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

Dennis Sundell¹ · Miika Rämä¹

Received: 9 December 2021 / Accepted: 5 September 2022 / Published online: 14 October 2022
© The Author(s) 2022

Abstract
The increased use of heat pumps to utilise low-temperature heat will undoubtedly be a part of future emission reduction measures within the heating sector. Identifying these heat sources and assessing their heat potential is essential for their utilisation. Different methods for estimating the potential of excess and natural heat sources found in the urban environment are presented in this study. The research aims to present a replicable estimation methodology which can be applied to any urban area. The methods are developed around publicly available data sources, or otherwise easily obtainable data. The research aims at producing data accurate enough to support decision-making on the district heating company or city level on utilising these heat sources. A wide range of excess and natural heat sources found in urban environments were identified in a literature review. Methods for estimating the potential of the heat sources were developed based on findings of the literature review and the expected availability of data. The developed estimation methods were applied in a case study where the potential of heat sources identified within the Turku area in Southwest Finland was estimated. The results of the case study show the potential of the heat sources within the studied area. The difficulty of obtaining raw, high-quality data are also highlighted. This emphasises the need for advanced processing of available data and insight on the related sources, e.g. building management systems or industrial processes. The methods presented in this study give an overview on how heat potential could be estimated. It can be used as a base for developing more refined methods and for detailed techno-economic assessment for utilising available excess and natural heat sources.

Graphical abstract

Keywords District heating · Excess heat sources · Renewable heat sources · Heat pumps

¹ District Heating and Cooling, VTT Technical Research Centre of Finland Ltd, Espoo, Finland

Abbreviations
DH District heating
CO₂ Carbon dioxide
COP Coefficient of performance
E-PRTR European pollutant release and transfer register

Dennis Sundell
dennis.sundell@vtt.fi

Miika Rämä
miika.rama@vtt.fi
GIS Geographic information system
DSO Distribution system operator

Introduction

Heating and cooling make up roughly half of the final energy consumption within the European Union. Of this energy approximately 75% is produced using fossil fuels, which are commonly used to produce heat in district heating (DH) systems. The global community has pledged to reduce carbon dioxide (CO₂) emissions to minimise the impact of anthropogenic climate change. An increased utilisation of excess waste heat and naturally occurring heat using heat pumps will certainly be a part of the efforts to reduce the CO₂ footprint of the heating and cooling sector (European Commission 2016).

Large excess heat sources or natural heat sources, such as communal wastewater or seawater, have been utilised as heat sources for DH production since the 1980’s (Averfalk et al. 2014, 2017). The potential of waste heat and natural heat sources found in urban environments is significant, but these resources are often unutilised due to low temperature or low potential as a single point source. Recent development in DH technology is trending towards lower distribution temperatures, increasing the feasibility of utilising low-temperature heat sources. This also represents a significant emission reduction potential for urban areas. However, estimating the heat potential of available heat sources is time consuming due to the effort required. At the same time, DH companies need reliable data to support their own decision-making concerning future investments in developing DH systems. This paper reports the findings of a recent study (Sundell 2021) addressing this urgent need. The study focused on the development of a replicable methodology for the systematic assessment of heat sources in an urban area. The work also identified and assessed few heat sources that have not been widely discussed or considered earlier. The resulting methodology was applied in a case study in the city of Turku, Finland. During the case study, practical experiences regarding availability and quality of data were encountered that provided valuable feedback for further research concerning the topic.

Efforts to estimate the heat potential of specific heat sources or potential within limited areas have been done previously. Lund and Persson (2016) analysed the potential of different categories of heat sources from the perspective of DH systems in Denmark. The analysed heat sources were sea water, lakes, rivers, ground water, tap water, wastewater, grocery stores, and low-temperature industrial excess heat. McKenna and Norman (2010) estimated industrial waste heat potential in the United Kingdom using a reverse CO₂ emission calculation method. Mckenna (2009) presented an analysis of the technical heat recovery potential of the industrial sector in the United Kingdom. A general method based on calculating the quantity of recoverable heat based on a reverse calculation of CO₂ emissions and an assumed fraction of recoverable heat was presented. For the lime, steel, iron, and aluminium sectors, an estimation method based on production capacities was presented. Iglinski et al. (2021) estimated the potential of heat pumps in public buildings, together with other sources of renewable energy in northern Poland. The potential was estimated using building stock data. Saha et al. (2020) estimated the waste heat potential of the iron and steel sector, cement sector, food processing sector, glass sector, pulp and paper sector, and chemical and petrochemical sector in India. Persson et al. (2014) presented a method for assessing the available excess heat from industrial and energy sector facilities as part of the Heat Roadmap Europe project. The available heat was estimated using a reverse calculation of the facility-specific CO₂ emissions, available from the European Pollutant Release and Transfer Register (E-PRTR). López et al. (1998) analysed the amount of available excess heat in the Basque country based on the specific energy consumption of the available industrial process. Sejbjerg et al. (2015) estimated the potential of excess heat from grocery stores in Denmark, based on the assumption that stores of similar sizes produce similar amounts of excess heat.

North et al. (2013) studied the secondary heat sources available in the London area. The available heat from both urban waste heat sources and natural heat sources were estimated. The studied urban waste heat sources were power production, building cooling systems, industrial sources, wastewater treatment plants, underground trains, electricity infrastructure, sewage infrastructure, as well as commercial buildings with internal heat production, such as grocery stores and data centres. The studied natural heat sources were ambient water bodies, geothermal heat, and ambient air.

The results from these projects and publications give insight into the potential of the studied heat sources and make a significant contribution to estimating a potential of a heat source within specific area. However, the estimation of heat potential in previous work has often been based on detailed data obtained through field measurements, been limited to a specific area, considered a limited selection of heat sources, been based on rough averages, or a combination of these. The results from these studies cannot thus be used to support decision-making on a DH system level or city level as such. This shortcoming is addressed in this study by a comprehensive assessment of all heat sources, pragmatic investigation on what sources of data exist and possible methods for processing this data.
Scope and purpose

The aim of this study is to present a methodology for estimating the potential of heat sources found in the urban environment. The methods for estimating the potential of specific heat sources are developed around publicly available data sources or otherwise easily obtainable data. They are also based on earlier research concerning the topic when possible. The goal of the research is to present a relatively quick estimation methodology which could be applied to any urban area, providing an adequate dataset to support the utilisation of the available heat sources. The presented work also provides a comprehensive overview of potential heat sources and can function as a base for further development of the included methods. In the future, the methodology can provide input for detailed techno-economic studies concerning the utilisation of heat sources available in a specific area.

This paper consists of an introduction providing background and information on recent studies concerning the topic. Next, the estimation methods and their input data requirements are described representing the findings of the literature review in the presented study (Sundell 2021). Then, the results are applied to a case study in Turku, Finland, to demonstrate how the methods could be applied and where potential sources of data can be found in the Finnish context as an example. The case study was also used as a tool to provide insight on data availability and to study the specific, practical challenges involving the estimation of potential of heat sources in an area. Finally, the relevance of the results is discussed, and overall conclusions presented.

Methods and input data

An estimation method consists of available data combined with a set of relevant assumptions, processed in a certain way to get results. The data used in the estimation methods presented in this study is data expected to be publicly available or easily obtainable, without the need for field measurements or detailed operational data. The assumptions are based on findings from the literature review, local legislation and internal estimations made during research (user input). The overall process concerning a specific heat source is visualised in Fig. 1.

Potential heat sources available in urban environments were identified in an extensive literature review. Typical properties were identified for each heat source. These properties include the typical temperature level, size, energy profile, location, controllability, availability, reliability, seasonal and diurnal fluctuations, and the origin of the heat. More details on the properties can be found in the referenced articles summarised in a previous study (Sundell 2021). Possible existing estimation methods were also studied in the literature study.

The findings of the literature study were then used to develop estimation methods for each heat source. The relevant assumptions and data requirements were also based on the literature review. Existing estimation methods found in the literature study were adapted as such if applicable, i.e. the data required by the method was expected to be available.

The identified heat sources have been divided into urban waste heat sources, which are a result of human activity, and natural heat sources, which exist naturally. Urban heat sources have been further divided into infrastructure, buildings, refrigeration equipment, and industrial processes and production. Natural heat sources have been further divided into geothermal heat, water bodies, air, and solar.

It should be noted that the division between urban and natural heat sources is based on the characteristics of the heat source in question—not e.g. the definition given in the revised Renewable Energy Directive (European Parliament Council of the European Union 2018). In the directive, excess heat from residential buildings is not recognised and wastewater is defined as a renewable

![Fig. 1  Estimation process flow, carried out for each studied heat source](image-url)
| Heat source                                      | Estimation method                        | Required data                                                      | Assumptions                                           |
|-------------------------------------------------|------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------|
| Industrial processes and production             | Reverse calculation of emissions         | Amount of CO₂ emissions, type of process                           | Fraction of recovered heat                           |
| Literature source(s): Ammar et al. (2012), Brueckner et al. (2014), Brueckner et al. (2015), López et al. (1998), Mckenna (2009), McKenna and Norman (2010), Pellegrino et al. (2005), and Persson et al. (2014) |
| Data centres                                    | Based on electricity consumption         | Electricity consumption                                           | Power usage effectiveness                           |
| Literature source(s): Ebrahimi et al. (2014), Lu et al. (2011), North et al. (2013), Ojala et al. (2020), Rasmussen (2005), The Green Grid (2007) and Wahlroos et al. (2018) |
| District cooling                                | Based on cooling production              | Cooling production or electricity consumption                      | Coefficient of performance (COP)                    |
| Literature source(s): Werner (2017)             |                                          |                                                                   |                                                       |
| Wastewater                                      | Based on water flow                      | Plant water flow of capacity                                      | Water temperature decrease                          |
| Literature source(s): Averfalk et al. (2014, 2017), David et al. (2017), Guo and Hendel (2018), Mazhar et al. (2018) and Neugebauer et al. (2015) |
| Public transportation systems, underground train system | Based on electricity consumption        | Electricity consumption                                           | Heat load shares                                     |
| Literature source(s): Abi-Zadeh et al. (2003), Ampofo et al. (2004), Ninikas et al. (2019), North et al. (2013), Revesz et al. (2016) and Sandberg (2015) |
| Public transportation systems, buses            | Reverse calculation of emissions         | Amount of emissions or fuel consumption                           | Engine efficiency, fraction of recoverable heat      |
| Literature source(s): Nylund et al. (2007)      |                                          |                                                                   |                                                       |
| Power transformers                              | Calculation based on load                | Load, equipment specifications                                    | –                                                    |
| Literature source(s): Hazi et al. (2013), Kulkarni and Khaparde (2004), North et al. (2013) and Strbac et al. (2014) |
| Electric cable tunnels                          | Calculation based on load                | Load or capacity                                                   | Resistance losses                                    |
| Literature source(s): Davies et al. (2017, 2019) and Strbac et al. (2014) |
| Buildings, ventilation                          | Based on building heat consumption       | Building specific heat consumption, building floor area           | Fraction of recovered heat, share of relevant buildings |
| Literature source(s): Liddament and Orme (1998) |                                          |                                                                   |                                                       |
| Buildings, grey water                           | Based on water consumption               | Water consumption                                                 | Warm water fraction, water temperature decrease      |
| Literature source(s): Mazhar et al. (2018) and VanSchenkhof (2011) |
| Buildings, cooling                              | Based on cooling energy consumption      | Building floor area, cooling energy consumption                    | COP, share of buildings                              |
| Literature source(s): Persson et al. (2014) and Reindl and Jekel (2007) |
| Refrigeration equipment, grocery stores         | Benchmarks based on store size           | Size of the store                                                 | COP, benchmark                                       |
| Literature source(s): Arias (2005), Department for Business and Energy and Industrial Strategy (2016), North et al. (2013) and Sejbjerg et al. (2015) |
| Refrigeration equipment, ice rinks              | Based on estimated electricity consumption| Electricity consumption or building size                          | COP, refrigeration equipment electricity fraction    |
| Literature source(s): Cronholm et al. (2009), Hemmila and Laitinen (2018), IIHF (2016), Makhnatch (2011) and Pachai (2009) |
A methodology for systematic mapping of heat sources in an urban area

2995

Heat source. Heat from natural sources, such as solar, geothermal, as well as heat from ambient air and water are also defined as renewable energy sources. Also, district cooling as a heat source to produce DH is currently awaiting clarification.

The estimation methods for each heat source are summarised in Tables 1 and 2. The columns in the tables contain the specific heat source, the presented estimation methods, the data required to use the method, and the assumptions associated with the presented method. Literature sources contributing to the development of a method or contributing to increased knowledge of the heat source are listed on a separate row below each heat source.

The location of potential heat sources is essential for their utilisation, for example as a heat supply in a DH system. A geographical information system (GIS) is a suitable tool for storing, analysing, and visualising spatial data. The presented methods work well when implemented in a GIS environment, but the use of a GIS is not required.

### Case study

The presented heat source estimation methods were applied in a case study in the Turku region in Southwest Finland, in which the potential of heat sources identified in the area was estimated. The purpose of the case study was to evaluate the presented estimation methods, and to provide an example of how the estimation methods can be used. The case study also functions as a tool to investigate data availability, as well as to highlight challenges involving estimation of heat potentials in an area. The local DH system in Turku spans over 600 km and is used to provide heat for 200,000 people in four municipalities: Turku, Raisio, Kaarina and Naantali (Turku Energia 2021). The annual heat production of the DH system is about 2100 GWh, and the share of renewables in production was 61% in 2019 (Turku Energia 2021).

The studied area was limited to areas approximately 1 km from the local DH system, with an exception made for heat sources with significant heat potentials, such as large industries. A map of the DH system in the Turku area was obtained from the local DH provider (Turku Energia 2021). The studied area is located on the coast of the Baltic Sea. The DH system is located around residential areas and urban centres, but the studied area also contains more rural areas, including the sea, lakes, forests, and agricultural lands. The analysis of heat sources could be done manually in this case due to the limited size of the studied area. If the studied area were larger, much of the manual work could be challenging due to the effort and time required.

Potential sources of heat in the studied area were identified and data sources concerning these heat sources were located. Relevant data for each heat source was obtained, and the corresponding potential was then calculated using the estimation methods presented in Tables 1 and 2. A GIS software (QGIS) was used for spatial analysis and data processing. A summary of the identified heat sources, used

### Table 2 Identified natural heat sources with methods to estimate heat potential, the required data and assumptions

| Heat source          | Estimation method           | Required data                                      | Assumptions                  |
|----------------------|-----------------------------|----------------------------------------------------|-----------------------------|
| Shallow geothermal   | Existing estimates          | Size of suitable area, existing estimates          | Borehole distance           |
| Literature source(a): Geologian Tutkimuslaitos (2021a), Kallio et al. (2019) and Signorelli (2004) |
| Deep geothermal      | Existing estimates          | Existing estimates                                 | –                           |
| Literature source(a): Geologian Tutkimuslaitos (2021b) and Signorelli (2004) |
| Groundwater          | Based on yield             | Groundwater source yield                           | Temperature decrease        |
| Literature source(a): Arola (2015) |
| Lakes                | Size of lake                | Lake area and depth                                | Temperature decrease        |
| Literature source(a): Averfalk et al. (2017), European Heat Pump Association (2015), Fink et al. (2014), Gaudard et al. (2019), Kindachi et al. (2015), Lund and Persson (2016), Mustafa Omer (2008) and Zhen et al. (2007) |
| Rivers               | Based on flow of river      | Flow of river                                      | Temperature decrease        |
| Literature source(a): Averfalk et al. (2017), Gaudard et al. (2019), Lund and Persson (2016) and North et al. (2013) |
| Sea                  | Suitable areas based on depth | Depth charts                                      | Required depth              |
| Literature source(a): Averfalk et al. (2017), HELEN (2019), Lund and Persson (2016), Müller (2015) and Zhen et al. (2007) |
| Solar                | Solar irradiance           | Size of suitable area, global irradiance on the horizontal plane | –                          |
| Literature source(a): JRC (2021) and solar-district-heating.eu (2018) |
The data used in the case study mostly consists of publicly available data. The data was downloaded from online sources, bought from relevant institutions, or is based on interviews with the involved stakeholders. The techno-economic aspect of heat utilisation is not considered during the case study. It is also a possibility that some heat sources are already in use locally and thus cannot be used in DH production. This possibility is mentioned, but otherwise not considered in the estimations.

Some of the heat sources described earlier in this study were not included in the case study due to the heat source not being relevant in the Turku area, or because the required data could not be obtained. There are no underground train systems in the studied area, and no potential could thus be estimated. The heat potential of ambient air, solar and seawater was not estimated due to the potential being directly dependent on the capacity of the heat recovery system. Data centres of varying size are

| Heat source                                | Used data                        | Source of data                                      | Annual heat potential (MWh) |
|--------------------------------------------|----------------------------------|----------------------------------------------------|-----------------------------|
| Industrial processes and production        | CO₂ emissions                    | E-PRTR (European Environment Agency 2021), Energiavirasto (2021) | 523,565                     |
| Data centres                               | –                                | –                                                  | –                           |
| District cooling                           | Amount of produced cooling       | District cooling producer (Turku Energia 2021)     | 2500–5000                   |
| Wastewater                                 | Water flow                       | Wastewater Treatment Plant (Turun Seudun Puhdistamo Oy 2021) | 191,169                     |
| Public transportation systems, underground trains | –                                | –                                                  | –                           |
| Electric cable tunnels                     | Cable load data                  | Local DSO (Turku Energia 2021)                     | 18                          |
| Power transformers                         | Transformer load data            | Local DSO (Turku Energia 2021)                     | 10,380                      |
| Building, ventilation                      | Building stock data, specific energy consumption | Statistics Finland (2021)                        | 427,552                     |
| Building, grey water from residential apartment buildings | Building stock data, water consumption per capita | Statistics Finland (2021), Motiva (2021)            | 108,211                     |
| Building, cooling                          | Building stock data, specific energy consumption | Statistics Finland (2021)                        | 37,080                      |
| Refrigeration equipment, grocery stores    | Store electricity consumption data, store sizes | S-Group (2021)                                    | 120,933                     |
| Refrigeration equipment, ice rinks         | Ice rink electricity consumption | Jäähalliportaali (2021)                           | 19,030                      |

| Heat source                                | Used data                        | Source of data                                      | Annual heat potential (MWh) |
|--------------------------------------------|----------------------------------|----------------------------------------------------|-----------------------------|
| Shallow geothermal heat                    | 300 m heat potential             | GTK (Geologian Tutkimuslaitos 2021a)                | 516,000*                    |
| Deep geothermal heat                       | –                                | –                                                  | –                           |
| Groundwater                                | Groundwater areas and heating potential | GTK (Geologian Tutkimuslaitos 2021c)               | 10,240                      |
| Lakes                                      | Lakes sizes and locations        | SYKE (Suomen Ympäristökeskus 2021)                 | 10,215                      |
| Rivers                                     | River flow, water temperature    | SYKE (Korhonen 2007; Pöyry Finland Oy 2016; Suomen Ympäristökeskus 2021) | 21,702                      |
| Sea                                        | Sea depth                        | Baltic Sea Bathymetry Database (Baltic Sea Hydrographic Commission 2021) | –                           |
| Air                                        | Air temperature                  | PV-GIS (Joint Research Centre 2021)                | –                           |
| Solar                                      | Solar irradiation                | PV-GIS (Joint Research Centre 2021)                | –                           |

*With a borehole heat exchanger distance of 175 m. This is a theoretical potential since the use of geothermal heat may be limited in some areas. Nevertheless, the magnitude of this heat source is shown
known to exist in the studied area, but no relevant data could be obtained during the study. Data centres as a heat source were as such not included in the case study.

The local DH company in Turku, Turku Energia (Energia 2021), produced about 2100 GWh of DH in 2019. The annual potential of urban waste heat sources was estimated to 1483 GWh, and the natural heat potential was estimated to 42 GWh, excluding air, solar, seawater and shallow geothermal heat. Air, solar, and seawater are likely significant heat sources in the area. A comparison between the Turku DH heat supply and the annual estimated potential for the studied heat sources is visualised in Fig. 3.

Geothermal heat is often considered as an option for heating in cities, sometimes as an alternative for DH, although it also has its uses for DH heat supply. The potential of shallow geothermal heat in the Turku region was estimated to give an insight into the magnitude of this heat source. The potential was estimated to 516 GWh per year, with the assumption that 8000 boreholes would be constructed within the studied area, each 300 m deep and with a minimum distance of 175 m between the boreholes. The potential of medium or deep geothermal heat is larger, but it could not be estimated in the case study due to insufficient data and lack of representative implementations.

**Discussion**

The study revealed the scope and complexity of the topic, while also confirming the current need for finding solutions for it. Targeted data is very much sought after as input for energy system modelling used in planning the development

---

**Fig. 2** Overview of the area studied in the case study, including the local DH network and selected point heat sources
of DH systems. The results and lessons learned from both the literature review and the case study are highly useful and provide a solid basis for further research concerning the topic. An example on how to use the presented methods was demonstrated in a case study on the Turku area.

The Turku case study showed that the availability of data can vary greatly from one heat source to another, and that nearly all heat source data required processing to attain an acceptable level of detail. This processing can require deep insight on the utilisation of a specific heat source, often resulting in a heavy process. On a more general level, the quality of data depends on how detailed, how accurate, and how available the data is. If the data is lacking in any of these qualities, the usability of the data is also lacking. Figure 4 illustrates the connection between the quality and the obtainability of the data. Data of insufficient quality cannot be used, but the usability of poor-quality data can be improved with assumptions. The estimation methods presented in this study are thus not always the best methods for all cases, but are they are examples of methods working well with the data which is generally assumed to be available. One aspect related to data quality is uncertainty. This is a relevant factor especially if lots of processing and assumptions are required in potential estimation. Perfect data are rare, and usually found in the form of time series of measured data from a reliable source.

Some of the described heat sources are more commonly used for heat production in both DH systems and local heating systems. Large sources of heat, such as wastewater treatment plants, industrial processes and power production are examples of sources utilised in DH. In many cases with smaller individual heat sources, the heat potential is best utilised where it is generated. Here, the temporal availability is important.

The seasonal and diurnal fluctuations of some heat source potentials can severely mismatch with the seasonal fluctuations of heat demand. The heat potential of especially natural heat sources, such as ambient air and water bodies, follows the seasonal ambient temperature. Urban heat sources often follow this same pattern. This results in the heat potential

![Fig. 3](image_url) Comparison between the estimated heat source (natural and urban) potential and DH supply in Turku

![Fig. 4](image_url) The data quality hierarchy: high-quality, accurate data harder to obtain; refining assumptions can improve the quality of data
being higher during the summer, and lower during the winter—just the opposite to what is needed. In the end, this is reflected in the value of a specific heat source; heat sources available throughout the year or especially during the heating season are very interesting. Only the best resources available outside the heating season are utilised in practice. For this reason, the option of using seasonal, large-scale thermal storages is to be considered.

The estimated potentials for several heat sources in the case study were only annual values, as seasonal fluctuations could not be modelled due to the quality of the obtained data. The fluctuation in the potential of rivers could be determined using monthly flow and temperature data. The typical daily profile of power transformers, electric cable tunnels and grocery stores could be determined using hourly load data. The results of the case study thus do not fully show if the heat is available when there is heat demand. This issue represents one of the most important topics for further research. One starting point could be to apply a typical availability profile for a specific heat source to the annual potential estimate. In this case local conditions and possible constraints must be taken into consideration.

Another topic for further research is the representation of the uncertainty related to potential estimations including numerous assumptions. In further work within the topic, estimated potentials could be presented as a range of values instead of single values in order to better show the uncertainties in the estimation process.

As the topic of utilising waste heat and renewable heat sources is highly interesting, more research on specific heat sources or groups of heat sources will accumulate. This study represents a framework that can utilise new results and methods—possibly including new heat sources. The results are and will be highly useful for modelling and planning, further leading to practical feasibility studies for the utilisation of the heat sources in question.

Conclusions

This paper summarises the findings of a recent study (Sundell 2021). The study addresses the shortcomings in previous work within the field. The results from these earlier studies and publications give insight into the potential of the studied heat sources and make a significant contribution to estimating a potential of a heat source within specific area. However, the estimation of heat potential has often been based on detailed data obtained through field measurements, been limited to a specific area, considered a limited selection of heat sources, been based on rough averages, or a combination of these. The results from these studies cannot thus be used to support decision-making on a DH system level or city level as such.

A replicable methodology for estimating the potential of urban waste heat sources and natural heat sources found in the urban environment is presented. Possible heat sources and previous efforts on the subject were identified in an extensive literature study. Estimation methods based on the literature study and developed around publicly available or otherwise easily obtainable data were presented.

The presented estimated methods were applied in a case study in which the potential of heat sources in Turku in Southwest Finland was estimated. The case study gives an example of how the presented estimation methods can be used and where the required data can be found. The difficulty of obtaining high quality relevant data is highlighted in the case study. The experience from the case study indicates that the used estimation approach could be applied to other cities or urban areas as well.

In short, this study presents a comprehensive assessment methodology for the potential of heat sources, pragmatic investigation on what sources of data exist and possible methods for processing this data. Future efforts within the subject include identifying additional heat sources, further refinement of the presented methods, and adding the techno-economic aspect of heat use.

Author contribution Both authors contributed to the planning and implementation of the study. The literature study, development of methods, and acquisition and analysis of data in the case study was mostly done by Dennis Sundell with the assistance of Miika Rämä. The final version of this paper is mostly prepared by Dennis Sundell, with input and improvement suggestions from Miika Rämä. Discussion and analysis were carried out jointly.

Funding Open Access funding provided by Technical Research Centre of Finland (VTT). The work carried out was funded by VTT Technical Research Centre of Finland, Finnish Energy and Turku Energia.

Data availability A large part of the data used and obtained during the study is publicly available, while other data was acquired through other means and is not publicly available. The resulting generated datasets are thus not freely available due to them containing confidential data. A slice of the generated datasets, excluding confidential data, can be acquired via a request to the corresponding author. The sources of data are naturally included in references.

Declarations

Conflict of interest The authors of this study have no relevant financial or non-financial conflicts of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated
otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Abi-Zadeh D et al (2003) King’s Cross St Pancras Underground Station redevelopment: assessing the effects on environmental conditions. Undergr Constr (December): 641–653

Ammar Y et al (2012) Low grade thermal energy sources and uses from the process industry in the UK. Appl Energy 89(1):3–20. https://doi.org/10.1016/j.apenergy.2011.06.003

Ampofo F, Maidment G, Missenden J (2004) Underground railway environment in the UK Part 2: investigation of heat load. Appl Therm Eng 24(5–6):633–645

Arias J (2005) Energy usage in supermarkets: modelling and field measurements. Doctoral dissertation, KTH. http://www.diva-portal.org/smash/get/diva2:7929/FULLTEXT01.pdf

Arola T (2015) Groundwater as an energy resource in Finland. Academic dissertation, University of Helsinki. https://helda.helsinki.fi/bitstream/handle/10138/158293/groundwa.pdf?sequence=1

Averfalk H et al (2017) Large heat pumps in Swedish district heating systems. Renew Sustain Energy Rev 79(June 2016):1275–1284. https://doi.org/10.1016/j.rser.2017.05.135

Averfalk H, Ingvarsson P, Persson U, Werner S (2014) On the use of surplus electricity in district heating systems. In: The 14th international symposium on district heating and cooling, pp 7–12. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A754855&amp;dswid=67

Baltic Sea Hydrographic Commission (2021) Baltic sea bathymetry database. http://data.bshc.pro/#4/60.21/23.02 (Sept 2021)

Brueckner S et al (2014) Methods to estimate the industrial waste heat potential of regions—a categorization and literature review. Renew Sustain Energy Rev 38:164–171. https://doi.org/10.1016/j.rser.2014.04.078

Brueckner S et al (2015) Industrial waste heat recovery technologies: an economic analysis of heat transformation technologies. Appl Energy 151:157–167

Cronholm L-A, Grönkvist S, Saxe M (2009) Spillvärme Från Industri Och Lokaler. Swedish District Heating Association, p. 116. http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A775871&amp;dswid=691

David A et al (2017) Heat Roadmap Europe: large-scale electric heat pumps in district heating systems. Energies 10(4):1–18

Davies G et al (2017) Metropolitan integrated cooling and heating. In: ASHRAE Winter Conference

Davies G et al (2019) CIBSE technical symposium electrical cable tunnel cooling combined with heat recovery, in Cities

Department for Business & Energy & Industrial Strategy (2016) Building Energy Efficiency Survey (BEES) 2014–2015. https://www.gov.uk/government/publications/building-energy-efficiency-survey-bees

Ebrahim K, Jones GF, Fleischer AS (2014) A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renew Sustain Energy Rev 31:622–638. https://doi.org/10.1016/j.rser.2013.12.007

Energivirasto (2021) Päästökaupan Julkaisut. https://energivirasto.fi/paastokaupan-julkaisut. 21 Sept 2021

European Commission (2016) An EU Strategy on Heating and Cooling (COM (2016) 51 Final)

European Environment Agency (2021) European Industrial Emissions Portal. https://industry.eea.europa.eu/. 21 Sept 2021

European Heat Pump Association (2015) The World’s Largest ‘Natural’ District Heat Pump. https://www.ehpa.org/about/news/article/the-worlds-largest-natural-district-heat-pump/. 21 Sept 2021

European Parliament Council of the European Union (2018) Revised Renewable Energy Directive 2018/2001/EU. http://data.europa.eu/eli/dir/2018/2001/oj. 21 Sept 2021

Fink G, Schmid M, Wüst A (2014) Large lakes as sources and sinks of anthropogenic heat: capacities and limits. J Water Resour Res 50(9):7285–7301

Gaudard A, Wüst A, Schmid M (2019) Using lakes and rivers for extraction and disposal of heat: estimate of regional potentials. Renew Energy 134:330–342. https://doi.org/10.1016/j.renene.2018.10.095

Geologian Tutkimuslaitos GTK (2021a) Geothermal energy potential: 300 m Geoenergy Potential. https://tupa.gtk.fi/paikkatieto/meta/geoterminen_energiapotentiaali_300_m_geonenergiapotentiaali.html. 21 Sept 2021

Geologian Tutkimuslaitos GTK (2021b) Geothermal energy potential: deep geothermal energy potential. https://tupa.gtk.fi/paikkatieto/meta/geoterminen_energiapotentiaali_syva_geoterminen_energiapotentiaali.html. 21 Sept 2021

Geologian Tutkimuslaitos GTK (2021c) Hakku—Portti Suomen Geologiseen Tietoon. https://hakku.gtk.fi/fi/locations/search. 21 Sept 2021

Guo X, Hendel M (2018) Urban water networks as an alternative source for district heating and emergency heat-wave cooling. Energy 145:79–87

Hazi A, Hazi G, Vernica S-G (2013) Opportunity study for heat recovery from large power transformers in substations. Termotechnica Supliment 1(2013):1871–2247

Helsingin Energia (2019) Merivesilämpöpumput Kiinnostava Mahdollisuu Myös Helsingissä. https://www.helen.fi/helen-oy/vastuullisuus/ajankohtaista/blogi/2019/merivesilampopumput. 21 Sept 2021

Hemmilä K, Laitinen A (2018) Tavoitteena Nollaenergialikuntarakenne. VTT Technical Research Centre of Finland, p.81. https://publications.vtt.fi/pdf/technology/2018/T320.pdf

Iglitski B et al (2021) Can energy self-sufficiency be achieved? Case study of Warmińsko-Mazurskie Voivodeship (Poland). Clean Technol Environ Policy 23(7):2061–2081. https://doi.org/10.1007/s10098-021-02103-1

International Ice Hockey Federation (2016) IIHF Ice Rink Guide: 108. http://www.iihf.com/fileadmin/user_upload/PDF/Rink_Guide/IIHF_Ice_Rink_Guide_web_pdf.pdf

Jäähalliportaalit (2021) Ice Stadium Portal. https://jaahalliportaalit.fi/. 21 Sept 2021

Joint Research Centre (2021) Photovoltaic geographical information system. https://re.jrc.ec.europa.eu/pvg-tools/en/. 21 Sept 2021

Kallio J et al (2019) Helsingin Geoenenergiapotentiaali. Helsingin Kulkunen & Kaupunkiympäristön Toimiala

Kondaichi S, Nishina D, Wen L, Kannaka T (2015) Potential for using transformer cooling combined with heat recovery, in Cities

Korhonen J (2007) Suomen Vesistöjen Virtaaman Ja Vedenkorkeuden Vaihtelut. Suomen Ympäristö, Päiväys

Kulkarni SV, Khaparde SA (2004) Transformer engineering transition and finalization. Marcel Dekker, New York

Korhonen J (2007) Suomen Vesistöjen Virtaaman Ja Vedenkorkeuden Vaihtelut. Suomen Ympäristö, Päiväys

Kulkarni SV, Khaparde SA (2004) Transformer engineering transformation engineering. Marcel Dekker, New York

Liddament MW, Orme M (1998) Energy and ventilation. Appl Therm Eng 18(11):1101–1109

López L et al (1998) Determination of energy and exergy of waste heat in the industry of the Basque Country. Appl Therm Eng 18(3–4):187–197
Reindl DT, Jekel TB (2007) Heat recovery in industrial refrigeration. ASHRAE J 49(8):22–28
Revesz A et al (2016) Ground source heat pumps and their interactions with underground railway tunnels in an urban environment: a review. Appl Therm Eng 93:147–154. https://doi.org/10.1016/j.applthermaleng.2015.09.011
Saha BK, Chakraborty B, Dutta R (2020) Estimation of waste heat and its recovery potential from energy-intensive industries. Clean Technol Environ Policy 22(9):1795–1814. https://doi.org/10.1007/s10098-020-01919-7
Sandberg, K (2015) Jarrutusenergian Talteenotto Helsingin Metro- Ja Raitioliiikenteessä
Sejbjerg A et al (2015) Overskudsvarme Fra Dagligvarebutikker. Bachelor’s thesis. Aalborg University
S-Group (2021) Data received through discussions with the company. https://s-ryhma.fi/en. 21 Sept 2021
Signorelli S (2004) Geoscientific investigations for the use of shallow low-enthalpy systems. PhD (15519): 175. https://doi.org/10.3929/ethz-a-010025751
Solar District Heating EU (2018) Ranking list of European Large Scale Solar Heating Plants. Solar-District-Heating.Eu: 1. http://solar-district-heating.eu/ServicesTools/Plantdatabase.aspx#. 21 Sept 2021
Statistics Finland (2021) Data received after discussions with the Organization. https://www.stat.fi. 21 Sept 2021
Strbac G et al (2014) Management of electricity distribution network losses. http://www.westernpower.co.uk/docs/Innovation-and-Low-Carbon/Losses-strategy/SOHN-Losses-Report.aspx
Sundell D (2021) A method for systematic mapping of heat sources in an urban area. Master’s thesis: 86. https://aaltdoc.aalto.fi/handle/123456789/103047
Suomen Ympäristökeskus (2021) Ranta10 - Rantaviiva 1:10 000. https://ckan.ymparisto.fi/dataset/%7BC40D8B4A-DC66-4822-AF27-7B382D89C8ED%7D. 21 Sept 2021
The Green Grid (2007) The green grid data center power efficiency metrics: PUE and DCiE. White paper. The Green Grid
Turku Energia (2021) Data received after discussions with the Company. https://vsk2021.turkuenergia.fi/en/business-review/. 21 Sept 2021
Turun Seudun Puhdistamo Oy (2021) Turun Seudun Puhdistamo. https://www.turunseudunpuhdistamo.fi/tulopumppaus. 21 Sept 2021
VanSchenkhof M (2011) An investigation of water usage in casual dining restaurants in Kansas. Kansas State University, Manhattan
Wahlroos M et al (2018) Future views on waste heat utilization—case of Data Centers in Northern Europe. Renew Sustain Energy Rev 82(July 2017):1749–1764. https://doi.org/10.1016/j.rser.2017.10.058
Werner S (2017) District Heating and Cooling in Sweden. Energy 126:419–429. https://doi.org/10.1016/j.energy.2017.03.052
Zhen L et al (2007) District cooling and heating with seawater as heat source and sink in Dalian. China Renew Energy 32(15):2603–2616

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.