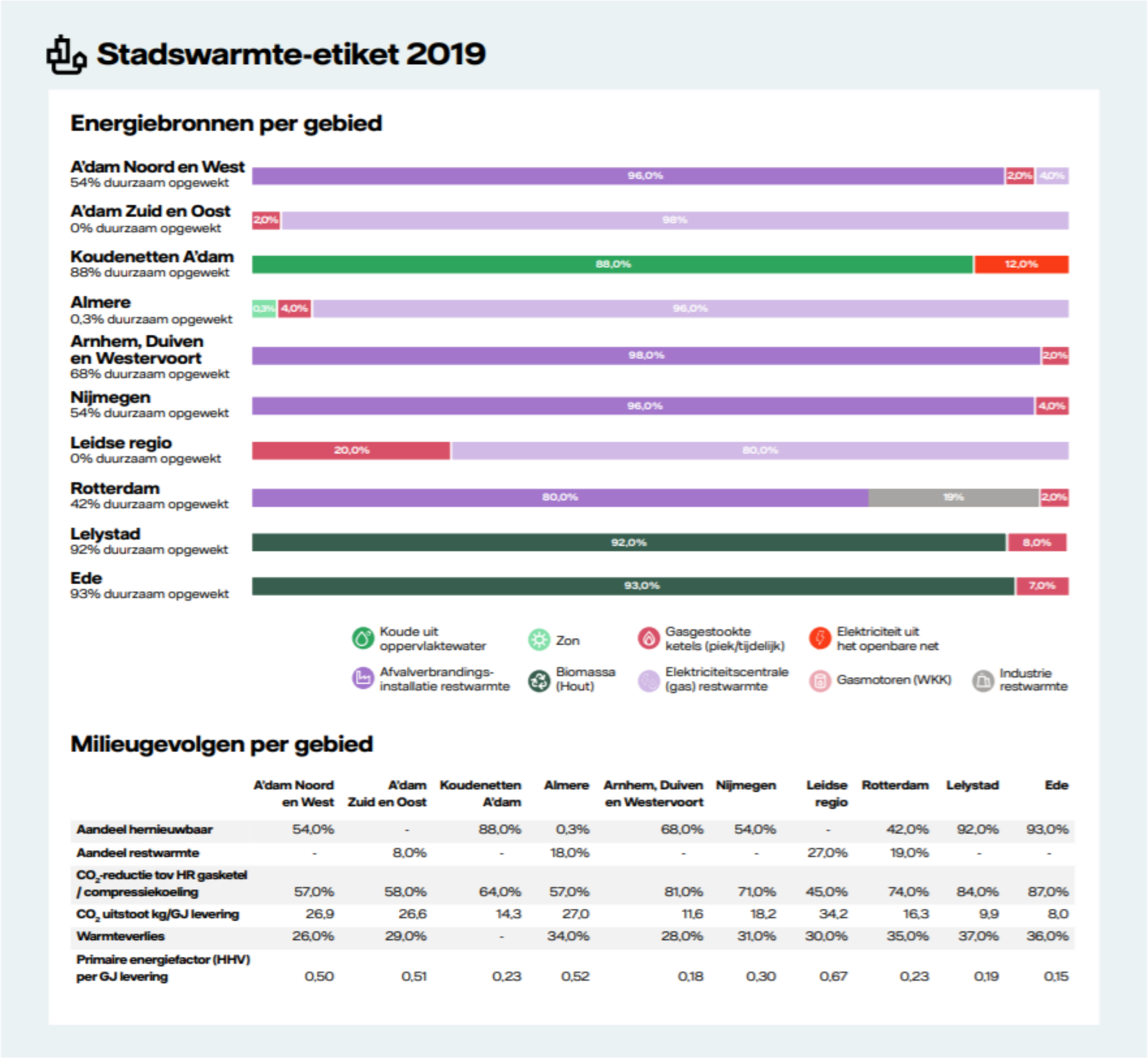
- More data center capacity is developing, and new data centers will be built. Rooms can be arranged more efficiently to allow more servers per area.
- Energy efficiency is increasing, and the PUE is getting better. This is due to the development of cooling technologies. The airflow is getting more optimal, and the required area can be smaller. Data centers can be cooled by conventional cooling technologies, but a new technology is commonly used where servers are cooled using liquid-cooled systems. Such systems are more efficient than air-cooled systems. Air cooling is still suitable because it is a universally applied technology, and liquid cooling through small pipes requires new setups.

6. *Temperature increase*

With liquid cooling, data center temperatures can increase and create higher efficiencies. This makes feeding in heat easier and waste heat becomes more useful. Emerged cooling is another kind of liquid cooling that can become suitable for so-called high-performance computing applications. New datacenters with such applications and emerged cooling systems might reach higher temperature ranges than the current ~30°C degrees. Heat pump needs to be allocated so that they are suited for possible increases in data center supply temperatures. However, temperature increases won’t go rapidly, and on the data center side, the maximum temperature in air-conditioned rooms with servers is also restricted to meet working conditions.

B: District heating network information Amsterdam

1. Heat label (in Dutch: warmte-etiket) Amsterdam 2019



Stadswarmte-etiket 2019

Energiebronnen per gebied

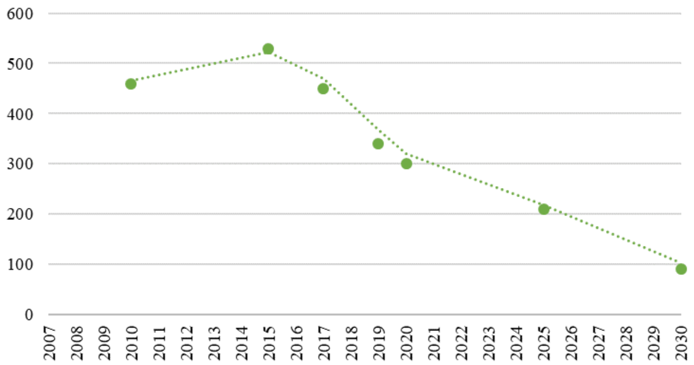
Milieugevolgen per gebied

	A'dam Noord en West	A'dam Zuid en Oost	Koudenetten A'dam	Almere	Arnhem, Duiven en Westervoort	Nijmegen	Leidse regio	Rotterdam	Lelystad	Ede
Aandeel hernieuwbaar	54,0%	-	88,0%	0,3%	68,0%	54,0%	-	42,0%	92,0%	93,0%
Aandeel restwarmte	-	8,0%	-	18,0%	-	-	27,0%	19,0%	-	-
CO_2-reductie tov HR gasketel / compressiekoeling	57,0%	58,0%	64,0%	57,0%	81,0%	71,0%	45,0%	74,0%	84,0%	87,0%
CO_2 uitstoot kg/GJ levering	26,9	26,6	14,3	27,0	11,6	18,2	34,2	16,3	9,9	8,0
Warmteverlies	26,0%	29,0%	-	34,0%	28,0%	31,0%	30,0%	35,0%	37,0%	36,0%
Primaire energiefactor (HHV) per GJ levering	0,50	0,51	0,23	0,52	0,18	0,30	0,67	0,23	0,19	0,15

Vattenfall (2020)

C: Efficiency and CO_2 emission factor of electricity

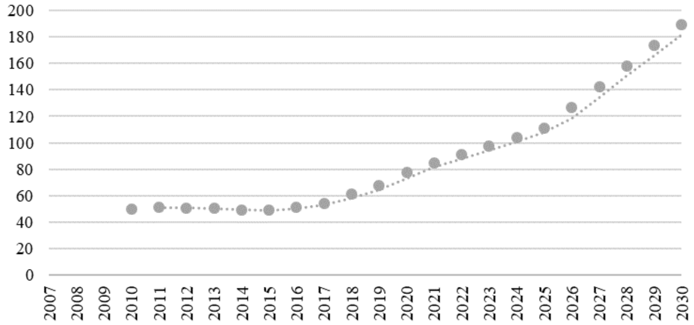
1. CO_2 emission intensity electricity graph



CO_2 emission intensity of electricity in kg CO_2/MWh based on realities and predictions (PBL, 2019).

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020		2025		2030
	460	474	488	502	516	530	490	450	395	340	300		210		90

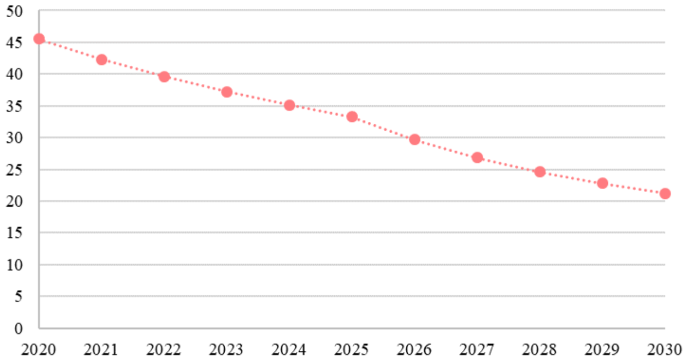
2. Efficiency primary fossil graph (EOR)



The efficiency of primary fossil energy (EOR) in percentage based on realities and predictions (PBL, 2019).

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020		2025		2030
	49,8	51,7	50,4	50,7	48,9	49,1	51,4	54,5	61,1	67,8	78		111		190

3. CO_2 intensity heat in Amsterdam South East (Diemen Heat)

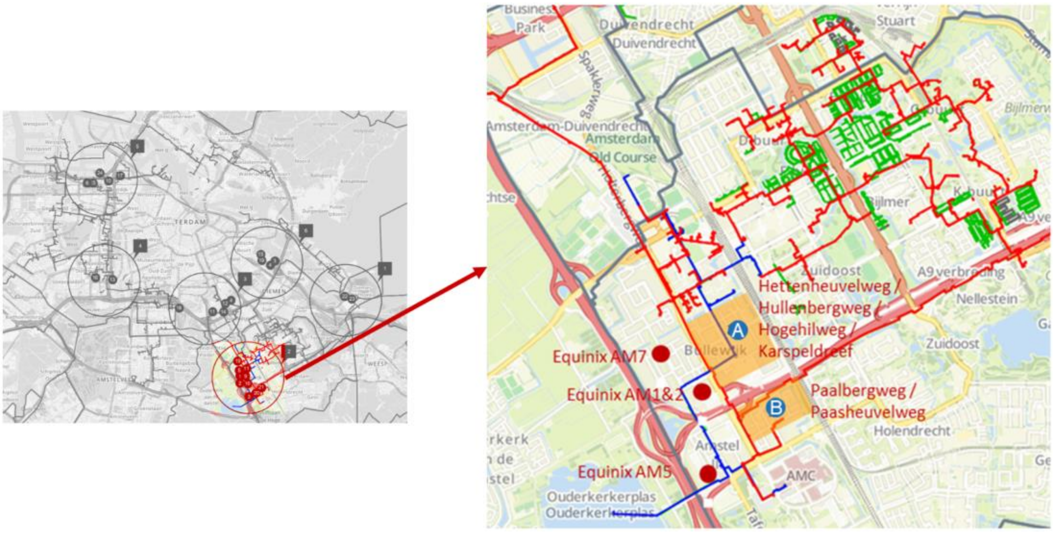


CO_2 emission intensity of Diemen Heat in kg CO_2/MWh based on realities and predictions (PBL, 2019).

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	45,6	42,4	39,6	37,2	35,1	33,3	29,7	26,7	24,6	22,8	21,2

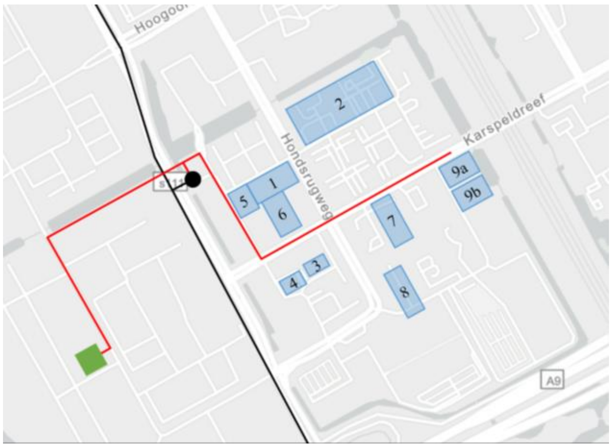
D: Kantorenstrook Amstel III

1. City map Amstel III



(Vattenfall heat NL, 2020a)

2. Kantorenstrook Amstel III map (green: data center, blue: building blocks)



(*Source*: *Author's own* figure)

3. Heat demand calculations

Area[8]	**Retail (m^2)**	**Office (m^2)**	**Community/ Education (m^2)**	**Residential apartments (#)**	**Row (#)**	**Affordable rent units (#)**
1. Hettenheuvelweg 50	-	4.000		83	82	103
2. Hogehilweg 5-11	3.000	20.000	1.200	300	300	500
3. Hettenheuvelweg 12-14		1.500		558		
4. Hettenheuvelweg 16		500		143		
5. Hettenheuvelweg 26		15.000				
6. Hessenbergweg 95		500		274		
7. Karspeldreef 4				82	164	28
8. Hullenbergweg 1		20.000		112		
9. Karspeldreef 14-16		13.400		512		
Total	3.000	74.900	1.200	2.064	546	631

Building types	**(m^2)**[9]	**(kWh/m^2)**[10]	**Occupancy**[11]	**Consumption (kWh/year)**	**Production (MWh/year)**[12]
Retail	3.000	50	100%	150.000	
Office	74.900	50	100%	3.745.000	
Community/ Education	1.200	50	100%	60.000	
Residential apartments	165.120	42,5	95%	6.666.720	
Row	65.520	42,5	95%	2.645.370	
Affordable rent units	31.550	42,5	95%	1.273.831	
Total				14.540.921	17.719

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[8] Data is retrieved from https://www.amsterdam.nl/projecten/amstel3 and internal data (Vattenfall Heat NL 2020b).

[9] A residential apartment has 80 m^2, a row has 120 m^2, and an affordable rent unit has 50 m^2 (Vattenfall Heat NL, 2020b).

[10] Domestic heat demand is 42,5 kWh/m^2 (25 kWh/m^2 space heating and 17,5 kWh/m^2 tapwater) (Vattenfall Heat NL, 2020b). Non-domestic heat demand isq 50 kWh/m^2 (BENG regulations, lente-akkoord.nl (2019)).

[11] Vattenfall has proposed to work with 95% occupancy (% of floor area / dwelling) for domestic apartments. Occupancy is already included in calculation for non-domestic apartments (so set at 100%).

[12] Losses are 17,9% of production (Vattenfall Heat NL, 2020b).

E: Modelling

1. Model verification: Heat supply (1,5MW and 3,0 MW)

1,5MW capacity		**DCI scenario**		**REF scenario**	
Heat demand	Kantorenstrook AMSIII	17.719,1		17.719,1	
Cooling demand	Data center	9.855,0		9.855,0	
Heat production (MWh/year)	Diemen Heat	7.217,0	40,7%	17.719,1	100,0%
	Data center HP1	7.418,5	41,9%	-	-
	Data center HP2	3.083,6	17,4%	-	-
	Electric chiller	0,0	0,0%	0,0	0,0%
	Total	17.719,1	100,0%	17.719,1	100,0%
Cooling productions (MWh/year)	Diemen Heat	0,0	0,0%	0,0	0,0%
	Data center HP1	5.563,9	56,5%	-	-
	Data center HP2	2.312,7	23,5%	-	-
	Electric chiller	1.978,4	20,1%	9.855,0	100,0%
	Total	9.855,0	100,0%	9.855,0	100,0%
Electricity consumed by energy units (MWh/year)	Data center HP1	1.854,6			
	Data center HP2	770,9		-	
	Electric chiller	395,7		1.971,0	
	Total	3.021,2		1.971,0	
Full load operating hours (hours/year	Diemen Heat	902		2.215	
	Data center HP1	7.418		-	
	Data center HP2	6.167		-	
	Electric chiller	1.759		8.760	
Fuels (MWh/year)	Diemen Heat	7.217,0		17.719,1	
	Total	7.217,0		17.719,1	
Costs district heating (euro/year)	Diemen Heat	€169.600	*(7.217,0*€23,50)*	€416.400	*(17.719,1*€23,50)*
	Heat pump 1	€100.148	*(1.854,6*€54,00)*		
	Heat pump 2	€41.629	*(770,9*€54,00)*		
	Total costs DH	€311.377		€416.400	
Costs data center (euro/year)	Electric chiller	€21.368	*(395,7*€54,00)*	€106.434	*(1.971,0*€54,00)*
	Total costs DC	€21.368		€106.434	
	Total costs	**€332.744**		**522.834**	
Emissions (tonne CO_2)	Power	634		414	
	Diemen Heat	240		590	
	Total	875		1.004	

3,0MW capacity		**DCI scenario**		**REF scenario**	
Heat demand	Kantorenstrook AMSIII	17.719,1		17.719,1	
Cooling demand	Data center	14.782,5		19.170,0	
Heat production (MWh/year)	Diemen Heat	3.823,2	21,6%	17.719,1	100,0%
	Data center HP1	9.258,4	52,3%	-	-
	Data center HP2	4.637,6	26,2%	-	-
	Electric chiller	0,0	0,0%	0,0	0,0%
	Total	17.719,1	100,0%	17.719,1	100,0%

Cooling productions (MWh/year)	Diemen Heat	0,0	0,0%	0,0	0,0%
	Data center HP1	6.943,8	35,2%	-	-
	Data center HP2	3.478,2	17,6%	-	-
	Electric chiller	9.288,0	47,1%	19.710,0	100,0%
	Total	19.710,0	100,0%	19.710,0	100,0%
Electricity consumed by energy units (MWh/year)	Data center HP1	2.314,6		-	
	Data center HP2	1.159,4		-	
	Electric chiller	1.857,6		3.942,0	
	Total	5.331,6		3.942,0	
Full load operating hours (hours/year	Diemen Heat	478		2.215	
	Data center HP1	4.629		-	
	Data center HP2	4.638		-	
	Electric chiller	4.128		8.760	
Fuels (MWh/year)	Diemen Heat	3.823,2		17.719,1	
	Total	3.823,2		17.719,1	
Costs district heating (euro/year)	Diemen Heat	€89.845	*(3.823,2*€23,50)*	€416.400	*(17.719,1*€23,50)*
	Heat pump 1	€124.988	*(2.314,6*€54,00)*		
	Heat pump 2	€62.608	*(1.159,4*€54,00)*		
	Total costs DH	€277.441		€416.400	
Costs data center (euro/year	Electric chiller	€100.310	*(1.857,6*€54,00)*	€212.868	*(3.942,0*€54,00)*
	Total costs DC	€100.310		€212.868	
	Total costs	**€377.752**		**€629.268**	
Emissions (tonne CO_2)	Power	1.120		828	
	Diemen Heat	127		590	
	Total	1.247		1.418	

2. Model configuration: Free cooling

Free cooling		**DCI scenario**		**REF scenario**	
Heat demand	Kantorenstrook AMSIII	17.719,1		17.719,1	
Cooling demand	Data center	14.782,5		14.782,5	
Heat production (MWh/year)	Diemen Heat	4.749,5	26,8%	17.719,1	100,0%
	Data center HP1	8.703,2	49,1%	-	-
	Data center HP2	4.266,5	24,1%	-	-
	Electric chiller	0,0	0,0%	0,0	0,0%
	Free cooling	0,0	0,0%	0,0	0,0%
	Total	17.719,1	100,0%	17.719,1	100,0%
Cooling productions (MWh/year)	Diemen Heat	0,0	0,0%	0,0	0,0%
	Data center HP1	6.527,4	44,2%	-	-
	Data center HP2	3.200,1	21,6%	-	-
	Electric chiller	2.338,0	15,8%	3.732,7	25,3%
	Free cooling	2.716,1	18,4%	11.049,7	74,7%
	Total	14.782,5	100,0%	14.782,5	100,0%
Electricity consumed by energy units (MWh/year)	Data center HP1	2.175,8		-	
	Data center HP2	1.066,7		-	
	Electric chiller	467,8		746,5	
	Free cooling	135,8		552,5	

	Total	3.846,1		1.299,0	
Full load operating hours: (hours/year)	Diemen Heat	594		2.215	
	Data center HP1	5.802		-	
	Data center HP2	5.689		-	
	Electric chiller	1.386		2.212	
	Free cooling	1.610		6.548	
Fuels (MWh/year)	Diemen Heat	4.749,5		17.719,1	
	Total	4.749,5		17.719,1	
Costs district heating (euros/year)	Diemen Heat	€111.613	*(4.749,5*€23,50)*	€416.400	*(17.719,1*€23,50)*
	Heat pump 1	€117.493	*(2.175,8*€54,00)*	-	-
	Heat pump 2	€57.602	*(1.066,7*€54,00)*	-	-
	Total costs DH	€286.708		€416.400	
Costs data center (euros/year)	Electric chiller	€25.261	*(467,8*€54,00)*	€40.311	*(746,5*€54,00)*
	Free cooling	€7.333	*(135,8*€54,00)*	€29.835	*(552,5*€54,00)*
	Total costs DC	€32.594		€70.146	
	Total costs	**€319.303**		**€486.546**	
Emissions (tonne CO_2/year)	Power	808		273	
	Diemen Heat	158		590	
	Total	966		863	

3. Sensitivity: Operation range HPs (70-100% and 80-100%)

70-100%		**DCI scenario**		**REF scenario**	
Heat demand	Kantorenstrook AMSIII	17.719,1		17.719,1	
Cooling demand	Data center	14.782,5		14.782,5	
Heat production (MWh/year)	Diemen Heat	4.529,4	25,6%	17.719,1	100,0%
	Data center HP1	9.001,1	50,8%	-	-
	Data center HP2	4.188,6	23,6%	-	-
	Electric chiller	0,0	0,0%	0,0	0,0%
	Total	17.719,1	100,0%	17.719,1	100,0%
Cooling productions (MWh/year)	Diemen Heat	0,0	0,0%	0,0	0,0%
	Data center HP1	6.750,8	45,7%	-	-
	Data center HP2	3.141,5	21,3%	-	-
	Electric chiller	4.890,2	33,1%	14.782,5	100,0%
	Total	14.782,5	100,0%	14.782,5	100,0%
Electricity consumed by energy units (MWh/year)	Data center HP1	2.250,3		-	
	Data center HP2	1.047,2		-	
	Electric chiller	978,0		2.956,5	
	Total	4.27,5		2.956.5	
Full load operating hours (hours/year	Diemen Heat	566		2.215	
	Data center HP1	6.001		-	
	Data center HP2	5.585		-	
	Electric chiller	2.898		8.760	
Fuels (MWh/year)	Diemen Heat	4.529,4		17.719,1	
	Total	4.529,4		17.719,1	
	Diemen Heat	€106.441	*(4.529,4*€23,50)*	€416.400	*(17.719,1*€23,50)*

Costs district heating (euro/year)	Heat pump 1	€121.516	*(2.250,3*€54,00)*	-	-
	Heat pump 2	€56.549	*(1.047,2*€54,00)*	-	-
	Total costs DH	€284.506		€416.400	
Costs data center (euro/year)	Electric chiller	€52.812	*(978,0*€54,00)*	€159.651	*(2.956,5*€54,00)*
	Total costs DC	€52.812		€159.651	
	Total costs	**€337.318**		**€576.051**	
Emissions (tonne CO_2)	Power	898		621	
	Diemen Heat	151		590	
	Total	1.049		1.211	

80-100%		**DCI scenario**		**REF scenario**	
Heat demand	Kantorenstrook AMSIII	17.719,1		17.719,1	
Cooling demand	Data center	14.782,5		14.782,5	
Heat production (MWh/year)	Diemen Heat	4.985,8	28,1%	17.719,1	100,0%
	Data center HP1	8.408,4	47,5%	-	-
	Data center HP2	4.325,0	24,4%	-	-
	Electric chiller	0,0	0,0%	0,0	0,0%
	Total	17.719,1	100,0%	17.719,1	100,0%
Cooling productions (MWh/year)	Diemen Heat	0,0	0,0%	0,0	0,0%
	Data center HP1	6.306,3	42,7%	-	-
	Data center HP2	3.243,8	21,9%	-	-
	Electric chiller	5.232,5	35,4%	14.782,5	100,0%
	Total	14.782,5	100,0%	14.782,5	100,0%
Electricity consumed by energy units (MWh/year)	Data center HP1	2.102,1		-	
	Data center HP2	1.081,3		-	
	Electric chiller	1.046,5		2.956,5	
	Total	4.229,8		2.956.5	
Full load operating hours (hours/year	Diemen Heat	623		2.215	
	Data center HP1	5.606		-	
	Data center HP2	5.767		-	
	Electric chiller	3.101		8.760	
Fuels (MWh/year)	Diemen Heat	4.985,8		17.719,1	
	Total	4.985,8		17.719,1	
Costs district heating (euro/year)	Diemen Heat	€117.166	*(4.985,8*€23,50)*	€416.400	*(17.719,1*€23,50)*
	Heat pump 1	€113.513	*(2.102,1*€54,00)*	-	-
	Heat pump 2	€58.390	*(1.081,3*€54,00)*	-	-
	Total costs DH	€289.070		€416.400	
Costs data center (euro/year	Electric chiller	€56.511	*(1.046,5*€54,00)*	€159.651	*(2.956,5*€54,00)*
	Total costs DC	€56.511		€159.651	
	Total costs	**€345.581**		**€576.051**	
Emissions (tonne CO_2)	Power	888		621	
	Diemen Heat	166		590	
	Total	1.054		1.211	

4. Uncertainty heat demand curve

New demand curve		**DCI scenario**		**REF scenario**	
Heat demand	Kantorenstrook AMSIII	17.719,1		17.719,1	
Cooling demand	Data center	14.782,5		14.782,5	
Heat production (MWh/year)	Diemen Heat	3.901,1	22,0%	17.719,1	100,0%
	Data center HP1	9.769,1	55,1%	-	-
	Data center HP2	4.048,9	22,9%	-	-
	Electric chiller	0,0	0,0%	0,0	0,0%
	Total	17.719,1	100,0%	17.719,1	100,0%
Cooling productions (MWh/year)	Diemen Heat	0,0	0,0%	0,0	0,0%
	Data center HP1	7.326,8	49,6%	-	-
	Data center HP2	3.036,8	20,5%	-	-
	Electric chiller	4.418,9	29,9%	14.782,5	100,0%
	Total	14.782,5	100,0%	14.782,5	100,0%
Electricity consumed by energy units (MWh/year)	Data center HP1	2.442,3		-	
	Data center HP2	1.012,3		-	
	Electric chiller	883,8		2.956,5	
	Total	4.338,3		2.956.5	
Full load operating hours: (hours/year)	Diemen Heat	488		2.215	
	Data center HP1	6.513		-	
	Data center HP2	5.399		-	
	Electric chiller	2.619		8.760	
Fuels (MWh/year)	Diemen Heat	3.901,1		17.719,1	
	Total	3.901,1		17.719,1	
Costs district heating (euros/year)	Diemen Heat	€91.676	_(3.901,1*€23,50)_	€416.400	_(17.719,1*€23,50)_
	Heat pump 1	€131.884	_(2.442,3*€54,00)_	-	-
	Heat pump 2	€54.664	_(1.012,3*€54,00)_	-	-
	Total costs DH	€278.224		€416.400	
Costs data center (euros/year)	Electric chiller	€47.725	_(883,8*€54,00)_	€159.651	_(2.956,5*€54,00)_
	Total costs DC	€47.725		€159.651	
	Total costs	**€325.949**		**€576.051**	
Emissions (tonne CO_2/year)	Power	911		621	
	Diemen Heat	130		590	
	Total	1.041		1.211	