The Value of Place: Assessing Location-Based Economic Feasibility of Data Center Heat Recovery

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Summary

This thesis investigates the economic feasibility of reusing Excess Heat (EH) from Data Centers (DCs) for District Heating (DH) purposes, emphasizing how location-related factors influence financial viability of such projects. The study, grounded in Location Theory and Industrial-Urban Symbiosis, comparatively analyzes Net Present Value (NPV) and Discounted Payback Period (DPB) of six real-world Danish DC sites, identified through spatial analysis. The thesis identifies three key location-related input factors for the NPV model: DH connection costs, temperature difference between DC's EH and DH supply (HP's COP), and local EH price. Results show that differences in DC location can lead to significantly varied NPV outcomes, with costs of connection between DC and DH being a decisive factor. While, with input EH and electricity prices, only large-scale DCs with efficient liquid cooling show positive NPV within a 12-year timeframe, results suggest the need to account for local spatial and economic context when planning for DC's EH recovery. The project highlights the importance of integrating spatial planning and energy infrastructure decisions to unlock the potential of DC heat reuse in sustainable urban energy systems.

Contents

List of Abbreviations

Abbreviation	Explanation
4GDH	Fourth Generation District Heating
3GDH	Third Generation District Heating
CAPEX	Capital Expenditures
CE	Circular Economy
DC	Data Center
DE	District Energy
DH	District Heating
DPB	Discounted Payback Period
EH	Excess Heat
HP	Heat Pump
IT	Information Technology
NPV	Net Present Value
OPEX	Operational Expenditures
PB	Payback Period
PV	Photovoltaics

Chapter 1

Introduction

The heating of buildings accounts for a substantial share of global energy demand. As the urgency of the climate crisis grows and efforts to decarbonize intensify, it becomes increasingly important to reconsider the methods we use to warm our homes and workplaces. Although integrating renewable sources of heat remains a complex issue for various reasons, the presence of District Heating (DH) systems in densely populated urban areas offers a practical and scalable pathway. These systems hold considerable potential to support a shift toward more sustainable energy practices in cities.

DH systems, however, can be more or less sustainable and efficient. In order to improve the network's energy efficiency and decrease heat losses in the heating gird, DH utilities seek to lower the temperature of a heat carrier flowing in their systems. Lower temperatures in DH pipes open up the possibility to supply urban heating networks with unconventional, low-temperature heat sources, including ones that can often be found within city limits.

One of such sources, alongside e.g. wastewater plants or supermarkets, are Data Centers (DCs). As the current and future digital economy require a lot of computing power, these facilities consume great amounts of electricity. Eventually, all of this consumed power turns into heat, which can be captured and redistributed outside of a DC facility. As DCs operate, and in turn, generate heat all year long, for 24h a day, it makes them a stable source of low-temperature heat. Because of the above, there is a significant potential for symbiosis between DC and DH network, which can play a role in accelerating the decarbonization of urban energy systems.

However, such symbiotic relationships are highly dependent on the local context, including proximity between stakeholders engaged in symbiosis, i.e. between a DC and DH network, as well as infrastructure availability or land-use patterns (as seen in Chapter 5. These factors can either facilitate or hinder the realization of Industrial-Urban Symbioses, determining whether they are economically and technically feasible.

The purpose of this report is to investigate the influence of these location-related factors in economic feasibility of DC heat reuse projects. By focusing on existing DC sites in Denmark, the thesis analyzes how variations in spatial context affect the financial outcomes of such projects.

The following three chapters - Chapter 2, Chapter 2.3, and Chapter 3 - provide the contextual foundation for exploring heat reuse from DCs. The discussion begins with the growing need to integrate excess heat into urban heating networks, followed by an overview of DC operations, with particular attention to how heat is generated and removed. It then examines current state-of-the-art cooling technologies relevant for heat recovery, along with potential pathways for utilizing this heat, including within DH systems. Lastly, a review of existing research on DC heat reuse is presented to position this thesis within the broader academic discourse and highlight existing knowledge gaps.

Chapter 2

Problem Analysis - Data Centers in future energy systems

This Chapter highlights the role of the DC sector in future energy systems and their sustainable transition, with a particular focus on the Danish context, therefore serving as a background for the project's analysis. Beginning with the role of low-temperature EH in future energy systems and latest projections of global and Danish energy demand for DCs, it provides an overview of how the EH is generated and how can it be captured and utilized for different purposes, including DH. Finally, the Chapter concludes with the regulatory framework for utilizing EH from DCs, both at the European and Danish levels.

2.1 Excess Heat as an energy source for District Heating

Heating remains among the most significant energy demands – in Europe alone, it accounts for over 50% of the annual final energy consumption. The majority of this heat is still produced using fossil fuels, with natural gas making up nearly half of the supply (Piel et al., 2023). At the same time, EH represents one of the largest underutilized energy sources globally. The EU is estimated to have around 2,860 TWh per year of accessible EH, much of which holds potential for reuse (Connolly et al., 2013). This amount is nearly equivalent to the entire energy demand for heating and hot water in residential and service sector buildings across the EU. However, despite the abundance of EH, only a small fraction is currently being recovered and reused (Piel et al., 2023).

EH is typically recovered from heavy industrial processes, as they operate at very high temperatures, which means that the heat can be reused directly, due to its high quality. It can be reused internally, i.e. in the same building, or externally, most commonly to heat domestic space and water or to supply DH network. To give an example, this is the case in the city of Aalborg, which is the home of the largest energy consumer in Denmark, the cement factory Aalborg Portland. In 2016, 1,176 TJ was recovered for usage in the DH system in Aalborg, accounting for around 18% of total supply (Sorknæs et al., 2020).

However, DH networks can benefit from different sources of EH than heavy industry. It is all the more important, as, in order to decarbonize our energy systems, there is a need to develop sustainable, energy-efficient, low-temperature heating grids, often referred to as 4th generation of DH (4GDH) (Sorknæs et al., 2020). According to Lund et al. (2014), 4GDH system is a "coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems". This definition showcases the need for decentralized, low-temperature sources of heat to supply energy efficient and sustainable DH systems. Because of the above, many more sources of EH than high-temperature industry processes can be considered to supply the network. This way cities without large industry sites can also have numerous sources of EH that can add up to a considerable amount of energy available to be utilized. According to Persson et al. (2022), the most significant of low-temperature EH sources found in urban environments are DCs, food production facilities, food retail facilities (supermarkets), metro stations and wastewater treatment plants. Out of the above categories, DCs constitute the second largest volume of available EH in EU+UK, yielding only to wastewater treatment plants (only sources inside or within 2 kilometers of urban DH areas were considered in the cited study). Total number of 985 DCs could provide 179.6 PJ/year of available EH - this amount could be theoretically further improved to 269.4 PJ/year with the use of heat pumps (HPs) with the coefficient of performance (COP) of 3.0. As for Denmark, 27 identified DCs could provide 2.5 and 3.8 of available and accessible EH respectively (Persson et al., 2022). The significant upside of reusing heat from DCs in DH networks compared to other low-grade EH sources is that DC usually operates (and therefore generates heat) 24 hours per day, for the whole year (Pärssinen et al., 2019), providing continuous supply of heat. Moreover, as Lu et al. (2024) have shown, nearly all (97%) of DC's power consumption could be captured as EH. The study found that EH from a 1 MW DC, operating at 50% of its capacity, could meet the annual heating needs of more than 30,000 m^2 of nondomestic buildings. With the growing demand for computing power as well as data and information infrastructure, resulting from the digitization of global economy and our everyday lives, it is necessary to take DC facilities into account when discussing future sustainable energy systems.

2.2 The role of Data Centers in sustainable energy systems

According to the IEA (2023), since 2010, the number of Internet users worldwide has more than doubled, while global Internet traffic has expanded 20-fold. This trend, the raising digitization of the global economy and our everyday lives, results in the growing demand for data handling infrastructure and information technology (IT) equipment, such as DCs. The rapid growth of the DC market is an phenomena which needs to be considered from the environmental and energy planning perspective, as it is a very energy-intensive industry. The IEA (2023) estimated that DCs used between 220 and 320 TWh of electricity in 2021, i.e., 0.9%–1.3% of the global final electricity demand, and were responsible for about 300 Mtons of CO2-eq in 2020. While this share of energy demand, as well as the level of GHG emissions from the sector, are growing only modestly in the recent years, thanks to the IT energy efficiency improvements, renewable energy purchases and decarbonizing of the electricity grids in many regions, it is uncertain how long these efficiency gains can compensate for growing demand (Monsalves et al., 2023).

Another trend in the IT sector, which can have a meaningful impact on the energy systems, within which DCs operate, is increasing centralization of the sector. This means that a shift is taking place from traditional small-scale server installations to more efficient, large-scale cloud DCs. This results in the development of bigger facilities, with more computing power, requiring much more energy to operate (Cáceres et al., 2024). Although global electricity consumption of DCs has only increased slightly in the recent years, as previously mentioned, the clustering of large-scale DCs in specific regions or countries can significantly burden the local energy grid. For example, DC electricity use in Ireland accounted for 18% of total electricity consumption in 2022. Moreover, it is estimated that DCs, together with other non-industrial large energy users could account for 28% of national demand by 2031, unless generation capacity increases (EIRGRID and SONI, 2022).

The reason why some regions or countries attract significantly more interest from the DC industry than others is due to how strongly the DC facility's location influences its profitability. Several key factors influence the choice of a DC site location – among others, an access to affordable and reliable energy, political stability, and proximity to data consumption hubs (in order to minimize data transfer latency) (Wahlroos et al., 2018a). Moreover, factors like cold climate can significantly improve energy efficiency of the DC, and therefore the economic feasibility of its operation. The lower the outdoor temperature, the less mechanical refrigeration is needed to ensure stable operation of IT equipment. Also, low ambient temperature enables the use of free cooling (about which in the Chapter 2.3). The energy mix of the electrical grid powering the DC also plays a role. As businesses look for the ways to reduce their carbon footprint and to boost their ESG performance, the share of renewable energy in the grid can be a decisive factor in selecting the right location for a DC (Wahlroos et al., 2018a).

Because of the importance of the above factors, the Nordic countries are suitable for DC industry and are expecting growth in this sector. Denmark anticipates that energy use of DCs within its borders will account for almost 15% of the country's electricity use in 2030. Construction of new DCs is expected to be the main factor of the increase in energy consumption in the Danish service sector. In 2021, 4 PJ of electricity was used in data centers in Denmark, but this is expected to increase to around 28 PJ in 2030 and 36 PJ in 2035 (Danish Energy Agency, 2022).

The above considerations showcase that DCs, as an emerging electricity-intensive industry, can have a significant impact on energy systems, especially in the future. This also implies their important role in the context of climate crisis and sustainable energy transition. As stated by Koronen et al. (2020), in order to be considered sustainable from the system perspective, DCs must not only be energy-efficient - they have to contribute to a well-functioning renewable power system via sector coupling solutions. These solutions are mainly the demand response and EH recovery. Monsalves et al. (2023) assessed the economic and environmental benefits of integrating large DCs into highly renewable energy system of Denmark, focusing on the timeframe until 2035. Varying levels of DC integration were considered: "with the electricity sector through flexible cooling, with the DH sector through waste-heat recovery and with full integration through a combination of both" (Monsalves et al., 2023). The results shown that full integration could save up to 63% of costs and 180% of emissions that non-integrated DCs would otherwise generate. Moreover, according to the findings, DCs could provide up to 24% of the Danish DH supply in 2035 (Monsalves et al., 2023). This project will focus on the potential for heat recovery, leaving the flexible electricity demand aspect of DC integration outside its scope.

2.3 Data Center's Cooling Systems and Excess Heat recovery

To understand the potential of integrating DCs in energy systems by the means of EH utilization, it is crucial to realize how a DC operates, how does it generate heat, as well as how and for what purpose this heat can be recovered. This Section describes the current state-of-the-art DC cooling technologies relevant for heat recovery, as well as the possible EH utilization solutions.

A DC, according to the Dai et al. (2017), is "an industrial computing service infrastructure, with a facility to house computer systems and its associated components, such as storage devices, power supplies, communication devices, and security devices. It provides a cost-efficient way for companies and personal tenants to rent a slice of computation and communication resource to meet various requirements" (Dai et al., 2017).

Depending on the scale of the business, a DC might consist of a single rack of IT equipment, a few racks, or even many racks and cabinets. The racks are usually organized in rows occupying the DC's designated floor area, known as a DC's whitespace (as opposed to grey space, which doesn't consist of IT equipment, but back-end equipment such as cooling systems, generators etc.). Servers located in the DC's whitespace are the "heart" of the whole facility and together they are its largest energy consumer (Davies et al., 2016).

All the electricity used by the servers is eventually converted into heat. To ensure the stable, uninterrupted and correct operation of the servers, the IT equipment therefore needs to be continuously cooled as it is prone to overheating. According to Wahlroos et al. (2018a), to prevent malfunction of processors, the temperature of the air in the servers should be kept in the range of 18–27 °C. The DC cooling constitutes second largest power consumer in the DCs after servers, spanning from 10% in the most efficiently cooled DCs to nearly half of the entire energy demand in others. The required cooling energy in a DC varies between different cooling methods, the most popular being:

- Computer room air conditioners (CRACs), or computer room air handlers (CRAHs);

- Local air cooling methods;
- Direct liquid cooling (Davies et al., 2016).

Air-cooling system is considered as the most commonly used cooling solution for DCs. In such configuration, cooling units (CRAC or CRAH) are placed inside the DC's whitespace but at a distance from the IT servers, requiring the units to cool the entire room. The server racks are typically arranged in alternating rows of hot and cold aisles. In cold aisles, the front sides of the racks face each other - this is where servers draw in cool air. Hot aisles align the rear sides of the racks, where warm exhaust air is released. Chilled air is delivered to the cold aisles either from beneath a raised floor or via ceiling diffusers. The warm air from the hot aisles is collected and directed back to the CRAC/CRAH unit for recirculation (Davies et al., 2016).

Close-coupled or local air cooling methods include rack cooling, in-row cooling, and rear door water cooling. These methods still use air to cool the electronics, but they transfer heat to the cooling system much closer to the server racks - often through a chilled water heat exchanger. This eliminates the need of cooling the whole whitespace, which improves cooling efficiency (Davies et al., 2016).

Lastly, direct liquid cooling uses either water, refrigerant or dielectric fluids. Generally only the hottest server components (i.e. the processors and memory chips) are cooled with liquid, while the remaining lower temperature components are cooled using air (hybrid direct liquid/air cooled system). It is also possible to totally immerse the server boards in dielectric fluid and therefore fully avoid air cooling (Davies et al., 2016).

The simplified comparison of the above three cooling methods is shown in Figure 2.1. In the example a, servers in racks organized in cold/hot aisles are cooled with the CRAC or CRAH unit, which draw the hot air, cool it down with the use of refrigerant and blow cooled air through the raised floor. The heat absorbed by the CRAC/CRAH unit is then evaporated to the air outside of the building or is being transferred to the chiller and/or cooling tower in the form of water. The primary distinction between CRAC and CRAH systems lies in the size of the DC where they are used. CRAC units are typically employed in smaller DCs with a capacity of less than 100 kW, whereas CRAH units are more common in medium to large DCs exceeding 100 kW (Huang et al., 2020).

In the example b, rear door cooling (the form of local air cooling) is being used. This type of system is usually used for high energy density facilities (Huang et al., 2020). There is a heat exchanger located at the back of the server rack, which absorbs the heat coming out of the servers using cold water. The heated water is carried out of the building to a chiller and/or cooling tower, while freshly cooled air is released into the room at the ambient temperature.

Example c is the representation of direct liquid cooling system. Servers are immersed in non-conductive cooling liquid which absorbs the heat and transfers to the coolant distribution unit. Inside this unit's heat exchanger, heat moves from the server coolant to the building's cooling water, which then is taken to the chiller and/or cooling tower. This type of cooling method is not commonly spread, and is usually considered only for newly planned large DCs.

Significant part of energy-intensive mechanical refrigeration while conducting cooling via the described methods can be avoided by the use of so-called free cooling. In such case, DC's cooling system capitalize on the cooling capacity of ground, ambient air or seawater. Cool outdoor temperatures can for instance help the cooling tower produce cold water without using a chiller. Free cooling can be combined with mechanical refrigeration, constituting a combined cooling system (e.g. the ambient temperature is too high, so mechanical refrigeration is used to produce the additional cooling energy). By taking advantage of naturally cool environmental conditions, energy consumption of the cooling system is minimized (Wahlroos et al., 2018a). This is also one of the reasons why locating DCs in cold climate, such as Denmark or other Nordic countries is strongly preferred.

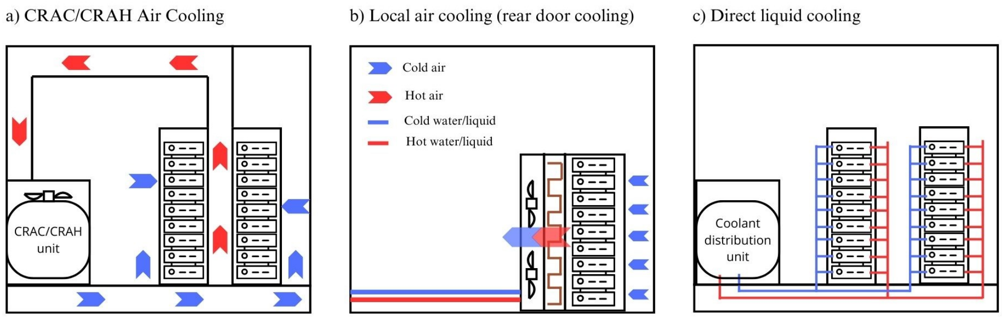

Figure 2.1. Comparison of different DC cooling methods. Reproduction from (Huang et al., 2020)

The type of DC cooling method strongly influences the quality (temperature) of EH and the potential to recover and reuse it. According to Davies et al. (2016), cooling system based on remote CRACs or CRAHs can produce recoverable heat in the range of 25–35 °C. Ebrahimi et al. (2014), based on the literature study, state that if captured in the optimal point, the heat from air-cooled systems can even reach a range of 35-45 °C. When racks are cooled with local air-cooling methods, together with chilled water heat exchanger, the heat can be theoretically recovered only from the chilled water, at the temperature range of 10-20 °C. And lastly, direct liquid cooling can generate EH of significantly higher temperatures of 60 °C. Typical temperatures and recovery potential for EH rejected from DCs based on Davies et al. (2016) are presented in the Table 2.1.

Cooling system	**Cooling medium**	**EH source**	**EH Temperature range (°C)**	**Recovery possible?**
CRAC/CRAH Air Cooling	Air	Air	25-35	Yes
Local Air Cooling	Air	Air/Chilled water	25-35 / 10-20	No/Yes
Direct Liquid Cooling	Liquid	Liquid	50-60	Yes

Table 2.1. Typical temperatures and recovery potential for DC's EH, depending on cooling method. Based on Davies et al. (2016)

In terms of how and where the recovered DC heat can be used, based on the literature survey conducted by Ebrahimi et al. (2014), main activities which are considered as heat sinks for DC's EH are:

- Domestic space and water heating in nearby buildings;
- DH networks;
- Cooling production in an absorption or adsorption cooling;
- Biomass processing;
- Clean water production in desalination process;
- Electricity production through Organic Rankine cycle, piezoelectrics or thermoelectrics (Ebrahimi et al., 2014).

Out of the above, space and water heating, both in nearby buildings and through DH networks, are considered the most common and relatively simple usage of DC's EH (Ebrahimi et al., 2014). However, while EH which can be recovered from air-cooled systems is typically of enough quality to be directly supplied to heat nearby spaces, DH supply temperatures are usually between 70-80 in typical 3rd generation DH networks (3GDH). Supply temperature of 4GDH, according to Sorknæs et al. (2020) should be between 55-65. This means that even with the most efficient DC cooling methods, the quality of the heat that can be recovered remains too low for direct integration to 3GDH networks and only the EH from direct liquid cooling have a potential to reach temperature levels needed by 4GDH systems. Therefore, in most cases upgrading the temperature of EH streams using HPs is necessary to make low-quality EH suitable for recovery and utilization (Ebrahimi et al., 2014).

HPs can be used in DCs twofoldly; to produce the cooling energy or to improve the quality of EH up to 95 °C and above, which would allow heat to be utilized in many processes, including heating spaces trough DH networks. HPs can be used in different cycles if there are, for example, heat loads at different temperatures. HPs in DCs typically have COP values around 2–7, depending on the number of cycles and the difference between input and output temperatures. The lower this difference is, the higher the COP of the HP is achieved, therefore improving efficiency of the heat reuse process (Wahlroos et al., 2018a).

Heat recovery methods, as well as the needed technical infrastructure depend, again, on DC'd cooling system. EH is typically captured in two key areas: the return hot aisle and the chiller condenser (Huang et al., 2020). The first scenario, illustrated in Figure 2.2, showcases an example of EH recovery for an air-cooled system, which, as previously mentioned, is the most common configuration. In this setup, a water-to-air heat exchanger is placed in the return hot airflow from the whitespace. As noted earlier, the temperature of the return air is typically around 25-35 °C. The hot air is then cooled by the water in the heat exchanger, which reduces the cooling demand for the chillers. The low-grade heat in the warmed water is then directed into a HP, where it is upgraded to a temperature suitable for the use in the DH supply line (Huang et al., 2020).

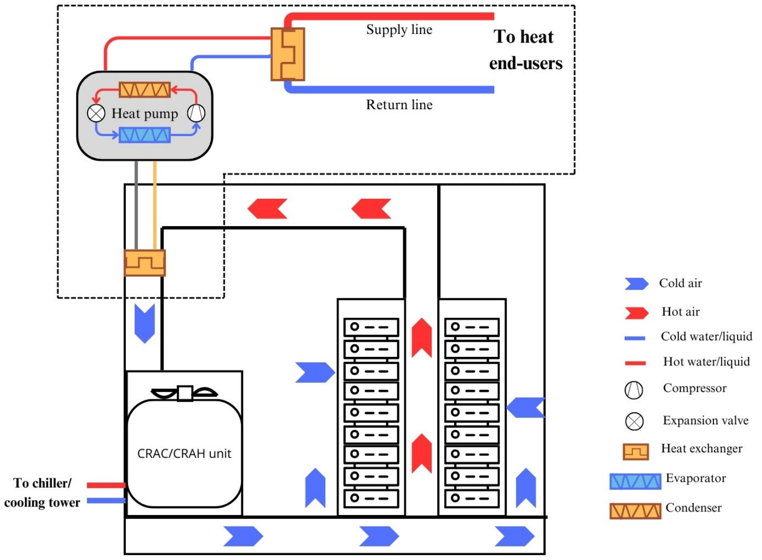

Figure 2.2. Schematics of waste heat recovery for CRAC/CRAH cooling technology. Reproduced from (Huang et al., 2020)

For local air cooling such as rear door cooling systems, either the operational air temperature is very low or recovery is not possible (Davies et al., 2016), and thus it is inefficient to recover heat at the air side. Moreover, the temperature of return water is also very low (as can be seen in Table 2.1), which makes this cooling method unsuitable for heat recovery.

Since direct liquid cooling does not produce hot air, it requires an alternative approach for EH recovery. One effective solution is to capture heat from the chiller condenser. In this case, a water-to-refrigerant heat exchanger is installed alongside the chiller's condenser. Some of the heat rejected by the chiller is released into the environment, while the remaining heat is captured by a secondary water circuit (Huang et al., 2020). As previously noted, the temperature of this heat typically ranges from 50-60 °C. The low-grade heat in the warmed water is then directed into a heat pump, where it is upgraded to a temperature suitable for use in the DH network. This heat recovery process is shown in Figure 2.3.

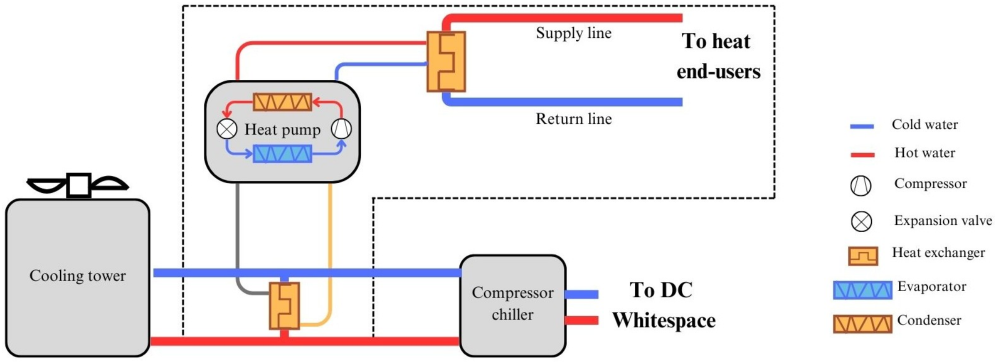

Figure 2.3. Schematics of waste heat recovery at condensate water side (applicable for e.g. direct liquid cooling). Reproduced from (Huang et al., 2020)

2.4 Policies and Regulatory framework on heat reuse from Data Centers

As EH reuse plays a key role in enhancing energy efficiency and reducing emissions, political action is essential at all legislative levels, from international frameworks to national regulations. The following section outlines key international policies and regulations that support EH reuse, followed by an overview of Denmark's national policies and legislative measures in this area.

2.4.1 International and EU policy

The Paris Agreement, the most significant of the UN's international treaties on climate change, aims to limit global temperature rise to well below 2°C, while striving to keep it within 1.5°C above pre-industrial levels (United Nations, 2015a). Prior to this, the United Nations (2015b) introduced the 2030 Agenda for Sustainable Development, which includes 17 Sustainable Development Goals (SDGs). These goals provide a comprehensive framework for human development, integrating social, environmental, and economic dimensions.

The SDG 7, "Ensure access to affordable, reliable, sustainable, and modern energy for all," is particularly relevant to the energy transition. Within this goal, Target 7.3 aims to double the global rate of improvement in energy efficiency by 2030. Additionally, several other SDG targets are directly or indirectly related to energy efficiency in industries. The goals of the Paris Agreement and the 2030 Agenda related to the energy transition are supported by the International Energy Agency (IEA), which tracks progress, provides guidance, and offers policy recommendations to member and non-member countries alike. Regarding DCs specifically, IEA (2023) warns that more efforts are needed to get on track with the Net Zero Emissions by 2050 (NZE) Scenario which means that the emissions from the sector need to be rapidly reduced over the upcoming decade. As one of the recommendations for accelerating the progress, the Agency points to energy efficiency improvements and EH utilization (IEA, 2023).

The need of improving energy efficiency of DCs, including heat recovery, has been recognized also by the European Union (EU). In the so-called Energy Efficiency Directive, European Parliament and the Council (2023) states that DCs will account for 3,21 % EU electricity demand by 2030 if current trends will persist and therefore impose various energy efficiency-related obligations on EU member states and DC operators.

First and foremost, operators of DCs with a power demand of the installed IT of at least 500 kW have to publicly report information regarding their energy performance, including energy consumption, power utilization, temperature set points, EH utilization, water usage and use of renewable energy (European Parliament and the Council, 2023). Although the first reporting deadline was set to September 2024, no information from the EU database were made public to the date of writing this project.

Especially relevant is the Directive's provision requiring member states to ensure that DCs with a total rated energy input exceeding 1 MW recover their EH unless they can indicate that it is not technically or economically feasible. On the other side, DH operators should, according to the EU legislators, aim for improved ability of DH networks to interact with other parts of the energy system in order to optimize the use of energy and prevent energy waste, including the utilization of EH from service facilities and nearby DCs (European Parliament and the Council, 2023).

The need of utilizing EH, not only from DCs, but in general, is expressed by the Directive's definition of an efficient district heating and cooling system. According to Article 26, district energy (DE) system is considered efficient if, until 31 December 2027, it is using at least 50% renewable energy, 50% waste heat, 75% cogenerated heat or 50% of a combination of such energy and heat. In subsequent years this demanded share is growing, up to 100% in 2050 (European Parliament and the Council, 2023). It is worth remarking that EH is treated here as of the same value as renewable energy. This shows that even if EH isn't considered as a renewable source of energy in the EU legislation, it is still considered as one of the main sustainable sources of energy in the sustainable energy transition.

2.4.2 Danish policy and regulation

As already mentioned, Denmark is a preferable location for establishment of DCs due to its favorable conditions. The country's cold climate reduces cooling costs, its well-established DH networks enable the utilization of EH, and its high share of renewable energy aligns with DC owners' sustainability goals and public image considerations. Recognizing this economic potential, Denmark has actively supported investments in DCs (Petrović et al., 2020).

As for EH recovery, Danish policies and regulations provide incentives and tools for it. In 2021, the Danish Parliament has amended the Act on Heat Supply and by doing so, established a regulatory mechanism designed to encourage businesses to optimize and make better use of their EH resources. The energy efficiency scheme for surplus heat provides companies with structured guidance, including energy reviews to identify improvements, implementation of efficiency measures, and verification by external experts (Klima-, Energi- og Forsyningsministeriet, 2024).

Until 2025, a price cap regulated the sale of EH from facilities with a capacity of at least 0.25 MW (Klima-, Energi- og Forsyningsministeriet, 2024). In January 2025, the Danish government, in agreement with several political parties, decided to remove this cap. This policy change eliminated a regulatory constraint that had previously restricted the integration of surplus heat from industries like DCs and manufacturing. As a result, DH utility companies can now negotiate directly with businesses to incorporate EH into their systems. DCs are further encouraged to recover their EH as the DC's recovered and sold heat is exempt from taxation if a DC company participates in the Danish Energy Agency's energy efficiency scheme (Danish Energy Agency, 2021).

To conclude this Chapter, the reuse of EH from DCs in DH networks is an effective and desirable method of integrating DCs with DH systems, particularly when coupled with low-temperature DH networks. While most existing DCs use air-cooled systems that generate low-grade EH, newer, larger, high-power density DCs can opt for liquid cooling systems, which produce higher quality EH. To make this heat suitable for use in DH networks, HPs are necessary to upgrade the low-temperature EH to a higher temperature. Both the EU and Danish policies and legislation provide either obligations or incentives to recover DC's EH, whenever it is economically and technically feasible.

Chapter 3

Literature review

To understand the amount of knowledge that has already been gathered and researched in regards of DC's heat reuse, a review of existing scientific literature within the field has been conducted. The review helps to identify knowledge gaps within the field, as well as main challenges and barriers in reusing DC's EH in DH networks. This way the review contributes to the framing of the main research question of the thesis. This section describes the outcome of the literature review, which has been based on more than 40 scientific articles. The methodology for the selection of this literature pieces, as well as the overall methodology considerations regarding literature review, are described in Section 6.1.1.

3.1 Outcomes of the literature search

In order to systematize the review of identified papers, they were grouped into three categories;

- Energy System Perspective on DC Heat Reuse in DH;
- DH System Perspective on DC Heat Reuse;
- DC Perspective on Heat Reuse in DH.

Articles which were found the most relevant for each category, are described below.

3.1.1 Energy System Perspective on DC Heat Reuse in DH

Some of the identified papers investigate the issue of DC's EH reuse from the perspective of national or (more rarely) regional energy systems perspective, taking into account both heat and electricity factors. For instance, Monsalves et al. (2023) assess the economic and environmental advantages of incorporating large-scale DCs into highly renewable energy systems, using Denmark as a case study and focusing on the transition up to 2035. Their findings indicate that integrating DCs - both via flexible electricity demand and heat recovery - can lower the overall costs of the Danish energy system by 5.1% and cut carbon emissions by 1.4% over the analyzed period. Additionally, the integration results in up to 63% cost savings and a 180% reduction in emissions compared to scenarios where DCs are not integrated.

Nielsen et al. (2020) evaluate the potential and cost-effectiveness of harnessing unconventional EH sources, such as DCs, within the national settings of Germany, Spain, and France. Their analysis highlights considerable opportunities in all three countries, though these are constrained by factors like competition with alternative heat supply options and the operational feasibility of HPs.

Several studies underline the importance of geographical location of a DC for the economic viability of EH reuse. For example, Cáceres et al. (2024) highlight that geographic context shapes the availability and integration of key infrastructures such as electricity, water, and DH, which are essential for both the operation of DCs and the reuse of their by-products. By comparing cases in Stockholm and Luleå, the authors show that municipalities can better adapt to DC developments when they proactively consider spatial and energy planning determinants tied to location, such as land use diversity, infrastructure readiness, and proximity between heat producers and users. Similar conclusions are drawn in works of Monsalves et al. (2023) and Wahlroos et al. (2018b).

3.1.2 DH System Perspective on DC Heat Reuse

Vast majority of reviewed articles treat the issue of DC EH reuse from the perspective of the DH network. Only few examples of them are described below. Hiltunen and Syri (2021) investigate the feasibility of supplying the future, 95% renewable DH system of Espoo, Finland, with, among others, EH from a large DC. The findings indicate that DC's EH is most effective when used as a baseload heat source, though electricity prices play a crucial role in determining the economic viability of its utilization. Implementing EH recovery also contributes to substantial reductions in CO2 emissions.

Miškić et al. (2024) present a holistic method to assess the economic, environmental and energy benefits of integrating urban EH sources, including DCs, into DH, based on the case of Zagreb, Croatia. They emphasize the importance of the strategic spatial planning in facilitating EH reuse in DH networks. Their work highlights how the temperature within DH network influences the economic feasibility of low-temperature heat reuse.

Davies et al. (2016) examine various methods used to cool IT servers, highlighting their potential for EH recovery and reuse. The study also explores how available EH could be matched with heating demands across several districts in London. Their results suggest that if the entirety of the EH produced by London's DCs were integrated into the DH network, a substantial share of the heat demand in many of London's boroughs could be met through this source.

3.1.3 DC Perspective on Heat Reuse in DH

The review of the aforementioned papers, along with additional relevant literature addressing the issue of EH reuse from the DC industry - whether at the level of DH networks or national energy systems - reveals a consistent trend. While DCs are recognized as promising sources of EH, from a system-level perspective, this heat is typically categorized alongside other forms of low-temperature EH originating from unconventional urban sources. However, many of the reviewed studies point out that the potential to reuse DC's EH is being only marginally utilized. To better understand the reason for the above, the attention was directed toward research examining the EH reuse in DH systems, but from the viewpoint of DC operators. This helps to identify the specific factors and challenges that make EH recovery in the DC sector different from similar efforts in other industries.

Several papers investigating the DC heat reuse from the perspective of DC facility were identified. Articles presenting very technical approach, e.g. on-site optimization of cooling system, were excluded from further review. Because of the above, most of the articles in this category refer to economic feasibility of heat reuse, on the part of DC operator or owner.

For instance, Pärssinen et al. (2019) have conducted an economic assessment of EH recovery in the DC sector. Their study analyzes the net present value and return on investment across three generalized cases of varying DC sizes, using realistic input parameters. The findings indicate that, for small air-cooled DCs, the investment in EH recovery systems is not economically viable, as the revenue from selling the recovered heat to DH operators does not offset the associated costs. In contrast, for medium and large DCs, EH utilization proves to be a financially attractive opportunity.

Similarly, Monsalves et al. (2023) investigate how revenues from heat sales to DH networks influence the economic viability of EH recovery for three differently sized DCs under selected conditions within the Danish context. The DC is modeled as an integrated system consisting of free cooling, chillers, and HPs, with its operation optimized to minimize overall cooling costs while accounting for heat sales. The study incorporates various factors, including techno-economic parameters, local environmental conditions, the capacity of the DH network to absorb the EH, and the heat sale price. The findings indicate that EH recovery becomes economically feasible only under highly favorable conditions, notably when the DC is granted priority access to the DH system, i.e. DH utility buys all of the recovered EH. Only under such circumstances, investigated DC cases note savings in cooling costs, up to 13%. The study was using the maximum heat prices permitted by Danish regulations at the time (price cap - see Chapter 2).

The study conducted by Miškić et al. (2024) demonstrates that the economic feasibility of recovering EH from DCs is strongly influenced by the temperature regime of the DH network. Specifically, lower DH supply temperatures enhance viability by reducing the costs associated with the operation of a HP. The study highlights that a reduced temperature regime not only lowers the need for costly HP operation but also allows for the use of more affordable integration technologies, resulting in both lower capital and operational expenditures for incorporating DC's EH into the DH system.

3.2 Main barriers in Data Center Excess Heat reuse

Based on the above literature review, main barriers and challenges in utilizing EH from DC in DH networks could be identified.

These are:

- Low temperature of the EH (Wahlroos et al., 2018a; Davies et al., 2016; Hiltunen and Syri, 2021);
- High investment and operational costs for the DC facility (Wahlroos et al., 2018a; Pärssinen et al., 2019; Monsalves et al., 2023);
- Remote location to the DH network (Monsalves et al., 2023; Cáceres et al., 2024);
- Lack of transparent business models between DC operators/owners and DH utilities (Wahlroos et al., 2017; Pakere et al., 2024).

The above challenges also emerged during the expert interviews with Turner (2025), Hansen (2025) and Dyrelund (2025).

Chapter 4

Research design and problem statement

4.1 Problem formulation

The problem analysis and the literature review revealed that despite the promising potential of EH reuse from the DC industry to contribute to the decarbonization and enhanced energy efficiency of urban heating systems, this potential remains largely underexploited. A primary barrier to the effective use of EH in DH networks is the significant capital investment required for heat reuse infrastructure. The geographic separation between DCs and DH networks, coupled with the low quality of the available EH, increases these costs, because of the need of extensive piping infrastructure and the deployment of energy-intensive HP to upgrade the EH temperature.

While Section 3.1.3 references studies that evaluate the economic feasibility of EH recovery from DCs, Pärssinen et al. (2019) notes that research specifically focused on the economic assessment of EH utilization in the DC sector remains limited. Furthermore, even existing techno-economical studies tend to overlook the spatial dimension of the issue. In many cases, the economic analyses omit even the influence of the distance between a DC and the DH network, thereby disregarding the variability in the cost of the required piping infrastructure. For example, in Pärssinen et al. (2019), the generalized DC cases are modeled assuming uniform proximity to potential DH infrastructure, which does not reflect real-world spatial variability.

The physical location of a DC affects not only the length and cost of piping infrastructure but also is a deciding factor on to which DH network (if any) can EH be supplied to. DH supply temperatures vary across networks which in turn can affect the economic viability of heat reuse in these systems. As highlighted by Miškić et al. (2024), lower temperature regimes in DH networks improve the economic viability of EH reuse due to reduced operational costs associated with HPs. Additionally, a DC's location may influence electricity prices, further affecting the operating costs of HPs as well as local prices of EH that can be sold to the heating grid. Despite the relevance of these space-related factors, no studies have been identified that place the geographic location of DCs at the center of their analysis when assessing the economic feasibility of EH reuse. However, such spatial approaches have been applied in evaluating other unconventional EH sources within DH networks, eg. wastewater plants (Dou et al., 2018; Neugebauer et al., 2015).

Because of the above, the research question posed in this thesis - intended to address the identified knowledge gap - is as follows:

How does the location of a Data Center impact the financial viability of reusing its excess heat in District Heating?

The research design of the project, set to address the above question is presented in Figure 4.1.

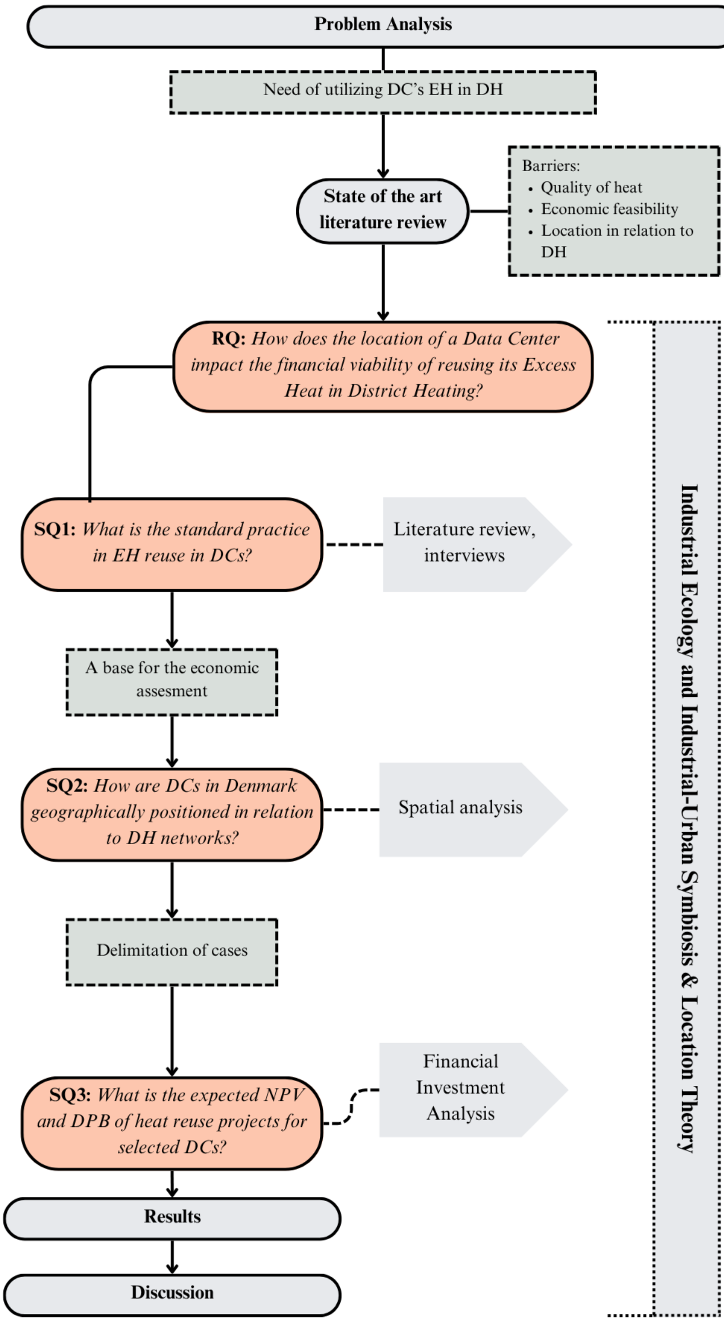

Figure 4.1. Research design of the report including research questions, research strategy, methods and theory

To find the answer for the main research question, posed on the basis of findings coming from problem analysis and literature review, three sub-questions are developed.

First sub-question i.e. *What is the standard practice in Excess Heat reuse in Data Centers?* has been addressed in Chapter 2.3. The overview of the EH reuse process provides a foundation for identifying the necessary infrastructure and technical components involved. Furthermore, the comparison of different cooling technologies, and their respective impacts on the quality of EH, supports the formulation of more precise and reliable assumptions and input parameters for the financial model.

As the geographical scope of the research was decided to be limited to Denmark, second sub-question, i.e. *How are Data Centers in Denmark geographically positioned in relation to DH networks?* seeks to analyze the spatial distribution of Danish DCs in relation to the existing DH infrastructure. This is done to find the potentials for symbiotic opportunities. Answering this question will also allow for choosing the most interesting cases for further financial analysis.

Finally, the third sub-question, *What is the expected NPV and DPB of heat reuse projects for selected DCs?* is building upon the answers for two previous questions and represents the core of the study. The economic viability of EH reuse from different real Danish DCs to the nearest DH network will be assessed by Net Present Value (NPV) and Discounted Payback Period (DPB) methods, in a way that allows for capturing the influence of the location-related factors on the final financial outcomes.

This way these three sub-questions, addressed one after another, will contribute to answering the main research question, therefore filling the knowledge gap identified earlier. The methodological approach for addressing the above sub-questions is detailed later in Chapter 6.

The project's problem statement and research questions are founded on two central principles. The first is that once energy is generated, it should be used and repurposed as efficiently as possible, thereby minimizing energy losses - in this case, through the reuse of EH. The second is that private business actors, including DC companies, are likely to adopt symbiotic practices like heat reuse only when these practices align with their individual economic interests. The core hypothesis is that the economic viability of such reuse is strongly influenced by locational factors - specifically, the geographical placement of a DC. These guiding principles, along with the hypothesis, form the basis for the use of two theoretical frameworks, which are introduced and discussed in the following chapter

Chapter 5

Theoretical considerations

To guide the research focus throughout the project and to provide analytical lenses, especially in the phase of discussing the results of the analysis, this project draws upon the concepts of Industrial Ecology and Location Theory. This Chapter introduces these theoretical frameworks and outlines their application within the context of the thesis.

5.1 Industrial Ecology & Industrial Symbiosis

The project aligns with the foundational idea of the Circular Economy (CE), which promotes the continuous use of resources and the minimization of waste, including energy losses. In many cases, successful CE requires cooperation between different stakeholders, which can foster new forms of collaboration across sectors and value chains. Rather than operating in isolation, both public and private actors, industries, businesses or municipalities can connect their material and energy flows and unlock mutual benefits (Cecchin et al., 2020). This type of symbiotic collaboration mirrors certain processes found in nature, where different species interact through exchanges of materials, energy, or information that benefit all involved. This analogy between industrial systems and ecological processes forms the basis of a concept that predates CE, known as Industrial Ecology (Cecchin et al., 2020).

Industrial Ecology is a concept that draws on a metaphor with ecosystems, suggesting that by mimicking the way nature efficiently cycles energy and materials, human economic systems can become more sustainable and resource-efficient (Cecchin et al., 2020). According to Chertow (2000), it provides a systems-based perspective, emphasizing that industrial operations should not exist in isolation but function in harmony with their surrounding systems. It advocates for optimizing the flow of materials and energy throughout the entire lifecycle - from resource extraction to product disposal - by integrating environmental, economic, and technical dimensions.

Industrial Ecology allows research focus at the facility level, at the inter-firm level, and at the regional or global level. The research under the Industrial Ecology framework can for example analyze settlement patterns (e.g. density of urban development etc.) that influence the industry's energy and material flows, planning strategies that facilitate or prevent symbiosis between the industry and other actors or policy actions to incentivize the ecosystem approach (Cáceres et al., 2024).

Within the Industrial Ecology studies focusing on inter-firm level, the concept of Industrial Symbiosis has emerged. Building on the natural ecosystem analogy, the expression "symbiosis" builds on the notion of biological symbiotic relationships in nature, in which at least two otherwise unrelated species exchange materials, energy, or information in a mutually beneficial manner - the specific type of symbiosis known as mutualism (Chertow, 2000). These exchanges are place-based, meaning they typically occur within a specific geographic area where proximity facilitates the efficient transfer of resources. The local context - such as infrastructure availability, spatial planning, and policy frameworks - plays a critical role in enabling and sustaining these symbiotic relationships (Chertow, 2000).

Because of the significance of the collocation of different industries, the Industrial Symbiosis in its purest form can be observed in so-called eco-industrial parks. Such park, according to Chertow (2007), is "a community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community" (Chertow, 2007).

According to Chertow (2007), in general, three primary opportunities for resource exchange are considered in Industrial Symbiosis:

- By-product reuse - when parties exchange residual materials from their operations that can serve as alternatives to conventional raw materials or commercial products for another party.
- Utility/infrastructure sharing - where parties use and manage common essential services like energy supply, water systems, or wastewater treatment.
- Joint provision of services - addressing shared operational needs, such as emergency services, logistics, or catering, through joint efforts among parties (Chertow, 2007).

The most notable example of an eco-industrial park is located in Kalundborg, Denmark, where several different industries, such as fish farming, agriculture, power plant, refinery and pharmaceutic plant share groundwater, surface water and waste water exchange their by-products that become feedstocks in other processes. One of the 'participants' and beneficent of this whole scheme is the city of Kalundborg, particularly its DH network, which is being supplied with the EH from refinery processes (Chertow, 2007). As industrial zones are an integral part of urban ecosystems, urban environments with their infrastructure can also be considered as potential partners in the development of Industrial Symbiosis solutions. According to Erol et al. (2023), combining urban and industrial symbiosis (Industrial-Urban Symbiosis) is a step toward better resource efficiency in both urban areas and industrial zones within urban areas.

There are various drivers behind the adoption of business practices alligning with Industrial Symbiosis paradigm, both as a direct strategy and as an outcome of efforts to achieve other objectives. One of the primary incentives is rooted in traditional business logic: resource sharing can lead to reduced operational costs or the creation of new revenue streams. Beyond immediate financial benefits, industrial symbiosis can also contribute to greater resource security over time by improving access to essential inputs - such as energy, water, or specific raw materials - often through formal agreements. Additionally, some companies are motivated by external pressures, such as regulatory requirements or permitting conditions, which push them to improve resource efficiency, lower emissions, or reduce waste. Having noted that, Chertow (2000) states that while investigating the potential for Industrial Symbiosis, it is reasonable to start with the assumption that companies will do what is in their individual economic interest, which was also observed in the model case of Kalundborg (Chertow, 2000).

Within this project, Industrial Ecology and Industrial-Urban Symbiosis serve as the foundation for understanding the potential symbiotic relationships between DCs and urban heating networks. Following the framework of these two concepts, DCs and DH grid are treated as two industries with the technological potential for mutualism, in the form of place-based by-product exchange (one-way exchange - heat as a by-product of DC operation, being bought by DH utility). Industrial Symbiosis, with its focus on mutual benefit from resource-sharing, particularly through proximity, is especially relevant to understanding the dynamics between DCs and nearby heat demand. By examining DCs in the context of their potential exchanges with nearby DH networks, the thesis can identify potential opportunities for EH reuse based on geographic and infrastructural factors. This aligns with the project's core principle of minimizing waste and optimizing energy use, as spatial relationships between DCs and DH networks are treated as crucial factors in determining the feasibility of such initiatives.

5.2 Location Theory

As the symbiotic practices are place-based, potential for their development can be assessed not only from the technological or material-flow perspective, but also by taking a spatial economic approach. The physical location of an enterprise plays a crucial role in shaping its profitability, operational efficiency, and economic outcomes. This connection between location and business performance has long been recognized within the field of economic geography and is explored through a set of concepts collectively known as the Location Theory.

The origins of Location Theory lie in mathematical problem-solving, but it was Johann Heinrich von Thünen who introduced a geographical model of land use, bringing a spatial dimension to the discussion. He conceptualized land use as concentric rings around a central location on an idealized, featureless plane, with the goal of minimizing transportation costs to the center. This framework aimed to address the question of where and why economic activities are located in specific areas. Over the years, scholars such as Alfred H. Thiessen, Walter Christaller, and Alfred Weber have refined and expanded on Thünen's ideas. Their work laid the foundation for modern location science, which has been further developed by geographers, economists, and regional scientists (Marianov and Eiselt, 2024).

The core assumption of the Location Theory has always been that enterprises will choose a location minimizing their total costs and therefore maximize their profits (Mccann and Sheppard, 2003). The profitability of a business is therefore determined, among others, by the location-specific economic conditions. It is important to distinguish between distance-related and location-specific factors. In economic terms, some costs are influenced by distance (e.g. transportation costs between raw materials source and a factory, energy grid losses), while others are determined by location (e.g. local cost of energy, taxes, local purchasing power). The above-mentioned classical theorists from the early 20th century associated distance-related costs with transportation expenses, whereas location-specific with factors such as local labor and land costs. Over the course of the development of the location studies, more complex factors were being identified, specific for different modern industries or businesses (Mccann and Sheppard, 2003).

Principles and methodologies developed on the base of the Location Theory, especially GIS modeling, are used for analyzing existing markets or distribution systems as well as the siting of individual business facilities (Mccann and Sheppard, 2003). As for the energy sector, Mccann and Sheppard (2003) state that the location theory studies have been largely descriptive, lacking a prescriptive approach to location modeling. This sector is shaped by complex ecological, geopolitical, and geoeconomic factors that operate at different territorial scales, which further complicates spatial decision-making.

In the context of this project, Location Theory offers a crucial geoeconomic framework, emphasizing the significance of spatial decision-making in determining the economic outcomes of DCs. Within the Location Theory framework, the EH reuse is treated as a business practice, which geographic location, treated not in isolation, but in relationship with DH network, impacts its investement and operational costs, and in turn, overall profitability.

The theory thus provides a structured approach to understanding these dynamics, treating the identified DC cases as individual enterprise entities, where decisions are guided by economic incentives, specifically the minimization of costs and maximization of profits. Additionally, Location Theory facilitates the distinction between distance-related factors (such as piping costs) and location-specific factors (such as local energy prices or infrastructure availability), both of which play a pivotal role in determining the economic feasibility of EH reuse. Finally, the theory supports the application of GIS methods, enabling the assessment of real DC locations in relation to DH systems. The methodology behind the focus on distance- and location-specific economic factors are described in detail in Chapter 6.

Chapter 6

Methodology

The purpose of this Chapter is to describe the methods used throughout the thesis, starting with methods for data collection, followed by the detailed overview of methodology for spatial and financial investment analysis. For the last two, the focus is put on explaining the process of conducting the analysis, outcomes of which are presented in Chapter 7.

6.1 Methods for data collection

6.1.1 Literature review methodology

A methodological literature review was applied to explore existing knowledge gaps related to the utilization of EH from DCs for DH purposes. This approach also served as a data collection method to identify key barriers and challenges in the field. The insights from this process significantly contributed to framing the research question and selecting appropriate analytical methods for the thesis.

The review followed a semi-systematic approach, emphasizing a curated selection of academic literature rather than aiming for exhaustive coverage (Snyder, 2019). This method is especially suited for integrating diverse academic perspectives to develop a broad understanding of the field and highlight areas that remain underexplored (Snyder, 2019). In this context, the literature review was instrumental in narrowing the problem field and framing the research question of the thesis.

A qualitative, content-oriented analysis was adopted to identify recurring themes across the selected literature. SCOPUS was chosen as the primary database, based on its strong track record of delivering relevant results in energy-related research. Before committing to the final key words, exploratory searches were conducted to evaluate the suitability of different keyword combinations and ensure a representative selection of publications. This preliminary step aimed to reduce the risk of overlooking important sources or misrepresenting gaps in the literature (Snyder, 2019). In the end, the final search was limited to English-language academic articles and used the following keyword string: ("district heating" OR "heating network" OR "urban heating") AND ("data centre" OR "data center" OR "data centers" OR "data centres") AND ("waste heat" OR "excess heat" OR "surplus heat"), capturing literature at the intersection of these thematic areas.

The database search was conducted in March 2024 as part of the initial phase of thesis research. A total of 97 articles were retrieved. Each article was screened by its title and abstract to assess its relevance to the research topic, following the approach described by Snyder (2019). Based on this screening, 37 articles were selected for full-text review. Additionally, more articles were identified through a snowball approach, using tools such as Litmaps to track citations and find highly-cited, relevant studies, further enriching the pool of sources for the review.

6.1.2 Semi structured interviews and written communication

Semi-structured expert interviews have been used as a data collection method to both identify the main challenges and barriers in the field of DC's EH reuse at the initial stage of the study, as well as to review the obtained results. Therefore, the interviews have supported the findings of the theoretical literature review and helped to frame thesis' research question, but also provide greater confidence in the obtained results. In total, three interviewees were selected based on their practical experience with the topic:

- Drew Turner, Danfoss Global Head of Sector Integration;
- Anders Dyrelund, Senior Market Manager at Ramboll Energy;
- Henrik Hansen, CEO of Danish Data Center Industry.

An interview guide was developed and adjusted to suit each of the two interview participants, serving as a general structure for the conversations. A sample of the guide can be found in Appendix A.1. The questions aimed to uncover key challenges and barriers in the field, thereby supporting the identification and framing of the core problem.

The interviews were mainly conducted online using Microsoft Teams, with each session lasting approximately 30 minutes. Prior to the start of each interview, participants were given an introduction to the thesis topic and asked for their consent to include their insights in the thesis.

The semi-structured format provided flexibility, allowing the interviewer to diverge from the predefined guide when appropriate and ask follow-up questions based on the participants' input. This created space for a more interactive and reflective dialogue.

Two other interview requests resulted in stakeholders answering the questions by means of written communication. This situation applies to Lene Solskov, Communication Advisor at Hofor (Utility Company responsible for DH network in Copenhagen) and Katrine Dahl Henriksen, Project Manager at Kredsløb (utility Company responsible for DH network in Aarhus). The written communication was carried out in April 2025, after the research problem, questions, and relevant cases had already been defined. At this stage, the focus of the communication shifted to gathering specific input for the financial model. Due to the structured nature of written communication and the progress made in earlier phases, the questions were targeted and practical - addressing aspects such as supply temperatures in DH networks and the unit price of EH within specific networks. The responses enabled a comparison between two DH networks, making it possible to incorporate location-based variables into the model.

6.2 Spatial analysis

The identification of real DC sites and investigating their location in relation to existing DH networks, and therefore answering the second subquestion of the research, was conducted through spatial analysis with the use of Geographic Information System (GIS). GIS is a computer system that stores, manages, analyses, and displays geospatial data (ESRI, 2024) - the data that describes both the locations and qualities of spatial features (Chang, 2006). GIS allows for vector and raster data to be superimposed on top of one another as layers on a single map, linking data to a map by combining geographical coordinates with various sorts of descriptive features. Using GIS enables the comparison of geospatial data to analyze their interactions and relationships which therefore can improve the analytical and decision making processes (Chang, 2006).

In this study, GIS is used in two ways: first, to map and visualize existing DC locations in Denmark using open-access data, providing an overview of their number and spatial distribution. Second, to analyze the spatial relationship between mapped DC locations and the geographic boundaries of DH networks, identifying symbiotic opportunities for EH reuse. This section will delve into details of how this was accomplished with the use of qGIS software.

6.2.1 Mapping Data Center locations

The data regarding geographic locations of DCs were obtained from Data Center Map (2024), which is both a database and an interactive map, "used by buyers and sellers of data center services, investors, analysts, real estate professionals, construction companies, public authorities and other decision makers in the industry, as both a research- and procurement tool" (Data Center Map, 2024). It gathers data about DC facilities from all around the world. The transparency and completeness of this source is satisfactory, which was checked by comparing its content with the results of desk-research on existing DCs in Denmark. Furthermore, the dataset provides not only the basic information about given DC (name, the owning company, address) but also the information on DC's fully built-out power and the size of its whitespace, alongside with some additional information on compliance, security or services provided. However, this kind of information is provided by only minority of the listed DCs.

The locations of the listed DCs had been geocoded and put on the map as a point layer, using qGIS's MMQGIS Plugin and were limited to geographical borders of Denmark. Out of 52 identified DCs, 41 are marked as operating and 11 are planned or under construction, based on the information from Data Center Map (2024). The final geocoding outcome with this differentiation taken into account can be seen in Figure 6.1. Each point represents one DC, either operating and planned, and contains the data on the fully built-out power and the size of DCs whitespace, if such data was available. The datasheet containing all of identified DCs in Denmark, together with their characteristics taken into account can be seen in Appendix A.2.

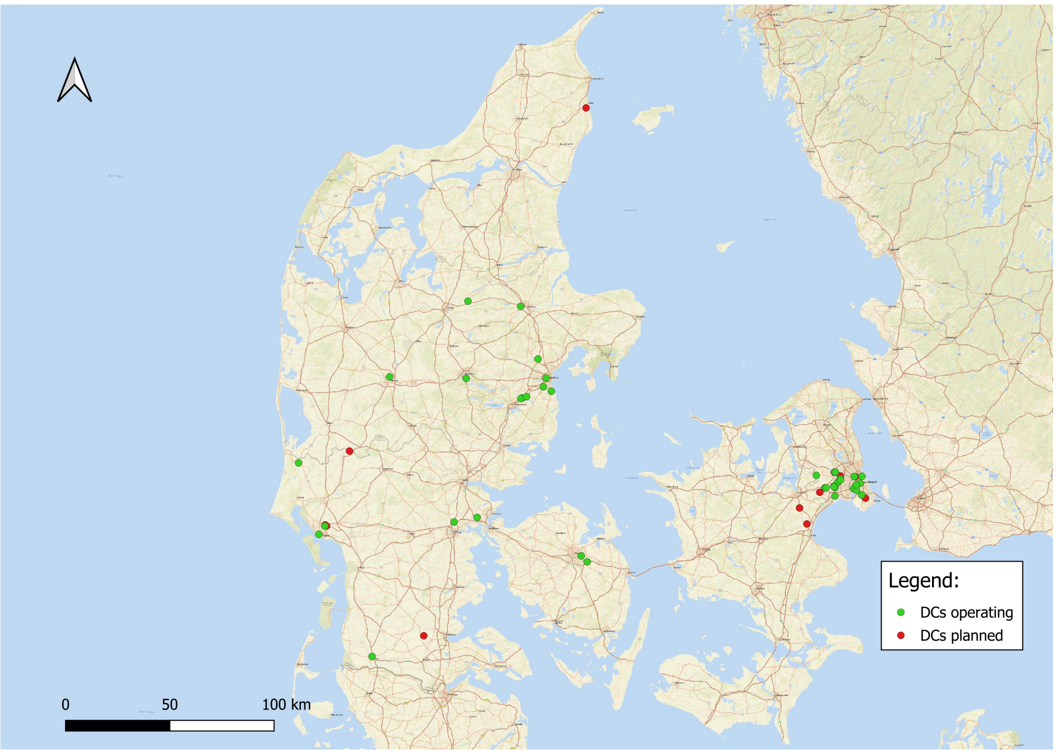

Figure 6.1. Operating and planned DC locations in Denmark based on (Data Center Map, 2024). Own production in qGIS.

6.2.2 Generalization of Data Center cases

As the geographical location of a DC, especially in relation to existing DH network, and its impact on economic feasibility of EH reuse is the object of the study, it was decided to generalize technical parameters of identified DCs. This is done because each DC have different specifications, which then would result in differences between technical feasibility of EH reuse, as well as the amount and the the temperature of available EH. Taking the above differences into considerations would make it more difficult to capture the influence of a location-related factors on a viability of heat reuse process.

Because of the above, it was decided that generalization of the technical specifications, and in turn the amount and the temperature of available EH, was needed for the purpose of further analysis. This is not unusual in identified literature, likely because of the lack of quality data on operating DCs. For example, Pärssinen et al. (2019) define three cases based on the number of racks in the DC whitespace. In their study, a small DC consists of 50 racks, representing a typical small-scale service provider. The medium-sized DC consist of 500 racks and the large DC case includes facilities with a maximum capacity of 5,000 racks, functioning as industrial-scale service provider. Wu and Buyya (2015) also use number of racks as a factor to distinguish between small, medium and large DCs. According to them, small DC has between 5 to 20 racks, medium between 20-100 and large - more than 1000. This approach of categorizing DC cases by number of racks in the facility's whitespace was adopted also in this thesis.

As can be seen from the above examples, the number of racks and the corresponding categorization of DCs can vary significantly between different sources. This is why it was decided that in this study, the categories will be determined based on the specifications of identified and mapped DCs, hence on information publicly available in Data Center Map (2024) database. However, no DC listed in this source provide an infomration about the number of server racks within the facility, and - as mentioned earlier - only a minority of DCs provide information regarding their technical specifications in general. This meant that the number of racks needs to be assessed indirectly, based on other available information - the size of a DC's whitespace.

Out of 41 mapped operating DCs, only 17 share the information about the size of their whitespace. These 17 cases served as the foundation for the generalization process. To establish three representative DC categories, statistical measures such as minimum, maximum, average, and median whitespace sizes were analyzed. Based on these insights, three generalized DC cases were defined: Small (400 m^2), Medium (1,000 m^2), and Large (4,000 m^2). Each of the 17 real-world DC cases was assigned to one of these categories according to its whitespace size. For example, if a DC's actual whitespace was closer to 400 m^2 than to 1,000 m^2, it was classified as a Small DC Case and assigned the standardized size of 400 m^2. The same principle applied to Medium and Large DC Cases. Initially, this process was intended to be applied to all 41 mapped operating DCs. However, due to the lack of available data on the actual whitespace size for many of these facilities, assigning a generalized value was not feasible. Consequently, the further analysis was limited to the 17 cases for which whitespace data was available. The location of these cases is presented in Figure 6.2.

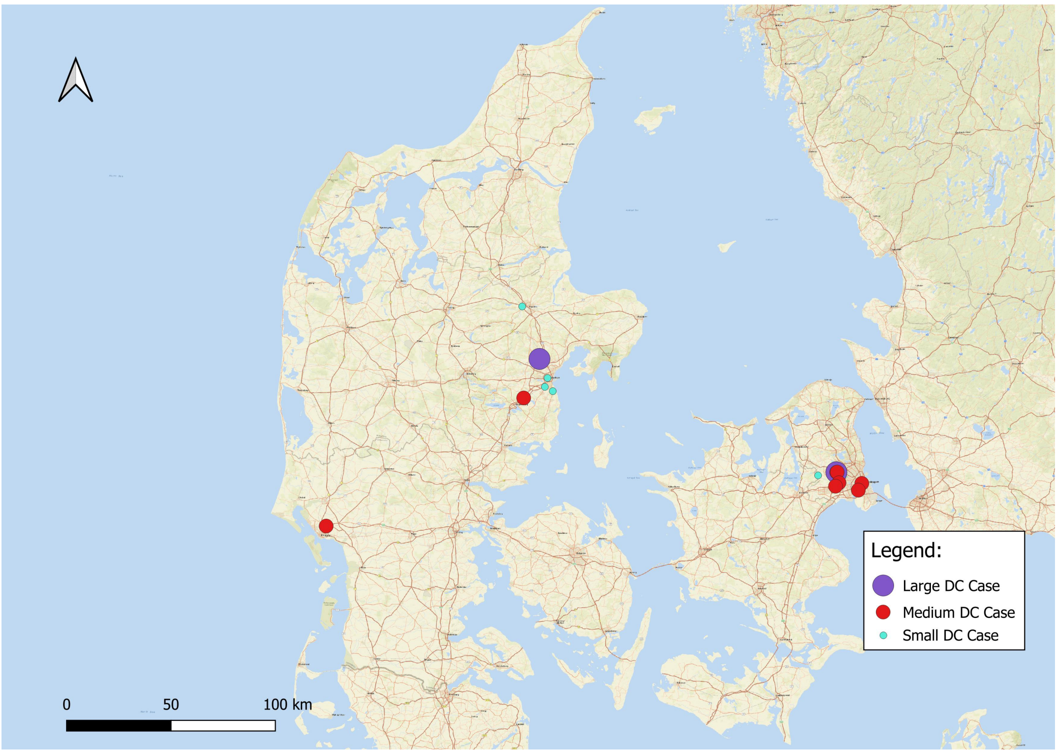

Figure 6.2. 17 DC cases grouped in size categories. Own production in qGIS.

Each of 17 DC cases have been assigned a corresponding number of server racks based on their generalized whitespace size. According to Wu and Buyya (2015), a standard server rack measures 600 × 600 mm, and it is reasonable to assume that each rack requires between 2 and 3 m^2 for access and cooling. In this study, a standardized value of 2.5 m^2 per rack is applied. Based on this assumption, each Small DC Case (400 m^2 whitespace) can accommodate up to 160 racks, while Medium and Large DC Cases can house up to 400 and 1,600 racks, respectively. These values are consistently applied to all 17 cases within each category.

The final outcome of this generalization process is presented in Table 6.1.

Name	Real whitespace size [m^2]	Category	Generalized whitespace size [m^2]	Number of racks
Fuzion Randers	245	Small	400	160
Cibicom København Vest	350	Small	400	160
Carl Jacobsens Vej 20 (CPH-RS)	390	Small	400	160
Cibicom Aarhus	400	Small	400	160
Fuzion Aarhus	425	Small	400	160
Fuzion Viby J	460	Small	400	160
Fuzion Skanderborg	740	Medium	1000	400
AtlasEdge CPH001	900	Medium	1000	400
Penta CPH01	1000	Medium	1000	400
Adeo Datacenter	1045	Medium	1000	400
Industriparken 24 (CPH3)	1403	Medium	1000	400
STACKInfrastructure CPOP1A	1600	Medium	1000	400
Cibicom Ballerup	1900	Medium	1000	400
Bulk Data Centers - DK01 Campus	2300	Medium	1000	400
Cibicom Kappa	2500	Large	4000	1000
Industriparken 20C (CPH1)	3484	Large	4000	1000
Industriparken 20-32 (CPH2)	4571	Large	4000	1000

Table 6.1. 17 identified DCs with their generalized specifications dependent on the whitespace size. Own production, whitespace size from (Data Center Map, 2024).

6.2.3 Identification of DH areas

To investigate the relation between the location of identified DCs and existing DH networks in Denmark, the geographical range of each DH system has to be known. However, to the author's knowledge, there is no publicly available data on this matter in Denmark, as DH infrastructure is considered a critical infrastructure. According to Persson et al. (2022), comprehensive datasets containing location-specific details on European DH systems are scarce and typically not included in standard statistical repositories. Due to these constraints, precise piping routes and network boundaries could not be directly incorporated into this project.

Given these limitations, other sources regarding the DH coverage had to be considered. Ultimately, the expected DH system boundaries in Denmark were obtained from the sEEnergies Open Data database. This database, developed as part of the sEEnergies Project - a collaborative effort involving European universities and private partners - contains GIS-based data designed to assess energy efficiency potentials across various sectors, including buildings, transport, and industry. One key dataset from this collection, D5.1 District Heating Areas, delineates expected DH zones using heat demand density data derived from the Heat Roadmap Europe 4 dataset. Specifically, it identifies DH areas as polygons corresponding to regions where heat demand density meets or exceeds 500 GJ/ha (sEEnergies, 2025). Persson et al. (2022) utilized this dataset to analyze the availability and accessibility of urban excess heat for potential integration into thermal grids across Europe.

The methodology behind the D5.1 District Heating Areas dataset involved classifying hectare-level heat demand density data and outlining DH coverage accordingly. The dataset was generated by isolating grid cells from the Heat Roadmap Europe 4 raster dataset with heat demand densities of 500 GJ/ha or higher (falling within density classes 3, 4, and 5). These selected raster cells were then converted into a polygon layer and supplemented with attributes from various sources, including data on existing DH networks from the Halmstad University District Heating and Cooling database. Following post-processing steps such as boundary refinement and aggregation, the final output is a publicly accessible polygon layer representing DH network coverage across Europe. These polygons indicate areas where DH distribution has likely been viable in recent decades, based on residential and service sector heat demands meeting or exceeding the 500 GJ/ha threshold (Persson et al., 2022). Additionally, the dataset distinguishes between confirmed DH areas and other regions based on multiple data sources, enabling further spatial analysis and visualization.

In this study, the polygons from the D5.1 District Heating Areas dataset were processed as follows. First, the dataset was clipped to align with Denmark's borders. Next, it was filtered to retain only those features explicitly classified in the GIS attribute table as actual DH areas (i.e., where the "Indicator for actual district heating area" was marked as "DH"). This resulted in the creation of DK_DH_areas_actual, a dataset representing the existing DH networks in Denmark along with their expected boundaries. These areas are visualized in Figure 6.3.

Figure 6.3. Expected DH areas in Denmark. Own production, based on sEEnergies (2025).

A significant variation in heat demand was observed across the identified DH areas. The largest polygon, located in Copenhagen, had an estimated annual heat demand of 34,4 PJ, whereas the smallest, in Haarby, had only 1,695 GJ of demand. This disparity highlighted the need to exclude DH areas with insufficient heat demand, as they could not be considered as economically feasible heat sinks for DC's EH.

To establish a threshold for exclusion, a minimum annual heat demand of 293.682,81 GJ/year was set. This value corresponds to the estimated annual EH output from the Large DC Case, assuming an upgrade via a HP with a COP of 3.5 (the calculation of the accessible EH follows the adjusted Equation 6.7 presented later in Section 6.3.3). By applying this threshold, DH areas with lower heat demand were removed from further analysis, ensuring that selected DH areas have a heat demand at least equal to the potential supply, making the integration of EH attractive and feasible. The result of this processing is presented in Figure 6.4.

Figure 6.4. Expected DH areas in Denmark after exclusion of the networks with smallest heat demand. Own production, based on sEEnergies (2025).

6.2.4 Identification of final Data Center cases

With the locations and generalized specifications of real-world Danish DCs, as well as with the expected geographic boundaries of sufficiently large DH areas, a spatial analysis was conducted to identify potential synergies. Figure 6.5 presents the map of Denmark with identified 17 DC cases and expected DH areas in overlay.

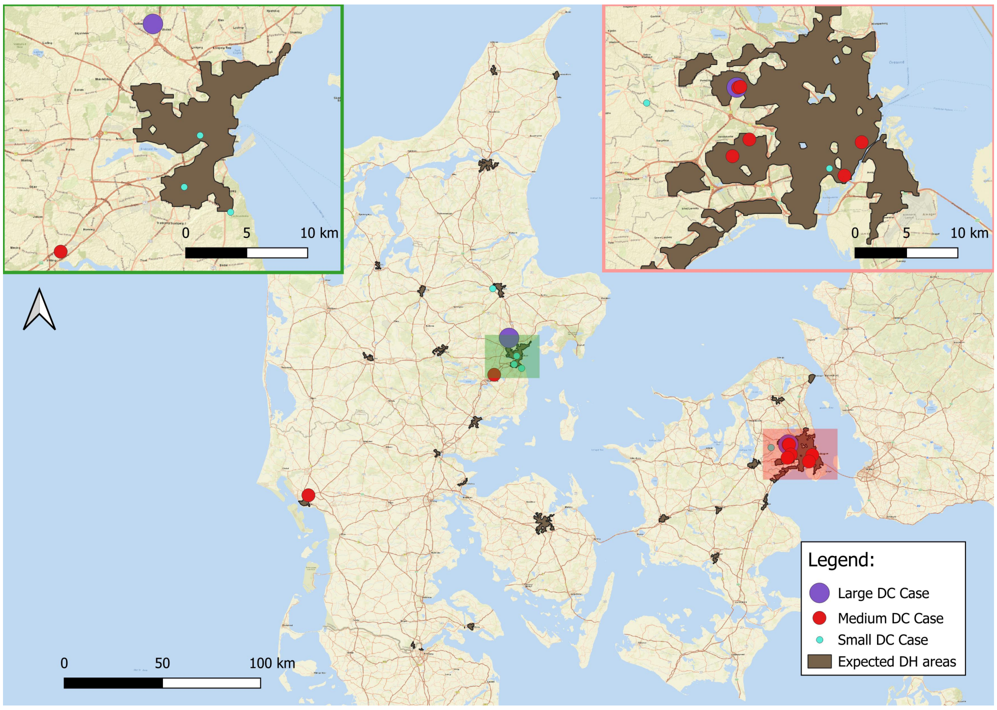

Figure 6.5. 17 categorized DC cases and expected DH areas. Own production.

Based on the overlay of the two datasets, the proximity of DCs to nearest DH areas was assessed. Using the 'Join Attributes by Nearest' qGIS tool, each of the 17 DCs was assigned the nearest DH area polygon, with the distance between the DC and the boundary of the polygon calculated and presented in meters. In some cases, this resulted in a distance of 0 meters, indicating that a DC was located within the DH area.

Based on this spatial analysis, six cases were selected for further analysis, two for each category (Small, Medium, and Large DC). The selection was primarily guided by a "most variability" approach - ensuring that each pair of DCs within a category differed significantly in terms of their closest DH network and their proximity to its boundary.

However, for the Small DC category, a slight adjustment was made to the selection criteria. Rather than strictly following the "most variability" approach, the selected pair was chosen to align with the Medium and Large DC categories, ensuring that all three categories focused on Copenhagen and Aarhus. This consistency across size categories strengthens the comparative aspect of the analysis, allowing for clearer insights into the differences and similarities between these two major urban areas, rather than introducing additional geographic variability.

The six chosen cases, presented in Table 6.2 and in Figure 6.6, formed the foundation for the subsequent techno-economic analysis.

Name	Category	Number of racks	Closest DH area	Distance to closest DH area [m]
Fuzion Randers	Small	160	Randers	365,3
Cibicom København Vest	Small	160	Stenlille	354,1
Carl Jacobsens Vej 20 (CPH-RS)	Small	160	København	0
Cibicom Aarhus	Small	160	Aarhus	134,7
Fuzion Aarhus	Small	160	Aarhus	0
Fuzion Viby J	Small	160	Aarhus	0
Fuzion Skanderborg	Medium	400	Aarhus	9.275,9
AtlasEdge CPH001	Medium	400	København	0
Penta CPH01	Medium	400	København	0
Adeo Datacenter	Medium	400	København	0
Industriparken 24 (CPH3)	Medium	400	København	0
STACKInfrastructure CPO1A	Medium	400	København	0
Cibicom Ballerup	Medium	400	København	0
Bulk Data Centers - DK01 Campus	Medium	400	Esbjerg	1.194,3
Cibicom Kappa	Large	1600	Aarhus	4.887,1
Industriparken 20C (CPH1)	Large	1600	København	0
Industriparken 20-32 (CPH2)	Large	1600	København	0

Table 6.2. 6 chosen DC cases. Own production.

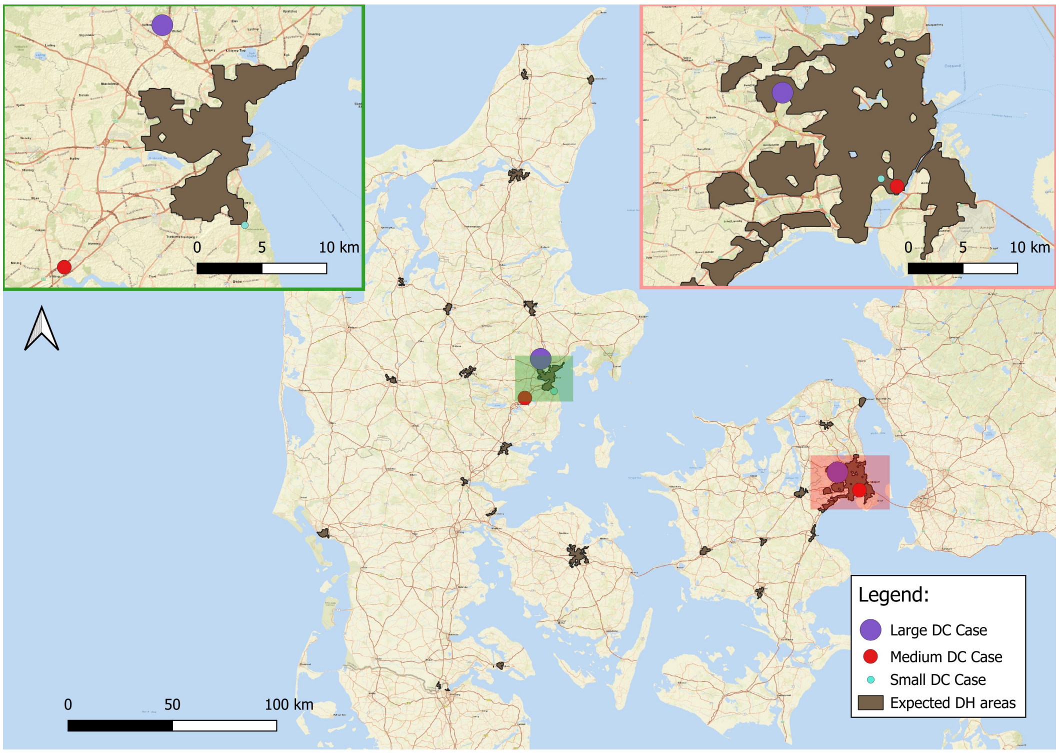

Figure 6.6. 6 chosen DC cases and expected DH areas. Own production.

6.3 Financial investment analysis

This thesis applies the approach to investigate the economic feasibility of EH reuse from curated cases. There are several financial analysis methods to choose from in this context. The most common one is evaluating the net present value (NPV) index. The process of calculating the NPV typically involves four key steps: projecting the expected future operating cash flows; second, determining an appropriate discount rate (r) and applying it to convert those future cash flows into present value terms; third, calculating the NPV by summing the discounted cash flows; and finally, interpreting the outcome to support investment decisions (Brealey et al., 2020). The discount rate r is used to reflect the time value of money - the idea that money today is worth more than the same amount in the future because of its earning potential, including the inflation factor. Cash flows are therefore discounted to their present value (PV) using the chosen rate, reflecting both the investment's risk level and the expected return from similar ventures (Pärssinen et al., 2019). NPV is particularly effective for passive, initial investment decisions, as it evaluates cash flows over a longer time horizon. By accounting for the time value of money (by using the specified discount rate r) and relying entirely on projected cash flows it supports more informed investment choices (Brealey et al., 2020).

To supplement the NPV results, it was decided to also use a different financial indicator, results of which are easier to translate and visualize - namely the Discounted Payback Period (DPB). Put simply, the payback period (PB) represents the estimated time required for a project to generate enough revenue to recover its initial capital expenditure (CAPEX) within the specified time period and is often used to supplement the NPV. It is typically calculated by dividing the total CAPEX by annual cash inflows (Pärssinen et al., 2019). To calculate the DPB, this calculation needs to be adjusted for the discount rate, the same way as in NPV method - to reflect the time value of money. The payback rule states that a project should be accepted if its payback period is less than some specified cutoff period, e.g. 20 years (Brealey et al., 2020). The acceptable cutoff period can vary depending on the industry and project type. Although this method has its limitations (e.g. it ignores all cash flows after the cutoff date), according to Brealey et al. (2020) it is often the simplest way to communicate an idea of project profitability. For this reason DPB was selected to highlight and compare the relative financial outcomes across the selected cases.

The Equations 6.1 and 6.2 present the way both NPV and DPB are calculated in this thesis. As the both formulas use the same input factors, whenever the project says "NPV input factor" it means also the input factor for DPB formula.

$$\text{NPV} = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - \text{CAPEX} \tag{6.1}$$

Where:

- CF_t is the net cash flow in year t,
- r is the discount rate,
- T is the investment period in years,
- CAPEX represents the total initial capital expenditure.

$$\text{DPB} = p + \frac{\text{CAPEX} - \sum_{t=1}^{p} \frac{CF_t}{(1+r)^t}}{\frac{CF_{p+1}}{(1+r)^{p+1}}} \tag{6.2}$$

Where:

- p is the last year before cumulative discounted cash flow becomes positive,
- CF_{p+1} is the discounted cash flow in the following year,

As can be seen in both equations, there are three main factors needed to be known in order to calculate NPV and DPB; CAPEX, annual cash flows in selected time period, and the discount rate r. The following sections explain how each of these elements is determined and applied in the analysis. This part of the thesis follows the general methodology outlined by Pärssinen et al. (2019), which serves as the primary source for the approach taken in constructing the NPV and DPB models. Most of the assumptions regarding the values of specific factors are taken from Monsalves et al. (2023), although - if relevant - some input values were adjusted to the size of the project's DC power loads. In order to structure the explanation of the NPV model, as well as to relate it to the Location Theory, input factors (both for CAPEX and annual cash flows) are categorized into the following three main types:

- **Universal factors** – factors that remain constant across all cases (Small, Medium, and Large DCs), also regardless of their geographic location;
- **Case-dependent factors** – factors that vary between Small, Medium, and Large DCs, but are not influenced by the geographic location of the DC;
- **Location-related factors** – factors that differ depending on whether a DC, regardless of its size, is located in the Copenhagen or Aarhus area. This category contains both distance-related factors and location-specific factors as understoon in the framework of Location Theory.

The overview of the input factors is presented in Tables 6.3–6.5.

NPV Input factor	Value	Source
Power consumption per rack [kWh]	4,286	(Pärssinen et al., 2019)
Heat recovery rate	97%	(Lu et al., 2011)
Tax rate for heat sold	0%	(Danish Energy Agency, 2021)
Rate of return	10%	(Monsalves et al., 2023)

Table 6.3. Universal NPV Input Factors (applicable for each case).

NPV Input factor	Small DC	Medium DC	Large DC	Source
Number of racks	160	400	1600	Estimated
HP's investment costs [EUR/kW]	1240	1240	670	(Monsalves et al., 2023)
DH connection investment costs [EUR/kW-km]	460	460	25	(Monsalves et al., 2023)
Electricity price [EUR/MWh]	116.68	112.73	111.07	(Statistics Denmark, 2025)
Fixed operation costs [EUR/kW]	2	2	2	(Monsalves et al., 2023)
Variable operation costs [EUR/MWh]	2.69	2.69	1.69	(Monsalves et al., 2023)

Table 6.4. Case-dependent NPV input factors (by size of a DC).

NPV Input factor	Copenhagen	Aarhus	Source
HP's COP	monthly fluctuations	monthly fluctuations	Estimated, based on Technology Catalogue
EH price	monthly fluctuations	monthly fluctuations	HOFOR, Kredsløb
Distance between DC and DH	20m	estimated	Own spatial analysis

Table 6.5. Location-related NPV input factors.

6.3.1 Technical setup of selected DCs

In order to appropriately identify both CAPEX and cash flow factors, technical characteristics of the chosen cases need to be specified, especially their cooling system setup. The number of racks for each DC Case have been already determined in Section 6.2.2. The value for power per rack is based on Pärssinen et al. (2019), which conducted a one-week observation of actual power consumption in a typical DC server rack, measuring an average power load of 4.286 kW per rack. This project uses the heat recovery rate proposed by Lu et al. (2011), who found that 97% of the power consumed in a DC is converted into heat. Since DCs operate continuously, consuming electricity 24 hours a day throughout the year, this study assumes an monthly operating time of 720 hours.

As underlined before, the cooling system of a DC can have a significant impact on the heat reuse potential. Therefore, the cooling setup has to be specified before looking into heat reuse investment. Because of the above, each case is evaluated under two distinct scenarios: (1) an air cooling scenario and (2) a liquid cooling scenario. In the first scenario, the DC's whitespace is cooled using a CRAH unit, as illustrated previously in Figure 2.2. Waste heat is recovered from the hot aisle at a temperature of 35°C and directed to a HP for temperature elevation. In the second scenario, liquid cooling is applied by immersing IT components in a dielectric fluid, resulting in a higher waste heat temperature of 60°C before being transferred to a HP (as visualized earlier in Figure 2.3). The difference in EH temperature between both scenarios have an impact on HP's COP, as will be explained further in the Section.

In both scenarios, the use of a compression HP is assumed. It is further assumed that the DC has not previously employed a HP for free cooling, and thus one must be purchased and installed to enable the heat reuse process. The NPV model does not consider the cost of the cooling systems (e.g. operating costs of chillers or installation of liquid cooling systems), as this infrastructure is assumed to be in place prior to the heat reuse investment.

It is important to note that when the cost of the HP is considered in NPV model, it encompasses the entire supporting infrastructure required for its proper operation - not just the unit itself. This includes components such as heat exchangers, internal piping, and the casing of the HP. The COP of a HP is not specified and applied generally, as it is treated as a location-related factor, estimated on monthly basis, which will be explained in the later part of the Section.

6.3.2 Finding the CAPEX

To determine the CAPEX associated with a heat reuse investment, several assumptions were made. In line with previous studies such as Pärssinen et al. (2019) and Monsalves et al. (2023), this analysis adopts an assumption that the DC facility bears the full investment cost. Although this does not typically reflect real-world practice - as will be discussed in Chapter 8 - the assumption is based on two main considerations.

First, assuming that it is the DH utility that covers the CAPEX, either wholly or partially, would necessitate accounting for additional variables such as the composition of the energy mix in the heating grid, the marginal cost of heat production, and other systemic factors which would e.g. influence when and by what amount the EH is being supplied to the DH network. Incorporating these elements would considerably broaden the scope of the analysis.

Second, as outlined in Chapter 2, the EU legislation mandates that DCs with a total rated energy input exceeding 1 MW will have to recover and reuse their waste heat externally, unless they can demonstrate that doing so is technically or economically unfeasible. The above implies that, in the absence of action from DH utilities, DCs may ultimately be held responsible for not reusing heat and would need to take action themselves. The financial analysis presented in this project is therefore situated within this regulatory context.

Having stated the above and bearing in mind the technical considerations described earlier, the two components of the CAPEX in the NPV model, following Monsalves et al. (2023) are considered to be: 1) a HP, 2) connection to the DH network (piping infrastructure).

The cost of both elements of the CAPEX are based on assumptions from Monsalves et al. (2023). The cost of a HP is dependent on a maximum heat load (heat captured) from each DC case. This is why the cost of a HP is treated as a case-dependent input factor (larger heat load require larger, more expensive heat pumps). Investment costs of the connection to the DH network depend both on the distance between the DC and DH network and the amount of heat captured in the DC. Following Monsalves et al. (2023), the cost of DH connection in Large DC case is significantly lower per kW-km, because it is assumed to be connected to transmission, rather than distribution DH network. The reference values used in the NPV model can be seen in Table 6.6.

CAPEX factor	Small DC Case	Medium DC Case	Large DC Case	Type of input factor
Heat Pump [EUR/kW]	1.240	1.240	670	Case-dependent
DH Connection [EUR/kW-km]	460	460	25	Case-dependent & distance-related

Table 6.6. Overview of CAPEX input factors.

The obtained CAPEX values have been compared with CAPEX presented in two different studies. In Pärssinen et al. (2019), the cost estimation includes the heat reuse infrastructure, connection to the DH network (noting only that the distance is *close*), project planning, piping, and a HP. When normalized per MW, the CAPEX values derived in the thesis are significantly lower than those reported by Pärssinen et al. (2019). The results also highlight a pronounced effect of economies of scale, as the cost per MW decreases substantially from the medium to the large case, much more than in Pärssinen et al. (2019) cases. On the other hand, a fictional 1 MW data center case examined by Oró et al. (2019) yielded a CAPEX of 838.077 EUR, which, when normalized, is notably more cost-efficient than all the cases in Pärssinen et al. (2019). This comparison underlines that approach to CAPEX estimation can lead to markedly different results and should therefore be carefully considered. The approach presented by Monsalves et al. (2023) has been adopted in this study due to its specific focus on the Danish context, as well as its relative recency.

6.3.3 Calculating annual cash flows

With the CAPEX established, the next step in calculating the NPV is to determine the annual cash flows until either the investment is paid back or the cut-off period is reached. This requires estimating both the yearly revenues and the corresponding operating costs (OPEX). According to Damodaran (1998), OPEX is an ongoing cost for running a product, business, or system. He uses an example of a photocopier - buying the machine involves CAPEX, and the annual paper, toner, power and maintenance costs represents OPEX. In this example, the income generated by selling copies is the revenue.

Translating the above to the case of waste heat utilization, the revenue originates from heat captured and sold to the buyer - in this case, a DH utility. As explained in Section 6.2, the spatial analysis conducted in this study has restricted the considered Danish DH networks to those where the expected heat demand exceeds the accessible EH from the DC cases. Consequently, the financial model assumes that the DH demand for EH will consistently exceed the supply available from the DC.

However, to reflect seasonal variability in DH demand, the model accounts for periods when EH cannot be sold due to reduced heating needs. Based on the findings of Kozarcanin et al. (2019), the months of January, February, March, April, October, November, and December are designated as the heating season, during which EH sales are assumed to occur. Furthermore, it is assumed that DH utilities prioritize the use of EH, allowing the full amount of captured heat to be delivered to the network and sold during the heating season, for all cases.

Prices indicating the revenue per unit of EH have been obtained from DH utilities operating in Copenhagen (HOFOR A/S) and Aarhus (Kredsløb A/S). These prices were described by the utilities Pedersen and Solskov (2025) and Kristensen and Henriksen (2025) respectively, as those foreseen in DH utilities' internal budgets, and can therefore be considered as realistic indicators of what these stakeholders are willing to pay. For Aarhus, the data were provided on a monthly basis, while in the case of Copenhagen only an annual average price was available. To ensure consistency, the monthly distribution pattern observed in the Aarhus data was applied to the Copenhagen case, normalizing the annual average accordingly. While the actual prices are used as input in the NPV model, they are not disclosed in the report, in accordance with the request of Kristensen and Henriksen (2025).

The last factor needed to be taken into account to obtain revenues is the HP's COP. While most reviewed studies, including Pärssinen et al. (2019); Monsalves et al. (2023); Oró et al. (2019) assume a fixed COP, that is stable throughout the entire analyzed period, this thesis takes a different approach. To investigate the significance of temperature difference between DC's EH and DH's supply, COP is calculated on monthly basis for all cases.

To estimate performance, a theoretical COP is calculated. As outlined by Danish Energy Agency (2025), this can be approached using either the Carnot or Lorenz formulation, both of which relate mechanical work to temperature differences in systems such as power generation, refrigeration, and HPs. The Lorenz COP is more appropriate for DH applications. The formula for calculating the Lorenz COP is presented in Equation 6.3.

$$COP_{\text{Lorenz}} = \frac{T_{\text{lm,sink}}}{T_{\text{lm,sink}} - T_{\text{lm,source}}}, \quad where \quad T_{\text{lm}} = \frac{T_{\text{in}} - T_{\text{out}}}{\ln\left(\frac{T_{\text{in}}}{T_{\text{out}}}\right)} \tag{6.3}$$

According to Danish Energy Agency (2025), the actual COP is typically lower than the theoretical Lorenz COP due to mechanical and thermal losses, which usually account for 40-60% of the theoretical value. For the purposes of this study, a reduction factor of 45% was applied.

Because of the use of Lorenz formula, the final COP of a compression HP, which serves as an input factor for the NPV model, is influenced by the temperature difference between the DC's EH and the supply temperature of the DH network. For the purposes of the equation, it is assumed that the return temperature for cooling in the DC is 20°C, while the return temperature for both DH networks is set to 40°C, based on information provided by Kristensen and Henriksen (2025). In the "air cooling scenario," the EH temperature is set to 35°C, while in the "liquid cooling scenario," it is set to 60°C. The temperature of the DH supply in relation to ambient outdoor temperature were obtained from Kristensen and Henriksen (2025) and Pedersen and Solskov (2025). The same monthly fluctuations were applied to all annual cash flows (i.e. the COP in January of year 1 will be the same as COP in January of year 10). All of the relevant input factors for calculating the Lorenz COP are listed in Table 6.7.

Parameter	Copenhagen	Aarhus	Source
DC's EH temp. [°C] (air cooling)	35	35	(Davies et al., 2016)
DC's EH temp. [°C] (liquid cooling)	60	60	(Davies et al., 2016)
DC return temp. [°C] (both)	20	20	(Davies et al., 2016)
DH supply temp. [°C] (both)	monthly temp-dependent	monthly temp-dependent	(Kristensen and Henriksen, 2025) (Pedersen and Solskov, 2025)
DH return temp. [°C] (both)	40	40	(Kristensen and Henriksen, 2025)

Table 6.7. Temperature assumptions for Lorenz COP modeling.

The final COPs on monthly basis for cases in Copenhagen and Aarhus are shown in Tables 6.8 and 6.9.

Month	Average outdoor temperature [°C]	Temp in DH [°C]	COP (air cooling)	COP (liquid cooling)
January	1,1	80	**4,7**	**7,5**
February	4,6	75	**5,0**	**8,4**
March	5,4	75	**5,0**	**8,4**
April	8,3	70	**5,4**	**9,7**
May	15,1			
June	16,1			
July	17,5			
August	18,5			
September	15,8			
October	11,2	70	**5,4**	**9,7**
November	6,7	75	**5,0**	**8,4**
December	5,3	75	**5,0**	**8,4**

Table 6.8. HP's COP fluctuations in Copenhagen-located DC cases.

Month	Average outdoor temperature [°C]	Temp in DH [°C]	COP (air cooling)	COP (liquid cooling)
January	0,4	90	**4,1**	**6,1**
February	4	85	**4,4**	**6,7**
March	4,7	85	**4,4**	**6,7**
April	7,2	85	**4,4**	**6,7**
May	14,1			
June	14			
July	15,6			
August	16,7			
September	14			
October	10,1	80	**4,7**	**7,5**
November	5,5	85	**4,4**	**6,7**
December	4,8	85	**4,4**	**6,7**

Table 6.9. HP's COP fluctuations in Aarhus-located DC cases.

With the input factors for revenue established, annual revenue was calculated as a sum of monthly revenues for each case individually. This allowed for the consideration of seasonal fluctuations in EH prices, as well as variations in the HP's COP. Monthly revenues were calculated using equations 6.4–6.8, following the methodology presented by Pärssinen et al. (2019).

$$\text{Total energy consumed by IT (MWh/month)} = \frac{\text{Number of racks} \times \text{Power per rack (kW)} \times 720}{1\,000} \tag{6.4}$$

$$\text{Heat captured (MWh/month)} = \text{Total energy consumed by IT} \times \text{Heat recovery rate} \tag{6.5}$$

$$\text{HP's energy consumption (MWh/month)} = \frac{\text{Heat captured}}{(\text{COP} - 1)} \tag{6.6}$$

$$\text{Heat supplied to DH network (MWh/month)} = \text{Heat captured} + \text{HP's energy consumption} \tag{6.7}$$

$$\text{Monthly revenue} = \text{Heat supplied to DH network} \times \text{EH price} \tag{6.8}$$

The total annual revenue is therefore a sum of monthly revenues for seven months constituting the heating season. Appendixes A.4 and A.5 present the results obtained by applying the above equations with input data from the referenced earlier sources for both Copenhagen and Aarhus DC Cases, under both cooling scenarios.

To get the annual cash flow, the OPEX need to be subtracted from the annual revenue. In this study, OPEX includes; 1) cost of HP's operation, as well as 2) fixed and 3) variable operational costs, the latter two representing all the other costs of heat reuse process. This approach is based on Monsalves et al. (2023).

Annual fixed and variable operating costs were obtained directly from Monsalves et al. (2023) and depend on the power consumption of a DC, as well as on HP heat output.

Costs of HP's operation are calculated using the equation 6.9.

$$\text{Cost of HP's operation} = \text{HP's energy consumption (MWh/month)} \times \text{Electricity price} \tag{6.9}$$

Electricity prices used in the model were sourced from Statistics Denmark (2025) and reflect average rates for non-household consumers over the 2020–2024 period. Because electricity prices vary for the consumers with different consumption levels, different prices were applied to each category of DC cases (Small, Medium, or Large DC cases) based on their respective consumption profiles. In line with typical industry conditions - where DCs can get most of the electricity taxes refunded - the applied prices included only non-recoverable taxes and tariffs. No price fluctuations were accounted for during the payback period, as forecasting future electricity prices is highly uncertain, especially in energy systems increasingly reliant on renewable energy sources.

Finally, the discount rate in the NPV model has been set at 10%, a common benchmark, as suggested by Brealey et al. (2020), also used for DC heat reuse investment project in Monsalves et al. (2023). The analyzed time period, used also as a DPB cut off period, is set to 12 years.

Chapter 7

Results

This Chapter presents the outcomes of the NPV model for all six DC cases, along with detailed outcomes of key components such as annual cash flow and CAPEX. Finally, it concludes with an assessment of how location-related input factors have influenced the final results.

7.1 Overall results of DPB model

Table 7.1 and Chart 7.1 present the NPV results for the six cases under the air cooling scenario. None of the cases gives a positive NPV. Although all cases generate positive annual cash flows - i.e. annual revenues exceed annual OPEX - the total discounted cash flow over the 12-year period remains lower than the initial CAPEX. The Small DC Cases in both Aarhus and Copenhagen achieve the highest NPVs, which can be attributed to their relatively low CAPEX. In contrast, the Aarhus Medium DC Case records the lowest NPV. This outcome is primarily driven by high piping costs, as this case features the most remote location among all scenarios -an effect that becomes evident when comparing its NPV to that of the corresponding Copenhagen Medium DC case.

Since the discounted payback rule only accepts projects with a positive NPV, the variation in payback periods between the cases cannot be illustrated.

	Small DC Case		Medium DC Case		Large DC Case	
	Copenhagen (Carl Jacobsens Vej 20, Copenhagen)	Aarhus (Ny Moesgårdvej 61, Hoejbjerg)	Copenhagen (Borgmester Christiansens Gade 55, Copenhagen)	Aarhus (Niels Bohrs vej 35, Skandenborg)	Copenhagen (Industriparken 20C, Copenhagen)	Aarhus (Kappa 10, Hinnerup)
ANNUAL CASH FLOWS [EUR]						
Undiscounted annual cash flow	**28309,46**	**45935,78**	**78926,87**	**124652,96**	**387021,97**	**572745,08**
Discounted cash flow in year 1 (r=10%)	25735,87	41759,80	71751,70	113320,87	351838,16	520677,34
Discounted cash flow in year 2 (r=10%)	23396,25	37963,46	65228,82	103018,97	319852,87	473343,04
Discounted cash flow in year 3 (r=10%)	21269,31	34512,23	59298,93	93653,61	290775,34	430311,85
Discounted cash flow in year 4 (r=10%)	19335,74	31374,76	53908,12	85139,65	264341,21	391192,59
Discounted cash flow in year 5 (r=10%)	17577,95	28522,51	49007,38	77399,68	240310,19	355629,63
Discounted cash flow in year 6 (r=10%)	15979,95	25929,55	44552,16	70363,34	218463,81	323299,67
Discounted cash flow in year 7 (r=10%)	14527,23	23572,32	40501,97	63966,68	198603,47	293908,79
Discounted cash flow in year 8 (r=10%)	13206,57	21429,38	36819,97	58151,52	180548,61	267189,81
Discounted cash flow in year 9 (r=10%)	12005,97	19481,26	33472,70	52865,02	164135,10	242899,82
Discounted cash flow in year 10 (r=10%)	10914,52	17710,23	30429,73	48059,11	149213,72	220818,02
Discounted cash flow in year 11 (r=10%)	9922,29	16100,21	27663,39	43690,10	135648,84	200743,66
Discounted cash flow in year 12 (r=10%)	9020,27	14636,56	25148,53	39718,27	123317,13	182494,23
Total cash flow in 12 years [EUR]	**192891,92**	**312992,26**	**537783,38**	**849346,83**	**2637048,45**	**3902508,46**
CAPEX [EUR]	**831144,59**	**865844,05**	**2077855,28**	**9376570,40**	**4460181,70**	**5295094,50**
NPV [EUR]	**-638252,67**	**-552851,79**	**-1540071,90**	**-8527223,57**	**-1823133,25**	**-1392586,04**
Payback period (in years)	**XXX**	**XXX**	**XXX**	**XXX**	**XXX**	**XXX**

Table 7.1. NPV of six cases in the air cooling scenario. Own production.

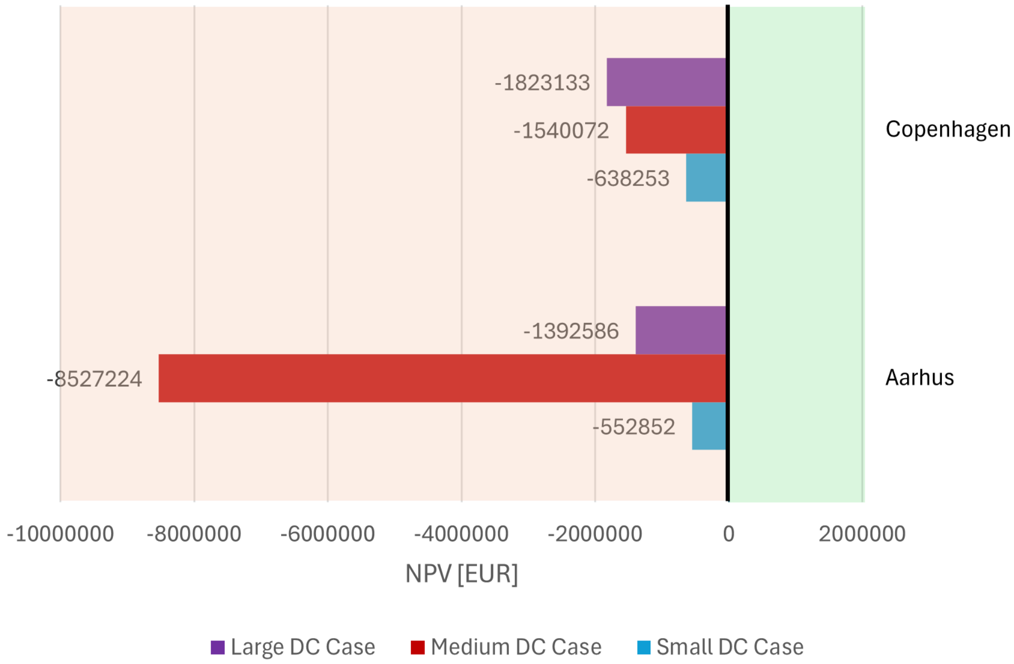

Figure 7.1. NPV of six cases in the air cooling scenario. Own production.

In the liquid cooling scenario, again the Aarhus Large DC case is the most economically infeasible, for the same reasons as in air cooling scenario. However, Large DC cases, both in Copenhagen and in Aarhus, are able to break even during the cutoff period, as a result of higher EH temperature. Aarhus Large DC shows a payback period of 10 years, while Copenhagen Large DC case - of 11 years. These results are visualized in Table 7.2 and Figure 7.2.

	Small DC Case		Medium DC Case		Large DC Case	
	Copenhagen (Carl Jacobsens Vej 20, Copenhagen)	Aarhus (Ny Moesgårdvej 61, Hoejbjerg)	Copenhagen (Borgmester Christiansens Gade 55, Copenhagen)	Aarhus (Niels Bohrs vej 35, Skandenborg)	Copenhagen (Industriparken 20C, Copenhagen)	Aarhus (Kappa 10, Hinnerup)
ANNUAL CASH FLOWS [EUR]						
Undiscounted annual cash flow	**60327,04**	**76992,70**	**155163,75**	**198247,23**	**685505,96**	**860249,57**
Discounted cash flow in year 1 (r=10%)	54842,76	69993,36	141057,96	180224,76	623187,24	782045,06
Discounted cash flow in year 2 (r=10%)	49857,06	63630,33	128234,51	163840,69	566533,85	710950,05
Discounted cash flow in year 3 (r=10%)	45324,60	57845,75	116576,83	148946,08	515030,78	646318,23
Discounted cash flow in year 4 (r=10%)	41204,18	43460,37	105978,93	135405,53	468209,80	587562,03
Discounted cash flow in year 5 (r=10%)	37458,35	39509,43	96344,48	123095,93	425645,27	534147,30
Discounted cash flow in year 6 (r=10%)	34053,04	24532,25	54383,95	111905,39	386950,24	485588,45
Discounted cash flow in year 7 (r=10%)	30957,31	22302,04	49439,95	101732,18	351772,95	441444,05
Discounted cash flow in year 8 (r=10%)	28143,01	11444,47	72385,04	92483,80	319793,59	401312,77
Discounted cash flow in year 9 (r=10%)	25584,55	10404,07	65804,58	84076,18	290721,45	364829,79
Discounted cash flow in year 10 (r=10%)	23258,69	4412,34	59822,34	76432,89	264292,22	331663,45
Discounted cash flow in year 11 (r=10%)	21144,26	3646,56	54383,95	69484,45	240265,66	301512,23
Discounted cash flow in year 12 (r=10%)	19222,05	1405,91	49439,95	63167,68	218423,33	
Total cash flow in 12 years [EUR]	**411049,86**	**352586,89**	**993852,47**	**1350795,54**	**4670826,37**	**5587373,41**
CAPEX [EUR]	**831144,59**	**865844,05**	**2077855,28**	**9376570,40**	**4460181,70**	**5295094,50**
NPV [EUR]	**-420094,73**	**-513257,16**	**-1084002,81**	**-8025774,86**	**210644,67**	**292278,91**
Payback period (in years)	**XXX**	**XXX**	**XXX**	**XXX**	**11,00**	**10,00**

Table 7.2. NPV of six cases in the liquid cooling scenario. Own production.

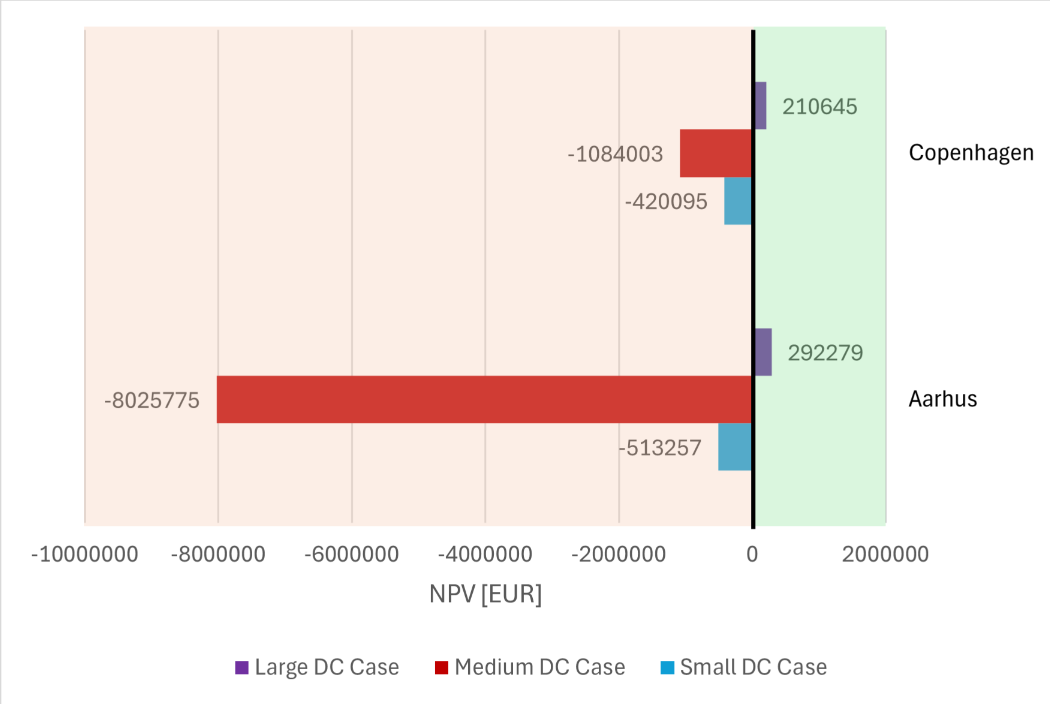

Figure 7.2. NPV of six cases in the liquid cooling scenario. Own production.

To capture the effects of location-related factors in the NPV model, the results will be investigated in-depth for each of three pair of cases.

7.2 The effect of the distance factor on CAPEX

As already mentioned, CAPEX of all six cases, in both cooling scenarios, consists of cost of HP and costs of connection to DH. Out of these two elements, the latter is dependent on the distance between a DC and DH network.

Figure 7.3 presents how individual components of investment costs affected the final CAPEX of two Small DC Cases. The results suggest that in both cases, the costs of connection between DC and DH network were marginal (0,76% of total CAPEX in Copenhagen Small DC Case and 4,74% in Aarhus Small DC Case). This is because of the low distance between the above cases and their closest DH networks.

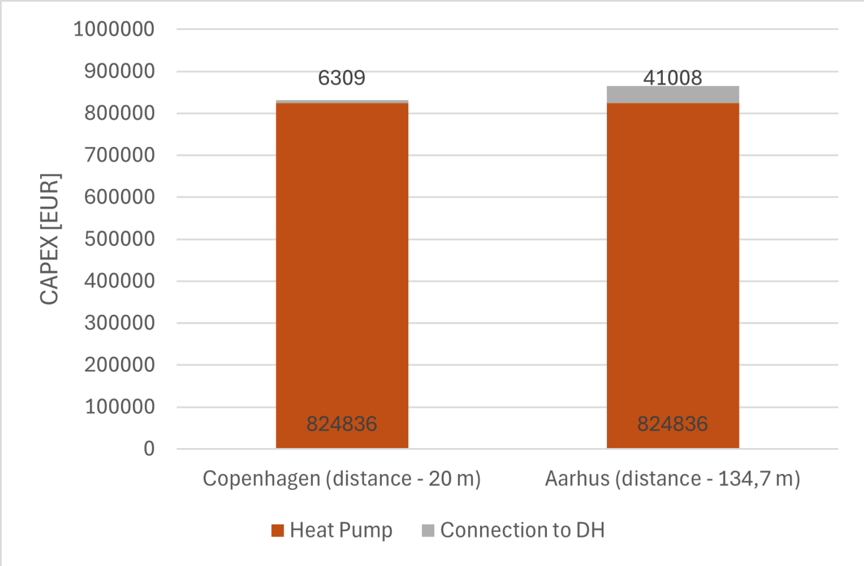

Figure 7.3. CAPEX of two Small DC Cases. Own production.

Similarly, Figure 7.4 presents the CAPEX breakdown for the Medium DC Cases, revealing a pattern far different than the one of the Small DC Cases. In the Copenhagen Medium Case, the share of piping costs in total CAPEX remains identical to that of the Copenhagen Small Case (0.76%), due to the consistent methodology used to estimate piping costs (depending both on the distance and EH output). However, a notable difference emerges in the Aarhus Medium DC Case, where the substantial distance between the DC and the DH network significantly impacts overall CAPEX - piping costs alone account for 78.01% of the total investment. The difference in distance results in a total CAPEX increase of 7,298,715 EUR, representing a 451% rise compared to its Copenhagen counterpart.

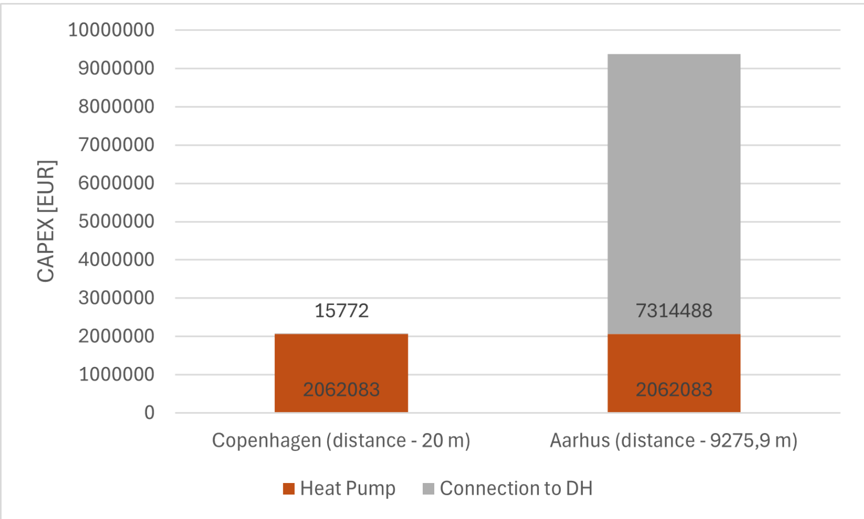

Figure 7.4. CAPEX of two Medium DC Cases. Own production.

Finally, the CAPEX of the Large DC Cases is less affected by the cost of connection to the DH network, as illustrated in Figure 7.5. This outcome stems from the adopted methodology, which assumes that connections to the DH transmission network - applicable to Large DC Cases - are significantly less expensive than connections to the DH distribution network used in other categories. Additionally, the relatively higher cost of the HP further reduces the proportional impact of piping costs. As a result, the connection cost accounts for only 0.08% of total CAPEX in the Copenhagen Large DC Case and 15.83% in the Aarhus Large DC Case, despite the latter involving a considerable distance of 4.887 km.

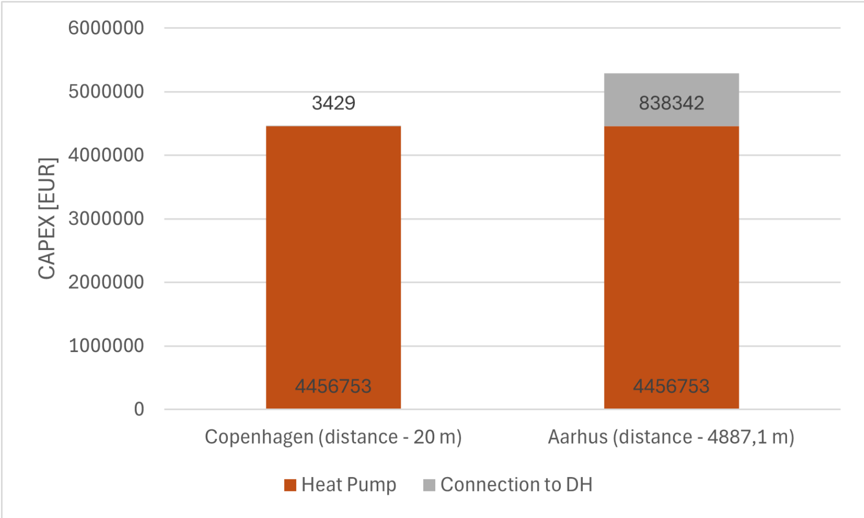

Figure 7.5. CAPEX of two Large DC Cases. Own production.

7.3 The effect of location-related factors on annual cash flows

Graphs presented in Figures 7.6–7.8 show detailed undiscounted cash flows of all 6 cases, under both air- and liquid cooling scenarios. The annual cash flows are broken down to annual revenue, cost of electricity consumed by a HP and operation costs (sum of fixed and variable operation costs).

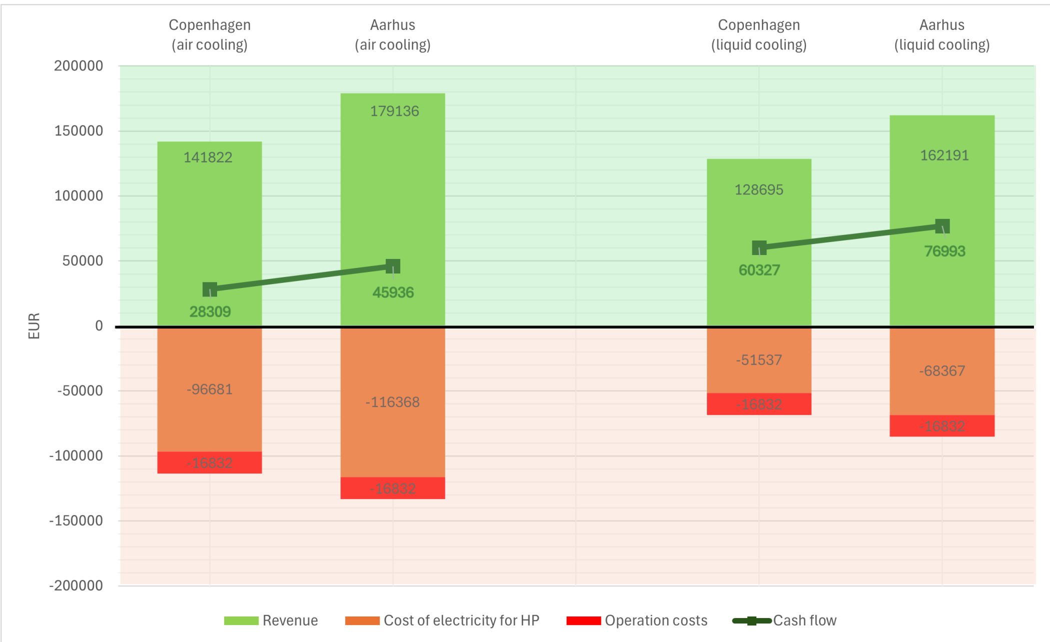

Figure 7.6. Cash Flow breakdown for Small DC Cases (Undiscounted annual cash flow in EUR).

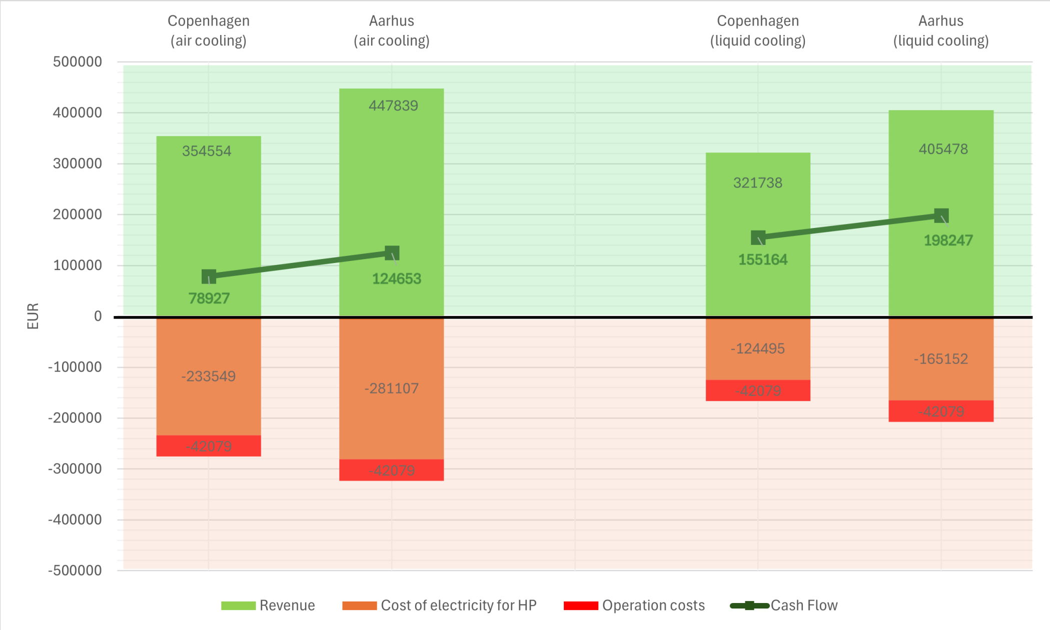

Figure 7.7. Cash Flow breakdown for Medium DC Cases (Undiscounted annual cash flow in EUR).

Figure 7.8. Cash Flow breakdown for Large DC Cases (Undiscounted annual cash flow in EUR).

Based on the presented results, it is evident that location-specific factors significantly influence the final annual cash flow. Within each DC category, the case located in Aarhus consistently yields a higher annual cash flow compared to its counterpart in Copenhagen. Focusing first on the air cooling scenario, the Aarhus Small DC Case generates an annual cash flow that is €17.626,32 higher than the Copenhagen case - representing a 162% increase in profitability. Similar patterns are observed for the Medium and Large DC categories, where the Aarhus cases outperform their Copenhagen counterparts by 45.726,08 EUR(157%) and 185.723,11 EUR (148%) per year, respectively.

Interestingly, under the liquid-cooling scenario, the differences in annual cash flow between identical cases are less significant (yet still consistently favor the Aarhus locations). The Aarhus Small DC Case generates €16.665,66 more than its Copenhagen counterpart, representing a 128% increase. Similarly, the Medium and Large DC Cases in Aarhus outperform those in Copenhagen by 43.083,48 EUR (127%) and 174.743,60 EUR (125%), respectively. This difference between Large DC cases translates to the shorter payback time of Aarhus Large DC Case under the liquid cooling scenario.

To understand the source of the increased net revenue in the Aarhus cases, it is necessary to examine the components of the annual cash flows in more detail. Starting with revenue from EH sold to the DH utility, the Aarhus cases consistently generate higher income - approximately 126% more in each pair of cases, under both cooling scenarios. This is primarily due to higher prices offered by DH utilities in Aarhus, as well as a slightly greater volume of heat delivered. The latter results from the lower COP of HPs in Aarhus cases.

The difference in COP, however, leads to higher electricity costs in Aarhus cases. Results indicate that under the air cooling scenario, all DC cases located in Aarhus pay approximately 120% more for electricity used in the heat reuse process compared to their Copenhagen counterparts. In the liquid cooling scenario, this cost difference increases to 132%. The greater disparity observed in the liquid cooling scenario stems from the comparatively lower HP COPs in Aarhus resulting from a larger temperature lift. Finally, the other operation costs are fixed and therefore aren't influenced by a location of a DC.

Full, detailed results of the NPV model, including all of the elements of CAPEX and OPEX, are presented in Appendix A.3.

7.4 Summary of the results and their reliability

To conclude, the results indicate that location-related factors (both distance-related and location-specific) - such as investment costs for connecting to the DH network, the HP's COP, and local EH pricing - significantly influence both CAPEX, revenue, and OPEX. While the impact of distance on piping costs is relatively straightforward, a more detailed analysis of the annual cash flows reveals a more nuanced picture. In the selected cases, Aarhus locations incurred higher electricity costs due to lower COPs. However, these additional operational costs were outweighed by the higher prices that local DH utilities in Aarhus are expected to pay for EH, ultimately resulting in greater annual profits compared to the Copenhagen cases.

The results presented in this Chapter are significantly influenced by the chosen approach to financial analysis and the literature-derived values used to populate the NPV model. As such, it is important to emphasize the inherent uncertainty associated with these findings. Although the methodology and data sources are grounded in the literature referenced in Chapter 6, various studies addressing the economics of DC heat reuse present differing assumptions regarding the components of CAPEX and OPEX. Furthermore, expert interviews conducted after the initial analysis confirmed that each business case is highly context-specific, making it difficult to generalize all input parameters with precision (Turner, 2025; Hansen, 2025; Dyrelund, 2025). Nevertheless, given that the primary objective of this thesis is not to conduct a detailed investment appraisal but rather to highlight the relative impact of location on feasibility, the adopted assumptions and simplifications are considered acceptable within the scope of the study.

Chapter 8

Discussion

The goal of this Chapter is to interpret the obtained results in the context of the research questions posed in this thesis as well as to discuss them by applying concepts of Industrial Ecology and Location Theory. Moreover, this Chapter places the results in broader context of DC's EH reuse, addressing the issues of relevance and limitations of the chosen approach. It also proposes alternative approaches for investigating the topic of interrelation between spatial context in which DCs operate and their impact on the energy transition.

8.1 Interpretation of results

The results presented in Chapter 7 confirm the initial hypothesis that the location of a DC significantly affects the economic feasibility of the heat reuse process. Following the framework of the Location Theory, this thesis identified three main location-related factors; the cost for connection between DC and DH network (being distance-related), HP's COP and local price of EH (latter two being location-specific). These factors influence the CAPEX, OPEX and revenue respectively, making a difference in every element of NPV model.

Among the three location-related factors, the cost of connecting to the DH network has the greatest impact on the business case, particularly for small and medium-sized DCs. This is especially evident when comparing the NPV results of the Medium DC cases. If a DC is located far from the DH network, the piping costs can constitute a substantial majority of the total CAPEX.

The difference in temperature delta between DC's EH and a heat carrier in DH network (and in turn the difference in electricity consumed by a HP) also has an impact on the final NPV. The impact of this factor is sensitive for electricity prices - the higher the prices, the more important it is to have an efficient HP. However, it is important to note that the supply temperature differences between the Copenhagen and Aarhus cases in this analysis are relatively small. As a result, the significance of this factor may be underestimated. If the analysis had compared highly efficient, low-temperature DH network with a 3GDH system operating at supply temperatures as high as 120°C, the impact of HP's COP would be far more pronounced.

The differences in operational costs resulting from the above are however offseted by the difference in the price that DH utilities are willing to pay for an unit of EH. The difference between Aarhus and Copenhagen (average 10 EUR difference per MWh on monthly basis) is a crucial factor which allowed Aarhus Large DC Case to be profitable quicker than its Copenhagen counterpart, even while having the higher CAPEX (resulting from more remote location).

Despite the considerations discussed above, it is important to emphasize that only the two largest cases - and only when high-temperature heat is available due to efficient cooling methods - achieve a positive NPV within the 12-year period. This pessimistic outcome is influenced by several assumptions and literature-based input values, which contain uncertainty. For example, the investment costs for HPs may be overestimated and might not accurately reflect current market prices. However, the negative NPVs appear to be primarily driven by the combination of low excess heat prices and high electricity costs, which significantly limit the financial feasibility of heat reuse projects.

According to Turner (2025), the EH prices provided by the two DH utilities in this study fall on the lower end of the expected DH price range. Simultaneously, the electricity prices applied in the model (based onn current Danish electricity prices) are relatively high - more than twice the average price recorded in the first half of 2020 in Denmark (Statistics Denmark, 2025). To illustrate the sensitivity of the business case to these two price parameters, the NPV model can be recalculated using the values applied by Pärssinen et al. (2019), who report an average EH price of 49.57 EUR/MWh and an electricity price of 85.24 EUR/MWh for the same heating season as in this thesis. Table 8.1 present the updated NPV and DPB results for all six cases under the liquid cooling scenario, using these adjusted prices.

	Small DC Case		Medium DC Case		Large DC Case	
	Copenhagen (Carl Jacobsens Vej 20, Copenhagen)	Aarhus (Ny Moesgårdvej 61, Hoejbjerg)	Copenhagen (Borgmester Christiansens Gade 55, Copenhagen)	Aarhus (Niels Bohrs vej 35, Skandenborg)	Copenhagen (Industriparken 20C, Copenhagen)	Aarhus (Kappa 10, Hinnerup)
Distance [m]	20,00	134,70	20,00	9275,80	20,00	4887,10
CAPEX [EUR]	831144,59	865844,05	2077855,28	9376570,40	4460181,70	5295094,50
NPV [EUR]	36584,13	9394,04	91466,53	-7188475,18	822107,50	549668,01
Payback period (in years)	**10,01**	**11,04**	**10,01**	**XXX**	**4,01**	**5,04**

Table 8.1. NPV and DPB results for six cases under the liquid cooling scenario with prices for EH and electricity obtained from Pärssinen et al. (2019)

The results presented in Table 8.1 highlight the strong sensitivity of the model to the prices of EH and electricity. When these relatively high prices of EH and low electricity costs are applied to both Copenhagen and Aarhus cases, 5 out of 6 cases have a positive NPV and a PB within 12 years. In this scenario, the influence of connection costs on the total NPV and DPB models becomes even more pronounced. In each case pair, the Aarhus cases (more distantly located) show lower profitability and longer payback periods compared to their Copenhagen counterparts. Notably, the Aarhus Medium DC case - characterized by the longest distance to the DH network - is the only one that fails to break even within the 12-year time frame.

To conclude this part of the discussion, the above findings demonstrate how economic outcomes of DC's EH reuse are influenced by the spatial context. As could be expected from the standpoint of the Location Theory - the economic viability of heat reuse is not determined only by the technical characteristics of the DC, but also by its geographical position, both in micro (distance between DC and DH) and macro scale (different EH and electricity prices depending on the city/region/country). The analysis showed that the profitability of each DC case depends on whether the spatial context minimizes capital and operational costs while maximizing revenue.

8.2 The results in the context of Industrial-Urban Symbiosis

The analysis, because of its spatial economic approach grounded in Location Theory, can be easily adapted to studies regarding Industrial-Urban Symbiosis with different low-temperature urban heat sources, such as wastewater treatment plants or supermarkets. Project's focus on DCs was dictated mostly by the high potential of this particular industry to supply large amounts of heat continuously. At the same time, facilitating such symbiotic relationships between urban environment and DCs, being privately owned facilities, presents different challenges than e.g. heat recovery from municipality owned wastewater plants. One of the main principles on which this project has been based on, is that DC operators will engage (and invest) in the heat recovery project only if it provides them with the economic profit.

Although the primary objective of this thesis was to investigate the hypothesis that location-related factors influence the economic feasibility of heat reuse projects, the findings should also be interpreted in light of their implications for the role of DCs in decarbonizing urban heating networks. The results of the financial analysis offer a rather pessimistic outlook on the viability of utilizing EH from existing DCs in Denmark, as the conclusion would be that most of heat reuse projects are not economically feasible and therefore there is no incentive on DC operators to invest in them. Taken at face value, these outcomes may suggest that Industrial-Urban Symbiosis involving urban DCs offers limited potential to support the energy transition through the decarbonization of DH systems.

However, such a conclusion may be overly simplistic. To gain a comprehensive understanding, the results must be examined within a broader context - one that includes factors intentionally excluded from the scope of the simplified financial model. The aim of this section is to provide that broader perspective and reflect on the limitations and real-world relevance of the findings.

8.2.1 Different business models of DC heat reuse

This thesis has been following an assumption that the DC operator/owner is the stakeholder which covers all the investment costs of the heat reuse project. Although this simplification was made because of the future requirements set by the EU legislation (as explained in Section 6.3), this business model is not usually, if ever, a case.

According to Turner (2025), Dyrelund (2025) and Hansen (2025), a typical business model between a DC and DH utility, at least in the Danish environment, usually implies sharing the investment costs between these two stakeholders. As stated by Turner (2025), a DC operator usually covers the costs of internal heat reuse infrastructure such as heat recovery unit and internal hydronics, while DH utility invests in industrial HPs, and in connection (piping) between DC and DH. This framework means that a vast majority of investment of heat reuse process is covered by a DH utility - the opposite of the assumptions of this thesis.

This business model results in significantly lower initial costs for the DC operator and grants much greater control over the EH supply to the DH utility, which can, for instance, choose not to accept EH on days when electricity prices are high. Moreover, investment projects led by DH utilities typically tolerate longer payback periods, allowing them to pursue infrastructure developments that might not be attractive to private investors focused on shorter-term returns. This strategic alignment makes the utility-led model more resilient to price fluctuations and better suited for long-term integration of EH into DH systems.

However, as it was explained in Section 6.3, the thesis approach to put all of the investment costs on DCs was influenced by numerous factors, one of each was the impact of upcoming requirements for DCs arising from the EU legislation. To recap, both already existing and planned DCs in the EU, with the total rated energy input exceeding 1 MW will be obliged to recover their EH unless they can indicate that it is not technically or economically feasible. At the same time, there is currently no EU legislation directly requiring DH utilities to cooperate with DC operators in order to facilitate the heat reuse for DH purposes, which is a point of critique from DC industry (Hansen, 2025).

To illustrate the potential implications of the above, one can consider a scenario in which the operator of the e.g. Copenhagen Medium DC case seeks to comply with the EU requirement by initiating a heat reuse project. If the DH utility in Copenhagen is either unable or unwilling to co-invest or accept the recovered EH, the financial analysis conducted in this study indicates that the project would not be economically viable when investment costs fall solely on the DC operator - even if all available EH is purchased during the entire heating season. If there are no nearby alternative low-temp heat sinks (e.g., a horticultural facility), the recovered heat remains unused. These findings suggest that, particularly for existing collocation DCs, the legal obligation to recover EH may prove difficult to fulfill on a bigger scale.

The above considerations makes it interesting to investigate the DC heat reuse issue from different approaches. For instance, by conducting a financial analysis of DC heat reuse investment based on this specific business model, accounting for the shared investment.It would be interesting to include expected economic and CO_2 savings in the DH system, stemming from replacement of other heat sources in the grid.

Because of different power mix in the grid, these savings would also vary between different DH networks, even if EH supply and quality would be the same across all cases. Such analysis could be made with the use of Total Cost of Ownership (TCO) Method - which takes replacement costs into account.

Another approach worth considering is the spatial analysis of possible industrial-urban synergies between a DC and nearby heat sinks, other than DH networks. As mentioned in Chapter 2, there are many different applications for DC's EH reuse, some of which don't require elevating the heat temperature, therefore saving both investment and operating costs of the whole project. Identifying such possible synergies in urban areas could help DC operators in thorough technical and economical assessment of heat reuse options.

8.2.2 Different motivations for DC heat reuse

One of the principles on which this thesis is based on is the belief that private business actors, such as DC companies, are likely to invest in practices like EH reuse only when it aligns with their economic interests. This is why the approach of financial analysis was chosen as a primary research method. However, according to Hansen (2025) and Dyrelund (2025), the financial outcome is not the only motivation behind reusing EH by DCs.

According to Dyrelund (2025), the business model described in previous Section, based on trust and cooperation between a DC and DH utility, may not include a financial transactions whatsoever. Instead, it resembles a barter relationship - DC can supply the EH to DH grid, and in return, can get free cooling from district cooling grid (if it exists), getting rid of unwanted heat and improving the cooling efficiency (and reducing costs) at the same time.

Moreover, as stated by Hansen (2025), companies owning or operating DCs, may view the heat reuse as an opportunity to improve their ESG ratings. DC sustainability is a matter of pressing concern, because of the significant environmental footprint. Various indicators are used for measuring DC's environmental impact, the most commonly used, specifically used for DC assessment, being Power Usage Effectiveness (PUE). (Wahlroos et al., 2017). The PUE is calculated by dividing the total power consumption of a building site by the power used solely by IT equipment, as seen in the equation below:

$$PUE = \frac{\text{Total Energy}}{\text{IT Energy}} = \frac{Cooling + PowerDistribution + Misc + IT}{IT}; 1.0 \leq PUE \leq \infty$$

As the result, the lower the PUE (ideally close to 1 value), the more energy efficient a DC is. The Uptime Intelligence conducts annual surveys, gathering data on DC average PUE globally. Based on their data, the average PUE of a DC in 2024 was 1.56 and this value has been steady for 4 last years (Uptime Intelligence, 2024). At the same time, frontrunners in the DC industry, like Google or Meta, have achieved high energy efficiency with PUE values below 1.1 (Koronen et al., 2020).

However, the metric has been criticized for its limitations. One issue is that it does not differentiate between DC communication systems and computing servers, as both fall under IT equipment. As noted by Wahlroos et al. (2017), PUE is considered as overly simplistic and lacking the technical depth needed for thorough engineering analysis. Moreover, PUE cannot take heat recovery into account. With energy reuse, the PUE value could go below 1, which is contrary to the metric definition.

Because of these limitations, and to capture the impact of energy reuse on the energy efficiency of a DC, there have been propositions for the use of a different metric. The Energy Reuse Effectiveness (ERE) metric is a modified version of PUE and is determined using the following equation:

$$ERE = \frac{\text{Total Energy - Reuse Energy}}{\text{IT Energy}} = \frac{Cooling + PowerDistribution + Misc + IT - Reuse}{IT}; 0 \leq ERE \leq \infty$$

To be considered in the metric, recovered heat has to be utilized externally, i.e. outside of the DC building (Wahlroos et al., 2018a). Value of 0 in ERE means that 100% of the energy brought into the DC is reused that way.

The decision on which of the above two metrics a DC operator will use to assess the energy efficiency of their facility, can give significantly different perspectives on a given DC, especially when EH is being recovered. To give an example: heat reuse can result in increased overall electricity consumption of a DC due to the HPs operation (if a HP counts as a DC's infrastructure, as in this projec's analysis), which means that the PUE value of the system increases (i.e. lower energy efficiency). At the same time, the ERE value will decrease, meaning higher effectiveness of energy reuse. Moreover, ERE of 1.0 does not imply any level of efficiency in the base DC infrastructure. It could represent a very efficient infrastructure design with a small amount of energy reuse or a system with an inefficient infrastructure base design with a lot of energy reuse. This shows that these two metrics serve different purposes and should not be mixed, but rather used in combination.

The majority of DCs today do not reuse their EH and, as a result, do not use the ERE metric, instead prioritizing PUE as their primary efficiency measure. However, as Wahlroos et al. (2018a) argues, this approach must evolve - except for the smallest DCs, the industry must move beyond efficiency alone and incorporate heat reuse strategies, including existing facilities. Nevertheless, this transition presents significant challenges. A survey conducted by Danish Radio in 2022 revealed that only 4 out of 54 DCs in Denmark have been capturing their EH, highlighting the long and complex path ahead for widespread adoption (DR, 2022).

The effects of the EU legislation obliging DCs to reuse their EH could be strengthened by making ERE a common, legally required measurement. In this context, it would be particularly relevant to assess how both PUE and ERE values change before and after a heat reuse system is implemented in a specific DC. However, such analysis was not possible within the scope of this thesis due to the lack of detailed data on potential electricity savings resulting from the integration of heat reuse infrastructure.

Social responsibility (the "S" in ESG) may also be an important factor in the consideration of DC's EH reuse. As stated by Dyrelund (2025), *"Data Centers no longer want to be seen as these big ugly buildings behind a gray wall. They want to give something back to the community"*. This is especially relevant in the urban context, where DC buildings may be perceived as unattractive or even hostile architecture. If the local community make use of DC's resources such as heat, this negative perception may be mitigated. This way the heat reuse can be seen not only as an industrial-urban synergy that creates revenue or decreases operational costs, but also improves public image of a DC company.

Incorporating this wider perspective, both regarding the different business models as well as other incentives to proceed with heat reuse projects, helps to explain why EH reuse projects may still be viable in cases where simplified financial analysis such as the one in this project predicts limited or no profitability. It underlines the importance of collaboration between stakeholders and suggests that aligning interests across sectors - in the spirit of Industrial Ecology - can help unlock EH reuse potential.

8.2.3 The importance of strategic planning

The results of the project's analysis should be considered from the point of view of Industrial Ecology and Urban-Industrial Symbiosis. Results have proven that the local context, in which DCs operate can play a crucial role in enabling symbiotic relations between them and broader urban environment, making these symbioses feasible or unfeasible from the economic standpoint. DC companies are aware of the dependencies that spatial factors imply for their business cases, and therefore carefully curate the best possible locations for new facilities, including the considerations on the average outdoor temperature, electricity prices and mix in the grid (Hansen, 2025). While local authorities such as city councils have little or no power over these determinants, they can hugely influence the feasibility of DC heat reuse by minimizing one of the main barriers - high investment costs for DH connection.

As shown in the study conducted by Cáceres et al. (2024), municipal spatial planning plays an important role both in making the best use of the resources which DC generates, as well as in minimizing the negative effects caused by the high consumption of the ones it consumes. According to the researchers, the urban planners' role in establishing DCs could guarantee the relationship and interaction with the local social, economic, and environmental ecosystems following the Industrial Ecology principles. Allowing DCs to be built in specific areas can increase the adaptive capacity of a local energy system. On the contrary, allowing DCs to be located in remote locations not only rules out or hinder possible urban-industrial symbiosis between DC and urban environment (considering not only DE networks, but also other industries or facilities that could use low-temperature heat), but also can create infrastructure or resource-related issues. In this context Cáceres et al. (2024) give an example of Facebook's DC in Luleå, Sweden. They state that the municipality was unexpectedly (the Facebook's DC site was not planned ahead in spatial planning documents) required to allocate 58 million Swedish crowns to accommodate Facebook's anticipated infrastructure needs. This included the installation of high-voltage power lines, the relocation of stormwater infrastructure, and the enhancement of drinking water systems to support an estimated power demand of 120 MW and daily potable water usage of 900,000 liters. At the same time, there have been no plans to utilize DC's excess heat, neither in DH network (because of the relatively high supply temperature in the local network) nor for other purposes (because of the distance to facilities such as indoor swimming pool or food drying site) (Cáceres et al., 2024).

As can be derived from the above, energy issues and spatial planning should not be considered in isolation, as they are interwoven. In the context of the symbiosis between DCs and urban environment, coordinating urban developments with the careful development of energy systems could result in more efficient urban forms that support the integration of DCs resources into urban metabolism.

However, to achieve this, a shift in conventional planning practices is required. Specifically, stronger collaboration between municipal departments responsible for spatial planning and those focused on energy is essential. Instead of treating energy considerations as a separate or secondary step, planning processes should be conducted concurrently (Pärssinen et al., 2019). The above considerations are at the core of the Integrated Spatial and Energy Planning paradigm. It emphasizes the fact that spatial structures, such as the mix of functions in urban land-use, the density of built environment, as well as the size of it, have significant implications for the distribution of energy demand, level of energy efficiency or renewable energy provision. According to Stoeglehner et al. (2016), planning for the energy transition has to carefully consider spatial structures, because of the long-lasting character of these structures. To put it in the context of the topic of this thesis, the Urban-Industrial Symbiosis with the DC as a key stakeholder can be either facilitated or hindered by a spatial planning process. And once a DC is built, the effect of this planning on this potential symbiotic relation with nearby environment is there to stay, likely for many years to come.

Because of the above, a different approach to investigating the interrelation between spatial context in which DCs operate and their impact on the energy transition can be proposed. A study on municipal planning practice from the Integrated Spatial and Energy planning perspective, would allow to assess, if city planners are aware of the potential of incorporating urban low-temperature heat sources such as DCs into the heating network, how do they try to leverage this symbiotic potential, how do the different planning departments collaborate on the issue, as well as what challenges they face in this context.

To conclude the discussion, this project is believed to be a valuable addition to the discourse regarding the utilization of DC's heat reuse, particularly by introducing a spatial perspective into the analysis. Despite its limitations, it has shown the significant importance of a DC location on the economic feasibility of heat reuse investment. This core finding can also be related to other potential low-temperature urban heat producers, such as supermarkets or other facilities with high cooling demand. However, given the complex reality discussed in this Chapter - including differing business models, varied motivations for heat reuse, and the essential role of stakeholder cooperation - the results of this project should be interpreted with caution. They were obtained under a somewhat controlled, simulated environment and should not be viewed in isolation from the broader economic, technical, and political context. That being said, the project can serve as a seedbed for further studies or a supplement for the existing ones, following the Industrial Ecology and Urban-Industrial Symbiosis principles.

Chapter 9

Conclusion

DC sustainability is a matter of pressing concern, because of the significant environmental footprint of these facilities. As digital services become increasingly common and advanced, servers burden the energy systems and environment with their high resource consumption, including electricity and water. The above makes the energy efficiency of DCs a pressing issue.

At the same time, governments and authorities, both national and local, are making efforts to decarbonize their energy systems. On the city scale, the big promise lies in DE networks - urban heating grid have a high potential to phase out fossil fuels as a heat source. The current trend of lowering the temperature of the water flowing in the DH network opens up the possibility to supply it with unconventional, low-temperature heat sources, ones that can often be found within city limits.

This thesis has explored the potential for synergies between DCs and DH networks, in order to investigate the ways to solve both of the above problems - improve the energy efficiency of DCs and incorporate the EH into urban heating grids. As such symbiotic relations are place-based an highly dependent on the local spatial context, it was chosen to focus the analysis on spatial factors. With the main hypothesis being that the location of a DC should have an impact on economical feasibility of EH reuse project, the financial analysis was conducted.

To test this hypothesis, first, a typical model of DC heat reuse configuration was identified, based on insights from the literature and expert interviews. Secondly, this model, alongside with generalized values such as available EH and its temperature, was applied to six DC cases located in Copenhagen and Aarhus, grouped in three categories, depending on their size and the amount of heat they can supply. Cases within each category were then compared, in order to note the differences in economic feasibility of heat reuse project, dependent on location-related factors.

The obtained results suggest that the hypothesis stated earlier should be considered true. When considering DCs with exactly the same amounts of available EH, as well as with the same temperature of it, the location-related factors make a difference in the final NPV and DPB of the heat reuse business cases. Following the framework of Location Theory, these factors were identified to be; the cost of connection between DC and DH network, temperature difference between DH supply and EH (and in turn the HP's COP), and local price of EH. These factors influenced the CAPEX, OPEX and revenue respectively, i.e. all of NPV major elements.

The difference in NPV resulting from location in the investigated cases could account for up to a 454% lower NPV, as seen in the Copenhagen Medium DC case (−1.540.072 EUR) compared to the Aarhus Medium DC case (−8.527.224 EUR) after a 12-year period. The analysis suggest that the cost of connection between DC and DH can be accountable for significant majority of the investment costs, making the business case economically infeasible, when a DC is located remotely from the heating network.

Both the local EH price and the supply temperature in DH network have an impact on annual cash flows, and in turn, on a financial feasibility of the investment. Higher prices offered by Aarhus DH utility help to acquire higher annual revenue than in Copenhagen-located cases, while the sligthly lower temperature in Copenhagen's DH supply line reduces the operating costs, compared to Aarhus-located cases. The latter difference in operating costs is decreasing, when DC cases are cooled with more efficient, liquid cooling system. Finally, the financial model is very sensitive both for EH prices and electricity prices. When tested with different values (higher EH price, lower electricity price), the NPV model gives far more optimistic results for all six cases.

The NPV model contains uncertainty and was meant to identify relative differences between differently-located DC cases. While the results proven the hypothesis, they shouldn't be treated as the answer to the question if a heat reuse project is aligned or contradictory with the economical interest of any given, real DC. This clarification is especially important, since business models for heat reuse projects can vary significantly. Moreover, economic value of heat reuse project may result from increased cooling efficiency or improved ESG performance, rather than direct revenue from heat sales. To accurately assess the economic feasibility of a specific DC heat reuse project, a more detailed approach is required - one that accounts for the technical infrastructure needed, the specific contractual and regulatory framework, as well as the operational characteristics of the DC and local DE system.

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List of Figures

Appendix A

Appendix

A.1 Guide for initial semi-structured interviews

1. Introduction of the author and the topic of the project.
2. What challenges and barriers do you see in DC's heat reuse?
3. How important, in your opinion, is a location factor when considering DC's heat reuse?
4. What is the usual business model between a DC and DH utility regarding EH recovery?

A.2 List of all mapped DCs in Denmark together with the data provided on their whitespace and fully built-out power. Based on (Data Center Map, 2024)

This attachment is provided separately as part of an additional upload.

A.3 Detailed NPV outcomes for all six cases under air- and liquid cooling scenarios

This attachment is provided separately as part of an additional upload.

A.4 Detailed revenue of Copenhagen DC Cases under both cooling scenarios

This attachment is provided separately as part of an additional upload.

A.5 Detailed revenue of Aarhus DC Cases under both cooling scenarios

This attachment is provided separately as part of an additional upload.