A method for systematic mapping of heat sources in an urban area

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Abstract of the master's thesis

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Abstract

The utilization of excess and natural heat sources will inevitably be a part of emission reduction efforts within the heating sector. This thesis work discusses and presents different methods for estimating the heat potential of heat sources in the urban environment. The purpose of this work is to present a working methodology for estimating the heat potential of urban areas using publicly available or otherwise easily attainable data. The techno-economic feasibility of utilizing the heat sources is not considered.

Potential heat sources in an urban environment were identified and discussed in a literature review. Industrial processes, infrastructure, buildings and refrigeration equipment, as well as sub-categories of these were identified as possible sources of waste heat. Geothermal heat, ambient water bodies, ambient air and solar radiation, as well as sub-categories of these were identified as potential natural heat sources. Methods and relevant data to estimate the potential of these heat sources were identified.

Methods to estimate the heat potential were developed based on the findings of the literature review. The presented methods were applied in a case study, during which the potential of heat sources within the Turku area in Finland was estimated. Relevant heat sources in the studied area were determined. Relevant and available data was identified and obtained during the case study. The heat potential of the heat sources were estimated using the presented methods and available data.

Results from the case study show the potential of the heat sources in the studied area and highlight the difficulty of obtaining high-quality data. The experience and result from this work can be used to improve the quality of available information on urban heat sources to a level that is needed for detailed techno-economic studies for utilizing chosen heat sources.

Keywords district heating, urban waste heat, heat pumps, carbon neutrality

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Tiivistelmä

Hukkalämmön ja luonnon lämmönlähteiden hyödyntäminen lämmöntuotannossa tulee vääjäämättä olemaan osa tarvittavia toimenpiteitä hiilineutraalisuuden saavuttamiseksi. Tässä opinnäytetyössä käytiin läpi eri tapoja kaupunkiympäristön lämmönlähteiden potentiaalin arvioimiseen. Työn tavoitteena oli menetelmä kaupunkiympäristön lämpöpotentiaalin arvioimiseen käyttäen julkisesti tai muuten helposti saatavilla olevaa tietoa. Lämmöntuotannon teknistaloudellista toteutettavuutta ei oteta huomioon työssä.

Kirjallisuuskatsauksessa tunnistettiin mahdolliset kaupunkiympäristön lämmönlähteet. Esimerkkeinä mahdollisista hukkalämmönlähteistä käytiin läpi teollisuus, infrastruktuuri, rakennukset, kylmälaitteet sekä näiden alakategoriat. Luonnon lämmönlähteistä taas maaperä, vesistöt, ilma, aurinko sekä näiden alakategoriat käytiin läpi. Menetelmiä ja tarvittavat tiedot lämmönlähteiden potentiaalin arvioimiseen tunnistettiin.

Kirjallisuuskatsauksen tulosten perusteella kehiteltiin menetelmiä lämmönlähteiden potentiaalin arvioimiseen. Kehiteltyjä menetelmiä sovellettiin tapaustutkimuksessa, jossa lämmönlähteiden potentiaali Turun alueella arvioitiin. Alueelle oleelliset lämmönlähteet ja näiden arviointiin käytetyt tietolähteet tunnistettiin. Alueen lämmönlähteiden potentiaali arvioitiin kehiteltyjä menetelmiä ja haettua dataa käyttäen.

Tapaustutkimuksen tulos näyttää tutkitun alueen lämpöpotentiaalin, sekä korostaa korkealaatuisen tiedon hankkimisen vaikeutta. Opinnäytetyössä saatua kokemusta ja tuloksia voidaan hyödyntää kaupunkiympäristön lämmönlähteistä saatavilla olevan tiedon laadun kehittämiseen tasolle, jolla mahdollistettaisiin tarkemman teknistaloudelliset selvitykset valitulle tai valituille lämmönlähteille.

Avainsanat kaukolämpö, hukkalämpö, lämpöpumppu, hiilineutaalius

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Sammandrag

En ökad användning av spillvärmekällor och naturliga värmekällor inom värmeproduktion är oundvikligt för att minska utsläppen inom värmesektorn. I denna avhandling diskuterades och presenterades olika metoder för uppskattning av värmepotentialen för värmekällor i stadsmiljön. Syftet med avhandlingen var att utveckla en metodik för uppskattning av värmepotentialen i en urban miljö med hjälp av offentligt tillgängliga eller annars lättåtkomliga data. Den tekno-ekonomiska lönsamheten för användning av värmekällorna tas inte i beaktande.

Möjliga värmekällor i stadsmiljön identifierades och diskuterades i en litteraturgranskning. Industriella processer, infrastruktur, byggnader och kylutrustning, samt underkategorier till dessa identifierades som möjliga källor till spillvärme. Geotermisk energi, vattendrag, luft och solens strålning, samt underkategorier till dessa identifierades som möjliga naturliga värmekällor. Metoder och relevant data för uppskattning av dessa värmekällors potential identifierades.

Metoder för uppskattning av värmepotential utvecklades baserat på resultatet från litteraturgranskningen. De utvecklade metoderna tillämpades i en fallstudie, i vilken potentialen för värmekällorna i området kring Åbo i Finland uppskattades. Relevanta värmekällor och tillgängliga data identifierades. Värmepotentialen i området uppskattades med hjälp av de utvecklade metoderna och tillgängliga data.

Resultaten från fallstudien visar värmepotentialen i det undersökta området, samt belyser svårigheten att skaffa användbar data av hög kvalitet. Erfarenheten och resultaten från avhandlingen kan användas för att förbättra kvaliteten av den tillgängliga informationen om värmekällor i den urbana miljön till en nivå, som krävs för detaljerade tekno-ekonomiska analyser för utnyttjande av valda värmekällor.

Nyckelord fjärrvärme, spillvärme, värmepump, kolneutralitet

Preface

I would like to thank my advisor Miika Rämä for his invaluable support during this process. I also want to thank Professor Risto Lahdelma for his participation in this work. Mirja Tiitinen, Lotta Lyytikäinen, and many others have participated in this work with valuable insight and information.
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Dennis Sundell

Contents

Symbols and abbreviations

Symbols

ΔT	Temperature difference [K]
η_{el}	Electric efficiency
η_{heat}	Fraction of recoverable heat
ρ	Density [kg/m^3]
A	Area [m^2]
c_p	Specific heat capacity of water [kJ kg^{-1} K]
$c_{p,air}$	Specific heat capacity of air [MJ kg^{-1} K]
c_{WW}	Wastewater heating capacity [kWh/m^{3}K]
C_x	Sector-specific fuel use fraction [–]
COP	Heat pump coefficient of performance [–]
d	Depth [m]
E	Energy [MJ/ a]
f_{CO2}	CO_2 emission factor [–]
f_{DC}	Fraction of recoverable energy from a data centre [–]
f_{el}	Fraction of heat from electrical sources [–]
f_{vent}	Fraction of the heat load exiting through the walls [–]
$f_{recovery}$	Fraction of energy which can be recovered [–]
$f_{buildings}$	Fraction of buildings from which heat can be recovered [–]
f_{warm}	Fraction of warm water [–]
G_0	Global irradiance on a surface [kJ/m^2]
k_{res}	Cable resistance losses [kJ m^{-1}]
k_{refr}	Fraction of total electricity consumption by refrigeration equipment [–]
K_{heat}	Building specific heat consumption [kWh/m^2]
K_{cool}	Building cooling equipment specific energy consumption [kWh/m^2]
K_T	Sector-specific emission factor [kg$_{CO2}$/MJ]
K_x	Fuel-specific emission factor [–]
l	Length [m]
m	Mass [kg]
PUE	Power usage effectiveness [–]
P	Power [kW]
P_{WW}	Wastewater heating power [kW]
Q_{use}	Volume flow [m^3/s]
S	Apparent power [kW]
SEC	Specific energy consumption [MJ t^{-1}]
t	Time [s]
V	Volume [m^3]
V_{WW}	Wastewater flow [m^3/h]

Abbreviations

BHE	Borehole Heat Exchanger
CLHR	Cold led heat recovery
CO_2	Carbon dioxide
COP	Coefficient of performance
DC	Data center
DH	District heating
DSO	Distribution system operator
E–PRTR	European Pollutant Release and Transfer Register
EU	European Union
GHG	Green house gas
GIS	Geographic information system
GLA	Greater London Authority
GTK	Geological Survey of Finland
HLHR	Heat led heat recovery
HP	Heat pump
HSL	Helsinki regional transport (Helsingin Seudun Liikenne)
JRC	Joint Research Centre
OSM	Open Street Maps
PUE	Power usage effectiveness
PV–GIS	Photovoltaic Geographic Information System
RES	Renewable energy source
SEC	Specific energy consumption
sHE	Specific heat exchange
SYKE	Finnish Environment Institute
VTT	Technical Research Centre of Finland
WW	Waste water
WWTP	Waste water treatment plant

1 Introduction

It is generally agreed that human activities are causing a change in the climate of our planet [1]. The main factors driving a change in the climate is the increased amount of green house gases (GHG) in the atmosphere. The most important of these GHGs is carbon dioxide (CO_2). The increase of CO_2 levels in the atmosphere is a result of using fossil fuels. The global community has pledged to recognize and combat the threat of climate change in the Paris agreement [2]. The aim of the agreement is to limit the global temperature increase to 1.5 °C to 2 °C compared to that of the pre-industrial era.

Climate targets set by the European Union (EU) include reducing the CO_2 emissions by 55 % below the emission levels of 1990 by 2030. The EU aims to be fully carbon neutral by 2050. Decarbonization, a shift away from fossil energy sources, is one of the main methods in climate change mitigation. Current development is therefore focused on improving the efficiency of existing fossil-based energy systems, as well as developing technologies utilising renewable energy sources (RES) and integrating them into the energy system.

Roughly half of the final energy consumption within the EU was used for heating and cooling in 2012. About 75 % of this energy was produced using fossil fuels, 18 % using renewable sources, and 7 % using nuclear. Only 9 % of the heat within the EU is provided using district heating (DH) networks. The end use of heat within the EU during 2012 is shown in figure 1, with over half of the heat being used for space heating and water heating. Decarbonization of the heating and cooling sector is thus an important step towards the targets set by the EU. [3]

Steps toward a decarbonization of the heating and cooling sector include improving the efficiency of existing fossil-based energy systems, as well as increasing the share of RES and sources of waste heat. The amount of waste heat and natural energy sources in urban environments is significant. These resources are often overlooked due to the low temperature of the heat sources. End–uses for heat, such as domestic hot water production and current space heating through DH systems requires higher temperatures, which means a heat pump (HP) is required to utilize these heat sources.

The recent development of DH is trending toward lower supply and return temperatures, making the use of these low-temperature heat sources more feasible. Moreover, an increased share of intermittent renewable energy sources in the electricity sector results in fluctuations in the electricity supply, potentially leading to momentary excess electricity production. These factors all positively contribute in the feasibility of using HPs for heat production as a substitute for fossil-based heat production. Abundant natural heat sources and urban waste heat sources function well as feedstock for HPs.

Sources of waste heat are present in urban areas and other areas with human

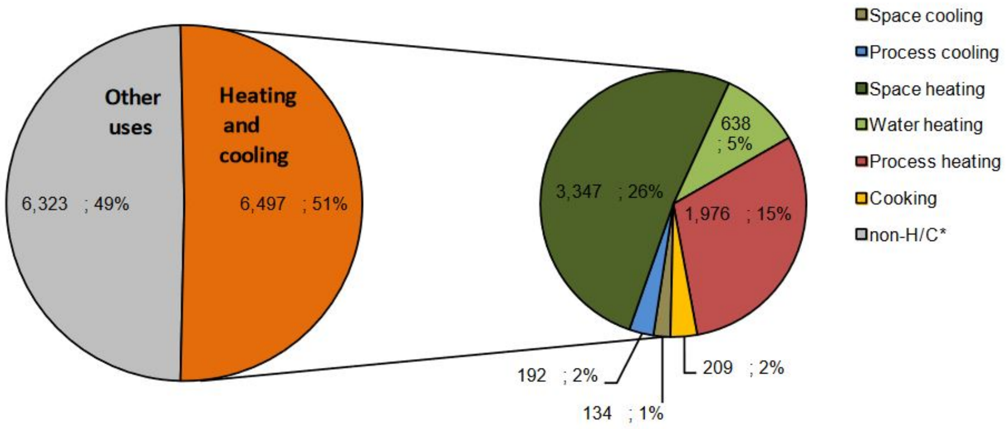

Figure 1: EU28 energy end use within the heating and cooling sector in 2012 [4].

activity. The heat potential of these sources varies from small refrigeration equipment to large industrial facilities. The larger sources with desirable temperatures are often recognized, and often utilized for heat production. Choosing which heat sources to use is a balance between temperature levels, availability and cost - and is influenced by the existing system. Knowing the potential and the availability of these heat sources is essential for future development. Recent efforts in projects, such as ReUseHeat, Heat Roadmap Europe and Recov'Heat have quantified the heat potential of specific sources in chosen areas. Previous publications [5][6][7] have described methodology to estimate the potential of specific heat sources within certain areas. Much of the previous work also considers the economic feasibility and the heat demand in the estimations.

The research subject of this thesis is the potential of urban waste heat and natural heat sources, and how this can be estimated in a systematic way. The aim of this thesis is to present a straightforward working methodology for quantifying the heat potential in a chosen area. The estimation methods are aimed to be relatively simple to use and are based on publicly available or otherwise easily attainable data.

Economic factors, possible heat demand, as well as the impact of the used equipment are out of scope in this thesis. The resulting heat potential represents the amount of heat before the use of heat pumps or other equipment unless stated otherwise. This restriction is more difficult with the natural heat sources, as the potential of these heat sources is often strongly dependent on the used equipment. Still, some technical aspect has to be considered, such as not decreasing the temperature of a heat carrier fluid below its freezing point.

The choice of estimation method is always a balance between accuracy and effort. Complex modelling with high-quality data often yields better results than a quick estimation based on lacking data and refining assumptions. While the presented estimation methods are not detailed enough to function as a base for investments for all heat sources, they all give an insight in the potential and availability of the heat sources in an area. They also represent more accurate information as a whole than has been available previously on a city level. The resulting assessment can function as a base for further, even more detailed analyses of a specific heat source.

A literature review of the different heat sources, as well as methods and efforts to estimate these, makes up the first part of this thesis. The second part of this thesis focuses on describing suitable estimation methods and the required data for these. In the third part, the described estimation methods are applied in a case study, during which the heat potential of the Turku area in Finland is estimated.

The end result of this thesis work will be a working method for mapping heat sources in an urban area. The method description will consist of a description of the required data, as well as what should be done with the data. Methods for acquiring the required data will most likely vary between different countries and regions, and will thus not be described in detail.

2 Urban heat sources

Waste heat can be defined as all sensible and latent heat escaping a system and not used by the process. This heat can either be released diffusely through radiation, conduction or convection from a surface, or through a heat carrier fluid such as exhaust gas, cooling fluids or steam [8]. Waste heat bound to fluids such as gases, air, liquid water or steam is of interest from a heat recovery perspective.

This section of this thesis describes the characteristics of selected urban waste heat sources. This includes the origin of the waste heat, typical temperature levels, typical fluctuations, as well as other factors regarding heat recovery. Some existing methods for estimating the heat potential of the described waste heat sources are also discussed.

2.1 Industrial processes and energy production

2.1.1 Industrial processes

Industrial production processes often require large amounts of high-enthalpy heat. A fraction of this heat can not be used in the process due to temperature limitations, and is released to the environment as waste heat. Depending on the size and type of the industrial facility, the waste heat can represent a significant heat source both by quality and quantity.

Facilities are seldom located within residential areas due to pollution, noise, zoning and heavy traffic. Waste heat from industries, which can still directly be used in other processes, is commonly used locally or sold further to be used in other industries and heating. Industrial excess heat is a broad concept which includes varying temperature levels, heat recovery limitations, and forms of waste heat. Likewise, the fluctuations, reliability and availability of this waste heat varies from facility to facility. Studies mapping the waste heat potential have been done locally and for larger areas, but accurate data on excess heat from industrial facilities is generally not available.

The fluctuations of industrial processes depend on the process, with energy intensive processes, such as steel production, often being operated continuously. Other processes on the other hand will produce more waste heat during certain times of the day, making these fluctuations predictable. The controllability of heat production from industrial waste heat is low, since it is unlikely that a facility would adjust their main production process according to the heat demand. On the other hand, it is reasonable to expect a facility to utilize the potential waste heat if possible.

Persson et al [7] describe a method for estimating industrial waste heat potential based on publicly available data from the European Pollutant Release and Transfer Register (E-PRTR). The E–PRTR contains plant-specific data, including geographical plant location, quantity of emissions, and the plant main activity. It is assumed, that carbon-based fuels are combusted on-site to produce heat or electricity for the process in the studied facility. The data of interest is thus the amount of released carbon dioxide (CO_2) per year m_{CO2} (kg/ year), as well as the main activity of the plant. The primary energy input per year E_{prim_a} (MJ/ year) can then be calculated using the characteristic CO_2 emission factor f_{CO2} (kg,CO_2 / MJ) for a specific industry sector.

$$E_{prim\_a} = \frac{m_{CO2}}{f_{CO2}} \tag{1}$$

The amount of rejected excess heat $E_{heat,o}$ (MJ/ a) can then be estimated using recovery efficiencies η_{heat} (%) for the corresponding sector. The fuel-specific CO_2 emission factor f_{CO2} is based on a weighted average of the standard carbon emission factors for stationary combustion and average national fuel distributions for main activities. The emission factors are based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for stationary combustion[9].

A similar method was used by McKenna et al. [6][10] to estimate the industrial waste heat potential in the UK. Plant-specific average CO_2 emissions were acquired from the EU Emissions Trading Scheme National Allocation Plan. A weighted sector-specific emission factor K_T (kg$_{\text{CO2}}$/MJ) was determined based on the typical fuel use in the sector and fuel-specific emission factors. The facility-specific energy consumption from combusted fuel can then be estimated if the facility-specific total emissions m_{CO2} and the fraction of emissions originating from combustion is known. The amount of recoverable excess heat is estimated as a fraction of the total input heat. It is assumed, that half of the excess heat can be recovered.

McKenna et al. [10] presents another method for the aluminium, chemical, lime, and iron and steel sectors. The waste heat potential for facilities in these sectors was instead estimated using the specific energy consumption (SEC) (MWh/ t) of the used processes, combined with the production capacity (t/ a) of the facility. Determining the process-specific fraction of recoverable heat, and combining it with the SEC and the production capacity can be used to estimate the waste heat potential. If there is insufficient data to determine the fraction of heat that can be recovered, a fraction of 5-10% is used. The SEC data was acquired from EU benchmarking studies and the European Commission Join Research Centre best available reference report. [10][6]

One shortcoming of the method described by Persson et al and McKenna et al. lies in the data source. The E-PRTR does not list facilities with CO_2 emissions under 100,000 t per year. Processes with emissions smaller than this threshold can thus be missed if E-PRTR is the only source of emission data. The actual potential in a region will most likely be higher. Another problem with this method is the lack of information about the availability and the fluctuation of the heat source over the year. Ammar et al. [11] argues, that estimation methods utilizing CO_2 emissions can highlight the potential of low grade waste heat recovery from industries well, but are likely to underestimate the potential.

Lopez et al. [12] estimated the industrial waste heat potential in the Basque

Table 1: Process exhaust gas temperature. Table data compiled by [14]. Several temperature ranges for the same process have different data sources.

Process	**Temperature (°C)**
Iron- and steelmaking	1450–1550
Nickel refining furnace	1370–1650
Steel electric arc furnace	1370–1650
Glass melting furnace	1300–1540
Basic oxygen furnace	1200
Aluminum reverberatory furnace	1100–1200
Steel heating furnace	930–1040
Copper reverberatory furnace	900–1090
Glass oven without regenerator	900–1300
Iron cupola	820–980
Cooper refining furnace	760–820
Reheating furnace without regenerator	700–1200
Hydrogen plants	650–980
Fume incinerators	650–1430
Coke oven	650–1000
Glass oven with regenerator	600–800
Cement kiln	450–620
Heat treating furnace	430–650
Melting oven	400–700
Gas turbine exhaust	370–540
Reciprocating engine exhaust	320–590
Reheating furnace with regenerator	300–600
Blast furnace stoves	250–300
Drying and baking ovens	230–590
Steam boiler exhaust	230–480
Finishing soaking pit reheat furnace	200–600
	300–400
Steam boiler	200–300
Coke oven	190
Stack gas	
Container glass melting	160–200
	140–160
Flat glass melting	160–200
	140–160
Ceramic kiln	150–1000
Drying, baking, and curing ovens	90–230
Cooling water from annealing furnaces	70–230
Cooling water from internal combustion engines	70–120
Exhaust gases exiting recovery devices in gas-fired boilers, etc.	70–230
Conventional hot water boiler	60–230
Process steam condensate	50–90
Condensing hot water boiler	40–50
Hot processed liquids/solids	30–230
Cooling water from air conditioning and refrigeration condensers	30–40
Cooling water from air compressors	30–50
Cooling water from furnace doors	30–50

Table 2: Process temperature of lower temperature processes. Table data compiled by [14]. Several temperature ranges for the same process have different data sources.

Industry	**Process**	**Temperature (°C)**
Food and beverages	Cleaning	60
	Cooking	110–115
	Pasteurizing	65
		80–110
	Whitening	85
	Drying	30–90
		30–120
		50–90
	Washing	40–85
		40–80
	Sterilizing	140–150
		80–90
	Boiling	95–105
	Heat treatment	40–60
	Drainage	38–104
Textile	Dry heating	88
	Ironing	100
	Washing	40–80
	Bleaching	60–100
	Dyeing	100–160
	Drying	75–250
	Steaming	100–130
Chemical	Boiling	95–105
	Distilling	110–300
		90–130
	Various chemical processes	120–180
Paper industry	Pulp drying	95–120
	Paper drying	95–120
		50–120
Non-metallic mineral processes	Drying of rocks, bricks, sand and other minerals	35–150
Wood	Drying	70–90
Other	Metal Cleaning	60–90
	Painting drying	80–120

Table 3: Discussed heat potential estimation methods

Author	**Method**	**Data source**
Person et al (2014)	CO_2 emission reverse calculation	E–PRTR, IPCC Guidelines for National Greenhouse Gas Inventories
McKenna et al (2009)	CO_2 emission reverse calculation, process SEC	UK National Allocation Plan
Lopez et al (1998)	SEC	Local energy agency database
Pellegrino et al (2004)	SEC	Energy consumption survey

country. The amount of waste heat was determined based on the SECs of the studied processes. The SECs of the processes were determined using a database provided by the local energy agency. The information in the database was acquired through surveys sent to the industries in the area. Pellegrino et al. [13] used energy use data from the 1998 Manufacturing Energy Consumption Survey to estimate the process SEC, flow and loss values. The results were then used to estimate the waste heat potential of the energy-intensive US industry. Table 3 summarizes the methods and used data sources for the mentioned estimation studies. A comprehensive review of methodologies used to estimate the waste heat potential of industrial processes is done by [8].

The temperature levels of industrial processes vary from facility to facility. Brueckner et al. [14] has compiled a table of common process temperatures. These sector-specific temperatures can be seen in tables 1 and 2. Sectors with several given temperatures have different sources, see [14] for more detail.

2.1.2 Data centres

In the age of digitalization and internet services, an increasing amount of computational power is required. Traditional desktop computers are being superseded by smartphones, laptops, and other smart appliances. The share of cloud-based services and applications increases, as does the amount of data traffic. This trend can be seen in the rapid increase in number of data centres (DC) worldwide.

The specific electricity consumption of data centres is significant; Ebrahimi et al. [15] states that the power densities of DCs range between $430\,\mathrm{W/m^2}$ to $10\,764\,\mathrm{W/m^2}$. Most of the electricity consumed by the server components is rejected as heat which has to be removed using a cooling system [16]. Lu et al. [17] claim, that 97 % of the total electricity consumption could be recovered as heat, making data centres a potent heat source. This waste heat would be a cheap source of heat, with a large part of the investment made already.

DC energy efficiency can be measured using the Power Usage Effectiveness (PUE) metric [18].

$$PUE = \frac{TotalFacilityPower}{ITpower} \tag{2}$$

where the total facility power is the combined facility power consumption of cooling equipment, lighting, IT equipment, etc. IT power is the power consumed by the IT equipment, meaning the servers. A value of 1.0 would be ideal, meaning all electricity would be consumed by the IT equipment. DC PUE generally fall between 1.1 and 3.0. [18][16]

The heat generated by the components must be removed from the data centre, in order to ensure low enough component temperatures. Removing this heat is expensive, and can increase the DC energy consumption with 10 % to 100 % [16]. Recovering the heat and providing cooling to a DC could thus be seen as a service, for which the DC operators are willing to pay for. Waste heat recovery would thus be of mutual interest for both the DC operator and the DH provider. The cool ambient air temperatures in the Nordic countries can be used for free cooling, where ambient air is used to cool the DC equipment without additional heat recovery or cooling system.[16]

A method for estimating DC heat recovery potential is presented in [19]. The total heat rejected by a DC can be calculated based on the DC floor area using benchmark cooling loads. The required data consists of the locations and the floor areas of the data centres, as well as a cooling load benchmark value. The scarce availability of data on DC locations and capacities is mentioned in the report, and the locations and floor areas of the DCs are thus estimated using Google Earth and other publicly available data. The amount of heat rejected from the DC is then calculated using the floor area and a power density value.

Ebrahimi et al. state, that the power density of DC's is increasing. The power densities being 430 W/m^2 to 861 W/m^2 for older facilities and 6458 W/m^2 to 10 764 W/m^2 or higher for newer facilities. The increased power leads to an increase in cooling demand, which is difficult to satisfy with air-based cooling. Due to this, newer facilities show a trend towards systems using liquid or phase change materials as cooling fluids. [15]

Rasmussen [20] presents different methods on how the power density of a DC can be defined. These differences combined with the differences in power densities make it infeasible to estimate DC heat potential only based on the building area.

The temperature of heat recovery depends on the cooling method used in the DC. [15] state, that different server components have different maximum temperatures during operation. The heat recovery temperature limit is thus determined by the component with the lowest maximum operational temperature if all components are cooled by the same fluid flow. If components are cooled separately, higher heat recovery temperatures can be achieved. DC cooling systems utilizing air have a potential heat recovery temperature of 30 °C to 45 °C, depending on the heat recovery system. Cooling systems using water as cooling fluid can have higher heat recovery temperatures due to lower temperature differences between the components and the fluid, as well as the possibility of component-specific cooling. The temperature of water-based systems can be up to 70 °C to 75 °C, while phase change material systems can reach up to 60 °C to 80 °C. [15]

Results from a study by [21] indicate that the load and energy consumption profiles of data centres are relatively uniform for each hour of the day. The study also concluded, that the power consumption positively correlates with increasing ambient temperatures. This means, that the peak waste heat potential of a DC coincides with the lowest heat demand during the summer, and the lowest waste heat potential occurs during higher heat demand in the winter.

Data centres are an important part of the infrastructure, and information on the locations and specifications of data centres is thus sensitive and difficult to obtain. Due to the sensitive nature of DCs and other heat sources based on infrastructure, the access to the heat source may be limited.

2.1.3 District cooling

The cooling demand of offices, shopping malls, hotels, among others can be supplied using a distribution network with centralized cooling supply. This is called district cooling. Cooling supply can consist of natural cold sources, cold storages, as well as absorption and mechanical chillers [22]. The absorption and mechanical chillers produce cooling by removing heat from the cooling fluid and rejecting the heat. The removed heat can in turn be used as a heat source, presenting a possible synergy between district cooling and DH systems [22]. This thesis considers district cooling produced by absorption or mechanical chillers, since these production methods reject heat which can be recovered. The amount of waste heat at the condenser of a mechanical chiller is larger than the amount of cooling power, and depends on the coefficient of performance (COP) of the chiller.

The amount of waste heat from district cooling production depends on the cooling demand. Diurnal and seasonal ambient temperature fluctuations cause fluctuations in cooling demand. This results in higher demands during the days than the nights, and generally a higher demand during summers than winters. Consequentially, the heat potential is thus higher during the summers when the heat demand is generally low, and lower during the winter, when the heat demand is generally higher.

A large part district cooling is consumed by offices, shopping malls, hotels and residential buildings, causing a diurnal fluctuation with higher cooling demands during the day and lower during the night. Some cooling consumers, such as industrial processes and data centres may be operated continuously, and cause smaller fluctuations.[22]

The controllability of district cooling production as a heat source is low, since the cooling production is determined by the cooling demand. It is also probable, that the chiller will be operated during the summers when the cooling demand is high and heating demand is low.

As an example of an implementation related to district cooling, the Katri Vala Heat pump plant in Helsinki produces both district cooling and DH from treated waste water. During heat production heat is extracted from the waste water, and during cold production heat is dumped to the waste water. [23]

2.1.4 Power production

Electrical power is traditionally generated using combustion of carbon-based fuels to power a generator. The electrical efficiency of conventional combustion power plants is about 30 % to 60 %, depending on the used technology. The remaining input heat can not be utilized for electricity production due to temperature limitations in the process. This excess heat exits the process through exhaust gases, condenser heat, generator losses and more. Combined heat and power (CHP) plants utilize a part of the excess heat available from power production to produce heat for DH systems. CHP plants are a more efficient alternative to electricity-only power plants, reaching efficiencies up to 90 %.

Power production is a well-known and commonly utilized source of waste heat. The temperature levels and the amounts of the available heat depend on the production process. Large amounts of heat are generally available. The fluctuations of the waste heat varies depending on how the facility is operated. The typical fluctuation profile depends on the type of the production process. Base load plants, such as condensing coal-fired plants, have a stable potential, while peaking plants, such as single-cycle internal combustion engine plants, often have a more varying potential.

2.2 Infrastructure

2.2.1 Wastewater

Used water from residential and industrial areas is led to a centralized wastewater treatment plant (WWTP). The water is then purified, and released to the environment, or recycled back into the water system. WWTP's are often located close to an ambient water body where the treated waste water can be released into the environment. The facilities are often located close, but not within, residential areas. Wastewater (WW) flows from the residential or industrial source to the WWTP through underground sewers. The WW can also be gathered locally in an isolated location without sewer connection, and then transported to the WWTP. Urban runoff is commonly directed to the WWTP in older sewer systems.

Heat recovery from WW using large-scale heat pumps has been widely used since the 1980's [24][25]. The thermal potential of WWTP heat recovery is also significant. The Katri Vala heat pump plant uses treated WW from the Helsinki area as a heat source during heating season, and as a cold source during cooling season. The heating capacity of the Katri Vala [23] plant is 105 MW and the cooling capacity is 70 MW, providing 5 %–7 % of the Helsinki DH and 70 %–75 % of the Helsinki district cooling demand [26]. A similar system exists in Turku, with a heat production capacity of 42 MW, and a cold production capacity of 29 MW. [27]

Neugebauer et al. [28] presents a method for estimating the thermal potential of WW by calculating the recoverable energy when the temperature of the WW is decreased by a set amount.

$$P_{WW} = V_{WW} * c_{WW} * \Delta T \tag{3}$$

where P_{WW} (kW) is the thermal extraction output from the WW as a product of the WW flow rate V_{WW} (m^3/h), the heat capacity of water c_{WW} (kWh/m^3K), and the temperature difference ΔT (K). Neugebauer assumes the average temperature of the waste water to be 10 °C during the heating season. The temperature after heat recovery is 5 °C, meaning the temperature of the water decreases by 5 K. The relevant information being used in this method is the location of and the water flow through the WWTP, as well as the temperature decrease during heat recovery.

The temperature of the WW depends on the location and design of the system. The temperature at the WWTP depends on the temperature of the WW source, as well as the distance between the source and the WWTP. The temperature of residential greywater at different heat recovery locations can be seen in figure 4. A minimum WW temperature into the WWTP is given as 10 °C–13 °C due to requirements of de-nitrification in the process [29]. Guo et al. also mentions a upper temperature of 25 °C in order to limit bacteria growth in the sewers. Existing WW heat recovery is commonly located after the WWTP due to this lower temperature limit, as well as the risk of heat exchanger fouling and clogging due to impurities and sludge in the WW. The temperature at the WWTP varies, 13 °C–35 °C [29], 10 °C–20 °C [30], 12 °C–20 °C [24], 10 °C–20 °C [31]. In addition, lower water temperatures can occur in systems mixing urban run-off with waste water. Different water treatment processes may affect or limit the temperature of heat recovery.

Guo et al. [29] states the water temperature of residential WW sources to be 27 °C–35 °C. Mazhar et al. [31] reviews, that the temperature of domestic greywater is 30 °C–65 °C immediately as the water exits the drain of an appliance, 15 °C–30 °C at a district level when the greywater is combined with the sewer lines, and 10 °C–20 °C at the WWTP. The flows at these locations depend on the system, but values of $2\,\mathrm{L\,min^{-1}}$–$20\,\mathrm{L\,min^{-1}}$, $< 10\,000\,\mathrm{L\,min^{-1}}$ respectively $>10\,000\,\mathrm{L\,min^{-1}}$ are given. The amount of recoverable energy per original energy content is 70 %–90 % at a building level, 40 %–50 % at a district level and 10 %–30 % at the WWTP.

Mazhar et al. [31] also reviews different heat recovery methods and key parameters from domestic greywater. Domestic greywater is domestic WW from which the toilet WW is separated. Greywater is thus WW from showers, bath tubs, handwash basins, etc., and is cleaner and has a higher temperature than unseparated WW. An average person produces 136 l–150 l of greywater per day. In hotels, 184 l is produced per room per day, and in hospitals 327 l is produced per bed per day.

WW can vary from being a reliable and stable heat source, to being unpredictable and fluctuating, depending on the location of heat recovery and time resolution considered. The flow at large WWTP's is stable and predictable, while locations closer to the WW sources are more intermittent and fluctuating. [29]

2.2.2 Public transportation systems – Buses

Buses have traditionally been powered by heavy-duty diesel engines running on fuel oil. Demands for reduced CO_2, nitrogen oxides and particulate emissions have resulted in the use of increasingly efficient buses operating on natural gas, biofuels, hydrogen, as well as hybrid and fully electric vehicles. Despite this, buses are and will for a long time be powered by internal combustion engines.

Helsinki Regional Transport (HSL) is a local authority responsible for organizing public transport in Helsinki and the surrounding area. The Helsinki area has several tram lines, a metro, and train lines. Buses stood for over half of the total public transport use in 2017 (180.1 million out of a total of 347.4 million) [32].

Based on a report, the annual CO_2 emissions of the bus traffic organized by HSL amounts to about 85 000 t [33]. It can be assumed, that most of these emissions are a result of the use of fuel oil in diesel buses. Diesel oil has a CO_2 emission factor of $74.1\,\mathrm{kg\,GJ^{-1}}$ according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories for mobile combustion [9].

Based on the values presented in the HSL 2015 annual report, the energy of the fuel consumed by the buses can be approximated as:

$$\frac{85\,000\,\mathrm{t/a} * 1000\,\mathrm{kg\,t^{-1}}}{74.1\,\mathrm{kg_{CO2}/GJ}} = 1\,147\,000\,\mathrm{GJ/a} = 318\,\mathrm{GWh/a}$$

The efficiency of internal combustion engines is relatively low. In an optimal environment, a well-tuned engine can achieve efficiencies of about 40 %–45 %. This value is around 20 %–25 % during normal operation of a bus[34]. This means, that 25 % of the energy contained in the fuel is used to move the bus, while 75 % are losses, most in the form of heat. This heat is rejected to the environment either through the exhaust gases or engine cooling. If the recovery of this heat was feasible, it could represent a significant source of heat. A part of this heat is usually recovered and used to warm the passenger compartment of the bus. Assuming only 10 % of this heat could be recovered and stored in an on-board heat storage, the amount of heat would still amount to 31.8 GWh/ a.

The hypothetical heat recovery equipment would consist of an on-board thermal storage, as well as heat exchangers to recover heat from the engine and the exhaust gases. The excess heat would be stored in a fluid circulating in this system, and unloaded at terminal locations. The weight of this added system depends on the capacity of the thermal storage.

[34] mentions a fuel consumption of approximately 33 l/100km–44 l/100km. A fuel oil density of $840\,\mathrm{kg/m^3}$ and a heating value of $42.5\,\mathrm{MJ\,kg^{-1}}$ is also mentioned. The amount of fuel consumed annually can be calculated when the total energy amount and the heating value of the fuel are known.

$$\frac{1\,147\,000\,000\,\mathrm{MJ/a}}{42.5\,\mathrm{MJ\,kg^{-1}}} = 26.99\,\mathrm{Mt/a}$$
$$\frac{26.99\,\mathrm{Mt/a}}{840\,\mathrm{kg/m^3}} = 32\,132\,\mathrm{m^3/a}$$

An amount of 20 251 bus starts per working day is given in the HSL annual report for 2015. Assuming each bus is driven an equal distance after each start, and that the number of starts is about 2/3 of normal during weekends, the amount of starts over the year would be approximately 6 669 000. The amount of fuel consumed per start could then be calculated as

$$\frac{32\,132\,\mathrm{m^3/\,a}}{6\,669\,000} = 0.004\,82\,\mathrm{m^3} = 4.8\,\mathrm{l}$$

HSL has 1366 buses, meaning each bus has on average 13.37 starts per day. With a heating value of $42.5\,\mathrm{MJ\,kg^{-1}}$ for fuel oil, the average amount of consumed fuel energy is then 204 MJ per start. With an recovery share of 10 %, 20.4 MJ, or 5.67 kW h, could be recovered per bus start, and about 273 MJ per day.

The size of the thermal storage to contain this amount of energy would be

$$\frac{273\,000\,\mathrm{kJ}}{4.19\,\mathrm{kJ\,kg^{-1}\,K} * 50\,\mathrm{K}} = 1300\,\mathrm{kg}$$

assuming a water temperature difference of 50 K. A thermal storage of $1.5\,\mathrm{m^3}$ would be sufficient, weighing around 1.5 t. According to [34], the fuel consumption increases by approximately 5 % for each tonne of added weight. This would mean an energy consumption increase of 7.5 %.

The heat consumption in Helsinki is about 7 TW h [35], not including the heat demand of the surrounding regions where the buses also operate. This means, that less than 0.5 % of the heat demand in Helsinki could be covered with bus waste heat, assuming a energy recovery share of 10 %. This short analysis does not take into account that not all of the buses have routes suitable for heat recovery. There could be a potential for excess heat recovery, but recovering this heat leads to an increase in the fuel consumption.

2.2.3 Public transportation systems – Underground train systems

Underground train stations have several potential sources of heat. The electric energy used to accelerate and move the trains is recovered as electricity or transformed to heat during braking. The passengers, as well as the electrical equipment used to operate the train and the station are also sources of heat. [36][37]

The public transportation system is often located in close vicinity of residential areas, and thus close to heat demand. Heat recovery directly from the underground trains is difficult, and heat would thus be recovered from the tunnel and station air, or from the ground surrounding the tunnels and stations [36]. In cold countries like Finland, the heat generated from the brakes can be used to warm up the carriage. If the heat is not needed, it is rejected to the tunnel air. [38]

Ampofo et al. [37]. used a model to study underground train tunnel heat loads during peak load hours on a warm summer day in August. The ambient air temperature was assumed to be 27.1 °C, the tunnel temperature 31.5 °C and the train carriage temperature 33.9 °C. The results indicate, that 85 % of the heat is from the braking of the trains, 13 % from the train cars, and 2 % is produced by tunnel lightning. 74 % of the heat generated in the train carriages comes from the passengers, while the rest comes from train carriage lighting. The results also suggested that 30 % of the generated heat is rejected through the walls of the tunnel, while 70 % is rejected through the air ventilation. The presented results indicate, that accurately estimating the heat recovery potential of underground train tunnels can be difficult due to many unknown factors.

A methodology for calculating the heat recovery potential from underground train exhaust ventilation air is presented in [19]. The first step was to identify the tunnel exhaust shafts and the air flow capacity of the exhaust shafts. After this the average air exhaust temperature was calculated based on data provided by the London Underground. The seasonal variation was then assessed, and the heat recovery method was chosen. Finally, the heat recovery potential was calculated. The data required in the methodology mentioned above consists of detailed system data on the London Underground, as well as the results of a detailed heat recovery study on the London Underground. This methodology is thus not easily applied to other underground train systems, unless detailed data is available. The method also takes the used technology into account.

One advantage of recovering heat from the ground close to the tunnels and stations is, that the ground can be used as a source of heat during winters and a source of cold during summers [36].

The heat recovery temperatures of underground train system air ventilation depends on the location of the system and the ambient temperature. Air ventilation heat recovery temperatures of up to 35 °C are proposed by [19], while surrounding ground heat recovery temperatures are 20 °C–30 °C. Revesz et al [36] mentions measurement data suggesting the London Underground train station platform temperatures vary between 20 °C during cold winter days to up to 26 °C–32 °C during summer peak hours. Abi-Zadeh et al. [39] compared the temperatures of stations and the ambient air in London. The results indicate, that station platforms located deeper constantly have higher temperatures than platforms located closer to the surface. The temperature at the deep and shallow stations varied between 23 °C–29 °C and between 16 °C–26 °C respectively, with the ambient air varying between 7 °C–24 °C. Overall, the daily variations of the station temperatures vary less than the ambient temperature. The temperature of the station also presents a phase shift compared to the ambient temperature. These findings indicate, that the thermal inertia of the ground surrounding underground tunnels is significant from a heat recovery point of view. It also causes the ground temperature to be higher in the autumn than in the spring during comparable ambient temperatures.

Ninikas et al. [40] studied the temperature, humidity and flow of air within the Glasgow subway system, and concluded that the temperature is relatively stable despite the yearly variations of the ambient air temperature in Glasgow. The ventilation exhaust temperature hovered around 15 °C–18 °C independently of the time of the year. Ninikas et al (2016) studied the performance of an air source heat pump recovering heat from the air ventilation exhaust at a subway station in Glasgow. The annual mean temperature of the air stream utilized by the heat pump was 16.7 °C, with an average flow of 15.82 m^3/h. The heat recovery system was operated during the operating hours of the train system. This resulted in an average heat pump heat output rate of 3.5 kW with an electric input of 1 kW.

As most of the potential heat in an underground train system comes from the trains or passengers, it is obvious that the heat load will be severely reduced when the trains are not in operation. Especially the heat recovery potential from the ventilation air could be reduced outside operation hours. Heat recovery from the ground surrounding the tunnels may have less fluctuations due to the thermal inertia of the ground.

It should be noted, that not all commuter train system stations are underground, even if they are part of a subway or underground network. Examples of this are most of the metro stations in eastern Helsinki. These stations are located above ground, despite being a part of the Helsinki underground train system.

2.2.4 Power transformers

Electricity is transported over longer distances using a high-voltage transmission grid, whereas transport over shorter distances and distribution to the points of consumption uses a lower voltage distribution grid. In Finland the transmission grid operates at 110 kV, 220 kV and 440 kV, while the distribution grid operates between

0.4 kV–110 kV [41].

Power transformers are used to decrease or increase the voltage in the power supply network. Operation of the transformers includes losses, which can be recovered as heat. Power grid transformers have high efficiencies, usually 95 %–99 % and up to 99.7 % in low-loss transformer designs [42]. Regardless of the high efficiency, high capacity transformers can still represent a significant heat source. Existing heat recovery projects with heat outputs of over 1 MW exist [43], and 1.3 MW is mentioned as a typical heat pump size [19].

The distribution grid can generally be found close to and within residential areas, while the high-voltage transmission grid is located outside residential areas. Most of the losses in an electric grid take place in the low-voltage part of the network, despite the size of the individual losses typically being small. These losses are difficult to utilize due to the low concentration of the losses. The losses in the high-voltage part of the grid are more concentrated and thus more suitable for heat recovery. [43]

There are different methods for recovering heat from transformers. The transformer coils are submerged in a dielectric fluid inside a casing. Heat generated from the coils is transferred to the fluid, and transported to the casing surface, from where it is collected by a cooling fluid such as air or water. The heat is further discharged to a secondary cooling fluid, such as air or water. The heat is then recovered from the secondary fluid, or rejected to the environment. In case of heat recovery, water is preferred. [43][19]

In a study commissioned by Greater London Authority (GLA)[19], the authors estimate the thermal potential of some large transformers in the UK power network. The authors state, that the quantity of heat from heat recovery is dependent on the peak load, load factor, efficiency, and fraction of recoverable heat of the transformer. The load factor is assumed to be 40 % and the amount of recoverable heat is assumed to be 1 %. These assumptions were based on a load profile analysis and previous experience respectively. The temperature of the heat is assumed to be constant with no seasonal variation. The required data is the location and maximum capacities of the transformers in the power grid. The data is acquired from the grid operator.

The report by GLA limits the considered transformers to have voltages of 11/33 kV or higher. These transformers could be expected to supply up to 300 kW of heat, while smaller transformers with voltages of 11 kV/400 V could be expected to produce about 8 kW of heat. [19]

The temperature of the recoverable heat depends on where and how the heat is recovered. The report by GLA mentions temperature of the transformer coils could be up to 85 °C and the top and bottom of the transformer casing could be 75 °C and 40 °C respectively [19]. 50 °C was considered to be a reasonable but conservative estimate of the recoverable heat, while a temperature of 55 °C was also mentioned.

In [43], the heat generated by distribution transformers is called low-grade with a temperature below 50 °C. Hazi et al. [44] mentions transformer oil reaching temperatures of 40 °C–60 °C.

The amount of heat generated by transformers depends on the load of the transformer; an increased load generates more heat. The heat potential will consequently be intermittent, and show both diurnal and seasonal variation. Increased electricity consumption during winter could thus match higher heat demand in countries with cold winters, like Finland. [19]

The controllability of the heat production of the transformer is low. Transformers generate heat during operation, which has to be rejected regardless of the heat demand. The uptime requirement of transformers is high, resulting in a reliable source of heat. The quantity of heat will also be predictable with clear daily peaks.

One problem with heat recovery from power grid transformers is the difficulty of adding heat recovery equipment after operation has begun. Shutting transformers down for equipment installation during operation can be tricky and expensive, meaning heat recovery is better suited for new installations. Transformers located in an closed ventilated space are an exception, where heat recovery from air is possible. [43]

2.2.5 Electric cable tunnels

Electric cable tunnels are used to transport electricity in locations where overhead lines are problematic, such as dense residential areas. The underground tunnels contain one or more cables, and possibly other infrastructure as well. As per Joules first law, a current flowing through a conductor or cable will result in losses, thus generating heat. This heat causes the temperature of the cables and the tunnel air to increase, and is rejected through the tunnel walls into the surrounding ground, or to the atmosphere via the ventilation air.

Like with power transformers, the heat generation rate of electrical cables increases with the load. This means, that the thermal potential of cable tunnels is higher during higher electricity demands. This is good from a heat recovery perspective, since the heat potential would match the higher heat demand in the winter.

A few cable cooling and heat recovery methods are listed in [43] report. Internal cable cooling using a fluid, cable surface cooling using a fluid, and cable space cooling are possible approaches. Central to these approaches is that heat generated by the cable is gathered and transported away using a fluid.

One challenge with cable cooling and heat recovery is the length of the object to be cooled. The temperature of a cooling fluid flowing along the cable will increase, reducing the rate of cooling. This limits the length the cooling fluid can flow along the cable without rejecting the heat. This means the cooling has to be done in segments in order to ensure proper cooling. [43]

Forced air ventilation is one method to remove heat from the cable and the tunnel. Air is blown into a section of the tunnel and heat from the cables is transferred to the air. Due to the gradual temperature increase along the tunnel, the cooling has to be arranged in shorter segments to prevent the ventilation air from being too warm to cool the cable.

Davies et al. [45] discusses two methods for heat recovery in cable tunnels. One method uses a heat pump to recover heat from the tunnel exhaust air, thus with focus on the heat recovery and called "heat led heat recovery" (HLHR). The other method uses a heat pump to cool down the supply air of the ventilation system, thus prioritizing cooling of the cables over heat recovery and called "cold led heat recovery" (CLHR). The second method essentially functions as an air-source heat pump from a heat recovery perspective. The first method provides a higher temperature air for heat recovery, but no cooling for the cables. The second method provides cooling for the cables, but a lower temperature heat source.

Davies et al. present the estimated heat recovery for both CLHR and HLHR systems for a 1.8 km long tunnel in London. A monthly average thermal power of 293 kW–298 kW was recovered by the HLHR heat exchanger, with an air ΔT of 10 K and air flow of 4 m s^{-1}. The tunnel was 2.5 m in diameter and contained six cable bundles, which results in a heat production of 31 W m^{-1} per cable.

For the CLHR approach the heat source temperature only depends on the ambient air temperature, while the temperature in the HLHR system is more stable and depends on system design. In a study by [45], the HLHR system temperature measured between 27 °C–32 °C when ambient outdoor temperatures fluctuated between 9 °C–20 °C.

In addition to the mentioned measured values, the maximum exhaust temperature is designed to be limited to 44 °C when the temperature of the ambient air is 28 °C [45], while [46] states a temperature of 55 °C.

The cable tunnels contain essential infrastructure with a high demand for reliability. The ambient air temperature as well as the load of the cables affect both the thermal potential as the heat recovery temperature of the system. The part of the fluctuations caused by the load change is somewhat predictable and periodic with a daily and weekly cycle.

Like with the transformers, installing heat recovery or cooling equipment after the cables have begun operation can be expensive and difficult. [43]

2.3 Buildings

2.3.1 Building ventilation

Maintaining a good quality of indoor air is essential for buildings. This is done by supplying fresh air using a ventilation system. The intake air temperature has to be increased close to room temperature from the ambient air temperature, resulting in a significant heat load. This is relevant especially in countries with cold ambient air. Ventilation air heat recovery is used to recover heat from the ventilation exhaust. About 30 %–50 % of the total heat consumption can be lost in buildings with mechanical ventilation without heat recovery from ventilation exhaust air. [47]

Heat generated by electronic equipment, cooking appliances and humans are so called internal heat gains. Solar radiation is another source of heat in buildings. [47] Different types of buildings (by age, use and size) have different energy use profiles, and thus different heat recovery potentials.

Liddament et al. [47] state that two factors are necessary in order to estimate the energy impact of building ventilation: the mass flow rate of the ventilation exhaust air, and the enthalpy difference between the outgoing air and the ambient air. Liddament states, that the mass flow rate can be estimated based either on the air change rate, or on the amount of people staying in the building.

According to Finnish building regulations [48], the air exchange rate should fill the following criteria: 6 dm^3/s per person staying in the area and the building total air exchange should exceed 0.35 dm^3/s per m^2 of floor area. Residential apartments must however have an air exchange in excess of 18 dm^3/s.

It should be noted, that heat recovery from ventilation exhaust air is commonly in use in modern buildings, and have been used since the 1980's in Finland.

2.3.2 Grey water

Waste water from residential buildings sources can be divided into two distinct parts: greywater and blackwater. Greywater is WW from which the toilet waste water, also called blackwater, is separated. Greywater is thus WW from showers, bath tubs, handwash basins, etc., and is cleaner and has a higher temperature than unseparated WW. Greywater is generally cleaner than blackwater, containing less sludge and pathogens. The used water is often discharged without heat recovery, especially in locations with small water volumes. Some cleaning of the greywater may be necessary in order to prevent fouling and clogging of heat exchanger surfaces.

WW as a heat source is mentioned previously in this thesis. The use of WW as a heat source is often done in a larger scale at WWTP's. The greywater ultimately flows to a WWTP, meaning heat recovered from greywater reduces the heat recovery potential at the WWTP. The temperatures of grey water, especially at a building or

Table 4: Heat recovery characteristics depending on the heat recovery location of greywater.[31]

Parameter	House level	District level	WWTP level
Temperature	30 °C–65 °C	15 °C–30 °C	10 °C–20 °C
Flow	$2\,\mathrm{L\,min^{-1}}$–$20\,\mathrm{L\,min^{-1}}$	$< 10\,000\,\mathrm{L\,min^{-1}}$	$>10\,000\,\mathrm{L\,min^{-1}}$
Utilizable energy fraction	70 %–90 %	40 %–50 %	10 %–30 %

district level, are more favourable from heat recovery perspective than the temperatures at the WWTP.

Mazhar et al. [31] reviews, that the temperature of domestic greywater is 30 °C–65 °C immediately as the water exits the drain of an appliance, 15 °C–30 °C at a district level when the greywater is combined with the sewer lines, and 10 °C–20 °C at the WWTP. The flows at these locations depend on the system, but values of $2\,\mathrm{L\,min^{-1}}$–$20\,\mathrm{L\,min^{-1}}$, $< 10\,000\,\mathrm{L\,min^{-1}}$ respectively $>10\,000\,\mathrm{L\,min^{-1}}$ are given. The amount of recoverable energy per original energy content is 70 %–90 % at a building level, 40 %–50 % at a district level and 10 %–30 % at the WWTP.

Mazhar reviews, that an average person uses about 136 l–150 l of greywater per day. Hotel rooms produce 184 l per day, while a bed in a hospital produces 327 l per day. According to [49], the average water consumption of restaurants was found to be $6.681\,\mathrm{m^3/d}$, $48.42\,\mathrm{l\,d^{-1}}$ for each seat, and $29.74\,\mathrm{l/m^2/d}$.

Public swimming pools and water parks produce large amounts of greywater. These facilities also require large amounts of heat in order to increase the temperature of the incoming water, reducing the practical recovery potential from these sources.

The flow of domestic greywater at a building level is intermittent with clear daily fluctuations. The highest supply occurs during the morning, day and evenings. This matches well with the demand. The heat source is thus a direct consequence of heat use in residential buildings, with a minor delay. The supply will thus match well with the demand. Heat recovery from greywater requires that greywater and blackwater are kept separate until after the heat recovery. This would require significant changes in the sewage system, which is why greywater heat recovery is better suited for new buildings.

2.3.3 Cooling

Buildings, such as shopping malls, hospitals or offices with large groups of people, may require active cooling equipment to maintain specific temperature and environmental conditions. The required cooling can be produced locally on site, or be supplied by district cooling. Producing cooling is essentially using refrigeration equipment to remove heat from a cooling fluid, such as water. The removed heat is then recovered or rejected to the environment, representing a heat source. Heat recovery from cooling equipment is explained in detail later in this thesis.

The cooling demand of different buildings should correlate with the size of the buildings. The heat is generated by electric equipment, humans, and solar radiation, meaning two office buildings of the same size can have vastly different cooling demands. A proper estimation method would thus take into account the building itself, its electricity consumption, the amount of people and other potential sources of heat within the building. When the cooling demand is known, the amount of waste heat can be estimated when the refrigeration equipment COP is known or estimated.

The fluctuations of the heat recovery potential of the cooling equipment depends on the type of the building. Offices and shopping malls have clear peak hours during the day and dips during the night, while hospitals require cooling around the day.

2.4 Refrigeration equipment

This thesis work considers different types of refrigeration equipment: grocery store refrigeration, ice rink refrigeration, district cooling and building air conditioning. District cooling and building air conditioning are presented under 2.1 industrial processes and 2.3 buildings subtopics respectively.

Refrigeration equipment are typically heat pumps, meaning a large part of the heat recovery investment is already done [7]. This is not always the case, with some systems unable to increase the condensation temperature high enough to be used in heating applications.

Possible heat recovery temperatures of refrigeration equipment vary depending on the design of the heat pump and the used refrigerant. The heat from the refrigeration equipment has to be rejected, meaning the condensation temperature has to be higher than the temperature of the heat sink at all times. Most of the recovered heat is latent heat at the condensation temperature of the heat pump, and a smaller fraction sensible heat at higher temperatures due to the refrigerant being superheated. Some heat can also be recovered from compressor cooling. [50]

The electricity consumed by a compression heat pump is converted to heat, which has to be rejected at the condenser together with the heat recovered from the heat source. The cooling power of a compression heat pump in relation to the electric power of the compressor can be calculated as

$$P_{cooling} = COP * P_{el} \tag{4}$$

The amount of waste heat from compression heat pumps can consequently be estimated when the electricity consumption or the cooling power is known, in combination with the COP.

$$P_{heating} = P_{el} * (COP + 1) \tag{5}$$

$$P_{heating} = P_{cooling} * \frac{COP + 1}{COP} \tag{6}$$

2.4.1 Grocery stores

Grocery stores of different sizes can be found in urban centres. Larger cities typically have several stores, with a higher density of smaller stores than larger stores. The largest grocery stores are often located in less densely populated areas due to the higher property price in denser areas.

Various temperature levels are required by various products to prevent spoiling and decay. Temperatures between 1 °C–15 °C are used to prevent spoiling of chilled food products, while frozen products require temperatures of between −12 °C–−18 °C [51]. A comfortable temperature level in the store is required by customers and staff. These different temperature levels are in conflict, requiring both refrigeration and heating equipment in the store. Warmer ambient temperatures may require cooling for the store as well. Modern supermarkets typically have centralized refrigeration equipment for freezers and large display cabinets. Smaller display cases can have separate refrigeration systems. Centralized refrigeration systems are more suitable for heat recovery than small stand-alone systems.

One method described by [52] estimates the thermal potential based on the electricity consumption of grocery stores in Denmark. An extract from the CVR Central Business Register is used as the base data for this method. The grocery stores are isolated from the rest of the data and separated into four subcategories based on the assumed size of the store. It is assumed that stores of similar sizes would produce a comparable amount excess heat. An electricity consumption of the refrigeration equipment is then assumed for each of the four categories. Multiplying the electricity consumption with a coefficient between 1.2–1.5, depending on the store category, results in the estimated amount of usable thermal heat.

Another method is presented in a study conducted by the GLA [19]. The amount of rejected heat is calculated based on the floor area of the different areas requiring cooling in a supermarket, such as freezers and display cases. The areas of these are estimated based on the size and type of the store. The heat recovery temperature is assumed to be constant despite possible variations depending on the used equipment.

According to [53], large food shops with a floor area of more than 750 m^2 have a total energy consumption of 400 kWh/m^2–740 kWh/m^2, with an median value of 581 kWh/m^2. The same values for electricity consumption are 260 kWh/m^2–480 kWh/m^2 and 387 kWh/m^2 respectively. Approximately 35 %–50 % of the energy use in supermarkets is consumed by the refrigeration system [51].

Excess heat from the refrigeration equipment can also be utilized locally for heating of the store space. One drawback of using the condenser waste heat directly for heating is, that the condenser temperature has to be kept higher, as mentioned by [51]. The condenser temperatures in heating solutions are around 36 °C. This higher condensing temperature increases the amount of energy consumed by the refrigeration equipment. This temperature is also too low to be used for direct DH production without an additional heat pump. Condenser temperatures of 30 °C–40 °C are typical in grocery store refrigeration systems, but the temperature may vary depending on system design. [51]

A connection between the store indoor temperature and compressor power was shown in a study by [51] Measurements indicate that the recoverable heat from refrigeration equipment increase with increasing ambient temperatures. This indicates, that the peak heat recovery potential coincides with the lowest heat demand during the summer.

Many grocery stores add additional insulation for cold areas and reduce the indoor temperature when the store is closed, thus reducing the heat load. This leads to lower cooling load and reduced waste heat potentials when the store is closed, such as during nights. Other fluctuations could be caused by shifting ambient temperatures. [51]

The controllability of this heat source is low, since maintaining the correct temperature zones in the stores is the main priority. On the other hand, reducing the condenser temperature in flexible systems can decrease the electricity consumption. Higher heat recovery temperatures can thus cause higher electricity consumption.

2.4.2 Ice rinks

Large-scale refrigeration equipment are also utilized in ice arenas, where a large ice surface for skating purposes has to be maintained. Ice rinks can be divided into three categories: training halls, spectator halls and event halls. This division can be done based on the purpose and the spectator capacity of the halls. [54][55]

The electricity consumption of ice rinks varies depending on the hall category, location and construction year [55][54]. This makes it difficult to accurately estimate the waste heat potential unless the electricity consumption of the refrigeration equipment is known.

Maknatch [54] states, that depending on the location, most ice rinks shut down for maintenance during the warmest months of the year. The heat production of ice rink refrigeration equipment thus matches the higher heat demand during lower ambient temperatures. On the other hand, lower ambient temperatures result in a lower heat recovery potential.

Average energy consumption figures for Swedish ice rinks are described by [54]. Like other refrigeration equipment, the amount of waste heat can be estimated if the electricity consumption is known.

The quality of the rejected heat from ice rink refrigeration systems vary depending on the used coolant. [56] states, that a 30 °C condensing temperature is typical for ice arena refrigeration units, while a temperature range of 20-40°C is mentioned by [54][57].

Around 50 % of the total energy consumption is consumed by the refrigeration equipment. The share varies between papers; [56] suggests 45 %, and the technical guidelines by the International Ice Hockey Federation suggest 57 % [58]. A large part of the waste heat from the refrigeration system can be used internally in the ice rink, but a part can be sold. [55]

3 Natural heat sources

This section of this thesis is focused on describing the characteristics of selected natural heat sources. This includes the origin of the heat, typical temperature levels, typical fluctuations, as well as other factors regarding heat recovery. Some existing methods for estimating the heat potential of the described waste heat sources are also discussed.

3.1 Air

Ambient air as a heat source is abundant, everywhere, and virtually unlimited. However, temperature and humidity of the ambient air limits its utilization in practice [59]. Air-source heat pumps are used to extract heat from the ambient air. The used heat pump technology also affects the amount of recovered heat.

Meteorological data on average air temperatures exist for most urban regions [60], and e.g. in case to Finland from [61][62]. The urban heat island effect results in the temperature of the air in urban areas to be higher than that of surrounding rural areas. In addition, solar radiation and patches of stagnant air can result in local temperature variations, such as on different sides of buildings.

Similar to other natural sources, the temperature of the ambient air mostly depends on the amount of solar radiation. The air temperature will thus fluctuate seasonally and diurnally. Lower temperatures coincide with high heat demands in the winter, and higher temperatures with cooling demands in the summer. [61]

In practice, the potential is closely tied to the used technology and size of the economic investment of the equipment, and is thus outside of the scope of this thesis. The potential of ambient air as an heat source will thus not be discussed or estimated in detail in this thesis, beyond the temperature data.

3.2 Geothermal heat

The heat in the ground has three main sources: 1) heat remaining from the formation of the planet, 2) heat produced by radioactive decay in the ground, and 3) sunlight absorbed as heat. The temperature in the core of the earth is high enough to sustain molten rock and metals, while the temperature at the ground surface is close to the ambient air mean temperature. Geothermal heat can be divided into three distinct geothermal heat sources; deep geothermal heat, shallow geothermal heat, and groundwater heat. Deep geothermal heat is found deep below the ground surface, and shallow geothermal heat and groundwater, is found closer to the surface.

The advantages of geothermal energy as a heat source is its abundance and reliability. Geothermal energy is found everywhere on earth and is virtually unaffected by seasonal or daily variations in weather. [63]

The temperature levels of geothermal heat varies. The temperature of the geothermal heat source generally increases as the heat recovery depth increases. The geothermal gradient within the crust of the earth is generally 25 °C km^{-1}–30 °C km^{-1}. Deep geothermal heat is thus of a higher temperature, and can be used directly for power or heat production. Temperatures of 100 °C can be found at depths of 5 km–10 km in Finland [65]. Shallow geothermal heat and groundwater are of a lower temperature and require heat pumps to upgrade the heat. High temperature geothermal heat can be found close to the surface in areas with high geothermal activity, such as Iceland or Italy.

Two phenomena can be used to describe heat transport in the crust: conduction and advection. Heat is conducted through materials in the crust. Heat is also transported through advection, with the movement of subsurface water.

Shallow geothermal heat is typically harvested using either closed-loop borehole heat exchangers (BHE) down to depths of about 300 m, or horizontal heat exchangers located directly below the surface. Closed loops with circulating water are often used in both cases. Utilizing deep geothermal heat requires deeper boreholes, making the initial investment cost higher than for shallow geothermal.

Estimating the geothermal heat potential accurately is difficult. The detail of the employed methods vary, with the most accurate methods requiring a plethora of starting data in order to produce accurate results. Phenomena, such as groundwater flow, can have high spatial variations, and thus require high-resolution measurement data.

Ondreka et al. [64] describes a method combining geological structure with thickness maps and other data in order to create a subsurface model of the different rock types in the studied area. Standard specific heat extraction values for different rock types were used in order to calculate two raster layers containing thermal power potentials for 50 m respective 100 m deep BHEs. The resulting raster layers can be used to highlight areas with potential for ground source heat pump use.

The Geological Survey of Finland (Geologian Tutkimuskeskus, GTK) provides freely available map sources for different geological data [65]. The amount of bound thermal energy and renewable thermal heat potential for 300 m deep BHE's, as well as the amount of thermal energy bound in the ground down until a depth of 10 km are two data resources of interest in this thesis. These data are presented in the form of raster layers, with a resolution of 1 km x 1 km. The data generation process is described for both resources [66][67].

The data used by GTK in preparing the geothermal potential map for Finland is based on previous measurements. The first process is described for the thermal potential of 300 m BHEs. A ground structure dataset was combined with results from rock and sediment thermal conductivity measurements, assuming the sediment deposits are fully saturated with water. A constant specific heat capacity was chosen for all rock types and a volumetric heat capacity for all sediment types. The ground surface temperature was derived using average air temperature data from the Finnish Meteorological Institute and a air-ground temperature relation. The geothermal heat flux was estimated by combining the geothermal heat flux emanating from the core with radiogenic heat production. Combining these datasets and information results in datasets presenting the sustainable possible heat production from a 300 m BHE in the area, as well as the amount of energy bound in the ground surrounding the BHE.

Korhonen et al. [68] estimated the geothermal heat potential in Helsinki. The thermal properties of the rock below the Helsinki area were determined based on field samples and a bedrock map. The geothermal heat flux and the theoretical amount of heat stored in the ground were then estimated. The heat potential was estimated for two different setups; BHE fields with a distance of 20 m between the BHEs, and independent BHEs at a distance where two BHEs do not interfere. The heat potential was estimated assuming heat extraction over 50 years. The optimal rate of heat extraction was optimized using finite element modelling of the BHEs and the surrounding ground, aiming for the temperature of the BHE walls to be 0 °C after the heat extraction period. After the assumed heat extraction period, the heat yield of the BHEs would be significantly reduced.

For heat pump applications using BHEs, the thermal potential is usually described as specific heat exchange (sHE) or specific heat extraction (sHE), with units being $\mathrm{W\,m^{-1}}$. The thermal power can then be calculated as the sHE multiplied with the length of the borehole.

One problem with shallow geothermal heat applications is the required area. While a BHE is drilled straight into the ground and thus not requiring much surface space, the amount of BHE's in a area is limited. According to [63] the minimum distance between BHE's in shallow thermal applications should be at least 7 m. Based on modelling results in [68], BHE's with a distance of 20 m negatively impacted each other. A distance of 162 m was required to avoid interference between two 150 m BHEs and a distance of 176 m was required to avoid interference between two 300 m or two 1000 m BHEs. Drilling in the ground can also be prohibited in certain areas.

Groundwater can be found at varying locations, depths and temperatures. The availability of groundwater is spatially dependent with extreme variations. It is thus difficult to estimate the heat potential of the groundwater in an area without measurements. Deep geothermal heat is of higher temperature and can be used directly for heat (in Finland) or even power production (countries with volcanic activity). The potential of deep geothermal heat is difficult to estimate without proper studies and measurements.

As of 2020, there are no plants utilizing deep geothermal heat operating in Finland. The construction of a pilot plant takes place in Espoo, close to Helsinki, where two 6.5 km deep production wells are drilled [69]. The plant is expected to produce up to 40 MW of heat. A pilot plant utilizing medium-depth geothermal heat at 1300 m has begun its operation in January 2020 in Espoo, Finland [70]. The plant is expected to produce up to 1000 MW h of heat per year. Another plant utilizing the heat from a depth of about 2 km is under construction and is expected to begin operation during 2020, producing an expected 1400 MW of heat per year.[71]

3.3 Ambient water bodies

Surface water bodies, such as rivers, lakes and seas can function as a natural source of low-temperature heat [72][73]. Studies show, that the utilizable heat in large lakes and rivers is significant; in Switzerland the potential for thermal use of lakes and rivers exceeds the regional demand by an order of magnitude [75]. Fink et al. [74] state, that a heat recovery rate of 2.1 GW ($4.4\,\mathrm{W\,m^{-2}}$) did not affect the temperature of a large lake in Switzerland significantly. The thermal potential is nearly unlimited in the oceans [76][77]. Heat pumps utilizing ambient water as heat sources have been used since the 1980's [25].

Gaudard et al. [75] describe a method for estimating the thermal potential for ambient water bodies. The method is based on calculating the energy required to increase or decrease the whole water volume of the water body by a set amount. Only lakes with depths below 30 m and volumes larger than 20 million m^3 were considered.

$$E_{lake} = c_p * \rho_{water} * V_{mix} * \Delta T * \frac{COP}{COP-1} \tag{7}$$

Where E_{lake} is the thermal potential in the lake, c_p is the specific heat capacity of water, ρ_{water} is the density of water, ΔT is the temperature difference, V_{mix} is the volume of water the thermal discharge is expected to mix with, and COP is the coefficient of performance for the used heat pump. [75]

In a study, [75] chose the temperature difference for heating applications in large Swiss lakes to be 1 °C. This value was chosen to minimize the impact on the ecosystem of the lake. A lower temperature limit of 2 °C was set for water being discharged back into the lake. The available mixing volume was assumed to fluctuate seasonally due to thermal stratification; during autumn the surface water is cooled down and sinks to the bottom, mixing the water in the lake and evening out temperature differences. During spring the surface water is heated, leaving the denser cold water to the deeper parts of the lake and causing different temperature layers in the lake. The mixing volume is therefore assumed to be the whole lake during winter, and a certain temperature layer in the summer. The study further assumes, that the temperature of the intake water is always the most favourable, meaning the highest temperature for heat production and the lowest for cooling.

Gaudard et al. [75] also estimated the potentials of rivers. The potential recoverable heat energy was estimated in a similar fashion as the lakes, with mass flow Q of the river instead of mixing volume.

$$E_{river} = c_p * \rho_{water} * \Delta T * Q_{use} * t_{op} * \frac{COP}{COP-1} \tag{8}$$

where E_{river} is the thermal potential of the river, t_{op} is operational time, ΔT is the temperature decrease of the used water and Q_{use} is the mass volume flow of the used water. In this case ΔT is set to 10 °C, with Q_{use} adjusted to ensure the temperature change of the whole river water is below the legal limit of 1.5 °C. A lower temperature limit of 1 °C was set for the discharge water. In theory the method above would mean a potential of the whole mass flow being cooled by 1.5 °C, but there are practical limitations for using the whole river for such purposes, i.e. the whole volume led through a heat exchanger. Large lakes can have one large outlet. In this case the thermal potential of the lake can be modelled like the rivers, assuming the discharge is fed into the outlet. This potential can be added to the potential of lake the lake, since it is assumed, that the thermal potential is limited by the allowed temperature increase of the water in the lake.

Based on the method used by [75], the potential of rivers could thus be estimated as if the temperature of the total water flow of the river was decreased by 1.5 °C. A limitation to this is a minimum thermal discharge temperature of 1 °C.

Gaudard et al. [75] also discusses limiting the use of river water to once per river, despite the potential for reuse if the distances between the extraction points are sufficiently far away for the river water to acquire the recovered heat or to reject the gained heat. The downstream potential is only estimated in case of tributaries adding water.

In this thesis, the technological aspects of heat recovery are not included. Eq. 7 by [75] can thus be modified by removing the impact of the heat pump.

$$E_{lake} = c_p * \rho_{water} * V_{mix} * \Delta T \tag{9}$$

Similarly, Eq. 8 can be modified by removing the effect of the heat pump.

$$E_{river} = c_p * \rho_{water} * \Delta T * Q_{use} * t_{op} \tag{10}$$

Lund et al. [5] used similar methods for estimating the heat source potential of lakes and rivers. A minimum discharge temperature of 2 °C was set for both lakes and rivers. For lakes, the potential was estimated as cooling the total volume of the lake by 2 °C every year. The volume of the lake was estimated as the area of the lake multiplied with a depth d of 2 m.

$$E_{lake} = c_p * \rho_{water} * \Delta T * A_{lake} * d_{lake} \tag{11}$$

Using this method can severely underestimate the potential of larger lakes with average depths larger than 2 m. This simplified approach roughly addresses, that seasonal temperature fluctuations are not considered and water temperatures close to the lower limit of 2 °C during winter may limit heat potential. [5]

Lund et al. also estimated the potential of rivers. A maximum temperature difference of 5 K between the inlet and the outlet was mentioned, as well as a minimum discharge temperature of 2 °C. The rivers used in the estimation had a minimum flow of 5 m s^{-1}.

The possibility of using sea water as a heat source was also mentioned by [5]. The potential of this source is not calculated, but sea water is addressed as a nearly limitless heat source. It is also mentioned, that seawater could be cooled down below 2 °C, discharging an icy slurry from the heat pump. Zhen et al. [76] suggest, that 2 °C is the lowest temperature at which a seawater heat pump can be operated.

Helen, an energy actor in Helsinki, discusses the potential of seawater heat pumps in a blog post [78]. A study conducted by Helen in cooperation with the Finnish meteorological institute indicates, that depths larger than about 70 m are required in order to guarantee an annual minimum water temperature higher than 3 °C. 3 °C was considered a minimum temperature at which heat recovery from sea water could be feasible.

A method for assessing the suitability of ambient water bodies as heat sources is described within the Stratego project [79]. An exact estimate of the thermal potential of lakes is not given, but rather a proximity to the lakes. An exact method for estimating the potential of rivers is also not described. It is assumed, that the amount of potential heat is proportional to the run-off volume of a river. The proximity for each location is described by the area of lakes, rivers and sea within a 5 km radius. The proximity is then presented with a scale of 1 to 5, with 5 as the highest availability of surface water.

Gaudard et al. and Lund et al. both mention similar limiting factors used in the methods. These factors are environmental legislation, and the freezing point of water. These factors are also relevant for other heat sources. Environmental regulations limit the thermal use of ambient water sources. These regulations exist to protect the organisms and biodiversity in the used water bodies. Minimum and maximum temperatures of discharged water, maximum fraction of flows of rivers, and more are examples of these regulations, and vary from country to country. In Finland, the practice is based on legislation concerning assessing impacts on the environment [80]. While the scope of this thesis does not take into account the environmental impacts of the use of the heat sources, it can be mentioned, that several studies have been conducted concerning the effects of the use of ambient water as heat sources [81].

The temperature of ambient water bodies depends on factors such as climate, depth and currents. The temperature of ambient water bodies is mostly determined by the temperature of the surrounding air. Thermal inertia causes the temperature of large water masses to lag behind the ambient air temperature, resulting in smaller diurnal and delayed seasonal temperature fluctuations. Efficient water mixing in rivers generally results in the temperature being closer to that of ambient air.

The temperature of ambient waters is often relatively low, meaning the temperature difference available during heat extraction is low. This means, that large volumes of water are required for large-scale heat production. This can become problematic when the heat extraction location is far away from the heat demand, requiring long transfer pipes.

Zhen et al. [76] mention, that the temperature and temperature fluctuations of the sea depend on factors such as depth, climate and currents. This can also be applied to lakes and rivers. Averfalk et al. [24] claim ambient water temperature in Sweden to be approximately 2 °C to 14 °C.

Ambient water bodies can be thermally stratified due to different water densities at different temperatures. The highest density of water is around 4 °C. This guarantees a minimum water temperature of 4 °C in larger water bodies. Ambient water bodies show strong seasonal fluctuations, and smaller diurnal fluctuations. Heat recovery is mostly limited by the available volume of water, the temperature of the water, and environmental legislation. Ambient water is a predictable and reliable heat source in the short term. The controllability of ambient water bodies depends on the used water body. Heat in lakes and seas can, in a sense, be saved for later use, while the heat in rivers flows past if it is not used.

In a study commissioned by GLA [19], it is stated that the potential of heat from river water sources is dependent on the flow rate and its temperature. The amount of water and the minimum return temperature are identified as limiting factors.

3.4 Solar thermal

The sun has been used as a source of heat for thousands of years, by humans and animals alike. Heat from solar radiation has successfully been used for DH purposes in several countries [82].

The potential of using solar heat mainly depends on the intensity of the solar radiation reaching the solar thermal collector. The intensity reaching the ground depends on the inclination of the radiation compared to the ground, and the amount of radiation being absorbed or dispersed by the atmosphere. The share of radiation being absorbed or dispersed by the atmosphere increases as the rays pass through the atmosphere. The atmosphere itself absorbs or disperses a part of the radiation, but higher amounts of aerosols, particles or water vapour in the atmosphere cause a higher share to be absorbed. Locally, terrain such as mountains or hills can hinder the solar radiation from reaching the ground. The output of the thermal collectors also depend on the ambient air temperature and the wind, which affect the thermal losses.

Solar irradiance has a predictable annual and diurnal temporal fluctuation. The solar thermal potential decreases during the winter, with areas closer to the poles, such as Finland, Canada, and Norway having little to no sun. The sun also sets during nights, meaning no heat is produced. Clouds, snow, rain or dirt on the collector surface reduce the collector heat output adding an unpredictable, yet manageable factor to the fluctuation. Solar thermal heat is not controllable, and should be used when it is available.

The heat recovery temperature of depends on the design and location of the collectors. Concentrating collectors won't need heat pumps due to the high achievable temperature, while non-concentrating collectors may require heat pumps, depending on other factors.

The Joint Research Centre (JRC) provides tools for estimating meteorological phenomena such as air humidity, temperatures and wind [60]. The photovoltaic geographic information system (PV–GIS), is an interactive tool providing information on solar radiation and estimates of the performance of solar applications.

4 Methods and input data

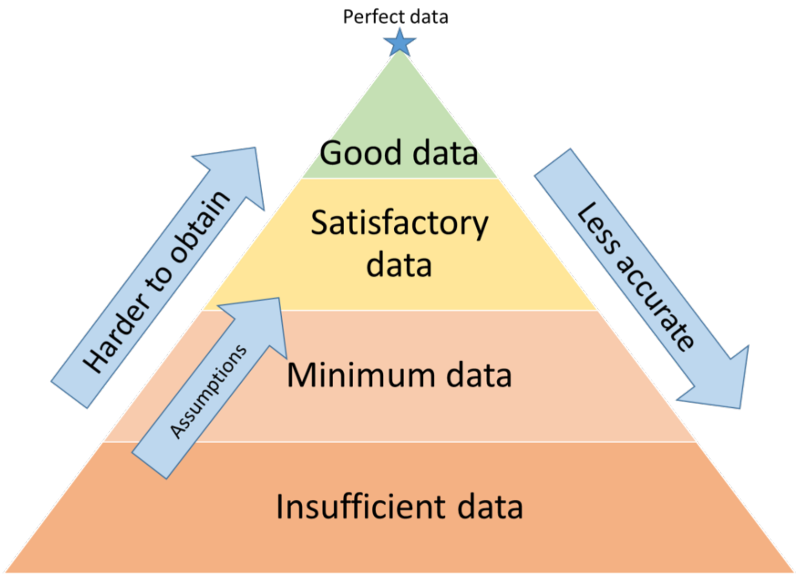

Figure 2: The relationship of the obtainability, accuracy and availability of data.

Estimating the potential related to a specific heat source is carried out by combining available data with a set of assumptions. The exact estimation method depends on the heat source in question and the data available. The estimation methods utilized in this study might not always be the best possible or the most accurate, but combine well with the available input data. The presented estimation methods, the necessary data and the required assumptions are summarized in table 5.

Assessing the quality of data can be further divided into how detailed, available, and accurate the data is. The usability of data is limited by each of these characteristics. A higher quality data means, that less assumptions have to be made, and that more accurate estimation methods can be used.

Generally, perfect data would thus be high detail, high accuracy, and high availability. From an estimation perspective, perfect data could be the measured heat potential of a certain heat source. In this case, no assumptions and no estimation method are required, since the ideal level of detail is already present. Perfect data is rare. Increased monitoring and digitalization is bound to increase the amount of high quality data.

An example with transformers to clarify how the detail, accuracy, and availability limit the usability of the data. Data with the average transformer capacity could be an example of low detail data. This usability of this specific data could be limited, despite it being available and accurate. The usability is also low for detailed and available data with a low accuracy or detailed and accurate data with a low availability.

Figure 2 is used to describe the problem with the availability and usability of data for a specific purpose. It is clear, that the accuracy of the estimation decreases when lower quality data is used in the estimation. Data which is perfect for the intended purpose, in this case estimation of heat potential, is difficult to obtain. On the other end of the spectrum lies insufficient data, which is common and easy to obtain. Minimum or satisfactory data lies between these extremes. The usability of the available data can be improved with assumptions.

Table 5: Estimation methods and required data for the discussed heat sources

Heat source	**Estimation method**	**Required data**	**Assumptions**
Industrial processes and production	Reverse calculation of emissions	Amount of CO_2 emissions, process type	Fraction of recovered heat
Data centres	Based on electricity consumption	Electricity consumption	PUE
District cooling	Based on cooling production	Cooling production or electricity consumption	COP
Waste water	Based on water flow	Plant water flow or capacity	Water temperature decrease
Public transportation systems, underground trains	Based on electricity consumption	Electricity consumption	Heat load shares
Public transportation systems, buses	Reverse calculation of emissions	Amount of emissions or fuel consumption	Engine efficiency, fraction of recoverable heat
Power transformers	Calculation based on load	Load, equipment specifications	–
Electric cable tunnels	Calculation based on load	Load or capacity	Resistance losses
Building, ventilation	Based on building heat consumption	Building specific heat consumption, building floor area	Fraction of recovered heat, share of relevant buildings
Building, grey water	Based on water consumption	Water consumption	Warm water fraction, water temperature decrease
Building, cooling	Based on cooling energy consumption	Building floor area, cooling energy consumption	COP, share of buildings
Refrigeration equipment, grocery stores	Benchmarks based on store size	Size of the store	COP, benchmark
Refrigeration equipment, ice rinks	Based on estimated electricity consumption	Electricity consumption or building size	COP, refrigeration equipment electricity fraction
Shallow geothermal heat	Existing estimates	Size of suitable area, existing estimates	Borehole distance
Deep geothermal heat	Existing estimates	Existing estimates	–
Groundwater	Based on yield	Groundwater source yield	Temperature decrease
Lakes	Size of lake	Lake area and depth	Temperature decrease
Rivers	Based on flow of river	Flow of river	Temperature decrease
Sea	Suitable areas based on depth	Depth charts	Required depth
Solar	Solar irradiance	Size of suitable area, global irradiance on horizontal plane	
Air			

5 Urban heat sources

5.1 Industrial processes and production

Two heat potential estimation methods were found during the literature study; the methods presented by [7] and [10][6]. Both of these methods are based on reverse calculation of the facility-specific CO_2 emissions in order to estimate the amount of recoverable waste heat. The input energy E_{prim_a} can be estimated as per eq. 1.

$$E_{prim\_a} = \frac{m_{CO2}}{f_{CO2}}$$

where m_{CO2} is the total amount of CO_2 emissions and f_{CO2} is the sector-specific emission factor. The amount of recoverable heat can then be estimated by multiplying with an assumed sector-specific heat recovery efficiency.

The disadvantages of using these methods with the CO_2 emissions as base data is the coverage of the data. E-PRTR as an example lacks facilities with CO_2 emissions of less than 100 000 t/a. Assuming a facility burning coal and a 10 % heat recovery rate, the waste heat thermal power is approximately 2 MW for a facility with CO_2 emissions of 100 000 t per year. This is a significant waste heat source, highlighting the issue of using limited data.

The E-PRTR acquires data from national authorities, which may maintain a more accurate emission database. This is the case in Finland with Energiavirasto, the national energy authority, maintaining a emission register containing the CO_2 emissions of smaller facilities as well.

McKenna et al. [6] described a different methodology for aluminium, iron, steel, chemicals and lime industries. This method includes estimating the amount of excess heat based on the specific energy consumption of the production process. The amount of input heat can be estimated when the amount of end products is known, and can be calculated as

$$E_{input} = SEC * m_{product} * \eta_{heat} \tag{12}$$

where SEC is the specific energy consumption of the process,$m_{product}$ is the amount of products produced in the facility, and $\eta heat$ is the fraction of input energy which can be recovered. The required data for estimating the heat potentials of these sectors is thus the SEC of the end product, as well as the production capacity of the facility.

With good input data, the method proposed by Persson et al (2014) is a sound estimation method for estimating the heat potential of industrial facilities. For industries in the iron, steel, chemical and lime industries, the method proposed by McKenna (2010) is sound.

Calculating the waste heat potential using the annual CO_2 emissions does not give insight into the daily, weekly, nor seasonal fluctuations in the potential. These variations can be facility-specific, and have to be determined separately for each potential source.

Industries using large amounts of electricity, such as car manufacturing, can not be identified when using this method. If these facilities are identified in the studied area, the method described for estimating the heat potential of building ventilation exhaust air can be applied. The CO_2 emissions can also be the result of some other process, such as the concrete curing process.

The heat potential of large industrial facilities can be high. It is thus recommended to also consider facilities which are located outside the initial studied area. An example for this would be to consider the Kilpilahti industrial area or the Loviisa nuclear plant site as potential heat sources for the Helsinki metropolitan area, located approximately 40 km and 100 km from Helsinki, respectively.

5.1.1 Data centres

A calculation method estimating the heat potential of data centres is described in a report by GLA, based on the floor area and the power density of the centre.

One clear problem in the method presented by the GLA is highlighted in the papers by Ebrahimi et al (2014)[15] and Rasmussen (2005)[20]. The problem with the approach by the GLA is the wide range of power densities found within data centres, as well as the lack of a standardized method for defining the floor area used to define DC power density. Ebrahimi et al (2014) mention, that the range of power densities can range between 430 W/m^2–861 W/m^2 in older facilities to 6458 W/m^2–10 764 W/m^2 in newer facilities. Rasmussen (2005) describes how different area definitions affect the power density of the DC.

It remains unclear what power density values have been used in the report. If the age of the server equipment in the data centres as well as the floor area used by the equipment is known, the amount of recoverable waste heat could be estimated. If neither of these parameters is known, the error of the estimation remains large. In lack of better data, the method described in the GLA report can be used to give a rough estimation of DC heat potentials. The accuracy and reliability of this estimate can be questioned due to the factors mentioned above.

The report also mentions the difficulty of finding reliable and comprehensive data on DCs. This observation is mentioned by other reports studying the subject as well [16]. Using Google Earth and other publicly available sources in order to estimate the location and the floor area of data centres is mentioned in the report by GLA.

Another possible method could be used if the electric power consumption of the IT equipment or the whole DC is known. If only the capacity of the equipment is known, the electricity consumption can be estimated using the PUE of data centres, usually ranging between 1.1 and 3.0 [16][18].

Lu et al. [17] mentions, that up to 97 % of the total electricity consumption of the DC can be recovered as heat. The fraction of recoverable energy f_{DC} can thus be assumed to be high. This can be used to approximate the heat potential of data centres, but requires detailed data on the electricity consumption of the facility. The heat potential of a DC can be estimated as

$$E_{heat} = E_{el_total} * f_{DC} \tag{13}$$

when the total electricity consumption is known, or alternatively when the IT equipment electricity consumption and the PUE is known.

$$E_{heat} = E_{IT_equipment} * PUE * f_{DC} \tag{14}$$

This approach requires energy consumption data, possibly acquired through the local DSO or the DC operators.

5.1.2 District cooling

Estimating the potential of district cooling production as a heat source is directly linked to the cooling supply of the system in question. The potential amount of heat can be estimated if the COP and the amount of cooling produced by a mechanical compression chiller is known. Similarly to other refrigeration sources, the amount of waste heat can then be calculated as

$$E_{heating} = E_{cooling} * \frac{COP + 1}{COP} \tag{15}$$

The amount of heat can also be calculated if the electricity consumption of a compression chiller is known. Similarly to other refrigeration sources, the amount of waste heat can then be calculated as

$$E_{heating} = E_{el} * COP \tag{16}$$

5.2 Infrastructure

5.2.1 Waste water

Neugebauer et al. [28] presents a method for estimating the heat potential of WW when the flow is known, as per eq. 3. The required data for this method would be the water flow at the WWTP. Acquiring exact data on the flow of WWTP's can be difficult, since most sources give the WWTP capacity in population equivalents.

Converting PE to water flow directly requires additional assumptions. If the population of an area is known, the waste water flow from residential sources could be approximated. The contribution of industry may be more difficult to estimate.

The temperature decrease of the water has to be assumed. The WWTP process often requires temperatures above 10 °C to function, which can be assumed to be the initial minimum temperature of the water prior to heat recovery. The temperature decrease should be chosen so, that the temperature of the discharged water is according to the environmental regulations of the studied area. It should also be chosen so, that no ice is formed in the heat exchanger. A minimum temperature of 2 °C is mentioned to prevent ice formation [76]

Modern waste water treatment is often centralized, meaning only a few WWTP's exist within the areas surrounding a DH system. It is thus often possible to obtain flow data manually, either from the website of the WWTP, or by asking the operators directly.

The advantage of the proposed method is the simplicity of the calculations, as well as the availability of the data.

5.2.2 Public transportation systems – Underground train systems

Underground train systems are identified as public transportation systems with heat recovery potential. A report by GLA [19] outlines a methodology for estimation of the heat potential, but the described method requires detailed data on the underground train system. Such detailed data is rarely available, meaning this method is seldom applicable. If detailed studies on the transport system have been done, the methodology can be followed.

Ampofo et al. [37] modelled the heat loads of a station in the London Underground. The results concluded, that about 90 % of the heat load was generated by braking of trains or lighting. The remaining 10 % of the heat load was generated by the passengers. The results indicate, that 70 % of the generated heat is rejected through the ventilation air, with the rest being rejected through the walls of the tunnel. If the electricity consumption of the station or the train system is known, the amount of heat can be estimated using the results of the study by Ampofo et al (2004).

$$E_{recoverable} = \frac{E_{electricity}}{f_{el}} * f_{vent} + E_{air} \tag{17}$$

where the recoverable amount of energy $E_{recoverable}$ can be estimated when the electricity consumption $E_{electricity}$, share of heat from electricity f_{el} and share of heat exiting through the walls f_{vent} are known. The method should take into account the potential of the ambient air E_{air} as well. Even without heat from the station, some heat can be recovered from the air. The potential of the air can be calculated as the heat capacity of the air.

If the temperature and the flow m_{air} of the exhaust ventilation air from a station is known, the heat potential can be calculated as the heat capacity $c_{p,air}$ of the air flow, assuming the temperature is reduced by a set amount ΔT.

$$E = c_{p,air} * m_{air} * \Delta T \tag{18}$$

The electricity consumption of public transportation systems can often be found in annual reports or on the website of the transport system. Public transportation systems are often centralized, meaning the required data can often be acquired from one or two sources. Publicly available sources would most likely list the energy consumption for the whole train system, meaning it would need to be divided for each station.

The thermal load model developed by [37]. is meant to model peak hours, but will most likely function well during other operational times as well. The heat load will likely decrease outside peak hours, since the amount of passengers decreases, and the frequency and the loads on the train may decrease.

5.2.3 Public transportation systems – Buses

Utilizing the heat potential of buses is an exotic idea. Excess heat from the internal combustion engine could be recovered and stored into a mobile heat storage, in the form of an on-board water tank. The heat stored in the tank would be fed into the DH system during longer bus stops, such as those in malls like Kamppi or Iso Omena in the Helsinki metropolitan region.

The efficiency of an internal combustion engine is low; less than 50 % of the input energy in optimal cases, and about 25 % during typical operation [34]. A fraction of the waste heat is recoverable, a part directly from the cylinder cooling and a part from the exhaust gases. Both of these are high-temperature sources, meaning the water in the energy storage can be fed into the DH system directly.

The amount of recoverable heat would thus be dependent on the input energy and the estimated heat recovery fraction.

$$E_{heat} = E_{input} * (1 - 0.25) * \eta_{heat}$$

The energy input can be estimated if the fuel consumption is known. The fuel consumption can be estimated if the emissions or the driven distance are known. Each fuel has a specific emission factor, as described in the industrial processes section.

5.2.4 Power transformers

A report by the GLA presents a method for estimating the waste heat from electrical grid power transformers. This method is based on the maximum capacities and load factors of power transformers, in combination with assumed efficiencies. The main idea of this method is that a certain amount of heat losses always occur, and can be estimated based on the electric load E_{el} of the component. The efficiency η_{el} is usually high, in the range of 95 %–98 %.

$$E_{heat} = E_{el} * (1 - \eta_{el}) \tag{19}$$

The disadvantage of the described method is the required detailed data. This data consists of the locations, capacities, and loads of the transformers in the distribution network. This data is rarely publicly available, and thus has to be obtained from the grid operator.

If detailed information about the transformer loading and transformer equipment is available, the heat losses can be calculated. The losses in an transformer consist of constant magnetizing losses, also called iron losses P_i, as well as resistance losses, also called copper losses P_{cu}. The magnetizing losses are constant during operation, while the resistance losses depend on the load of the transformer. The losses in a transformer can be calculated as

$$P_{loss} = P_{cu} + P_i$$

where the copper losses can be calculated as

$$P_{cu} = P_{loss,nom} * (\frac{S}{P_{nom}})^2$$

where $P_{loss,nom}$ is the resistive loss when the transformer is operated at nominal power P_{nom}. S is the apparent power at any given moment, for which the losses are calculated. S can be calculated as the hypotenuse of the real power P_{real} and the reactive power $P_{reactive}$. The losses in the transformer can be written in one equation as

$$P_{loss} = P_i + P_{loss,nom} * \frac{\sqrt{P_{real}^2 + P_{reactive}^2}^2}{P_{nom}} \tag{20}$$

The required data for this method consists of the equipment-dependent iron losses, the copper losses at nominal power, the nominal power, as well as the real and reactive powers. This data is detailed, and difficult to obtain.

5.2.5 Electric cable tunnels

The recoverable heat from cable tunnels results from resistive cable losses heating the surrounding air. The losses can be calculated as

$$E_{heat} = l_{cable} * k_{res} \tag{21}$$

where l_{cable} is the length of the cable and k_{res} are the resistance losses per length unit. The required data for this estimation method is thus the length of the cable and the cable resistance losses per length unit. The value of k_{res} can be calculated if the resistance of the cable and the current flowing through the cable are known.

5.3 Buildings

5.3.1 Building ventilation

A method to estimate the heat potential of ventilation exhaust heat pumps is presented in [83]. This method is employed in the report in order to estimate the heat potential of ventilation exhaust air, which could be utilized by a heat pump. Larger multi-floor apartment buildings built between 1960 to 1990 were the focus in the report by VTT, since the largest potential was identified to be in these buildings. The heat recovery potential of a single building can be estimated as

$$E_{rec,building} = A_{floor} * K_{heat} * f_{recovery} * f_{buildings} \tag{22}$$

where $E_{rec,building}$ is the recoverable energy from a building, A_{floor} is the floor area of the building, K_{heat} is the typical specific heat consumption depending on the type and construction year of the building. $f_{recovery}$ is the expected share of energy which can be recovered from the ventilation exhaust and $f_{buildings}$ is the assumed share of buildings from which heat can to be recovered. The estimated energy potential of the studied area is the sum of the potentials of the buildings in the area.

The required data for using this method would thus be detailed building stock containing the type, size, construction year and location of buildings in the studied area. The specific heat consumption, such as presented by Tuominen [84], of different buildings types and ages is also required.

One disadvantage of this estimation method is that buildings of the same type and age are all assumed to be similar. This means, that two areas with buildings of the same age can have similar estimated potentials, but differing actual potentials.

5.3.2 Grey water

No direct method for estimating the heat potential of residential grey water was found during the literature review. The heat potential can be estimated using the heat capacity of the used warm water, similar to other water-based heat sources.

$$E_{rec,person} = m_{person} * f_{warm} * c_p * \Delta T \tag{23}$$

where $E_{rec,person}$ is the potential of the grey water produced by one person, m_{person} is the average amount of water used by one person per day in the studied area, f_{warm} is the share of warm water, c_p is the specific heat capacity of water, and ΔT is the temperature decrease during heat recovery. Multiplying $E_{rec,person}$ with the amount of people living in the studied area will result in the heat potential in the area.

The data required for this method is the amount of water used per person, the share of warm water of the water consumption, as well as the population distribution in the studied area, such as the building stock. The estimated heat recovery temperature decrease should also be assumed. A temperature of around 30 °C can be assumed as the input temperature. A required minimum process temperature of 10 °C to 13 °C at the WWTP should also be taken into account when choosing the temperature of the water after heat extraction.

The spatial resolution of this estimation method depends on the resolution of the available population distribution data. This method doesn't take into account the warm discharge water from dishwashers and washing machines, as these appliances generally use electricity to heat the used water.

It should also be considered, that heat recovery upstream in the sewer system may ultimately result in a lowered heat recovery potential in the WWTP plant, or a risk of calculating the heat twice.

5.3.3 Cooling

The heat potential for building cooling equipment can be estimated using a similar method as for the building ventilation exhaust. The heat potential of the cooling system for a single building can be estimated as

$$E_{rec,building} = A_{floor} * K_{cool} * COP * f_{buildings} \tag{24}$$

where $E_{rec,building}$ is the recoverable energy from the building cooling system, A_{floor} is the floor area of the building, K_{cool} is the typical cooling system specific electricity consumption. COP is the coefficient of performance of the cooling system, and $f_{buildings}$ is the assumed share of buildings from which heat could be recovered. The estimated energy potential of the studied area is the sum of the potentials of the buildings in the area.

The required data for using this method is detailed building stock containing the type, size, construction year and location of buildings in the studied area. The specific cooling system electricity consumption of different building types and ages is also required.

5.4 Refrigeration equipment

5.4.1 Grocery stores

A method for estimating the heat potential of grocery stores is presented by [52]. This method is based on the assumption, that stores of similar size generate similar amounts of heat. The stores in the studied area should be categorized per size. Each store is then given an assumed heat recovery potential based on the size category they are in. Sejberg et al divided the studied stores into 4 different categories for stores, while the Finnish Grocery Trade Association frequently uses 3 size categories in publications.

The amount of recoverable heat at the condensate side of the refrigeration equipment can be estimated as

$$E_{recovery} = E_{el,total} * k_{refr} * COP \tag{25}$$

where $E_{el,total}$ is the total electricity consumption of the store, k_{refr} is the fraction of electricity consumed by the refrigeration equipment and COP is the coefficient of performance of the refrigeration equipment.

The required data to estimate the heat potential from grocery stores using the described method is thus the locations and sizes of grocery stores, the typical electricity consumption of stores of different sizes, as well as the assumed COP of the refrigeration equipment. The direct heat potential of different sizes of grocery stores can also be used, if this data is available. Approximately 35 % to 50 % of the total electricity consumption in a grocery store goes to the refrigeration equipment [51].

While the benchmarks used to estimate the heat potential of a store in a category are based on averages, the local average in the studied area can differ from the used average. For example an area developed in the 1990's will have most stores from that time as well, with the building and equipment being typical of that time. Newer areas developed during the 2010's will have the more modern equipment, with differing energy consumption and refrigeration equipment. Stores in different areas can thus have different heat potentials, despite belonging to the same size category.

5.4.2 Ice rinks

The heat potential of ice rinks is difficult to estimate due to the large variations in the construction and design of ice rink buildings. The heat potential of ice rinks can be estimated similarly to other refrigeration equipment, if the electricity consumption is known.

$$E_{recovery} = E_{el,total} * k_{refr} * COP \tag{26}$$

where $E_{el,total}$ is the total electricity consumption of the ice rink building, k_{refr} is the fraction of electricity consumed by the refrigeration equipment and COP is the coefficient of performance of the refrigeration equipment.

The required data for estimating the heat potential of ice rinks is thus the location and the electricity consumption of ice rinks in the studied area. If the electricity consumption is not known, it can be roughly estimated if the floor area of the building and the typical specific electricity consumption of ice rinks are known. k_{refr} can be assumed to be about 0.5 [56][58].

6 Natural heat sources

6.1 Air

No method for estimating the heat potential of ambient air will be presented in this work. The heat potential of air is strongly tied to the used equipment, and is therefore outside the scope of this thesis. Air as a heat source is virtually infinite, and its potential is limited by the used equipment and the ambient air temperature.

6.2 Geothermal heat

6.2.1 Shallow

Different methods for estimating the heat potential of shallow geothermal heat in an area were found during the literature review. The found methods require detailed data and knowledge for complex modelling of the subsurface ground, and are not suitable for the type of analysis carried out within the scope of this thesis. Geothermal heat has been extensively studied, and detailed potential estimations have often been made by geological institutes or other actors with an interest in geothermal energy. It is recommended to use these existing estimates, rather than to delve into the intricacies of geological modelling.

Existing estimations are often presented as rasters with an estimated heat potential per BHE length unit or per a BHE of fixed length. Assuming the minimum distance between two BHEs is a set distance, the maximum amount of BHEs in a chosen area can be calculated. The geothermal heat potential of an area can be estimated when these BHEs in a chosen area are assigned a heat potential based on the existing estimation.

It should be noted, that the use of BHEs can be limited in many urban areas. The areas for which the heat potential is to be estimated should thus be chosen with care.

6.2.2 Deep

No direct methods for estimating the potential of deep geothermal heat were found. Similarly to the shallow geothermal heat, estimation is complicated. It is recommended to utilize existing studies and reports with estimations. Geothermal heat has been extensively studied, and heat potential estimations have often been made [65].

While large amounts of heat exist deep within the earth, the potential is mostly a question of equipment and investment. Existing plants utilizing deep geothermal heat can give an idea of the potential of this heat source. The utilization of deep geothermal heat for heat production is still in the pilot phase in Finland, with one plant being under construction in Espoo, Finland [69].

6.2.3 Groundwater

No direct method for estimating the heat potential of groundwater was found. The spatial variation of the availability of groundwater as a heat source means, that estimations without measurements or data is difficult. The recommendation is to use existing estimations if available.

If no existing estimates are available, the heat potential of groundwater as a heat source can be calculated when the yield of water from a groundwater source is known. The amount of recovered heat can be calculated as

$$E_{recovered} = m_{yield} * c_p * \Delta T \tag{27}$$

where m_{yield} is the yield of the ground water source, c_p is the specific heat capacity of water, and ΔT is the temperature decrease of the water during heat recovery.

The required data for estimation is thus the yield of the studied groundwater areas, as well as the assumed temperature decrease during heat recovery.

It should be noted, that estimating the potential of groundwater without proper data is not recommended. T. Arola (personal communication, Sep 2, 2020), an expert at GTK, stated that the occurrence of groundwater is local, and the yields of known groundwater sources vary. Estimation of the heat potential without detailed data could thus prove unreliable.

6.3 Ambient water bodies

6.3.1 Lakes

Different methods for estimating the heat potential of lakes were found during the literature review. Like with other water sources, the potential of lakes can be estimated as per eq. 9.

$$E_{lake} = c_p * \rho_{water} * V_{mix} * \Delta T$$

where V_{mix} is the amount of water available for heat recovery over a time period, ρ_{water} is the density of water, c_p is the specific heat capacity of water, and ΔT is the temperature decrease of the water during recovery.

The required data for using the proposed estimation method is thus the volume of the water available for heat recovery, as well as the temperature decrease of the water during recovery. Lund et al. [5] estimated the volume of water available for heat recovery over the year as the area of the lake multiplied with 2 m.

The temperature of lakes follows seasonal fluctuation. It should be noted, that the water temperature in lakes may be too low for heat recovery during the winter. If the minimum recovery temperature and the monthly average temperature of the lake is known, the temperature difference available for heat recovery can be calculated. Environmental legislation can also affect the allowed temperatures for heat recovery. These limits may be case-specific and not stated directly in legislation [80].

6.3.2 Rivers

Different methods for estimating the heat potential of rivers were found. Similarly to other water-based heat sources, the potential of rivers can be calculated as per eq. 10.

$$E_{river} = c_p * \rho_{water} * \Delta T * Q_{use} * t_{op}$$

where Q_{use} is the flow of river water being extracted for heat recovery, c_p is the specific heat capacity of water, ρ_{water} is the density of water,ΔT is the temperature decrease of water during recovery, and t_{op} is the operational time.

The data required for estimating is thus the amount of water available for heat recovery over a time period, as well as the potential temperature decrease. The amount of water available for heat recovery is often limited in environmental legislation; the whole river flow can not be used as a heat source. Directing the full flow of a river through a heat exchanger is also not practical. The amount of water can thus be calculated as a fraction of the river total discharge. The temperature decrease is limited by the temperature of the river water and by environmental legislation.

6.3.3 Seawater

No generalised method for estimating the potential of sea water was found. In coasts of larger seas, the potential is virtually unlimited due to the large volume of water available for heat recovery. The factors limiting the practical potential is thus the used equipment, the temperature of the water, and resulting techno-economic feasibility.

Vicinity to deeper areas is crucial in colder regions where heat extraction of surface water could result in the water freezing. In these cases deeper areas are required, in order to be able to recover heat also during the winter. The depth required in order to sustain water warm enough for heat recovery depends on the area. In the sea outside Helsinki, a depth larger than 65 m is required in order to guarantee water temperatures above 3 °C during the winter. [78]

In deeper seas, such as off the coast of Norway, the availability of water warm enough for heat recovery during the winter is almost guaranteed. The area outside Helsinki or Turku is shallower, and the availability of water suitable for heat recovery may be limited to deeper sections during the winter.

6.4 Solar thermal

The heat potential of solar radiation is strongly tied to the used equipment, and is thus not within the scope of this thesis. The theoretical solar potential depends on the size of the suitable area for solar collectors and the amount of solar radiation on this area. If simplified, the amount of potential solar energy on an area can be written as

$$E_{theroetical} = A_{area} * G_0 \tag{28}$$

where A_{area} is the size of the area suitable for solar collectors and G_0 is the global irradiance on a fixed horizontal plane.

The expected solar radiation on an area anywhere on the planet is readily available using tools, such as PV–GIS [60] provided by the European Joint Research Centre. When the amount of possible energy from the sun is known, the practical potential depends on the used solar collector equipment and the size of the area used to collect the heat. The heat yield of solar collectors can be estimated using a model based on the European Standard EN12975 [85].

7 Case study: Turku

The developed heat source estimation method was applied to a case study in Turku, located in the South West region of Finland. The purpose of the case study was to evaluate the developed methods on a real case, as well as give an example on how the described methods can be used.

The Turku area as a whole is studied for large significant heat sources, but the focus of the case study will be on the areas close to the local DH network, as seen in fig 3. The studied area is located on a sheltered coast of the Baltic sea and mostly consists of urban and suburban areas.

Turku and neighbouring municipalities have a population of about 300000. The local DH system of 600 km is operated in four municipalities: Turku, Kaarina, Raisio and Naantali, providing heat for 200 000 people. In 2019 the renewable energy share in DH production was 61 % [86].

The data used in the case study is mostly based on publicly available data. No separate measurements were conducted for the case study. The data was acquired through direct download from online resources, obtained through contacts, or bought from relevant institutions. A limited amount of time was reserved to gather the data and estimate the heat potential. As noted in the introduction of this thesis, the economical feasibility or technological aspects of heat recovery are generally not taken into account in the case study, with exceptions being described.

The case study is performed in QGIS, an open source geographic information system (GIS) software. The use of a GIS software provides great spatial analysis tools and visualization of results.

Some of the heat sources described earlier in this work are not a part of the case study due to the heat source not being relevant for the Turku area, or due to no data being obtainable. A summary of the studied heat sources, used estimation methods, sources of data and estimated potential is summarized in tables 6 and 7.

It is possible, that a heat source is already in use locally and thus cannot be used as a heat supply for the DH system. This possibility is mentioned, but it does not affect the results of the case study.

Table 6: Summary of used methods, data sources and results for urban heat sources studied in the case study

Heat source	**Used data**	**Source of data**	**Annual heat potential** (MWh)
Industrial processes and production	CO_2 emissions	E–PRTR and Energiavirasto	523 565
Data centres	–	–	–
District cooling	Amount of produced cooling	District cooling producer website	2500 to 5000
Waste water	Water flow	WWTP website	191 169
Public transportation systems, underground trains	–	–	–
Public transportation systems, buses	–	–	–
Power transformers	Transformer load data	Local DSO	10 380
Electric cable tunnels	Cable load data	Local DSO	18.3
Building, ventilation	Building stock data, specific energy consumption	Statistics Finland	427 552
Building, grey water	Building stock data, water consumption per capita	Statistics Finland, Motiva	282 143
Building, cooling	Building stock data, specific energy consumption	Statistics Finland	37 080
Refrigeration equipment, grocery stores	Store electricity consumption data, store sizes	S-Group	120 933
Refrigeration equipment, ice rinks	Ice rink electricity consumption	Jäähalliportaali	19 030

Table 7: Summary of used methods, data sources and results for natural heat sources studied in the case study

Heat source	Used data	Source of data	Annual heat potential (MWh)
Shallow geothermal heat	300 m BHE potential	GTK	*
Deep geothermal heat	–	–	–
Groundwater	Groundwater areas and heating potential	GTK	10 240
Lakes	Lake sizes and locations	SYKE	10 215
Rivers	River flow, water temperatures		21 602
Sea	Sea depth	Baltic sea bathymetry database	–
Solar	Solar irradiance	PV–GIS	–
Air	Air temperature	PV–GIS	–

7.1 Base data

A tool for using Open Street Maps (OSM) as a background map is included in QGIS. This tool was used for visualization, but no calculations were performed on the OSM background map layer.

The first part of the case study was to define the area to be studied. A map of the local DH system was acquired in cooperation with the local DH provider in Turku. An area within approximately 1 km from the DH network was studied. A visualization of the studied area can be seen in figure 3. An exception was made for significant heat sources with high potential in the areas near Turku.

A boundary measuring approximately 40 km x 40 km was chosen, representing the larger Turku. This boundary was used to preliminary limit the acquired data before further refining and processing. One example where this is useful is the data containing the ambient waters, which originally included all the lakes and rivers in Finland. Limiting the data to the smaller, area around Turku significantly decreases the amount of data to be processed, resulting in smoother and faster working with the data.

The studied area is rather limited in size, meaning it is possible to manually go through some potential heat sources, such as data centres and large industries. The DH network has been built around urban centres and residential areas, but the studied area also contains rural areas with the sea, lakes, agricultural lands and forests.

7.2 Industrial processes

The heat potential of industrial processes is based on the CO_2 emissions of the plants. Data on emission was acquired both from the European Pollutant Release and Transfer Register and Energiavirasto (the Finnish Energy Authority). The material from E-PRTR only contains facilities with emissions above 1 000 000 t per year, while the data from Energiavirasto also contains facilities with lower emissions.

The acquired data was limited to the Southwest Finland based on the postal codes numbers found in the material from Energiavirasto. The feasibility of using the

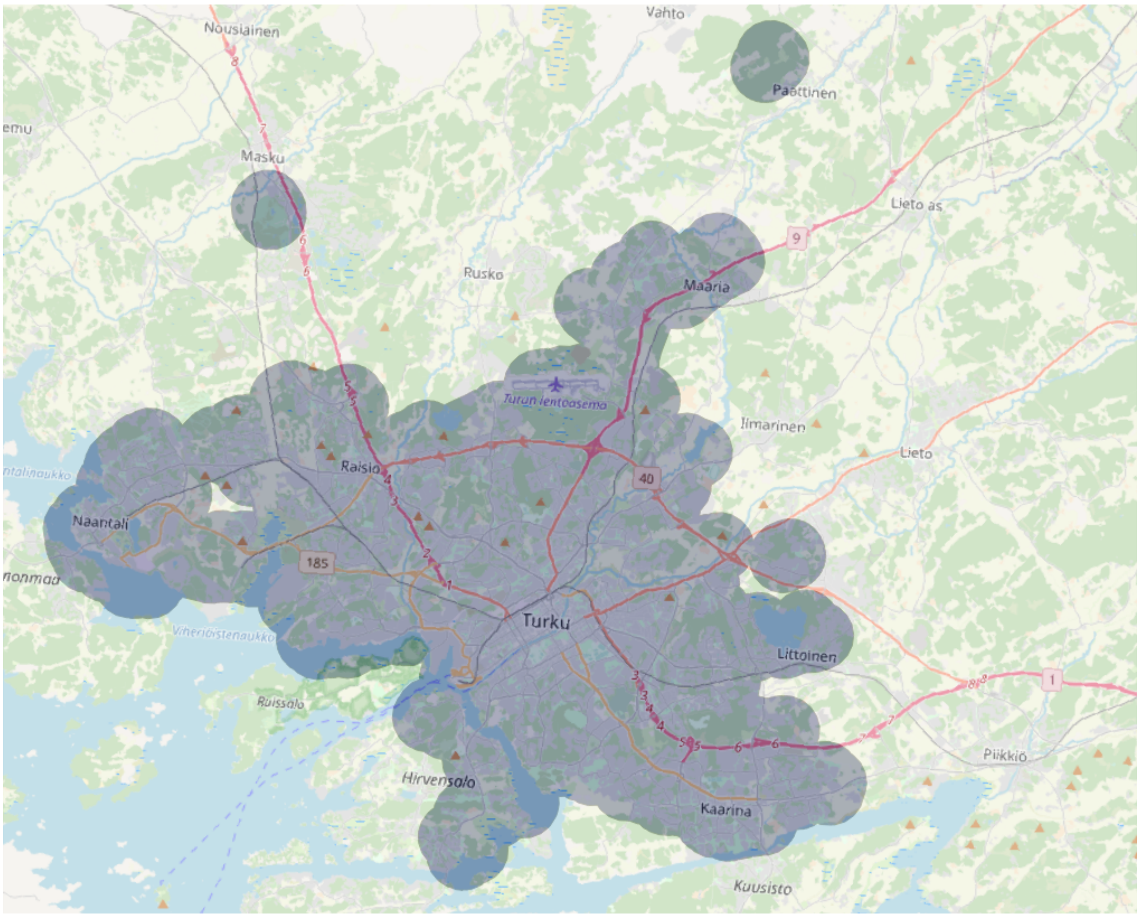

Figure 3: The area studied in the case study visualized.

industrial plants in the region as a heat source in Turku was considered based on the size of the emissions, the distance to Turku, and the existence of other DH networks closer to the facility. Facilities used specifically for heat or power production were also sorted out.

Out of the possible facilities in the region, only one facility fills the criteria of a potential heat source. The heat potential of this plant was calculated by hand using the method described in chapter 5.1, based on the work by [7] and [6]

The facility in question is an oil refinery, meaning the used fuel is most likely petroleum products originating from the refined crude oil. The emission factor in this case was obtained from the paper by [7], where characteristic emission factors for different activities in different EU member states are presented. An approximate heat recovery fraction for fuel refineries is also given in the article.

As the emissions and the emission factors are known, the amount of recoverable waste heat could be approximated to an estimated 524 GW h per year. The owner of the refinery has announced, that operation of the facility will cease in early 2021.

7.3 Data Centres

No usable data on DCs was found for the studied area. As consequence, DCs were omitted in the case study. Undoubtedly, some potential exists, but the exact potential could not be estimated.

7.4 District Cooling

A district cooling network is operating in the Turku central area. The amount of produced cooling is available from the website of the service provider. It is stated, that 90 % to 95 % of the cooling is produced using cleaned waste water, from which the heat has been recovered for DH supply. The remaining cooling is produced by compressor chillers.

The heat potential of the WWTP will be calculated separately. The heat removed during cooling production from waste water is essentially the same heat as the heat recovered from the WWTP. Calculating both would result in the heat being calculated twice, giving an invalid representation of the available heat. This section will thus focus on the heat potential of the compressor chillers producing 5 % to 10 % of the annual cooling load of about 40 GW h. The heat potential of these chillers was calculated as per eq. 15. The COP was assumed to be 4.0. The annual heat potential would thus be about 2.5 GW h to 5 GW h.

Information about the seasonal or diurnal fluctuation of district cooling was not utilized in this work. The cooling demand can be assumed to be higher during the summer, and lower during the winter. The cooling demand can also be assumed to be lower during the night than during the day, partly due to the opening hours of offices and shopping malls, and partly due to the daily fluctuations in the ambient temperature.

7.5 Waste water

The data for estimating the heat potential from waste water treatment plans is publicly available from the Finnish Environment Institute (Suomen Ympäristökeskus, SYKE). Each WWTP in Finland is represented as a point containing the name, location, capacity and load of the WWTP. Other factors, such as treatment method are also included in the data. Upon closer inspection of the data, it is clear that only one WWTP is in operation in the Turku area.

The capacity and load of the WWTP is only given in population equivalents in the data, but a waste water volume flow is given on the website of the WWTP [87].

The heat potential of the WWTP was calculated as per eq. 3, with the temperature reduction assumed to be 5 °C. The annual heat potential of the WWTP in Turku was estimated to approximately 190 GW h.

No conclusions about the daily or seasonal fluctuations of the heat potential can be done based on the obtained data. Waste water as an heat source is often stable with low temporal fluctuations.

The data used in the estimation is often publicly available due to the communal nature of the service. The cleaned water from the WWTP in Turku has been used as a heat source since 2009. Approximately 230 GWh/ a is recovered from the waste water. It is stated, that the temperature decrease at the WWTP in Turku is 5 °C to 10 °C, while a temperature difference of 5 °C is used in the estimation. The electricity consumed by the heat pump is also not taken into account in the estimation.

7.6 Public transportation systems

No estimates were done for the public transportation systems in Turku. There is no underground train system in the Turku region, and the data found about the bus system was insufficient.

7.7 Power Transformers

The waste heat potential of power transformers being part of the electricity grid was estimated using detailed hourly time series supplied by the local distribution system operator (DSO) in Turku. The obtained data contains the location, technical specifications and hourly loads of the transformers over 2019. The extent of the acquired data covers the city of Turku. No data was obtained for the remaining studied area outside the city of Turku, but the potential was estimated using supplementary information, as explained later in this chapter.

The losses were calculated as per eq. 20 for each hour of 2019. All the required data was provided by the local DSO in Turku. The supplied data contains the measured average hourly real and reactive powers for most hours of 2019, as well as the technical specifications for the transformers. Some transformers lack the measured reactive power, and a value of 0 is assumed instead. It is assumed, that the transformer losses are completely transformed into heat which can be recovered. The average, and annual heat potential could then be determined based on the losses.

The employed method requires detailed measured data from the DSO of the studied area. This case study lacks information of the locations or specifications of transformers being within the studied area but outside the city of Turku. The potential of these transformers was estimated by manually counting the number of transformers within the studied region using an online map service provided by

Fingrid, the transmission system operator in Finland [88]. The data provided by the local DSO shows, that several locations have parallel transformers for redundancy. This does not always show in the online map tool, meaning some transformers may have been missed during the counting.

The average transformer heat potential was then calculated using the time series data. The total number of transformers in the studied area was then multiplied with the average heat potential in order to estimate the total heat potential of transformers in the area. The total heat potential from power transformers was estimated to be about 10.4 GW h per year, while the average heat potential of one transformer amounted to approximately 240 MW h per year. The map tool provided by Fingrid [88] was also used to determine the approximate location of the transformers.

Daily and seasonal fluctuations of the power transformer heating potentials were determined by calculating the average losses for each hour of the day. The typical daily fluctuations in the heat potential for all transformers could then be determined. Figure 4 shows the typical daily fluctuation in the heat potential of power transformers, with the hour of day on the x-axis and the power of the heat losses relative to the average annual losses on the y-axis.

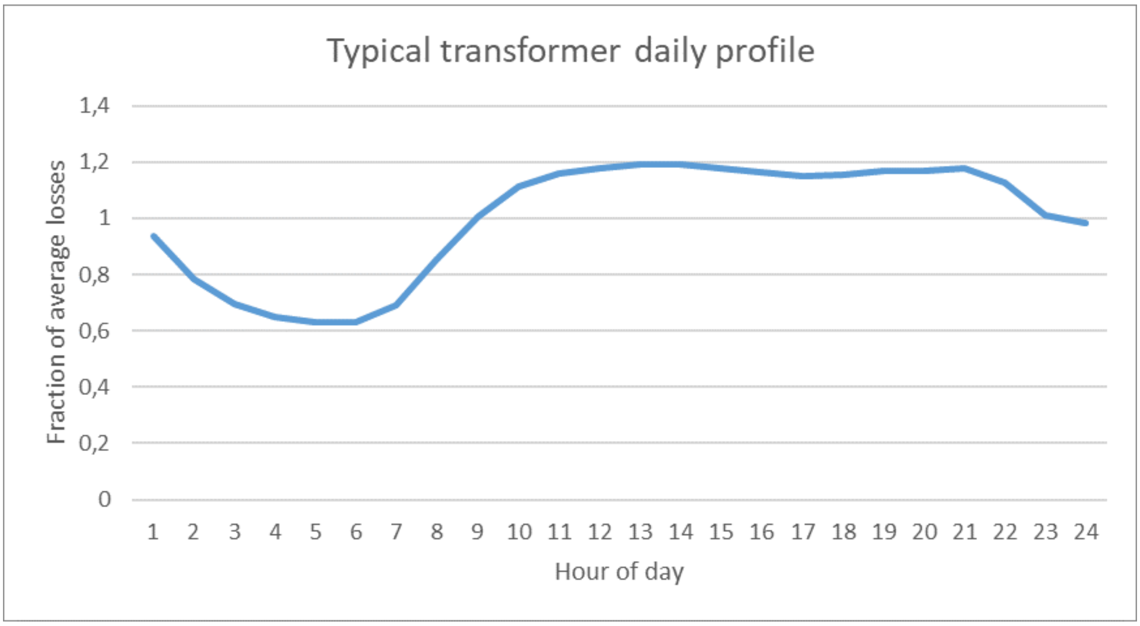

Figure 4: The typical daily fluctuations in the heat potential of power transformers in the studied area.

The quality of the data obtained by the local DSO is very high. Data of similar quality can be difficult to obtain, and future case studies will most likely have to be done using data of lower quality. The electricity grid is also an important part of infrastructure, which may limit the availability of data due to security reasons.

7.8 Electric cable tunnels

The heat potential of electric cable tunnels was estimated based on hourly time series data supplied by the local DSO in Turku. The obtained data contains the average current through nine separate cables in a tunnel in Turku for most hours of 2019. The obtained time series data is accompanied with the technical specifications of each of the conductors. It is assumed, that the resistance losses occurring in the cable can be recovered as heat.

The heat potential was calculated as per eq. 21. The technical specifications, in combination with detailed data on the load of each individual cable was used to determine the resistance losses through the cable tunnel. The heat potential of the tunnel was then determined by summing the individual losses of each cable. The heat potential of the ventilation air in the tunnel was omitted.

A typical daily 24 hour profile was computed as average over all days in the year. A typical loss profile was then calculated based on the typical hourly currents. The profile shows a clear daily fluctuation, with the minimum found during the night, and a peak after mid-day.

A typical weekly profile was determined by calculating the average losses for each day of the week over the whole year. The profile indicates, that the heat losses are stable during the weekdays, and that the heat losses are stable during the weekdays and 25 % lower during weekends.

The estimated heat potential of the tunnel in Turku is low, with the annual heat being estimated as 18 MW h per year. The potential could be higher, if the heat of the intake ventilation air would be taken into account as well. No data on the ventilation was available.

7.9 Building ventilation

Data on the buildings in the studied area was purchased from Statistics Finland, a Finnish authority. The obtained data contained the total floor areas and total numbers of different types of buildings, grouped according to the construction year of the buildings for each postal code area. This is a rough division, but gives an indication on the total potential in the area. The obtained data is sufficient for the case study, but building-specific data could have revealed interesting heat sources for further analysis. More detailed, building-level data is available for purchase from the Finnish Digital and Population Data Services Agency.

The heat potential for residential buildings built between 1960 and 1989 was in focus, as the largest potential has been identified in these buildings [83]. The specific energy consumption values for apartment buildings built within this period were obtained from [83]. The heat potential for the buildings in a postal code area built within a specific decade was thus calculated as per eq. 22. It was assumed, that the fraction of recoverable energy would be 0.5, and the share of houses where this is applicable to be 75 %. Summing together the potentials for each decade yields the total potential for the postal code area. The same procedure was then repeated for office buildings. The heat potential was estimated to be about 428 GW h per year. It should be noted, that a large share of the heat being recovered from the ventilation air is often used directly in the building in practice, (heat recovery, exhaust air HPs).

One problem with this approach was the coarse resolution of the data. The postal code areas and the studied areas had overlap, but different shapes. This resulted in some buildings being outside the studied area to be included in the study, while some buildings within the studied area were excluded. A more detailed data with building-level resolution would have given a more accurate result, but the estimation process remains identical.

It should also be noted, that the heat potential of this source would be higher if measured. This is due to the large amounts of heat supplied into the system with warmer ambient air during the summer. This results in a lower heat consumption during the summer, despite the temperature of the ventilation exhaust air being the same. This additional heat is not shown in the SEC, resulting in the estimation being lower than a measured value.

7.10 Grey water

The same building data mentioned in the building ventilation part was used to estimate the heat potential of grey water in residential apartment buildings. The building data was combined with data on the average water consumption per capita in Finland ($120\,\mathrm{l\,d^{-1}}$) [89].

The heat potential per person was estimated as per eq. 23. The share of warm water was assumed to be 35 % [89], and the temperature decrease was assumed to be 53 K. The approximate population in each postal code area was estimated based on the average floor space per capita in Finland. When the population was known, the total heat potential in a postal code area was estimated. The total heat potential of the Turku area was estimated to be about 108 GW h per year.

No conclusions regarding the fluctuations of this heat source can be made based on the data used in the presented work. Grey water in apartment buildings is the product of human activity, resulting in diurnal fluctuations in the potential.

It should be noted, that distributed heat recovery may reduce the heat potential of WWTP heat recovery to some extent, but it is not strictly a zero-sum game. The higher water temperature at residential sources means, that a part of the heat is lost in the sewer system regardless.

The size of the population in the whole Turku area was estimated to be about 380 000 based on the floor area per capita data. This is higher than the real population, resulting in the potential being overestimated in this case. This could be amended with more detailed data.

7.11 Building cooling

The same building data mentioned in the building ventilation and grey water part was used to estimate the heat potential of the cooling equipment in office, commercial and healthcare buildings. The building data was combined with assumed cooling equipment energy consumption values acquired using the E-PASS tool [90]. The energy consumption values for the cooling equipment were acquired based on the construction year of the building.

The cooling equipment heat potential for the relevant buildings in a postal code area built within a specific decade was thus calculated as per eq. 24. The COP of the cooling equipment was assumed to be 5.0 and the building share was assumed to be 75 %. The potential for a whole postal code area was then determined by summing the yearly potentials together. The heat potential of the Turku area was estimated to be about 37 GW h per year.

A district cooling system is operated within Turku. Due to this, some offices and commercial buildings may not have their own refrigeration equipment to provide cooling. This may also result in a part of the heat potential being calculated twice, both in district cooling and building cooling equipment.

7.12 Grocery stores

Most of the grocery stores in Finland are owned by three grocery store chains; the S-Group (S-Ryhmä), Kesko, and Lidl. These chains control over 90 % of the grocery store market share in Finland [91].

Detailed data on grocery stores was provided by the S-Group, a grocery store chain acting in Finland. The obtained data consists of detailed store-specific electricity consumption values. The detailed data consists of data for all of the stores owned by the chain in the Turku area. The detailed data also contains the size, location, and other technical aspects of the stores.

The provided data covers 49 grocery stores in the Turku region, of which 6 are hypermarkets, 17 are supermarkets, and 26 are convenience stores. The gross floor area of hypermarkets is given as 5000 m^2–12 000 m^2, supermarkets 400 m^2–5000 m^2,

Table 8: Grocery store categories and electricity consumption benchmarks.

	Prisma	**S-Market**	**Sale**
Store category	Hypermarket	Supermarket	Convenience store
Number of stores in data	6	17	26
Average store size (m^2)	14 000	5300	700
Average monthly energy consumption 2017 to 2019 (kW h)	239 163	69 089	24 367
Average electricity consumption 2017 to 2019 (kW)	328	95	33
Average heat potential with COP 4.0 (kW)	328	189	67

and convenience stores less than $400\,\mathrm{m}^2$.

It was assumed, that the grocery stores owned by the S-Group are representative of all the grocery stores in the Turku area. The electricity consumption data can thus be used to determine benchmarks values used for estimating the heat potential of grocery stores, as well as fluctuations in this potential.

Benchmark electricity consumption values were determined for each of the three store types using the recorded monthly electricity consumption data provided by the S-Group. The electricity consumption values for all three store types seem to have decreased significantly during the past 10 years, from which the data is available. It was thus decided, that the benchmark values were to be determined on the last 3 full years (2017 to 2019) in order to give an updated value. An average hourly electricity consumption was determined using the average monthly energy consumption during 2017 to 2019. Outlier values, assumed to be caused by the construction or renovation of the buildings, were removed. The resulting benchmark values are presented in table 8.

Information about the rest of the stores in the Turku area was available through the Liiteri online portal [92]. The name, location, type, and size of the grocery stores was part of the data. The data was incomplete, and inconsistent with other sources.

Each store found in the Liiteri data was placed in a grocery store category based on the name of the store. If the name was missing, the category was determined using the reported floor size. The electricity consumption of each store was then assigned the previously calculated benchmark values. The refrigeration equipment electricity share of the total electricity consumption was assumed to be 25 % for hypermarkets and 50 % in convenience stores and supermarkets. These values are based on consumption data provided by the S-Group. A COP of 4.0 was assumed for the refrigeration equipment. The heat potential for a store could then be calculated as per eq. 25. The total heat potential of all the grocery stores in the studied area was estimated to be 121 GW h per year. It should be noted, that a part of this potential heat could be used to heat the grocery store buildings directly.

The hourly electricity consumption of stores was used to determine the typical fluctuations of the heat potential. This was done by calculating the average electricity consumption for a specific hour of the day over the year. This results in 24 values, each based on 365 hourly values over the year. Dividing these 24 values with the

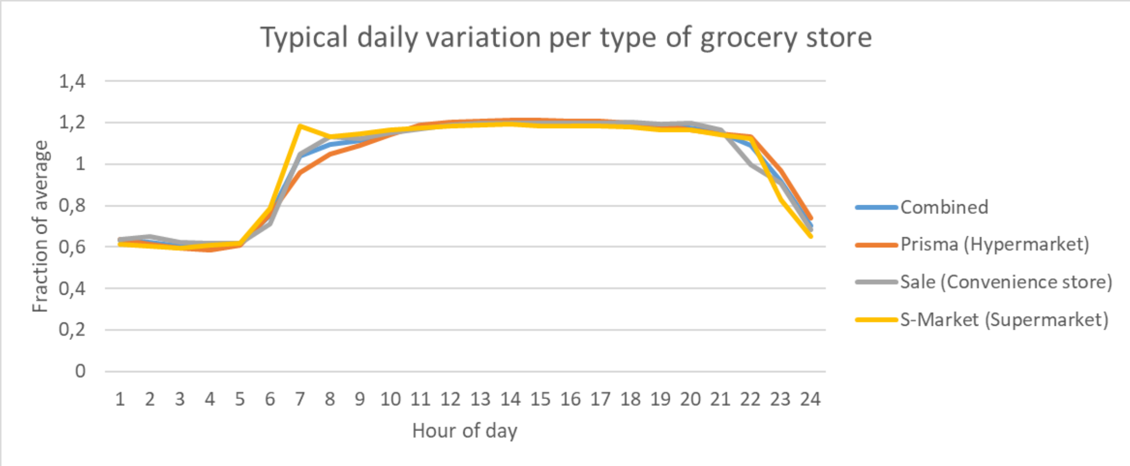

Figure 5: The typical daily fluctuations in the heat potential of power transformers in the studied area.

average/median electricity consumption of the store results in a store-specific typical electricity consumption for each hour of the day over the year. This process was repeated for 3 to 5 stores of each size category in order to determine the typical fluctuations of different store types. A typical fluctuation profile was then formed based on the studied stores. The typical daily fluctuations for different grocery categories is shown in figure 5.

The normalized profile was then multiplied with the average electricity consumption of each store in order to compare the typical profile with the measured average profile. The comparison indicates, that the typical profile describes the electricity consumption accurately(within 0,8–1,2) during opening hours. The electricity consumptions of individual stores differ from the typical profile more during the time the stores are closed.

7.13 Ice rinks

An online source [93] contains information about most of the ice rinks in Finland. This source contains information on location, construction year, seating capacity, temperature zones, as well as the number and sizes of ice rinks. Some ice rinks also have the reported heat and electricity consumption during the recent years. The data, excluding the electricity and heat consumption data, is available for download. The electricity and heat consumption is viewable in a web browser. The data source is upheld by Sport Venue, a data solutions company, in collaboration with some other relevant actors. The specification data is detailed, but incomplete with missing values.

After obtaining the data through download, the data was imported in QGIS as a point vector layer. The points located within the studied area were then determined, resulting in 9 remaining ice rinks. The heat and electricity consumption data for the remaining facilities were then manually acquired from the online source, and added as a field in the vector data. Five of the nine remaining ice rinks had information about the electricity and heat consumption, with the remaining four ice rinks lacking this data. The electricity consumption of the remaining facilities is estimated based on median electricity consumptions per floor area, as presented in [55]. The accuracy of this estimation is low, since there exists large variations in the electricity consumption of ice rinks which are difficult to pinpoint to a certain feature or parameter, such as age or type.

The acquired data contains the area of the ice rink building, used in the calculation. For facilities without data on the area, a value of $3000\,\mathrm{m}^2$ is used for training halls and a value of $3300\,\mathrm{m}^2$ is used for ice stadiums. These values are representative of the average values of all the ice rinks of a specific type in the obtained data.

The COP of ice rink refrigeration systems depends on system design and the used refrigerant. According to a study by [94], the COP depends on the used refrigerant and the temperature of the ice surface in ice rinks. Based on the obtained data, the average ice surface temperature given in the Finnish ice rinks data is around $-5\,°\mathrm{C}$. Ice rinks with a given ice surface temperature of $0\,°\mathrm{C}$ in the data were excluded from the calculation, assuming that no data was available. Based on this average temperature, the COP of refrigeration equipment using most refrigerants is around 4.0. About 50 % of the total electricity consumption is by the refrigeration equipment. The heat potential was then estimated as per eq. 26.

The total heat potential of all the ice rinks in the studied area was estimated to be about 19 GW h per year. It should be noted, that a part of this potential heat could be used to heat the ice rink buildings directly.

The used method proved to be relatively simple and easy to use due to the availability of data in Finland. Missing and low–quality data raised the need to estimate the electricity consumption of some venues using the floor area. The resulting estimations are indicative of the magnitude of the heat recovery potential, but a more detailed analysis could be done in order to accurately estimate the potential.

7.14 Air

The heat potential of the ambient air was not estimated. Data representing a typical meteorological year was obtained using the PV–GIS tool by JRC [60]. This data contained the typical ambient temperature in the Turku region. Based on the acquired data, there is a strong seasonal fluctuation in the potential of ambient air as a heat source. Large amounts of heat are available during the winter, but the fluctuating ambient temperature means that the efficiencies of the used air source HPs vary.

7.15 Shallow geothermal heat

Existing geothermal heat potential estimations are used in this thesis. GTK offers publicly available data on the geothermal heat potential in Finland [65]. The available data consists of three separate data sets. One set contains the bound and renewable energy for a 300 m BHE. The second data set contains information on the deep geothermal energy potential in Finland, while the third data set contains the energy potential of the groundwater in Finland.

The ground water dataset was publicly available for download from GTK, while the two other data sets are only visible using an online map interface. Contact with GTK revealed, that the other datasets are available if a special arrangement is made with GTK.

The dataset with the potential of 300 m BHEs contains both the amount of energy stored in the ground, as well as the rate at which this heat is renewed. The dataset is in a raster format with 1 km x 1 km pixel sizes. The raster data for the Turku area was obtained through the online map interface, and manually georeferenced in QGIS.

A grid with approximately 8500 points was generated within the studied area, each point representing a possible BHE. The distance between the points was 175 m. The chosen distance is based on the results of [68], where the minimum distance between two 300 m BHEs was determined to be 176 m in order to avoid negative interference between the BHEs. With distances shorter than 176 m, the BHEs interfere, resulting in a lowered heat potential per BHE. A shorter distance could have been chosen, but it remains unclear how the acquired data should be adjusted if the BHEs interfere.

Each point was then assigned a heat potential based on the data obtained from GTK. The heat potential with a set-up like this was estimated to be about 516 GW h per year within the studied area.

The estimated potential is not practical, since use of geothermal heat may be limited in some areas. Despite this, the potential of geothermal heat is shown. Defining the areas suitable for shallow geothermal heat extraction would be one method to improve this analysis.

7.16 Groundwater

The dataset downloaded from GTK contains the potential heating power of groundwater per groundwater area. The downloaded data is in vector format, consisting of about 3000 points scattered around Finland. The Turku area has a few dozen data points. The obtained data was limited to the studied area, leaving 7 points. The annual energy potential was then calculated based on the heating power found in the data. No further estimations were done, as the obtained data contained the values of interest. The heat potential of the groundwater sources within the studied area was estimated to be approximately 10.2 GW h per year.

No conclusions of potential fluctuations could be done based on the data. However, it can be assumed, that groundwater as a heat source is relatively stable with little daily fluctuations. Depending on the groundwater extraction location, the potential can fluctuate between seasons due to variations in the amount of precipitation and snow melt. These seasonal fluctuations should be unique for each groundwater well, and can not be determined without measurements.

7.17 Ambient water – Lakes

The thermal potential of lakes is estimated based on the heat capacity of the lakes. The used data contains information on most lakes and ponds in Finland, and was freely available by SYKE [95]. The name and id, as well as the geographical location, shape and area of the water body is contained in the data. The information is in polygon vector format.

The first step after obtaining the data is to limit the extent of the layer in order to reduce the amount of unnecessary data being processed. A manual inspection of the map reveals that no large lakes exist in the areas around Turku. The considered lakes should thus be located within the studied area.

SYKE also maintains an online database interface containing information on the lakes in Finland [96]. The average and largest depths of some lakes can be found here. The lakes can be queried using the region, name, id, among other parameters. In this case study the relevant data was gathered manually due to the limited number of lakes within the studied area.

A manual query on the larger Turku area was conducted based on the coordinates. The result showed that depth data only existed for three lakes within the Turku area, with only one lake being within the 1 km buffer from the DH system. The rest of the lakes had no depth information available. Vector datasets containing the depth areas and depth curves of the lakes in Finland are available by SYKE [95]. The datasets are open data and downloadable. Upon closer inspection, only one lake in the Turku area has depth data relevant for the case study. The lake with depth information had an average depth of 2.03 m, with the rest of the lakes having no information. It was thus decided that the heat recovery estimation method presented by Lund et al. [5] was used. An assumed depth of 2 m was used for all lakes in the calculations.

When the area and assumed depth of the lakes are known, the volume can be calculated. The potential of the lakes was then calculated as per eq. 9. The temperature decrease was assumed to be 2 K, and the density of the water 1000 kg/m^3.

The used material also contains small ponds, and even a few swimming pools in residential areas. The estimation results can be further filtered by removing lakes with a heating potential under a set threshold. The total potential of all the lakes with an estimated heat potential of over 200 MW h amounted to about 10.2 GW h per year.

The used method was simple to use, and the required data was easily obtainable. The accuracy of this analysis could be improved by using more detailed depth data for the studied lakes.

No conclusions regarding the seasonal or diurnal fluctuations of the potential could be done based on the available data. The seasonal fluctuations in the amount of available heat could be determined if the monthly average temperature of the lakes were known.

7.18 Ambient water – Rivers

There are three rivers that intersect with the studied area. One of these rivers, Aurajoki, is larger, while the two others, Raisionjoki and Maskunjoki, are smaller. The geographical extent of these rivers was included in data material available by SYKE [95].

The discharge of rivers in Finland usually have a strong seasonal variation. The snow, which has accumulated during the winter, melts during the spring. This can usually be seen as a clear peak in the discharge. The discharge then usually decreases towards summers, and increases during rainy autumns. Lakes in the catchment area dampen the effect rainfall has on the discharge. The monthly average discharge of Aurajoki is found in a report by SYKE [97]. The yearly average discharge of Aurajoki is $3.3\,\mathrm{m^3/s}$, with the highest discharge being in April and the lowest during the summer months. The monthly average discharge of Raisionjoki is found in a report by Pöyry [98]. The average discharge of Raisionjoki was $2.1\,\mathrm{m^3/s}$ between 1990 to 2015. The annual average discharge rate of Hirvijoki, of which Maskunjoki is a tributary, is $2.3\,\mathrm{m^3/s}$. The catchment areas of the rivers in the region have a low number of lakes, resulting in the discharge rates varying a lot. The catchment area of Maskunjoki is 21.2 % of the total catchment area of Hirvijoki. Due to the low amount of lakes in the area, it could be assumed, that the flow of Maskunjoki amounts to approximately 20 % of the discharge of Hirvijoki. The average discharge of Maskunjoki was thus estimated to approximately $0.44\,\mathrm{m^3/s}$.

River water temperature and discharge forecasts for Aurajoki are provided by SYKE [99]. Both short-term and long-term predictions are available. The forecasts are based on measured values for the previous years, and especially the long-term forecast should be a good representation of the yearly temperature profile. It was assumed, that the temperature profile of the three rivers are similar over the year.

It was assumed, that 10 % of the river discharge could be used for heat recovery and that the temperature of the water used for heat recovery could not sink below 1 °C. It was also assumed, that the maximum temperature decrease of the whole river was 1.5 °C, and the temperature decrease of the water used for heat extraction would be 10 °C. It was also assumed, that a minimum water temperature of 2 °C was required for heat extraction.

Based on these boundary conditions, the monthly heat potential of the three rivers could be estimated as per eq. 10. The total heat potential of the rivers in the studied area was estimated to be 21.6 GW h per year. The seasonal fluctuations in the heat potential of the studied rivers could be determined based on the acquired temperature data.

7.19 Ambient water – Sea water

The direct potential of seawater was not estimated. The locations of possible seawater heat extraction locations were identified. Possible suitable locations were determined based on depth data available from the Baltic Sea Bathymethry Database [100]. Vahtera [101] studied the seawater surface and bottom temperatures outside Helsinki. Depths larger than 35 m are often required in order to guarantee a water temperature suitable for heat recovery. It was assumed, that similar criteria would be required in the sea outside Turku.

A raster file with depth information of the sea within the studied area was obtained from an online source, provided by the Baltic Sea Bathymetry Database [100]. Possibly suitable areas were identified in locations where the depth was over 35 m. Sea areas located within approximately 10 km from the DH network were considered.

7.20 Solar

The solar heat potential was not estimated. Solar irradiance data was obtained using the PV–GIS tool by the Joint Research Centre [60]. This data contained data for a typical meteorological year and the expected solar irradiance in the Turku area.

The potential could be estimated by defining an area suitable for solar collectors, as well as defining the specifications of the used equipment. The fluctuations of the heat potential could be determined based on the obtained data.

8 Summary and conclusions

The utilization of excess and natural heat sources will inevitably be a part of the emission reduction efforts within the heating sector. This thesis work discussed and presented different methods for estimating the potential of these heat sources in the urban environment, as well as what type of data is required for the estimation. The purpose of the work is to provide a picture of the available heat sources in an area, as well as to estimate their magnitude. The analysis was extended to include the expected temperature levels and fluctuations when possible. The objective was to improve the quality of available information on urban heat sources to a level that supports practical decision-making on a city-level or within DH companies.

The discussed and described estimation methods were chosen based on findings in the literature review and data available for the analysis, and can be considered as examples of how to carry out the type of presented work. The most suitable methods should be chosen separately for each case, depending on what data is expected to be available. This became apparent while carrying out the case study. It was originally planned, that the described methods would be chosen based on the literature review, experience, and the expected available data. In the end, the availability of data in the case study partly affected which methods were used and described.

It became clear, that detailed knowledge of each heat source was necessary to be able to make relevant assumptions and decisions. This became a concern due to the vast scope of the work, and the limited time schedule. It feels like this thesis has only scratched the surface of the knowledge available on some heat sources.

Thought to be relatively simple in the beginning, the extent and amount of detail of this topic surprised those involved. The absence of certain heat sources and a lack of practical detail was seen as a flaw in other similar works. Urban heat sources have not been evaluated in the presented scope and detail in previous work. In the planning phase of this work, the ambition was to include all known heat sources in an urban environment, and to identify possible new ones. Some exotic heat sources, such as buses, were partly included in this work, but countless were ignored. Other heat sources, such as shallow lake bottom sediments, clean water, underground parking spaces, parking lots, and attic spaces were left out. These additional heat sources are similar to sources which have been discussed in this work, but despite this would require a more detailed estimation method.

The described methods were applied to a case study, during which the heat potential of the Turku area in South Western Finland was estimated. The case study functions as an example on how to use the described methods, as well as from where the required data could be obtained. The identification of these sources of information and collecting the data was a significant part of the work carried out. The difficulty of acquiring relevant data became clear during the case study.

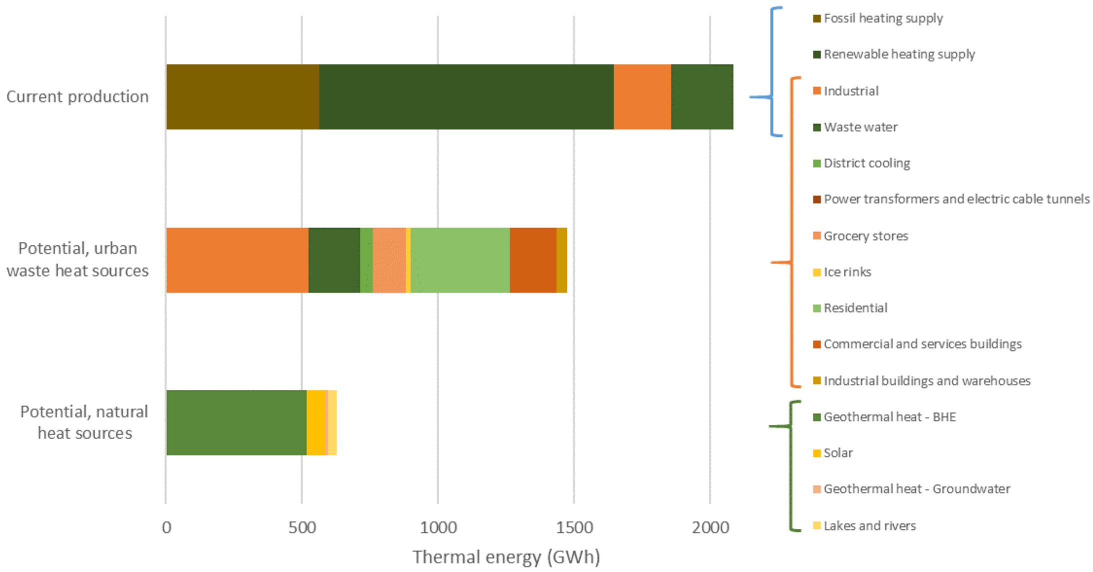

Figure 6: A magnitude comparison between the estimated heat potential in the Turku area and the current production situation in the DH system.

Turku Energia, the local DH company in Turku, procured approximately 2100 GW h of DH in 2019, of which over 70 % was produced without fossil fuels [86]. The estimated urban waste heat potential amounts to 1483 GW h, and the natural heat potential amounts to 42 GW h, excluding air, solar, seawater and shallow geothermal heat. A comparison between the estimated potential and the current heat production is shown in fig 6. The theoretical potential of air, solar, seawater and shallow geothermal heat is likely significant in the studied area. Additionally, combustion of by-products from local industries also takes place, although these are not within the scope of this work. Two of the urban waste heat sources, waste water and industrial waste heat, are currently partly utilized as heat sources for DH production in Turku. Heat from other waste heat sources, such as grocery store and ice rink refrigeration equipment, may also be in use locally.

Efforts to increase the amount of open data have caught on in recent years. Due to these efforts, diverse environmental and social data is available in Finland provided by the Finnish government, the EU and other actors. Similar development can be presumed to take place elsewhere as well, although in other countries the current situation is unknown. Despite this, problems concerning the availability and quality of data also became clear during the course of the study. Especially information on data centres proved difficult to come by, making the related potential as a heat source difficult to estimate. The quality of some of the data used in the case study exceeded all expectations. For example the obtained information on the power transformers is as good as perfect for the purpose of the case study. It is unclear how common such level of quality will become in future estimations concerning other heat sources.

It is difficult to validate the accuracy of estimations, since any effort concerning validation would rely on estimations as well. Existing use of heat sources can be used to check the accuracy, but only in one direction. The technical potential rarely reaches the theoretical potential, and the economic potential is even lower. The heat potential of a source is thus never completely utilized. It was originally planned, that the assessed heat potential would represent the theoretical potential of the heat source.

The potential magnitude of the heat sources was studied in this thesis work. A logical continuation on this work would be to identify additional sources of heat, and to further improve the estimation methods described in this work. Technical and economic aspects limiting the heat potential could also be considered, as well as the impact of the heat source being utilized locally at the source of the waste heat. Applying the estimation methods outside Finland would provide valuable experience for further improving the methods. A partial or complete automation of the estimation process could significantly reduce the amount of work, and can be seen as a long-term target. Continued research on this topic will inevitably increase the knowledge in the field and improve the quality of the results of the estimation methods.

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