TERMO

FRAMTIDENS VÄRME OCH KYLA

Final report to the project

HiReSoLo

High Resolution GIS District Heating Source-Load Mapping

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Foreword

This project has been a collaboration between multiple researchers at the Department of Energy Technology at Kungliga Tekniska Högskolan. It was conceived and awarded to Dr. Chang Su, who departed KTH in 2022, at which point the project was taken over by Assoc. Prof. Hatef Madani in collaboration with Dr. Nelson Sommerfeldt. The handover resulted in a modest pivot in methods that brought more focus into detailed energy systems modeling, particularly for buildings in small heating networks and data centers, while retaining as much spatial context as possible. We believe this pivot did not detract from the goals of the project and introduced a new and valuable perspective to the later studies.

This work could not have been completed without the valuable input of Johan Dahlgren from Stockholm Exergi, who provided insights into the operation of the Open District Heating market and inspiration on the formulation of our studies. Thanks also to visiting PhD researcher Amir Shahcheraghian for joining the team from Canada to bring his expert data analytics skillset. Masters students Jeremey Sintong, Chris Bay, and Nicolás Muñoz also went above and beyond the standard thesis work to deliver valuable contributions.

There is a substantial amount of additional research and detail in the appended publications, and interested readers are encouraged to explore those documents further.

Contents

Summary

Decarbonizing heat is gaining interest worldwide and in Sweden the focus is largely on district heating networks. Combustion of biomass and municipal waste are the largest contributors to the heat supply, and waste specifically comes with a high emissions factor. This project aims to provide novel insights on the integration of distributed renewable energy sources in existing Swedish district heating networks. The main advancement comes through improved GIS based methodologies, using high spatial and temporal resolution analysis of a district heating system incorporating demand and supply into one study. High spatial resolution means 1-10 meters, a 100x improvement over prior studies. High temporal resolution means hourly, a common standard for non-spatially relevant district energy studies but lacking in a GIS based analysis. Within this overall aim are two sub-objectives related to mapping and modeling:

1. Create a GIS database of renewable heat sources and demands
2. Develop demand and supply models to couple sources and demands

The primary contribution of this work is methodological in that it combines state-of-the-art techniques in GIS for mapping heating demands and sources and coupling them with building energy demand and heating supply models. The project is realized in four stages – two mapping and two modeling – using Stockholm as a case study:

1. Mapping of renewable and residual heat sources and quantifying their potential
2. Urban building energy modeling of a representative district
3. Techno-economic modeling of residual heat recovery in an open district heating network
4. Source-load mapping of residual heat sources with demands

The results show that water bodies are the most abundant source of environmental or residual heat with 3400 GWh/yr of potential, with data centers second at 500 GWh/yr and supermarkets third at 316 GWh/yr. In 2018 Stockholm delivered 6600 GWh of district heat meaning that all distributed sources of mapped heat could account for 4300 GWh, or 65%. Of the three main sources of mapped heat, all have examples of being utilized since Stockholm hosts the world's first open district heating market.

High temporal resolution prosumer modeling of a data center showed that of the total heat recovery potential, only 60% was economically viable using 2018 electricity prices mostly due to the low summertime value of heat. In 2022 when electricity prices were at their highest, only 42% of residual heat recovery was economically viable with less heat delivered during winter hours.

Demand side mapping shows that residual heat sources are ideally located to demand points and are cost-effective heat sources when compared to the purchase prices offered in the Open District Heating network. The combined cost of water bodies, data centers, and supermarkets ranges from 154 to 268 SEK/MWh for the heat demand clusters. It is also found that district heating sub-networks can be a suitable pathway for integrating residual heat sources due to the lower supply temperatures associated with more modern buildings.

Unlike source mapping data, which could be shared open source, demand side mapping data is restricted to research applications only and cannot be shared. Access to data within the project also presented a barrier to model validation, and future work is needed to generate high spatial and temporal resolution models which can also be validated.

Sweden is a world leader when it comes to extracting the energetic value of renewable and recycled waste, and Stockholm is a prime example where woody biomass, industrial waste, sewage, and sea water are all used as part of the system. Stockholm has unique access to water bodies compared to most Swedish cities, meaning it may be more difficult to replace combustion-based heat sources in other places around the country. However, more less dense cities also lend themselves to other environmental heat sources like the sun or ground, and other case studies using the methods developed here are encouraged. There is also a considerable amount of work that can be done on the demand side with regard to network temperature levels and sub-network integration towards the reduction of energy and exergy demands.

Sammanfattning

Dekarbonisering av värme väcker ökat intresse världen över, och i Sverige fokuseras det främst på fjärrvärmenätverk. Förbränning av biomassa och kommunalt avfall utgör de största bidragarna till värmeförsörjningen, och avfallet genererar särskilt höga utsläppsfaktorer. Det här projektet syftar till att erbjuda nya insikter om integreringen av distribuerade förnybara energikällor i befintliga svenska fjärrvärmenätverk. Den huvudsakliga framstegen uppnås genom förbättrade GIS-baserade metoder, med användning av hög rumslig och temporär upplösning i analysen av ett fjärrvärmesystem som inkorporerar både efterfrågan och tillgång i en och samma studie. Hög rumslig upplösning innebär 1-10 meter, vilket är en förbättring med en faktor på 100 jämfört med tidigare studier. Hög temporär upplösning innebär timvis, en vanlig standard för icke-rumsligt relevanta studier av fjärrvärme men som saknas i en GIS-baserad analys. Inom detta övergripande mål finns två delmål relaterade till kartläggning och modellering:

1. Skapa en GIS-databas över förnybara värmekällor och efterfrågan.
2. Utveckla modeller för efterfrågan och tillgång för att koppla samman källor och efterfrågan.

Det primära bidraget från detta arbete är metodologiskt genom att det kombinerar state-of-the-art tekniker inom GIS för att kartlägga värmebehov och källor och koppla dem med byggnaders energibehov och värmeförsörjningsmodeller. Projektet genomförs i fyra stadier - två kartläggnings- och två modelleringsstadier - med Stockholm som fallstudie:

1. Kartläggning av förnybara och restvärme-källor och kvantifiering av deras potential.
2. Modellering av stadens byggnaders energibehov för en representativ stadsdel.
3. Tekno-ekonomisk modellering av återvinning av restvärme i ett öppet fjärrvärmenätverk.
4. Källa-last-kartläggning av restvärme-källor gentemot efterfrågan.

Resultaten visar att vattendrag är den mest rikliga källan till miljö- eller restvärme med en potential på 3400 GWh/år, följt av datacenter med 500 GWh/år och stormarknader med 316 GWh/år. År 2018 levererade Stockholm 6600 GWh fjärrvärme, vilket innebär att alla distribuerade källor av kartlagd värme skulle kunna stå för 4300 GWh, eller 65%. Av de tre huvudkällorna för kartlagd värme har alla exempel på att användas eftersom Stockholm är värd för världens första öppna fjärrvärme-marknad.Modellering med hög temporär upplösning av ett datacenter visade att endast 60% av den totala värmeåtervinningspotentialen var ekonomiskt lönsam med elpriser från 2018, främst på grund av det låga sommarvärdet av värme. År 2022, när elpriserna var som högst, var endast 42% av återvinningen av restvärme ekonomiskt lönsam med mindre värme levererad under vintermånaderna.

Kartläggning av efterfrågesidan visar att restvärme-källor är optimalt belägna gentemot efterfrågepunkter och är kostnadseffektiva värmekällor jämfört med inköpspriserna som erbjuds i det öppna fjärrvärmenätverket. Den kombinerade kostnaden för vattendrag, datacenter och stormarknader varierar från 154 till 268 SEK/MWh för värmeefterfrågekluster. Det konstateras också att fjärrvärme-delnät kan vara en lämplig väg för att integrera restvärme-källor på grund av de lägre leveranstemperaturerna som är förknippade med modernare byggnader.

Till skillnad från kartläggningsdata för källor, som skulle kunna delas som öppen källkod, är kartläggningsdata för efterfrågesidan begränsad till forskningsapplikationer endast och kan inte delas. Tillgång till data inom projektet utgjorde också ett hinder för modellvalidering, och framtida arbete behövs för att utveckla modeller med hög rumslig och temporär upplösning som också kan valideras.

Sverige är en världsledande aktör när det gäller att utvinna den energetiska värdet av förnybar och återvunnen avfall, och Stockholm är ett utmärkt exempel där träbiomassa, industriavfall, avlopp och

havsvatten alla används som en del av systemet. Stockholm har unik tillgång till vattendrag jämfört med de flesta svenska städer, vilket innebär att det kan vara mer utmanande att ersätta förbränningsbaserade värmekällor på andra platser runt om i landet. Däremot lämpar sig mindre täta städer också för andra miljövänliga värmekällor som solen eller marken, och andra fallstudier med de här utvecklade metoderna uppmuntras. Det finns också en betydande mängd arbete som kan utföras på efterfrågesidan när det gäller nätverkstemperaturnivåer och integration av delnätverk för att minska energi- och exergikrav."

1 Introduction

District heating networks present great opportunities to rapidly transform energy supply in buildings and cities. Changes in heating plant fuel sources can increase renewable energy fractions or decarbonize heating supply with minimal actions needed from building owners. Sweden is a global leader in district heating, with about 500 cities or communities having heating networks and 55% of building area supplied with district heat [1]. The majority of heat is generated with combustion fueled with residuals from the forestry industry and municipal solid waste, with peaks often covered by fossil fuels [2].

Heating networks are typically built around centralized plants, however Stockholm's Open District Heating market created a new decentralized model [3]. It is now possible for facilities in need of large cooling demands to sell their residual heat to the network, creating a unique prosumer marketplace for heat comparable to more commonly known electrical prosumers. Heavy industry has supplied heating networks for many years in specially arrange cooperations, but this marketplace makes it possible for smaller, distributed stakeholders to participate, such as data centers, supermarkets, and ice rinks.

Identifying the potential for distributed heat sources to participate in district heating networks requires high spatial and temporal resolution. The increased accessibility of high-resolution geographic information systems (GIS) data has resulted in several district heating planning studies. On the demand side, large cities such as London [4], Berlin [5], and Helsinki [6] have mapped out their building energy demands. And studies in Switzerland [7] and China [8] have mapped ground source heat pump potential. High-spatial resolution mapping has thus far been limited to buildings, i.e. the demand for heat. Source load mapping is often performed with minimum 1 km resolution, which is not detailed enough for urban environments. Renewable heat sources are seasonally variable and typically at low temperatures requiring upgrades with heat pumps. This electrification of heat requires hourly time resolution to capture varying supply profiles and temperature levels that affect system efficiency. Additionally, the price of electricity varies hourly, and since the removal of Russian natural gas from the European market, prices have become considerably more volatile. High temporal resolution also plays a role in adequately modeling storage systems, particularly in a volatile price environment.

1.1 Objectives

This project aims to provide novel insights on the integration of distributed renewable energy sources in existing Swedish district heating networks. The main advancement comes through improved GIS based methodologies, using high spatial and temporal resolution analysis of a district heating system incorporating demand and supply into one study. High spatial resolution means 1-10 meters, a 100x improvement over prior studies. High temporal resolution means hourly, a common standard for non-spatially relevant district energy studies but lacking in a GIS based analysis. Within this overall aim are two sub-objectives related to mapping and modeling:

1. Create a GIS database of renewable heat sources and demands
2. Develop demand and supply models to couple sources and demands

The primary contribution of this work is methodological in that it combines state-of-the-art techniques in GIS for mapping heating demands and sources and coupling them with building energy demand and heating supply models.

1.2 Methodology and Scope

The project is realized in four stages – two mapping and two modeling – and are listed below:

1. Mapping of renewable heat sources and quantifying their potential
2. Urban building energy modeling of a representative district
3. Techno-economic modeling of residual heat recovery in an open district heating network
4. Source-load mapping of residual heat sources with demands

Each stage has unique models and methods which are described in further detail in their corresponding chapters. Wherever possible, open data and open-source models are used as inputs and resulting outputs published as open data. The city of Stockholm is used as a case study, which is relatively unique in Sweden for its size and diversity of heat sources, however the methods developed, results, and conclusions are broadly relevant for most Swedish cities.

This report is a capstone summary of the five studies performed during the project. Each chapter is only a summary of work with much more detail available in the full publications listed and appended at the end of the report. At the time of writing, four of them have been published with one more submitted for review.

2 High-Resolution Mapping of Clean Heat Sources

More than 80% of all buildings in Stockholm are connected to the district heating system, which is primarily supplied by four plants: Värtan, Högdalen, Hässelby and Hammarby. Total heating supply is about 6000 GWh per year and is supplied by municipal waste incineration, biofuel incineration, data center heat recovery, sewage heat recovery, and seawater heat. The final two are realized using heat pumps, meaning that a fraction of their final heat supply is also coming from electricity. According to Stockholm's climate action plan, the fossil sourced energy in municipal waste (i.e. plastics) must be reduced to meet 2040 fossil-free goals [9]. Therefore, replacement heat sources should be identified and located.

This study uses a GIS based integrative-analysis method to collect geolocation data, quantify the supply potential and reintegrate it into the GIS database, and visualize city-wide heating potential using high-resolution maps and clustering analysis. The full process is visualized in Figure 1. Candidate heat sources are separated into two categories; renewable and recovery. Renewable heat sources include water bodies (rivers, lakes, sea), forest biomass, and shallow geothermal. Residual heat sources for recovery include supermarkets, ice rinks, data centers, sewage plants, underground subway stations and lines, and excess industrial heat. Sources are marked in the GIS database as either a point, line, or polygon.

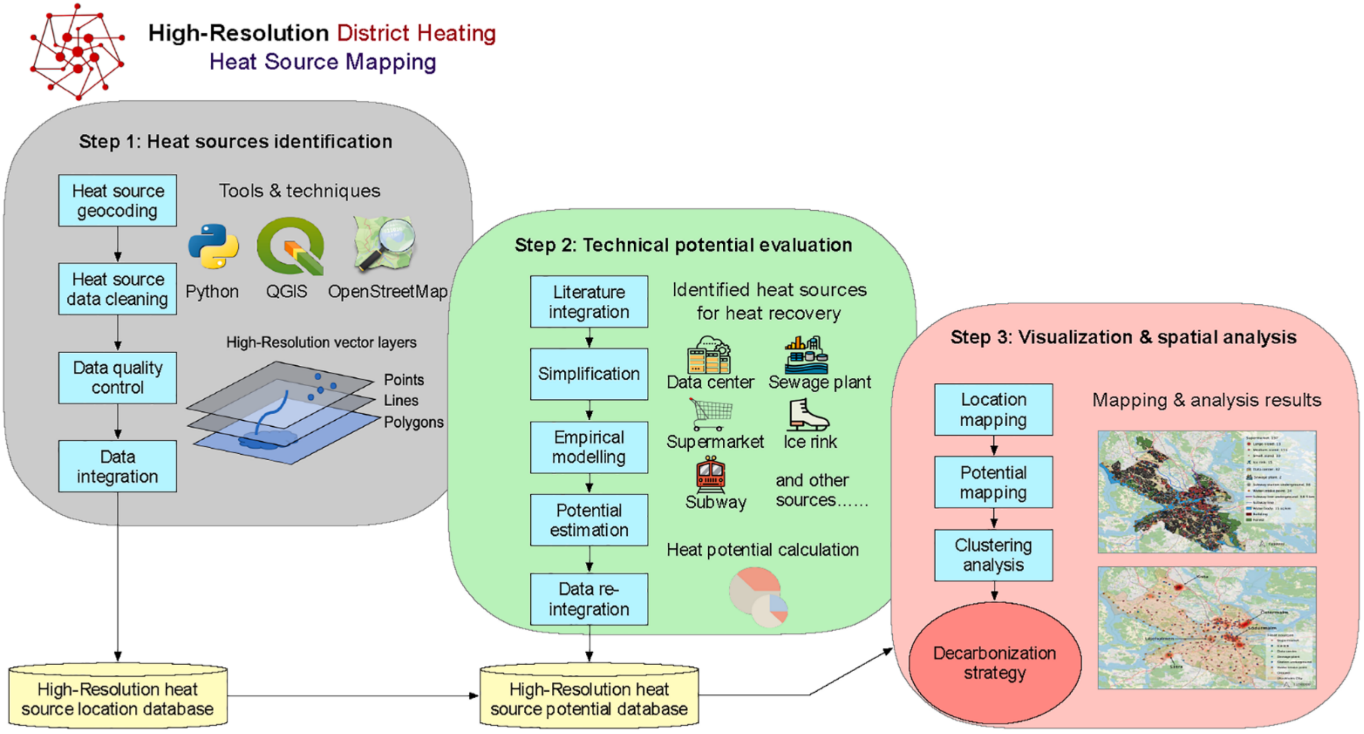

Figure 1 - Schematic of the method workflow

The resulting locations shown in Figure 2 are mapped with a 1-meter resolution and include 197 supermarkets, 15 ice rinks, 32 data centers, 2 sewage plants, 38 underground subway stations with 38.5 km of underground lines, 34 locations for intake from water bodies, and six open spaces for borehole heat exchangers. Biomass within the administrative boundaries of Stockholm is within protected nature reserves, therefore no locally sourced biomass is included in the database. Likewise no heavy industries are located within Stockholm and are therefore omitted.

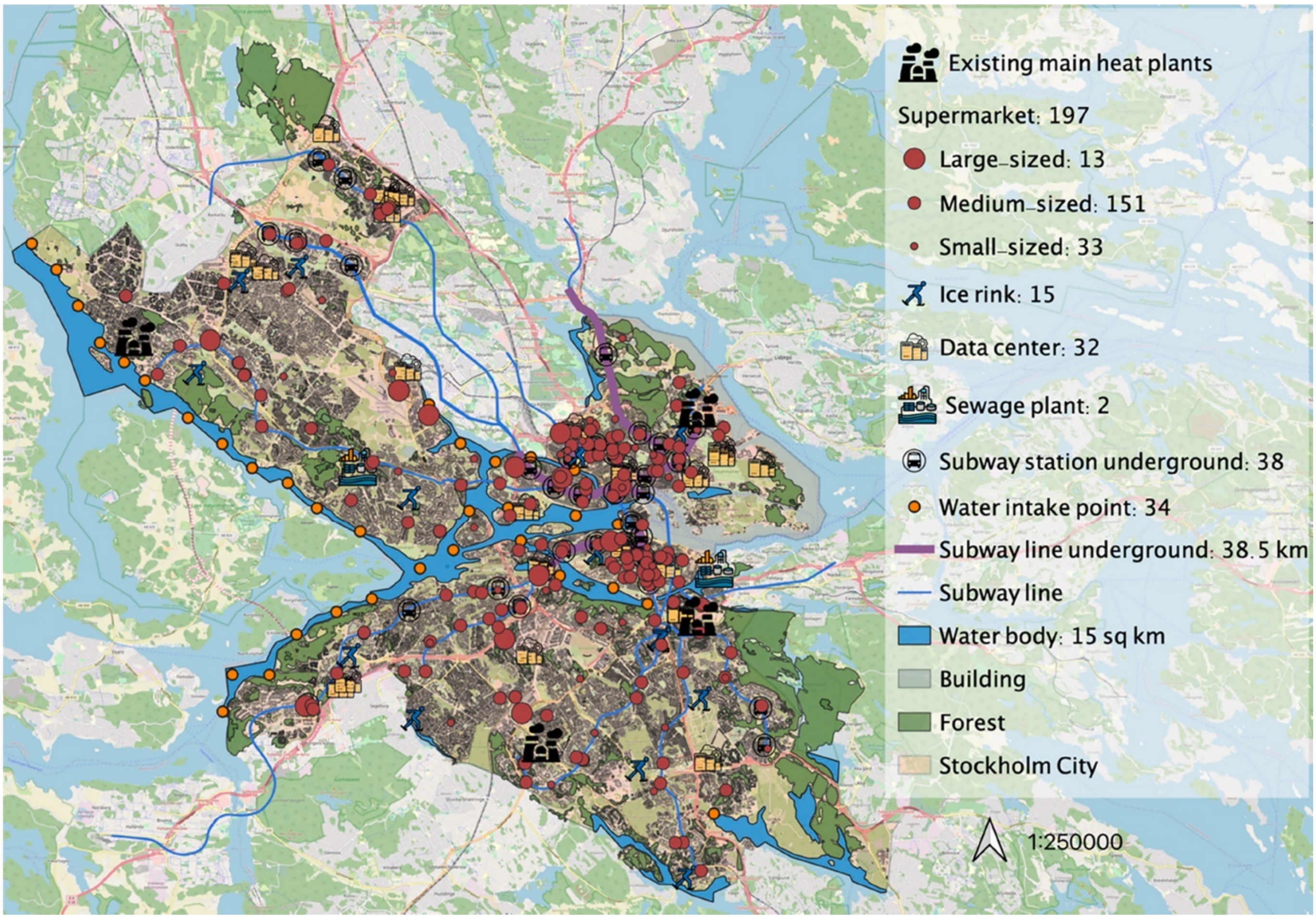

Figure 2 - Renewable and recoverable heat sources in Stockholm

Geographically most heat sources are found within the city center, which is logical given that it is the most densely populated area of the city. The total amount of recoverable heat is 7054 GWh per year, which is 17% greater than the current total supply by Stockholm's DH network. Figure 3 shows the relative amount of annual heat energy available by resource, where data centers and water sources make up 94% of all supply. Supermarkets, which are by far the most numerous in locations, make up 4.5% of available heat, and all other sources make up the remaining 1.5%.

While water body and data sources are nearly equal in number (34 and 32, respectively), the data centers have a notably higher concentration within the city, as shown by the k-means cluster analysis in Figure 4. Heat concentrations emerge in Östermalm, Södermalm, Kista, Sätra, and Liljeholmen due to the proximity of multiple data centers, suggesting that these locations should be exploited first. It should also be noted that data centers typically have a higher source temperature than water sources or supermarkets, meaning that for a given supply temperature, less electrical energy will be needed for heat pumping.

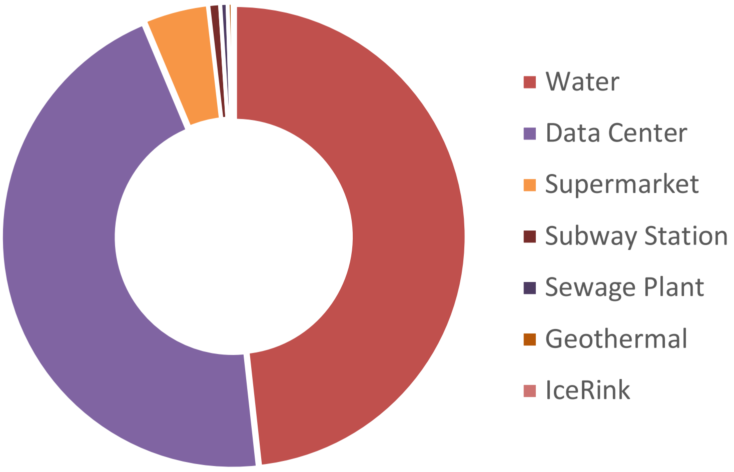

Figure 3 - Shares of heat source potential by source

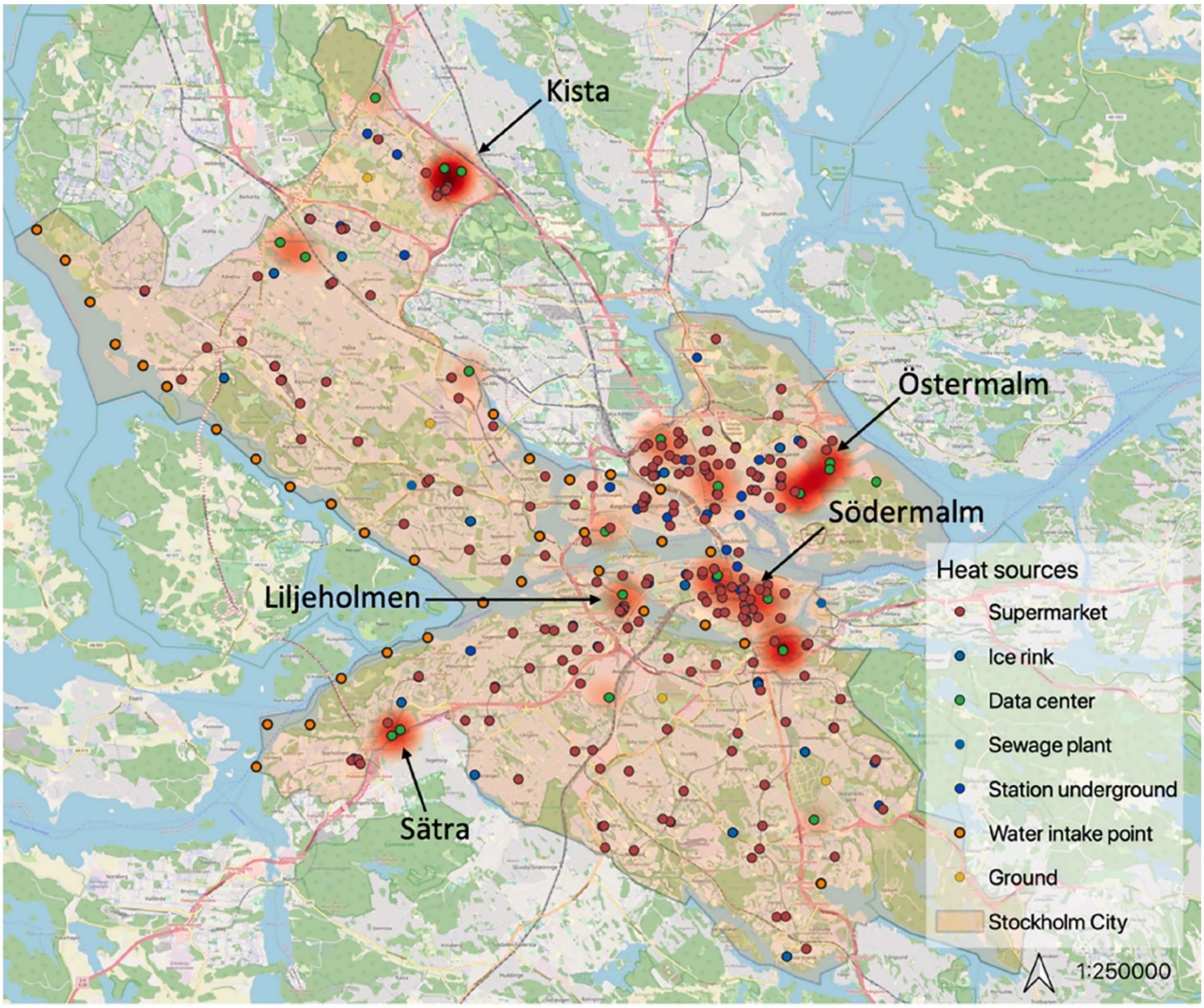

Figure 4 – High density heat source clusters

Identifying the location and scale of heat sources in the city is useful for DH utilities when planning future network expansions. This is particularly relevant for Stockholm which continues to experience rapid population growth and real estate expansion. However, nearly all of the heat sources identified in this dataset require heat pumps to make the heat useful exergetically, which would likely have a significant impact on the existing grid infrastructure. The electrification of district heating in combination with transportation would require further electrical grid reinforcements beyond what is already being planned [10], and is a barrier to exploiting the heat sources identified here.

In addition to higher residual heat temperatures, data centers also have the benefit of flexible location. While current data centers are unlikely to relocate, new data centers can be strategically placed within sub-networks where lower supply temperatures are required. The highest temperatures in a DH network are found close to large plants feeding mainline trunks, which in Stockholm peak near 95°C, but for most of the year are closer to the minimum temperature of 68°C. If a data center can, on average, eject heat at 40°C, then a temperature lift of 30K is not difficult and can result in high coefficients of performance (with an approximate Carnot or ideal COP of 11). This is in contrast to water bodies, which have temperatures between 0°C and 20°C during the year, requiring a much higher temperature lift and just more electrical input power.

Temperatures aside, perhaps the greatest weakness of water body sourced heat is the distributed nature and impact to the valuable waterfront property. Stockholm already today has a water source heat pump near the Ropsten subway station in the northeast corner of the city. It is a largely industrial area, and while the heat pump plant is a relatively small portion of this, placing facilities like this one every 1000 m along the shoreline would be highly controversial due to the many recreational, conservational, and aesthetic values of waterfront property. It may be possible to reduce the location dependency by installing extraction/injection pipes that run inland from the waterfront, but the economic feasibility would need to be tested on a case-by-case basis.

The same is true for any new heating plant, and even for data centers the cost effectiveness of selling heat is a function of distance to the existing network and the cost of alternative cooling methods. However, the opportunity for data centers to grow as a heating source in Stockholm is far more likely to be accepted than water source heat pumps. Looking back to supermarkets, the third largest heat source, studies have concluded that it can be economical for them to participate in Stockholm's open heating market [11,12], but it is most interesting to use the heat directly or sell to the building where they are located first [13,14]. Therefore, the main conclusion from this work is that data centers as a heat resource deserves further investigation, in particular with relation to the increase in electricity price levels and volatility associated with the removal of Russian natural gas from the European energy system. In Chapter 4, a detailed techno-economic analysis of data centers as prosumers is performed to quantify the technical, market, and economically available heat from data centers across the year.

Full details on the methods used to create the map are provided in:

Su, C., Dalgren, J., Palm, B. 2021. High-resolution mapping of the clean heat sources for district heating in Stockholm City. Energy Conversion and Management, 235, 113983. 10.1016/j.enconman.2021.113983 available with open access. The GIS shapefiles with all results are included as supplementary data.

3 Urban Building Energy Modeling

Utilizing data centers as a district heating supply source requires high-temporal resolution models of demand to ensure techno-economic feasibility. Since heat pumps are required to lift the ejected heat's temperature, it is therefore important to identify if renovations on the demand side are more necessary to ensure the heat pump efficiency remains high. The goals of this portion of the project are two-fold:

- Develop a building simulation methodology for estimation of building energy demand that can scale to thousands of buildings in a city
- Identify the temperature reductions within a heating network due to building renovation

Creating high temporal models or data for an entire city requires unique tools suited to simulate buildings at a large scale. This class of simulation tools are called urban building energy models (UBEM) and can have a variety of methods and features [15,16]. One common approach is to take existing single building energy models and create wrappers that enable the population of boundary conditions and simulation of many building instances at the scale of dozens or hundreds of buildings. This approach was also initially proposed within this project using TRNSYS as the building model and Python for the wrapper, exemplified graphically in Figure 5. Archetypal building characteristics are taken from Tabula [17] which also provides the validation baseline data but only in annual values per square meter (kWh/m^2-yr). The model was tested, results published, and Python code posted to GitHub (link in appendix), however the additional development work needed to map results to specific locations and simulate district heating networks drove the search for an alternative method.

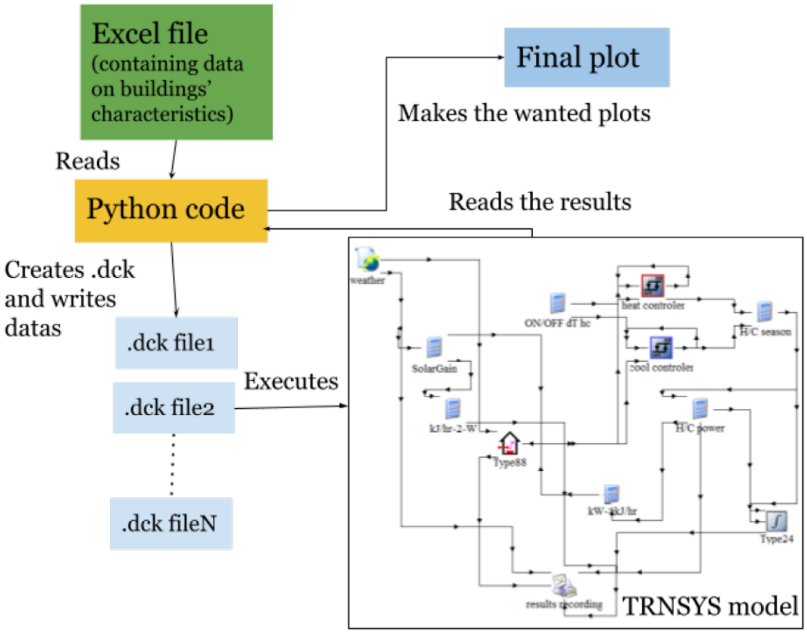

Figure 5 - Python wrapped TRNSYS model structure for building energy modeling

Following a detailed search of several alternatives, the tool City Energy Analyst (CEA) was selected for further building energy modeling due to its well-developed model base, graphical user interface, ability to simulate district heating networks, and open-source licensing [18]. Another advantage of using CEA is that the spatial component is already built into the tool. Not only does this locate the detailed features and demands of buildings, but it also handles inter-building solar shading which can be a significant factor in the thermal energy demand of a building.

Minneberg in the southwest neighborhood of Bromma was selected as the modeling target and consists of a mixture of residential and commercial buildings. For this study, the 32 multi-family buildings developed in 1987 are the target with a graphical representation of the model is shown in Figure 6. Building geometry is created by importing GIS data from Lantmäteriet and extruding building heights from the building footprints. CEA has an inbuilt connection with OpenStreetMap, however several buildings share the same footprint but have differing heights, requiring them to be broken into pieces. The district heating network, shown with red lines, is generated using an optimization algorithm within CEA and does not represent the actual heating network in the neighborhood. Given that it is a small district, it is assumed that differences between the actual network and the one proposed by CEA are negligible.

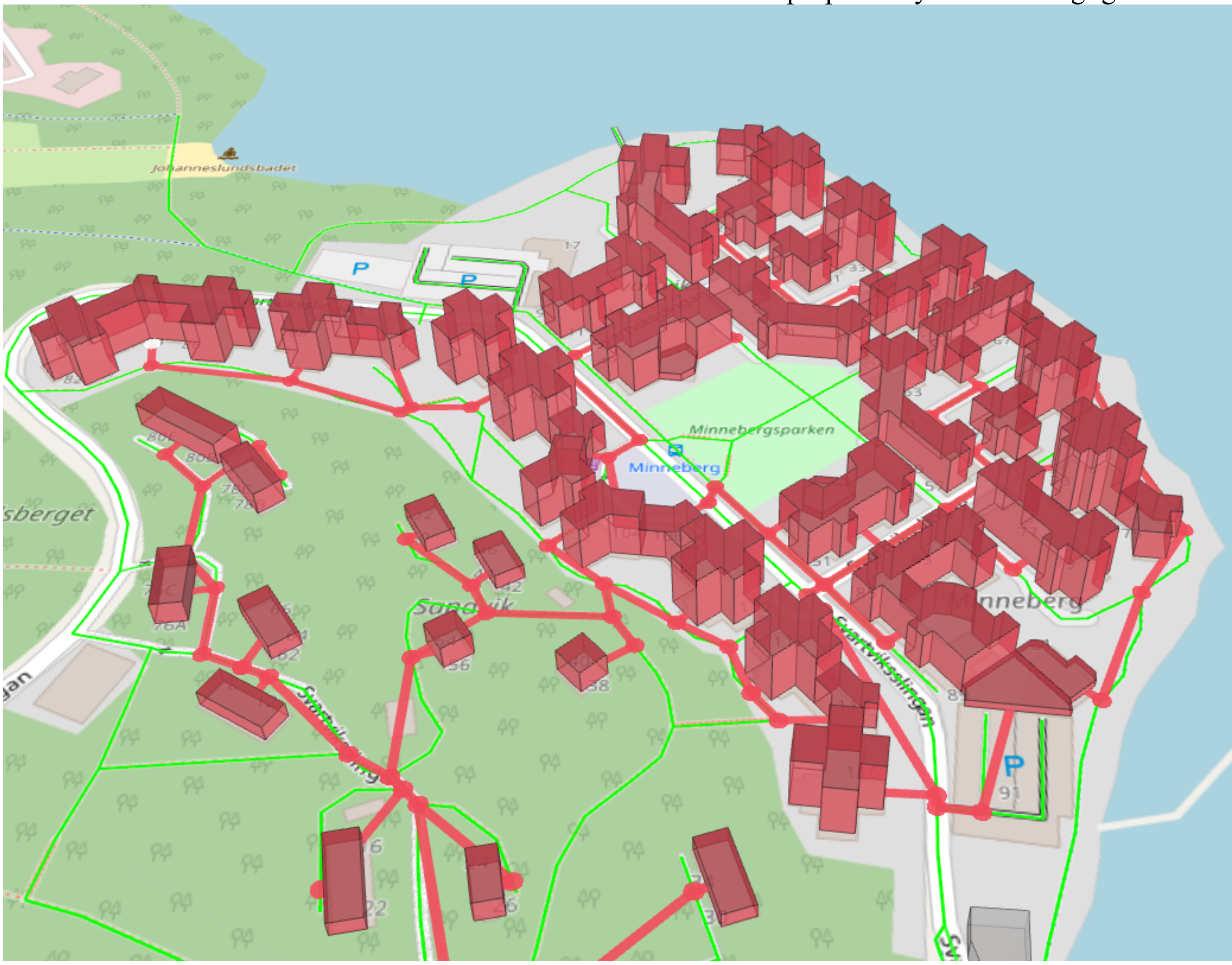

Figure 6 - UBEM geometry and DH network in City Energy Analyst

Boundary conditions for the model are provided by a range of sources. As mentioned above, building footprints are provided by Lantmäteriet but the extruded heights are set using Boverkets Energy Performance Certificate (EPC) database. Building envelope characteristics are supplied by Tabula [17], including the default values as well as two renovation alternatives. Internal gains due to activities are simulated using the stochastic model from Widén and Wäckelgård [19], however CEA did not accept an hourly timeseries profile and the output needed to be converted in a set of 24 hour representative profiles for weekdays, weekends, and holidays. Typical meteorological year weather data is taken from Meteonorm [20] using Bromma airport's weather station as the source.

One of the more challenging aspects of UBEM is model validation since it becomes more difficult, and at some point impossible, to individually calibrate buildings. In this study the EPC database was used to validate space heating, hot water, and shared electricity use independently. The advantage of using EPCs is that they are matched with specific buildings and include metered energy usage by type. At 32 buildings, it was still possible to manually calibrate models, however it is still a time-consuming process.

At a district level, the model performed very well, with absolute percentage errors for space heating, hot water, and electricity being 8.3%, 0.1%, and 2.0%, respectively. However, the mean absolute percentage error for all buildings individually were 16.9%, 23.2%, and 23.5%. The validation results are comparable to those found by Johari [21] who also used EPCs to validate district simulations, and more work is needed to auto-calibrate individual buildings such that each individual building model can be considered valid, not only the district.

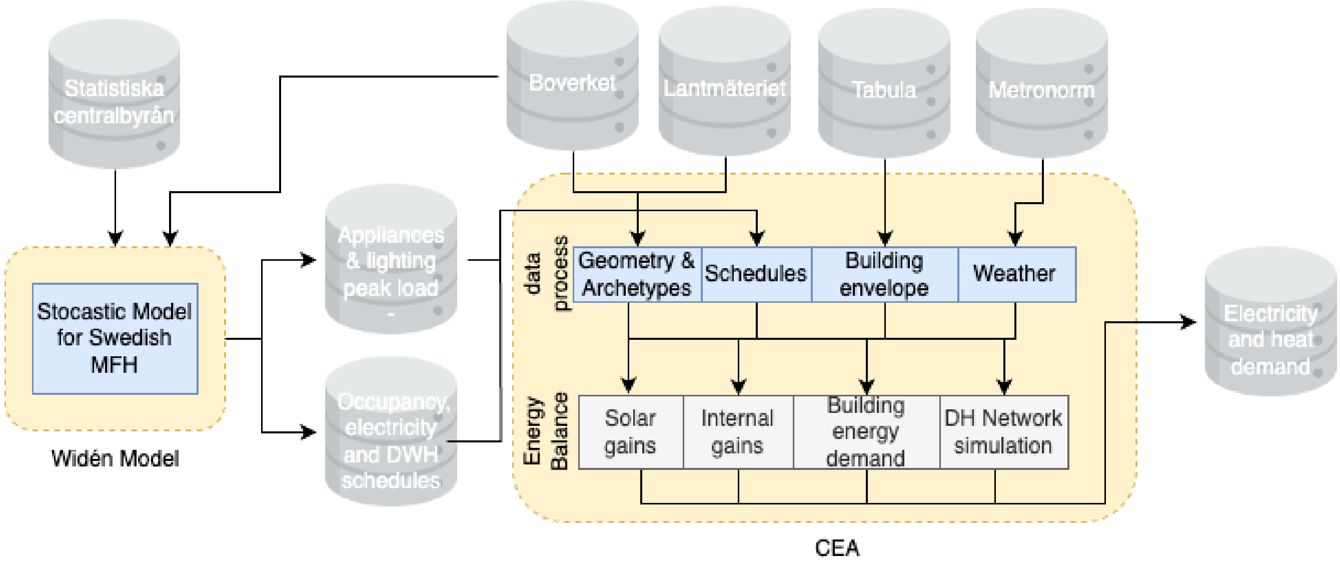

Figure 7 - Data and modeling structure for City Energy Analyst

Looking to the district heating temperature results, given by Figure 8, there is a marked decrease in time where elevated temperatures are required. The scatter plots on the left side show network supply temperatures as a function of outdoor temperature (i.e. heating signature) for each hour of the year. It shows that while upper bounds of supply temperature remain similar across renovation levels, the spread of temperatures widens such that lower supply temperatures can be suitable even during cold weather events. This is also shown in the duration curves on the right side of Figure 8, which more clearly shows that supply temperatures over the baseline 68 °C are needed 20% of the year in the current state, falling to 11% with the usual renovation and 9% with the advanced renovation.

The peak supply temperatures remain the same, and this is due to the heat exchanger sizing algorithm within CEA that cannot be overridden without custom modifications to the source code. Therefore, it was not possible to simulate a case where the DH substation remained the same while the building space heating demand was reduced. In this case, it would be expected that peak temperatures across all temperature levels would reduce, but it is uncertain by how much.

The results shown here are promising in that the district only requires 68 °C supply temperatures for nearly 80% of the year. This is approximately a 30K difference from the ejected heat of an air-cooled data center, suggesting that high efficiencies, and correspondingly good economy, can be achieved. Ideally a data center could be simulated directly with the heating network, however this was not possible within the available features of City Energy Analyst without source code modification. Future work developing the models can focus on more control on district heating network parameters, including controls and storage. Although it was not the main focus, it should also be mentioned that space heating demand was also significant reduced, down 42% for usual and 62% with advanced refurbishment.

The full report includes an extensive review on urban building energy modeling and tool selection, and substantial details on the method used to create the model:

Bay, C. and Muñoz, N. Dynamic simulation of Swedish residential building renovations and its impact on the district heating network. KTH Royal Institute of Technology, MSc. Thesis, 2023.
urn:nbn:se:kth:diva-329402

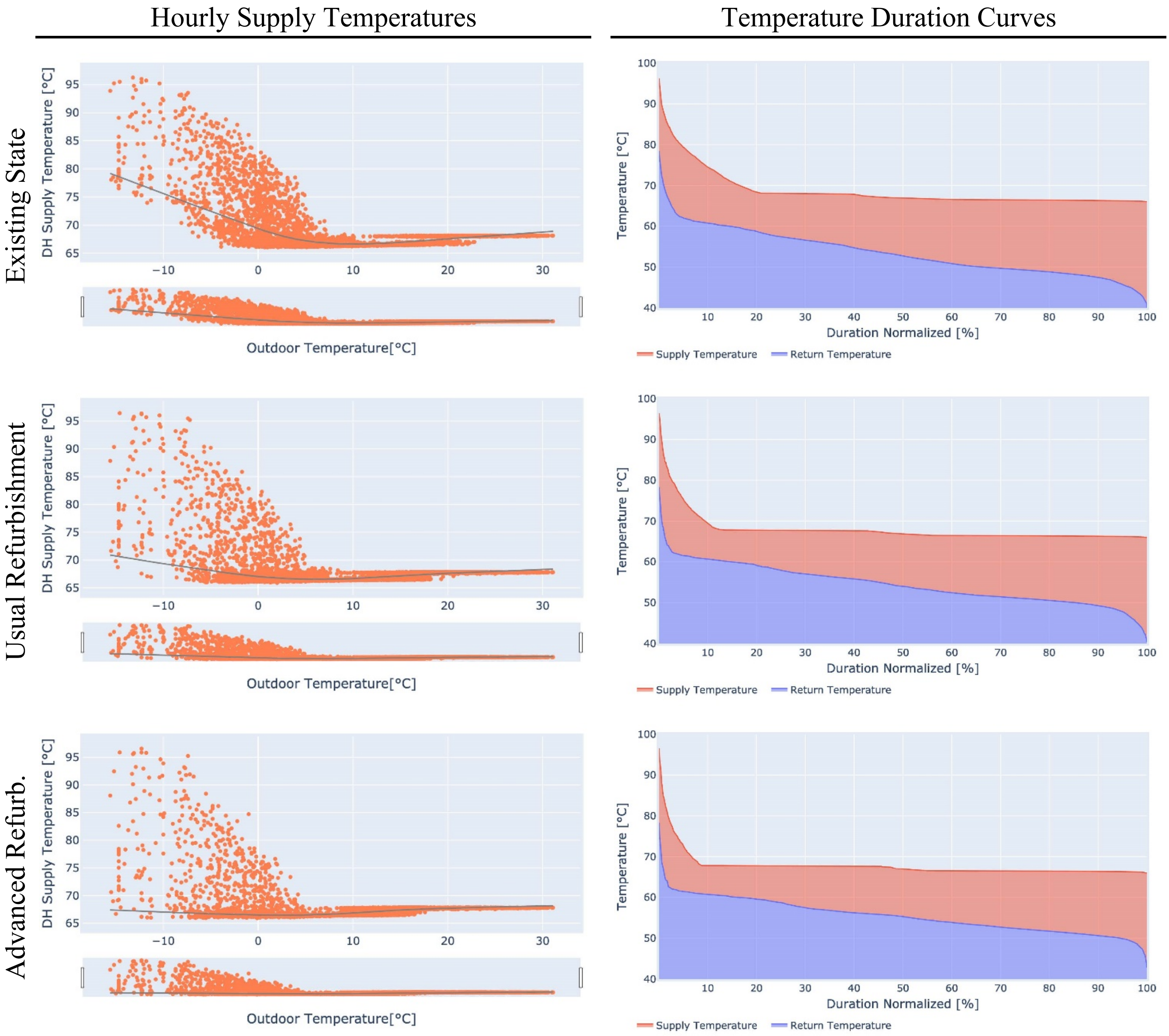

Figure 8 - DH supply temperatures by renovation status

4 Data Centers as Prosumers

The heat source mapping presented in Chapter 2 identifies data centers as the second largest non-combustible heat source in Stockholm based on 32 existing sites. According to Stockholm Exergi, many of these data centers are already participating in the Open District Heating marketplace [3]. With the dramatic change in electricity prices in 2021, both in absolute values and in volatility, it is worthwhile to investigate the techno-economic conditions of using data centers as a district heating resource.

Due to their criticality as information infrastructure, data centers are notoriously secretive about their design and operation. This was noted in the EU ReHeat project [22], which could not document available residual heat in their mapping, and in this project the residual heat available was estimated from two data centers in Stockholm. Likewise, information about energy procurement and export contracts are not public knowledge, making specific economic analyses more challenging. However, using a theoretical energy systems model and hourly spot market prices for electricity and heat, it is possible to create a techno-economic prosumer energy analysis.

With this approach, this study aims to identify the amount of recoverable heat from data centers on three levels: technically viable, market viable, and economically viable. Technically viable heat refers to all possible heat that the data center can produce. Market viable refers to the heat produced that Stockholm Exergi is willing to purchase, which is limited moments where the outdoor temperature is 12 °C or lower. Economically viable refers to heat which is cost-effective to sell, i.e. the electricity costs to produce the heat are lower than the revenues gained from selling it. Multiple sensitivity analyses are performed to test various operation conditions, such as multiple years of weather and electricity prices and temperature levels in the district heating network. This last point is directly connected to the demand modeling study in Chapter 3 to help identify potential temperature requirements for integrating data centers most effectively in the heating network.

The technical cooling system model is represented in Figure 9, which is based on the most common design of an air-cooled, cold aisle. The data hall model can gain or lose heat to the ambient through the building envelope, altering the air temperature (T_{RA}) entering the cooling system. The first cooling module is residual heat recovery, which includes an air-to-water heat exchanger, coupled to a heat pump with its condenser feeding the district heating network. The next module is free cooling which dumps heat directly into the atmosphere, and if this is not sufficient the heat can be removed with a standard chiller also rejecting heat into the atmosphere. There are four configurations tested from this complete system, including: A1 – chiller only, A2 – chiller plus free cooling, A3 – heat recovery, and A4- heat recovery with free cooling.

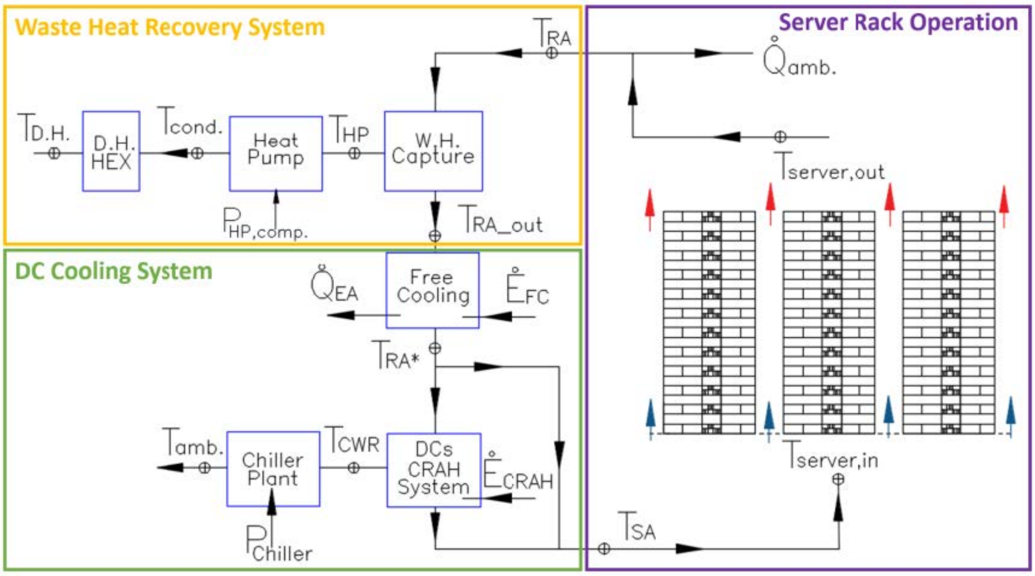

Figure 9 - Data center cooling system model diagram

The model uses computation load as the basis for heat generation, i.e. the cooling requirements and heat availability is based on the workload of the servers. The computation profile used in this study is taken from Ham et al. [23] and considered a representative profile for communications related demand, meaning it has the high loads during the weekdays, low loads during evenings, and the lowest loads on weekends. There are 12,600 servers in the data center with a 3 MW peak electrical load, making it a medium sized server hall for Stockholm [24]. Total annual electricity demand for the non-cooling equipment (servers and auxiliary electricity) is 28.3 GWh. Electricity needed for cooling varies by system configuration, as shown in Figure 10.

The gap between A1 and A2 represents the savings delivered by free cooling, i.e. mixing cold ambient air into the ventilation system, and is one of Sweden's core advantages as a location for data centers. Moving from A2 to A3, residual heat recovery is added and free cooling removed in order to direct as much heat as possible into network. Configuration A4 brings free cooling back into the system. Comparing A2, the baseline system, to A4, total electricity demand is reduced by 56% due to greater efficiency in the heat recovery sub-system as compared to the standard computer room air handling unit (CRAH) and chiller.

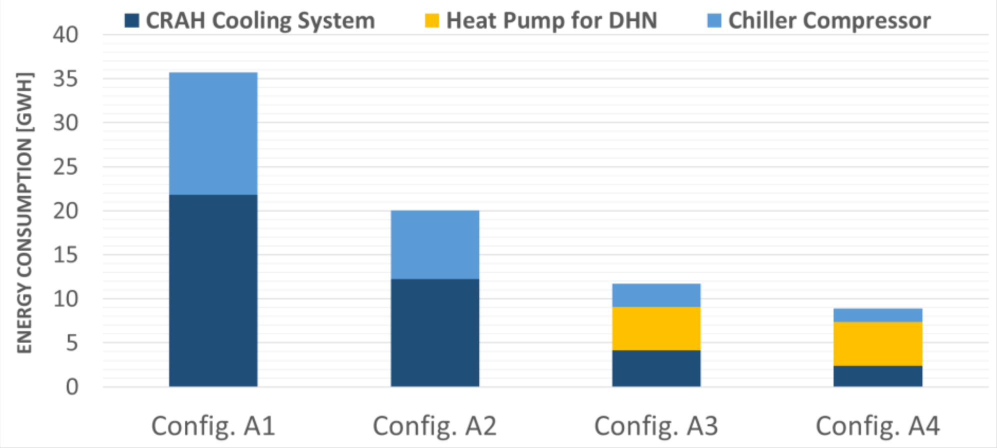

Figure 10 - Electricity requirements for cooling by system configuration

The monthly recovered heat from Configuration A3 is shown in Figure 11 and presents the three viability limits. If left unrestricted, the data center produces 22.5 GWh of heat per year. When limited to hours when the ambient air temperature is 12 °C or lower, annual deliveries drop by 32% to 15.3 GWh. Supply is further restricted when heat is only generated during profitable hours, dropping 40% to 13.5 GWh. This data is generated using TMY weather, but since there are no TMY electricity prices [25], 2018 is used a proxy since it reasonably represents the long-term Nord Pool average from the past five years. In this case, the difference between the market and price limits is driven not by electricity prices, but by the price for heat offered in the Open DH market. It can be said that the 12 °C limit is unnecessary given how low the value of heat is during the summertime when the system is heated entirely by residual incineration. When tested for specific years, the price-limited heat availability remains constant from 2018 through 2020. For the first half of 2021 the trends also remain consistent, however the winter of 2021 to 2022 had notably higher electricity prices, making it less economically interesting to sell heat. For example, in December of 2021, the price-limited heat delivery was 48% less than in 2018 and was 69% less in 2022. The year with the lowest price-limited deliveries is 2022, where only 9.4 GWh are economically viable, or 58% of the technically recoverable heat.

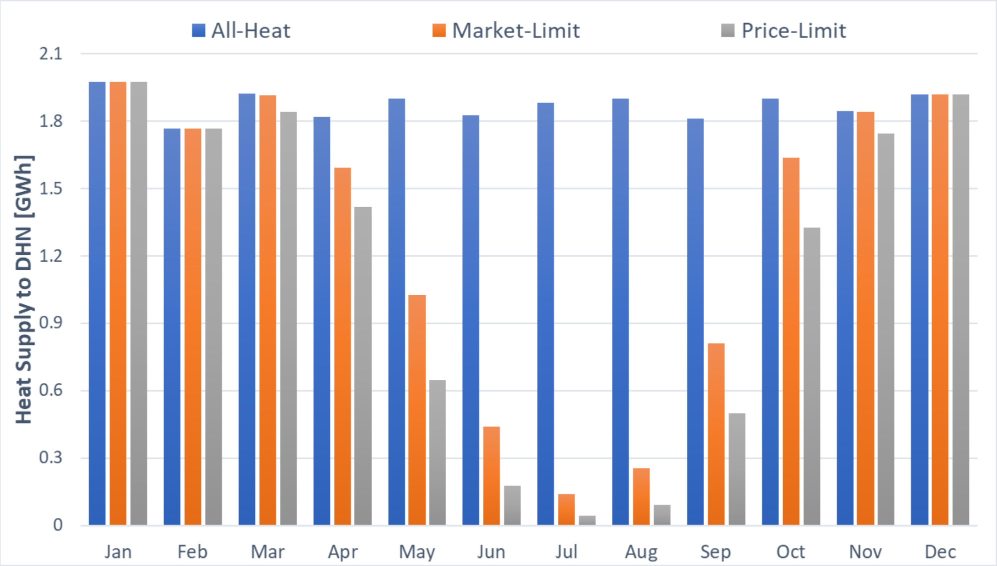

Figure 11 - Heat supply to DH network by limiting scenario

In addition to heat and electricity prices, it is important to consider the heating network temperature demands and their effect on the heat pump COP. Figure 12 shows total heat deliveries for each limitation scenario considering prices for 2018 and 2022. In 2018, heat is delivered up to 12 °C which is the market cap imposed by Stockholm Exergy, whereas in 2022 the economic limitations cap deliveries at 10 °C. Furthermore, between -3 °C and 10 °C there is a notable decrease in heat supply in 2022, which becomes less pronounced at colder temperatures due to the increasing value of heat. The frequency of very cold temperatures (-10 °C or lower) is also relatively low with winter temperatures averaging within a few degrees of freezing. Configuration A2 is simulated with weather files representing multiple climate change scenarios showing a mild but notable increase in cooling demand under more extreme cases; full results are given in the complete report.

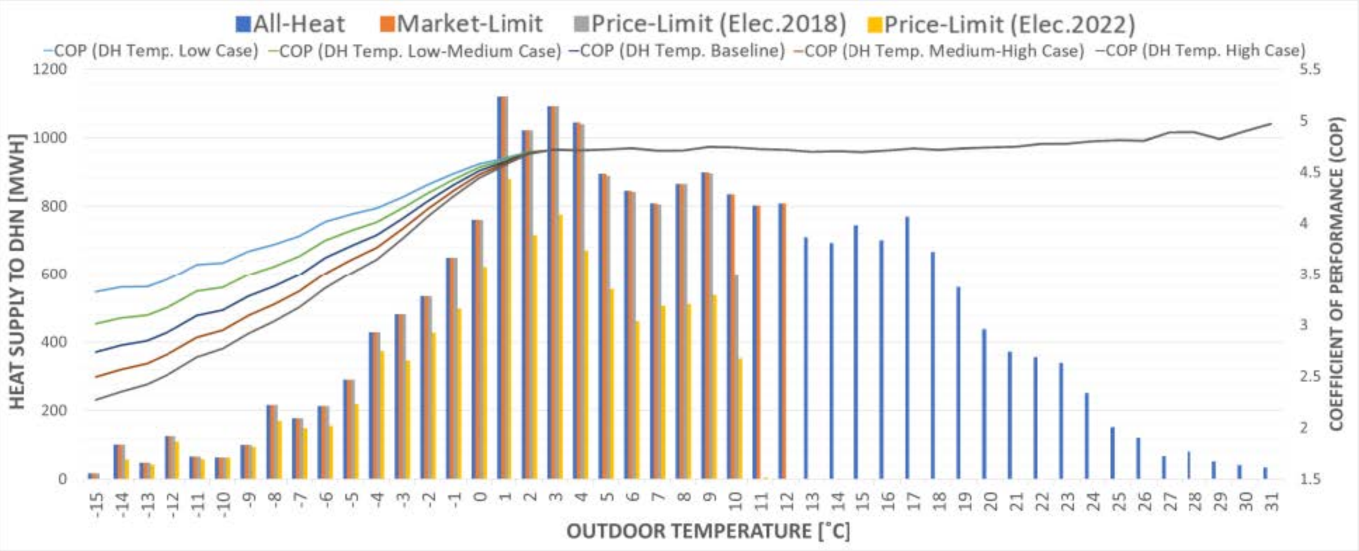

Figure 12 - Heat delivery and heat pump COP as a function of outdoor temperature

The heat pump COP results shown in Figure 12 cover all tested DH network temperature curves. All curves have a minimum supply temperature of 68 °C, which applies to all outdoor temperatures from 0 °C and higher. From 0 °C to -17 °C, all temperature curves increase linearly with the nominal curve used as a baseline peaking at 103 °C. The lowest and highest curves peak at 90 °C to 115 °C, respectively. The temperature curves do impact heat pump COP, where the gap between the lowest and highest temperatures is 2.1 to 3.5. However, the vast majority of heat is delivered when network temperatures are low and COP is above 4.0. The seasonal performance factor (SPF) of the data center considering the total heat energy delivered to the network as compared to the total electricity required to cool it is 1.9 when all possible heat is delivered. This value drops significantly in the price limited scenarios, with 2018 as the highest at 1.3 and 2022 the lowest at 0.9, due to the increased demand for electricity for cooling and the reduced supply of heat to the network.

These results show that the greatest influence on the viability of data centers as a heat source comes from energy prices, both in terms of the value of heat recovered and price of electricity required. The value of heat drops considerably in the summer when the heating network can be driven entirely by waste incineration. This can be a challenging scenario for data centers since their greatest ability to reject heat is during warmer months. This suggests that maximizing heat resources requires seasonal storage, either in an ability to store waste and avoid combustion in the summer, or through thermal storage mediums like boreholes. However, despite the limitations in economic heat recovery, the concept appears economically viable. It was found that operational costs are reduced by approximately 40% when heat is recovered, resulting in a maximum capital investment limit of 100 – 200 MSEK depending on future economic conditions. Investment costs of industrial scale heat pump installations could not be found for comparison, but this range can cover a heat pump costing 30 to 60 kSEK per kW of capacity, which is far above industry norms for building scale heat pumps [26].

The full report includes much greater detail on the model structure and boundary conditions, as well as numerous additional technical performance indicators specifically related to data centers:

Sintong, J. Data Centres and Prosumers: A techno-economic analysis. Uppsala University, MSc. Thesis, 2023. urn:nbn:se:uu:diva-507504

5 High-Resolution Source-Load Mapping

Thus far in the project, the most viable residual heat sources in Stockholm have been located, the supply temperature curves for residential heating sub-networks plotted, and the available heat supply of data centers updated with detailed prosumer simulations and multiple boundary limits. This study combines the work of previous chapters to create a high-resolution source-load map, which can then be used to identify the levelized cost of heating from all the distributed residual heat sources.

In this chapter, the marginal cost of environmental heat is found on a local level to identify impacts to the merit order of heat deployment and final cost of heat to the city. The heating demand of Stockholm is mapped using the energy performance certificate database linked to the GIS locations of each property using Swedish Land Survey data. After filtering for duplicate rows and matching property descriptions (fastighetsbeteckning in Swedish), 6560 unique buildings/properties are found. This is approximately 37% of the total Stockholm building stock and around half of the total buildings found by Pasichnyi et al. [27] when EPC data was linked with Stockholm Exergy metering points.

The resulting map is segmented into 10 districts using k-means clustering algorithm accessed via the scikit-learn library. Each district is allocated the heat sources within the cluster and water body sources connected to the district with the minimum connection distance. Heat supply from each source is calculated and the total cost determined using the marginal cost of heat. Figure 13 shows the demand mapping and clustering results, where each bubble represents a heat load and the size of the bubble corresponds to the annual energy demand. Total heat energy demand for each cluster is given in Table 1 along with the allocated residual heat supply by type. Given that the total allocated heat is greater than the demand but less than the known demand of Stockholm, the heating demand here is considered representative from the standpoint of spatial distribution.

Table 1 - Heat demand and allocation per cluster (in GWh/year)

Cluster	Heating Demand	Data Centers	Super-markets	Water Bodies	Total Allocation
1 (red)	6.869	0	24	100	124.0
2 (blue)	9.961	60	25.6	100	185.6
3 (green)	15.986	80	18.4	0	98.4
4 (purple)	4.363	20	23.2	0	43.2
5 (yellow)	10.328	60	50.4	800	910.4
6 (pink)	14.668	160	104.0	300	564.0
7 (mauve)	1.831	40	12.0	500	552.0
8 (grey)	1.522	0	8.8	700	708.8
9 (mauve)	9.732	20	16.0	500	536.0
10 (magenta)	4.764	40	16.8	400	456.8
Totals	80.024	480	299.2	3400	4179.2

Readers will note that the total available heat from data centers is considerable smaller than the 3200 GWh/year presented in the results of Chapter 2. There are two reasons for this; first, in the GIS data there are 24 data centers mapped within the administrative boundaries of Stockholm, with 32 being within Stockholm's DH network; and second, the amount of heat available from the average data center is less than previously estimated. Here is assumed that the typical data center can produce 20 GWh/year of heat which accounts for the inability to produce heat during warm periods (12 C or higher) and a more reasonable assumption about how large the typical data center in Stockholm is. Further discussion on this topic can be found in Chapter 6.

As was demonstrated in Chapter 4 with data centers and by Steuer et al. [12] and Adrianto et al. [13] for supermarkets, the marginal cost of heat varies in time due to the variable price of electricity. In the case of both technologies, it can also be seen that the operational costs are by far the most dominant in determining the levelized cost of heat. Therefore, it is predominantly the heat pump COP and cost of input electricity which determine the LCOH. Here capital costs are ignored which is technically the marginal cost of heat (MCOH) and used as a proxy for LCOH. MCOH is calculated as the price of electricity divided by the seasonal COP (SCOP).

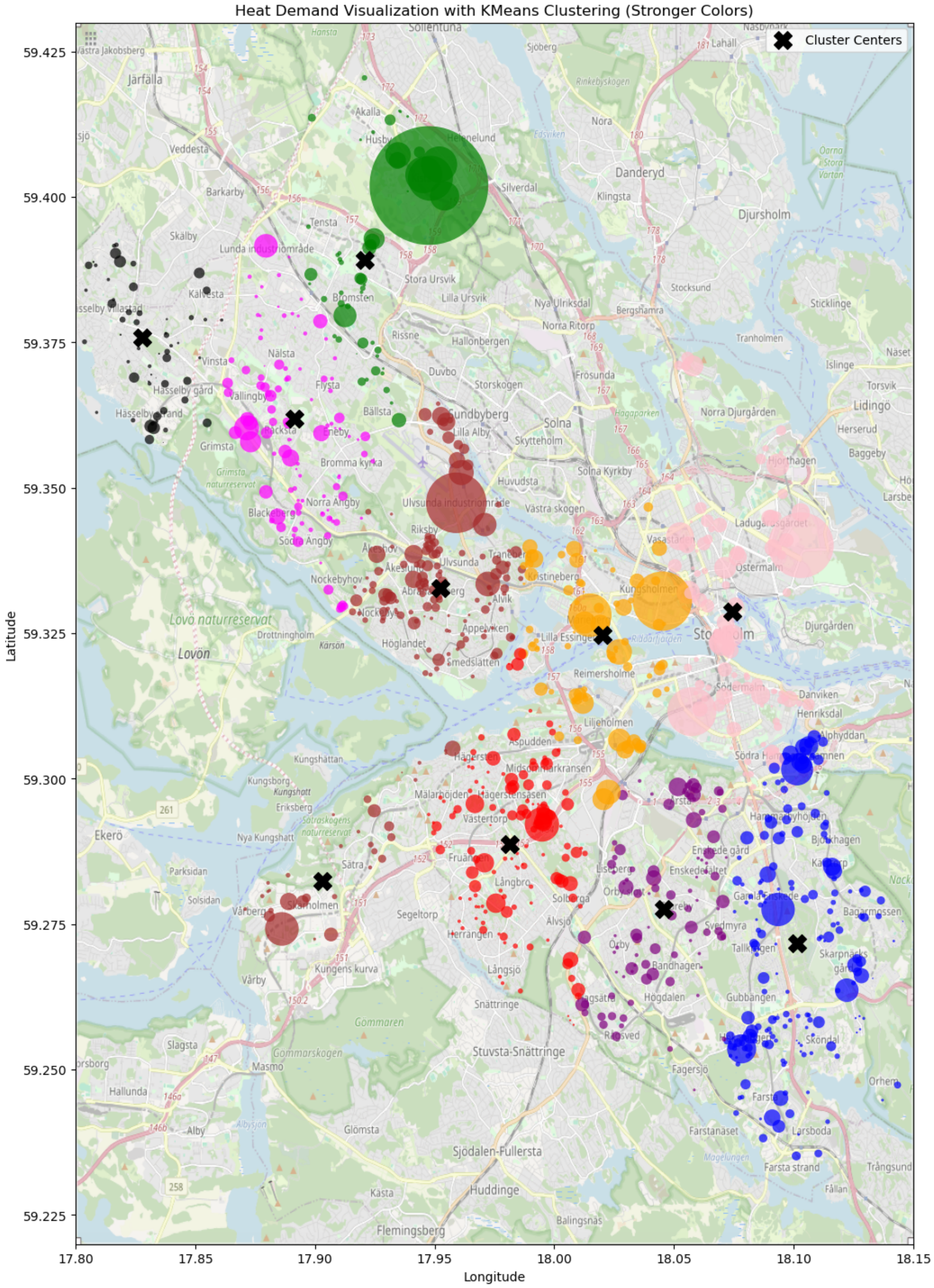

Figure 13 - Heat demand mapping of Stockholm with 10 k-means clustered districts

Figure 14 shows the MCOH (in SEK/MWh) for a range of SCOPs and electricity prices, with several key values. Three prices for district heating are shown to provide references on the general value of heat in Stockholm. Since the value of heat varies over the year, these are weighted prices based on data center supply, which is the most consistent of the three residual heat sources. In yellow is the weighted average sales price for the Open District Heating (ODH) market when there are no limits to supply at 253 SEK/kWh; in orange is the ODH price when market limitations are present at 12 °C, coming in at 315 SEK/MWh; the final price in red is the weighted retail price of heat at 453 SEK/MWh, which considers the 2024 prices from Stockholm Exergi of 309 SEK/MWh in the summer (May-Sep) and 813 SEK/MWh in the winter (Oct-Apr).

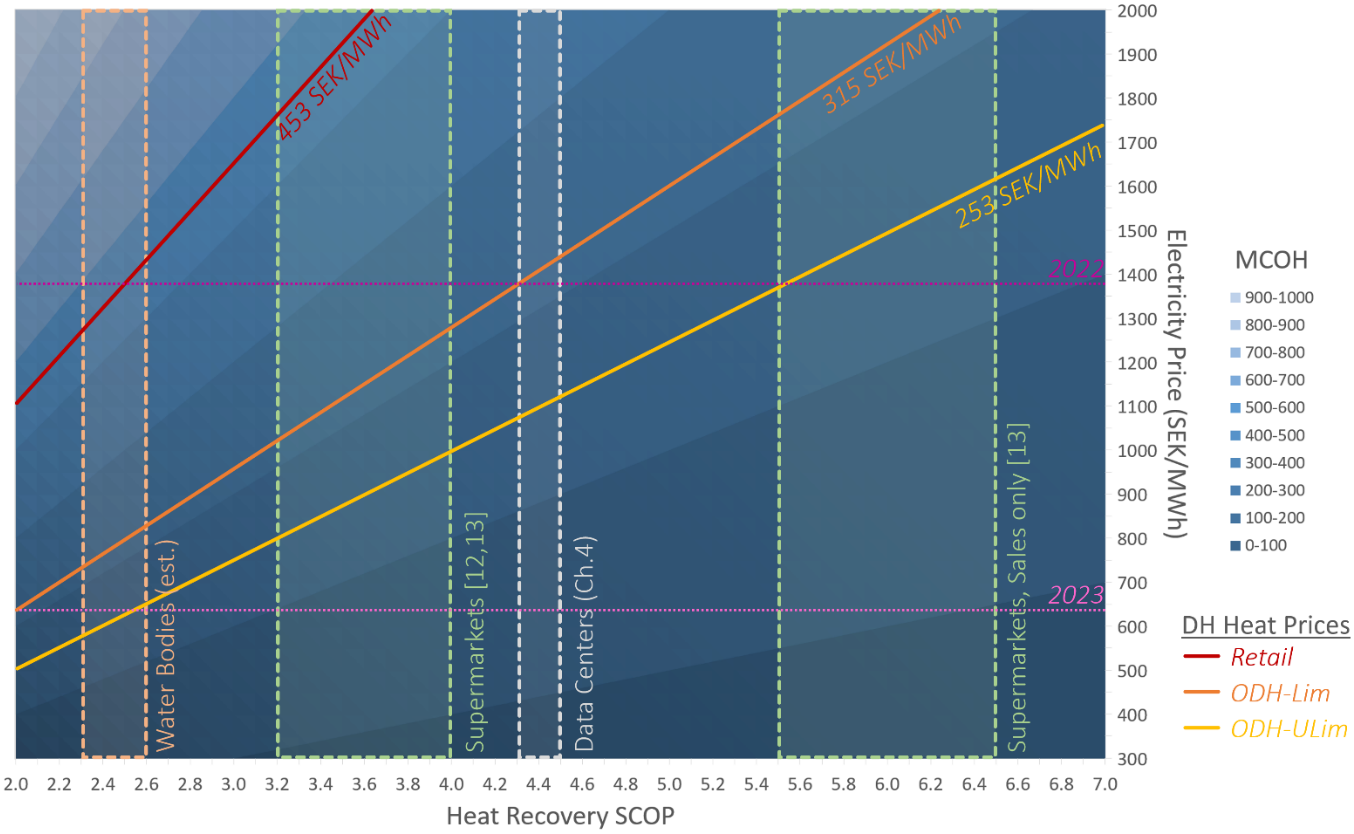

Figure 14 - Marginal cost of heat (in SEK/MWh) by source and electricity price

Seasonal COP values for the three most prominent residual heat sources, data centers, supermarkets, and water bodies are given as ranges taken from Chapter 4, literature [12,13], and a calculated estimate, respectively. In each case, only the COPs during operation are considered, which most closely represents the real operating conditions as compared to other novel indicators on residual heat recovery. Each source is given a range, but on average data centers are assumed to have a SCOP of 4.4, supermarkets at 3.5, and water bodies at 2.4. Supermarkets can deliver their heat for self-use to offset retail purchases and make sales to the ODH market, which have been shown to have significantly different COPs [12] and is the reason for two ranges in Figure 14, and a conservative assumption is made here. The water body SCOP range is calculated using the Carnot efficiency with a source temperature of 3 °C and sink temperature between 68 °C and 80 °C [28], and it is assumed the real heat pump can operating with 50% of this limit [29].

The removal of Russian gas from electricity networks has caused dramatic changes to Swedish electricity prices. Prior to 2020, the inflation adjusted, long-term Nord Pool spot price had been approximately 330 SEK/MWh on average. In 2020 there was a dip to 221 SEK/MWh followed by a spike to 1382 SEK/MWh (average) in 2022. While prices are still volatile, the overall levels have come down with 2023 averaging 645 SEK/MWh. The prices for 2022 and 2023 are highlighted in Figure 14 as a reference, and the marginal cost of heat used in the analysis is taken using 2023 prices. This is a assumption that foregoes uncertainty analysis about the long-term development of electricity prices in Sweden, which is outside the scope of this project.

With the 2023 average electricity price and SCOPs, the resulting MCOH values are 147, 184, and 269 SEK/MWh for data centers, supermarkets, and water bodies, respectively. All values are clearly below the 315 SEK/MWh value of heat in the ODH market during the main heating season, further demonstrating the economic benefits of residual heat recovery. Water bodies are the only source more expensive than the unlimited price, which is confirmed by the merit order shown in [30] where large heat pumps are the second source followed by CHP with waste incineration.

The MCOH values and total heat demand by district are combined to create a total heating cost by residual source, shown in Table 2. The total cost divided by total demand provides the weighted price, in SEK/MWh and provides an indication of the spatially diverse cost of residual heat sources around the city. Naturally these heat sources would need to be connected via a network whose costs are not included here, this is just the cost of acquiring heat. However, the weighted cost of heat for the entire city is just under 250 SEK/MWh, which is close to the 253 SEK/MWh value that would be if these heat supplies operated year-round and well under the value for operations at 12 °C and under.

Table 2 - Total annual costs and weighted prices for heat supplied by residual source and cluster

Cluster	**Data Centers** *MSEK/yr*	**Super-markets** *MSEK/yr*	**Water Bodies** *MSEK/yr*	**Total Cost** *MSEK/yr*	**Weighted Price** *SEK/MWh*
1 (red)	0.00	4.42	26.88	31.30	252
2 (blue)	8.80	4.72	26.88	40.39	218
3 (green)	11.73	3.39	0.00	15.12	154
4 (purple)	2.93	4.28	0.00	7.21	167
5 (yellow)	8.80	9.29	215.00	233.08	256
6 (pink)	23.45	19.17	80.63	123.25	219
7 (mauve)	5.86	2.21	134.38	142.45	258
8 (grey)	0.00	1.62	188.13	189.75	268
9 (mauve)	2.93	2.95	134.38	140.26	262
10 (magenta)	5.86	3.10	107.50	116.45	255
Totals	70.36	55.14	913.75	1039.25	249

The most recent Nordic Energy Outlook (NEO) [31] utilized the source mapping results from Chapter 2 to also study the economic feasibility of integrating residual heat from data centers, ice rinks, and sewage into the existing network. The conclusions state that nearly all (98%) of all residual heat sources studied would be economically viable already in 2022. Their result confirms the results found for data centers in Chapter 4 and complements the results found for supermarkets [12,13]. That study utilizes a far more complex model, whereas this simplified economic model is valuable for pre-feasibility studies in that it can quickly determine the cost of heat for a given sub-network now that demand and supply have been mapped.

The case study of Stockholm was used for consistency throughout the project but has its limitations in places where a well-developed district heating network already exists. As Pasichnyi et al. [30] show, there is a complex merit order of heat sources that are deployed based on marginal operating cost which will ultimately determine the capacity factor for residual heat sources. Regardless, the results here suggest that incorporating all available residual heat sources will have a marginal impact on the cost of heat and should be motivation for further decarbonization of the heating network. Furthermore, this simplified analysis approach can be followed by other European cities looking to develop a new district heating network can use it as an early part of their planning process. The main barriers are access to quality data for mapped supply and demand, but mainly on the demand side, since EPC data has its limitations as shown here and elsewhere [27].

At the time of writing, final documentation for this study is being prepared and will be submitted for journal publication. The preliminary title and authorship are:

Shahcheraghian, A., Sommerfeldt, N., Madani, H. Techno-economic potential of distributed heat sources into district heating – A case study of Stockholm.

6 Discussion

At the outset this project aimed to develop a high spatial and temporal resolution mapping platform for Swedish district heating systems. The platform's purpose was to aid in development planning to remove the remaining fossil fuels and integrate more renewables and residual heat, potentially complemented by seasonal storage facilities. The baseline work and methodologies required to create the platform have been completed, including;

- Mapping of renewable and residual thermal energy sources was performed with 1 m resolution, identifying the location and volumes of heat available to the city,
- Refining the availability of residual heat through a novel techno-economic prosumer analysis of data centers using hourly resolution and prices,
- Developing an urban building energy model capable of building-level resolution and heating network simulation to inform network temperature level requirements, and
- Mapping of thermal energy demands using energy performance certificate data and coupling them with residual heat sources to develop a pathway for further decarbonization of the heating network.

There are some notable challenges to integrating them into a single platform, particularly one available to the public. Perhaps the greatest limitation is that they require significant amount of private data to create. In the case of energy demand, to suitable validate individual building models, it is necessary to gain access to hourly energy usage data which would be managed by an energy utility like Stockholm Exergi. Under GDPR, Stockholm Exergi can only share this data if it is anonymized in a way that prevents third parties from tracing its owner, negating the purpose of using it to validate individual building models. It would be possible to cluster data prior to sharing, say by block or handful of buildings, which would retain anonymity and high spatial resolution. It may also be possible to use large data sets to create a more refined library of building archetypes using data driven models. This type of model would be analogous to existing stochastic models built for modeling building occupancy and appliance use, where some basic building parameters are used to generate representative time series demand profiles. This approach is current being developed in another project funded by the Swedish Energy Agency under the E2B2 program (P2022-00903).

Furthermore, the urban building energy models (UBEM) still required a considerable amount of manual work to calibrate due in part to the coarse geometry. While simple extrusions (also known as Level of Detail 1) can be suitable for thermal energy simulations, considerable effort is needed to break the building footprints into separate parts with separate heights. Ideally 3D geometry would be used directly, which is increasingly available from cities in a format known as CityGML and has been built into UBEM workflows [32]. One tool that utilizes the CityGML format is PyCity [33], which was intended to be the simulation model used for the UBEM portion of the project, however major bugs at the time prevented it from working and the team responsible for the open-source code said it would not be fixed within the timeline of our project. This led to the use of City Energy Analyst as a replacement, which is a great tool with many relevant features, but limited in its geometry representation.

For district heating planning, it may not actually be necessary to simulate every single building. As the UBEM results show, it is possible to simulate a small district with acceptably low errors, confirming results found in other district modeling studies [21]. Therefore, it should be possible to divide the city into relevant sub-networks which could then be studied for the integration of data centers or energy storage. A notable limitation to this approach is the inability for Stockholm Exergi to share the location of their heating network outside the company, making it difficult to divide the city into relevant sub-networks. It is unknown if this limitation exists for all district heating companies, but in the chosen case study for this project it became a notable limitation in establishing the UBEMs coupled with residual sources. It would certainly be possible to do this work inside Stockholm Exergi as commercial research, but not as publicly funded research.

Beyond methodology, this project also produced insights on the potential development of Stockholm's district heating network which can be taken as lessons for other Swedish cities. First, is that data centers are perhaps the most promising new source of thermal energy in cities. It was shown here that data centers are already being built close to thermal demands to reduce data latency, minimizing the cost of collecting heat from more distant sources and creating a natural co-benefit for using this residual heat for the city. It is also widely expected that the need for data centers will continue to grow, and these results help motivate their strategic placement in cities.

When it comes to scale, it was estimated in Chapter 2 that the existing data centers in Stockholm could supply 45% of all heat demand in 2020 based on an average heat supply of 100 GWh per year from 32 data centers. The example data center presented in Chapter 4 could at most produce 22.5 GWh/year and is more likely to produce around 15 GWh/year. It is meant to represent a medium sized data center of 3 MW electric peak making the heat production ratio 5 GWh per MW of electric capacity. By comparison, Bahnhof's proposed data center in Stockholm, Elementica, is planned with a 21 MW electric peak and is estimated to provide 112 GWh of heat per year to the open district heating network [34], resulting in a similar heat production ratio of 5.3. Elementica is one of the larger data centers proposed for the Nordics [35] suggesting that the modeled 15 GWh per year is more representative of a typical existing data center. If so, this would mean that total heat supply potential from current servers is closer to 500 GWh, around 8% of total demand, rather than the 3200 GWh estimated in Chapter 2. Using the 5 GWh/MW heat ratio, 3200 GWh of heat per year would correspond to 640 MW of computational capacity. Rapid data center construction is expected to continue; however the entire Nordic region is only forecast to have 296 MW of total computational power capacity by 2028 [36]. Therefore, it is unlikely that Stockholm will have more than 10-15% of its share of district heating covered by data centers in the near to medium term.

If data centers are not as large of a heat source as previously thought, then the water bodies around Stockholm become by far the greatest source of renewable and recovered heat energy. In addition to the barriers described in Chapter 2, it will be challenging to dramatically increase the electrical demands of Stockholm with heat pumps given that the city is already grid capacity constrained [10] and electric vehicle ownership is growing [37]. Future work will be needed to identify strategies for heat pump integration that minimizes grid impacts, including demand response strategies, centralized and decentralized storage, and market mechanisms to send the necessary signals.

Shallow borehole potential as a heat source was mapped out in Chapter 2, and was found to be relatively small, but could be investigated further as a store of energy. Borehole thermal energy storage (BTES) has been studied for several decades [38] but only a small number of systems have been constructed worldwide. The Swedish experience with BTES has been mixed, with three studied systems underperforming and two of them being decommissioned [39–41]. There remains a great potential, particularly with Sweden's good geological conditions and extensive experience in ground heating, and another pilot project is being constructed and tested in Linköping [42]. Perhaps the most cited BTES project globally is the Drake Landing project in Canada, which is a solar heated community performing better than expected with an average solar fraction of 97% and an energy efficiency of approximately 50% [43].

It may also be necessary to conceptualize district heating networks as an amalgamation of dozens or hundreds of small sub-networks rather than one large system. The temperature levels which define DH generations are usually the highest temperatures delivered by plants and are expected to drop over the length of the network. Lower supply temperatures can be used in a more distributed system, where heat sources can be placed closer to the loads. New construction is also more thermally efficient, further reducing temperatures. The high-resolution methods developed in this project can help plan such systems technically and help inform pricing models down to the individual district or building. Electricity networks have experienced a progression of more detailed and complex pricing models to encourage efficiency and flexibility, and it is possible that heating networks will need to follow suit. Further development of distribution network models within the source and load mapping performed here could unlock this potential and push the efficiency and flexibility of Sweden's district heating networks.

7 Conclusions

Decarbonizing heat is gaining interest worldwide and in Sweden the focus is largely on district heating networks. Combustion of biomass and municipal waste are the largest contributors to the heat supply, and waste specifically comes with a high emissions factor. The project aimed to develop a new method for district heating planning using high spatial and temporal resolution mapping. One-meter resolution source-load mapping and hourly resolution energy simulations were performed using Stockholm as a case study.

The results show that water bodies are the most abundant source of environmental or residual heat with 3400 GWh of potential, with data centers second at 500 GWh and supermarkets third at 316 GWh. In 2018 Stockholm delivered 6600 GWh of district heat meaning that all distributed sources of mapped heat could account for 4300 GWh, or 65%. Of the three main sources of mapped heat, all have examples of being utilized since Stockholm hosts the world's first open district heating market. The combined cost of water bodies, data centers, and supermarkets ranges from 154 to 268 SEK/MWh for the heat demand clusters, demonstrating their cost-effectiveness as compared to marginal costs within the network and to retail prices.

The main challenge to further development is that all sources require electric heat pumps to upgrade the temperatures to network levels. Connected to this, the main economic challenge is the high cost of electricity that has developed since 2021 to operate the heat pumps. The high-resolution prosumer modeling of a data center showed that of the total heat recovery potential, only 60% was economically viable using 2018 electricity prices mostly due to the low summertime value of heat. In 2022 when electricity prices were at their highest, only 42% of residual heat recovery was economically viable with less heat delivered during winter hours. Long-term storage methods have potential to shift the seasonal mismatch in supply and demand, with water pit storage the most frequently used in district heating networks combined with solar [44], but more research and development is needed to deliver cost-effective methods that are also less space-intensive methods.

Demand side mapping shows that residual heat sources are ideally located to demand points and are cost-effective heat sources when compared to the purchase prices offered in the Open District Heating network. It is also found that district heating sub-networks can be a suitable pathway for integrating residual heat sources due to the lower supply temperatures associated with more modern buildings. However, high spatio-temporal modeling of buildings at the same scale as the heat source mapping was found to have several barriers prevent full potential of the models. First is the high manual effort needed to create building geometry, which requires new workflows of data procurement and automated calibration. Second is the inability to validate building models with publicly available data due to the restrictions of GDPR. And third is the lack of access to existing district heating network locations for the creation of relevant sub-networks. Technically, urban building energy models are capable of simulating large sub-networks or even entire cities, however this project has demonstrated that public data access and sharing is the main limitation to their further development. New models of public-private partnership around data-intensive research could help streamline legal barriers, increase data and model availability, and accelerate high-resolution urban modeling. A notable example is the open-source business model developed by natural language processing company Hugging Face [45].

Sweden is a world leader when it comes to extracting the energetic value of renewable and recycled waste, and Stockholm is a prime example where woody biomass, industrial waste, sewage, and sea water are all used as part of the system. Decarbonization of heat supply can come from electrification discussed here and through carbon capture and storage which is currently being scaled up [46]. Given that Stockholm has unique access to water bodies compared to most Swedish cities, it may be more difficult to replace combustion based heat sources in other places around the country. However, more less dense cities also lend themselves to other environmental heat sources like the sun or ground, and other case studies using the methods develop here are encouraged. There is also a considerable amount of work that can be done on the demand side with regards to network temperature levels and sub-network integration towards the reduction of energy and exergy demands. Future work in high spatial and temporal planning should focus in this area, with efforts made to overcome public access barriers to data and encourage transparent development of district heating models and systems.

8 Publication List

Scientific Articles

Su, C., Dalgren, J., Palm, B. 2021. High-resolution mapping of the clean heat sources for district heating in Stockholm City. Energy Conversion and Management, 235, 113983. 10.1016/j.enconman.2021.113983

Shahcheraghian, A., Sommerfeldt, N., Madani, H. Techno-economic potential of distributed heat sources into district heating – A case study of Stockholm. Forthcoming.

Conference Papers

Colchen, T., Su, C., Guo, X. A hybrid novel tool for city scale building heating demand estimation. 15th International Conference on Heat Transfer, Fluid Mechanics, and Thermodynamics, 26-28 July 2021, Virtual, pp. 65-70.

Master Theses

Bay, C. and Muñoz, N. Dynamic simulation of Swedish residential building renovations and its impact on the district heating network. KTH Royal Institute of Technology, MSc. Thesis, 2023. urn:nbn:se:kth:diva-329402

Sintong, J. Data Centres and Prosumers: A techno-economic analysis. Uppsala University, MSc. Thesis, 2023. urn:nbn:se:uu:diva-507504

Supplementary Data

GIS shape files for the mapping data presented in Chapter 2 and the paper by Chang et al. 2021

https://ars.els-cdn.com/content/image/1-s2.0-S019689042100159X-mmc1.zip

GitHub repository for Python wrapper automating TRNSYS building simulations

https://github.com/colchent/AutomationTRNSYS

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