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Thermal Energy from Drinking water for District Heating

A case study on the potential of the drinking water distribution network as a sustainable energy source for district heating in Göteborg.

Master’s thesis in Industrial Ecology

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Thermal energy from drinking water for district heating: a case study on the potential of the drinking water distribution network as a sustainable energy source for district heating in Göteborg.

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Preface and acknowledgement

I am pleased to present this Master of Science thesis, titled ‘Combining the water and energy sector: a research on the potential of the drinking water pipeline distribution network as a sustainable energy source for district heating in Göteborg’, as the peak of my academic journey. This research effort would not have been possible without the guidance, support, and contributions of various individuals and resources that have shaped the trajectory of my work.

I extend my deepest gratitude to my supervisor, Thomas Petterson, and my examiner, Oskar Modin, for their support from the very beginning and their trust in my progress. Their insightful guidance and expertise have been instrumental in steering my research in the right direction. I want to convey my appreciation to my supervisor’s constructive feedback and valuable insights during the review process. His thoughtful comments have significantly contributed to refining the quality of this work and his mentorship and encouragement have enriched my growth as a researcher.
I am also sincerely grateful for Stefan Mol, whose help and expertise has significantly contributed to both my understanding of the subject matter and the execution of my analysis. His openness, knowledge and experience enhanced the quality of this report.
Furthermore, I wish to acknowledge Behroz Haidarian for his time, interest and support, which has enabled the execution of data collection.
Lastly, my sincere appreciation goes to my boyfriend, family and friends for their unwavering encouragement. Your belief in me has been a constant source of motivation.

This thesis is not only a representation of my academic pursuits but also a reflection of the broader scholarly conversations in Industrial Ecology, sustainable heating and Thermal Energy from Drinking water (TED) specifically. It is my hope that this work will inspire future researchers to explore these themes further.

I appreciate you joining me on this intellectual journey. I invite you to delve into the following pages and join me in the exploration of TED.

Pien A. Esmeijer
August, 2023

Executive summary

As an alternative to fossil fuels as energy sources for heating and cooling, there is thermal energy available in water that is left unused (KWR, 2022). Recovering thermal energy from drinking water (TED) presents itself as a feasible strategy to offer sustainable heating solutions for both newly developed and existing communities, facilitating the shift towards sustainable approaches to heating (KWR, 2022). The technology behind combining the water and energy sector through the supply of TED is already developed. TED installations have been implemented and operating in the Netherlands for about 15 years (Oesterholt & Moerman, 2022).

Through the analysis of three sustainability criteria, the sustainability of TED at a candidate TED location of Göteborg Kretslopp och vatten in Göteborg, as an input to a local district heating network (DHN) for residential houses is explored. These three criteria are energy supply, costs per house and CO_2emissions. This report compared three DHN scenarios in Göteborg, based on the results of these criteria. The DHN scenarios that are compared in this report are:

1. TED in a DHN of 70 °C with the use of gas
2. TED in a DHN of 70 °C without the use of gas
3. The current conventional DHN of 86 °C in Göteborg.

A heat and power chain template, provided by S. Mol (personal communication, June 7, 2023), is used to formulate the different scenarios, simulate, analyze and eventually compare them.

From comparison of the different district heating (DH) scenarios in Göteborg, first of all it can be concluded that a DHN including a TED installation can meet the heat demand of approximately 1000 multi-family houses in Göteborg, with a thermal energy input of around 9 million kWh. With the same amount of thermal energy input from the current DH energy sources, approximately 600 multi-family houses in Göteborg can be heated. Secondly, further research must be done on the costs of the DH scenarios in order to enable comparison. Thirdly, a DHN including TED shows lower levels of CO_2 emissions compared to a DHN with the current energy sources. Thus, based on two of the three criteria, a TED installation is a more sustainable option in a DH system in Göteborg than DH using conventional thermal energy sources for multi-family residential housing in Göteborg.

This research shows that Göteborg Kretslopp och vatten could fulfill a new role as energy supplier. The framework presented in this research gives insights into the theoretical potential of TED in a specific location and can be a good start for determining the theoretical potential of a TED project in a certain location and comparison of the sustainability of TED projects to other TED projects and heating systems. Further research is needed to map out other potential TED locations, which will give insights into the total potential of TED in Göteborg.

Keywords: Thermal energy, Drinking water, Thermal energy from drinking water (TED), Sustainability, District heating (DH), Renewable energy (RE), Sustainability criteria, Drinking water distribution system (DWDS).

List of abbreviations

ATES	Aquifer Thermal Energy Storage
BITES	Building Inertia Thermal Energy Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance (see “list of definitions” for the definition)
DC	District Cooling
DH	District Heating
DHN	District Heating Network
DHW	Domestic Hot Water
DWDS	Drinking Water Distribution System
HE	Heat Exchanger
HOB	Heat-Only Boiler
HP	Heat Pump
kWth	Kilowatt-thermal
MCDA	Multi-Criteria Decision Analysis
RE	Renewable Energy
SH	Space Heating
SMW	Solid Municipal Waste
SPF	Seasonal Performance Factor
TCO	Total Cost of Ownership
TED	Thermal Energy from Drinking water
TES	Thermal Energy Storage
TEW	Thermal Energy from Wastewater
VMK	‘Värmemarknadskommittén’ (‘The Heating Market Committee’)
WTP	Water Treatment Plant

List of definitions

Aquathermia	Aquathermia is the collective name for sustainable heating and cooling by extracting thermal energy from water.
COP	The coefficient of performance (COP) indicates how much thermal energy a component in a climate system supplies compared to the amount of (sustainable or fossil) energy that component itself requires. The definition of the COP is the quotient of the energy supplied and the energy used. The instantaneous COP varies greatly and depends on the occurring demand for heat or cooling and the exergetic value of the heat in the source. (van Bel et al., 2017)
Full load hours	A representative number at full capacity utilization of an installation.
Regeneration	Regeneration of an ATES is when the thermal energy source supplies heat or cold to the ATES.

Having a printed copy of this page while reading the report would assist the author in comprehending the content more effectively. The abbreviations listed here are used extensively throughout the report, and having them readily accessible would prevent any disruptions in the reading flow and enable a deeper understanding of the details in the report.

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1. Introduction

The societal relevance of this study concerns today's energy-use and its environmental effects. Because of the increasing scarcity of fossil fuels, the world is striving for more sustainable and renewable energy (RE) sources. It is time for us to search for and implement technologies working on alternative energy sources and making efficient use of resources to make the transition to a more sustainable world. The central challenge in advancing building sustainability revolves around fulfilling their heating requirements (KWR, 2022). Increasing gas prices and often environmentally unfriendly conventional heating systems ask for investigation and implementation of more efficient heating technologies, to create more sustainable urban lives. In the context of the energy transition, also for drinking water companies, reduction and sustainability of energy consumption and lowering the CO_2footprint are important objectives. As an alternative to fossil fuels as energy sources for heating, there is thermal energy available in water that is left unused. Recovering thermal energy from drinking water (TED) presents itself as a feasible strategy to offer sustainable heating solutions for both newly developed and existing communities. Implementing TED for the purpose of heating buildings holds substantial potential to contribute significantly at the community level, facilitating the shift towards sustainable approaches to heating and cooling. (KWR, 2022) Combining the water and energy sector in this way could be of significant value when it comes to sustainability in our society.

According to Van Alphen et al. (2016), for the drinking water companies, operational energy is essential for their own processes, while talking about thermal energy means a broadening of the sector. The report by Van Alphen et al. (2016), describes a cross-sectoral exploration of the package of (energy) services that the water chain can provide. The right conditions for projects in the field of energy and water to be successful are described as follows. Firstly, legal barriers must be overcome and stable project management with evaluation helps prevent repetition of errors. To make a sound business case, a longer term vision is important. In addition, the shared goal and the distribution of tasks and risks must be determined in advance. Good communication between the various parties is crucial for this. In addition, the right expertise creates trust. A binding sustainability objective that provides backing and motivation from the organization can speed up decision-making. Lastly, for the project to be successful, the involvement of a requesting customer (end user) is necessary. Hence, barriers and success factors in projects in the field of 'energy and water' at drinking water companies are stated to be of non-technological nature (van Alphen et al., 2016). The technology behind combining the water and energy sector through the supply of TED is already developed. TED installations have been implemented and operating in the Netherlands for about 15 years (Oesterholt & Moerman, 2022). Amsterdam was the first city to put TED into practice on an industrial scale, in the Waternet-Sanquin case (Reinstra et al., 2019).

There is an increasing attention for aquathermal energy (KWR, 2022), which calls for a knowledge bundling and sharing response. This study tries to enhance knowledge distribution internationally, by applying existing knowledge on a potentially new location for TED. To apply this existing knowledge, a generic framework based on sustainability criteria is created, in order to improve the possibility to compare the potential of TED projects. The potentially new location that is being studied in this research is a location of the drinking water distribution system (DWDS) of Göteborg Kretslopp och vatten in Göteborg, Sweden.

1.1. Aim

This study focuses on examination of the potential of TED, specifically from drinking water distribution pipelines in the urban environment. This study investigates and presents criteria that can be used for future decision making tools or sustainability assessments used for assessing TED, to contribute to knowledge sharing and exploration of potential TED locations and to generate a more generic and international approach. A comparison analysis is done on the results of the most relevant criteria for assessing the potential of a TED system. The different scenarios that are being analyzed and compared are:

1. Scenario 1: Energy and water sector are integrated. Göteborg Kretslopp och vatten utilizes TED, for heating of residential houses that are connected to a local district heating network (DHN). Utilization of gas is included.
2. Scenario 2: Energy and water sector are integrated. Göteborg Kretslopp och vatten utilizes TED, for heating of residential houses that are connected to a local DHN. No gas is used.
3. Scenario 3: Energy and water sectors are not integrated. Göteborg Kretslopp och vatten does not utilize TED. The input into a local DHN for heating of residential houses is from conventional thermal energy sources.

The results of the comparison are used to formulate a recommendation regarding potential implementation of TED at the candidate location of a drinking water pipeline of Göteborg Kretslopp och vatten in Göteborg, Sweden.

1.2. Research questions

1. What criteria are commonly included in sustainability assessments?
2. What sustainability assessment criteria are relevant for assessing TED?
3. What is the potential of TED implementation at the candidate location of Göteborg Kretslopp och vatten as heat input into a DHN?
4. Based on comparison of the sustainability assessment criterium 'CO_2 emission', would TED implementation as input into a DHN be more beneficial than the current DHN?

1.3. Limitations

The system boundaries of this study include the drinking water company as the provider of thermal energy, including its pipelines and the TED installation, and residential houses as the consumers of thermal energy (for heating purposes). This study limits itself to the comparison of two different scenarios on DH. Namely, a DHN of 70 °C including a TED installation as an input to the DHN and the conventional Swedish DHN of 86 °C. The total DHN systems (from the TED installation extracting thermal energy from the drinking water pipeline to the heat supply to the end consumer in the DHN) are included in the analysis, including the installation and operation. Lastly, this study limits itself only to calculation, study and comparison of the criteria that are selected in this report.

2. Theoretical background

In this chapter, first of all an introduction and explanation on aquathermia is provided. Moreover, the concept of TED and its generic construction are explained. Lastly, information on the thermal energy demand and supply in Sweden is provided.

2.1. Aquathermia

Aquathermia is the collective name for sustainable heating and cooling with water (Unie van Waterschappen, 2022). Aquathermia is the process of extracting thermal energy from water, specifically targeting water with temperatures between 7 and 25 °C. The water acts as a low-temperature heat source, making it ideal for capturing heat during the summer months, and cold during winter months. The harvested heat is stored and used during the colder winter months, requiring a system for seasonal storage. Using an underground aquifer seems like the best choice for this purpose. Aquifers are commonly used for open ground energy systems, an Aquifer Thermal Energy Storage system (ATES), storing heat and cold. Integrating such a system with aquathermia is a scientifically justified and practical approach. (Kruit et al., 2018)

Thermal energy extracted from water can be categorized into different water sources:
1. Thermal energy from wastewater;
2. Thermal energy from drinking water (TED);
3. Thermal energy from surface water;
4. Thermal energy from groundwater (van der Hoek et al., 2018).

This study focuses on thermal energy from drinking water (TED), and will further elaborated on in next chapter.

2.1.1. Thermal Energy from Drinking water (TED)

Heat and cold can be extracted from the drinking water running through the pipelines every day (de Fockert et al., 2022). The extraction of thermal energy from drinking water can be done at three positions in the drinking water chain: in the raw (ground or surface) water, in clean water reservoirs or in drinking water distribution pipes (van Bel et al., 2017). This study focuses on the latter.

A TED system is designed to either extract heat from drinking water or transfer heat to it. In practical terms, TED systems focus on the drinking water in distribution pipes, which are essential components of the public infrastructure for delivering drinking water. These pipes supply cooled or heated drinking water to consumers. The extracted or added heat is commonly used, either directly or indirectly through an ATES system, for heating or cooling one or more buildings, for example in a DHN (Kruit et al., 2018). In the case of heating, it is necessary to elevate the heat to a suitable higher temperature using an electric HP (de Fockert et al., 2022). This can be achieved by utilizing either a collective heat pump system or individual heat pumps for each building (Kruit et al., 2018). Eventually, this thermal energy exchange results in a reduced demand for primary or fossil energy to maintain the desired temperature levels within the buildings. (van Bel et al., 2017)

An advantage of TED is that it can be applied to existing infrastructure in urban areas. So often very little additional infrastructure construction is needed. Because drinking water networks are widely existing, the application of these types of heat and cold sources is promising and offers opportunities to contribute to more sustainable heat and cold supply. Besides, compared to extraction from surface waters or wastewater, pre-purification for the heat exchanger (HE) is not necessary, because purified drinking water is used. (de Fockert et al., 2022) Drinking water being more biologically stable than for example surface water, leads to less biofilm formation in the HE and less frequent maintenance in drinking water pipes (Oesterholt & Moerman, 2022). With TED, the cold and heat recovery are bound to the requirements that apply to the quality of the drinking water (de Fockert et al., 2022).

According to Van der Hoek et al. (2018) and De Fockert et al. (2022), to address the seasonal mismatch between supply and demand of heat or cold, a thermal energy storage (TES) system such as an ATES should be implemented (see **Figure 2.1.**). By incorporating such a system to compensate for the imbalance in demand for heating and cooling, the potential heating and cooling capacity increases significantly. A combination of TED and an ATES means that drinking water heats up in the winter and cools down in the summer (de Fockert et al., 2022). In this way, the potential of TED can be used to the maximum.

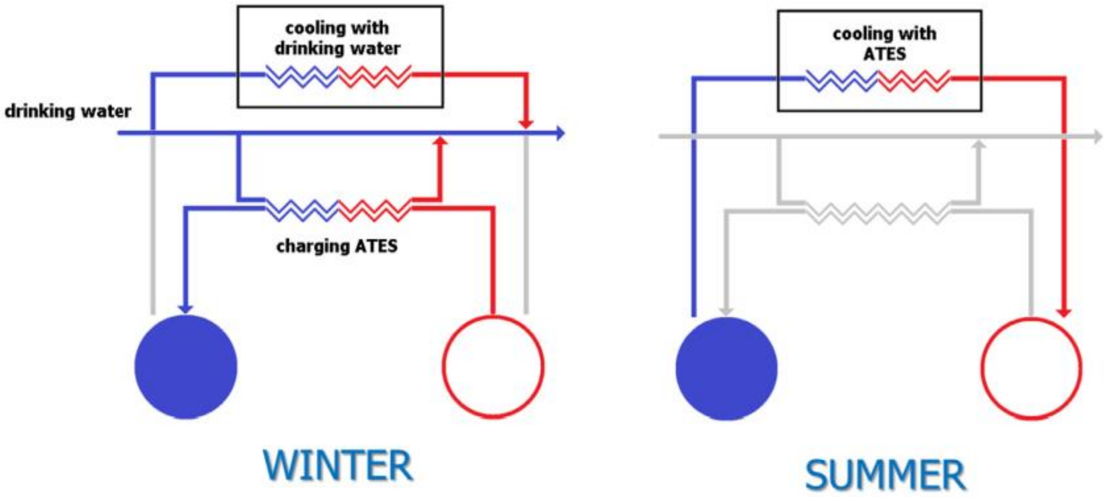

Figure 2.1. *The process of cooling using TED during different seasons (winter and summer) including the use of an ATES. (Figure from van der Hoek et al., 2018).*

To give an idea of the energy potential of TED, for the whole of the Netherlands at a temperature (T) difference of 2°C and taking into account the volumetric heat capacity of water of 4.2MJ/m^3/K, the potential thermal energy to be supplied from drinking water is 6.3 PJ (6.3·10^{15} J). The total heat demand of the built environment in 2015 was 463 PJ, of which 327 PJ households and 136 PJ service sector. The potential of TED in the Netherlands then amounts to a maximum of 1.4% of the total heat demand of the built environment. (van Bel et al., 2017)

The role of TED in the energy transition therefore seems to remain limited, however in many cases a bigger temperature difference can be realized and there are more issues and applications that should be further researched and could increase the efficiency and potential of TED. For example, De Fockert et al. (2022) calculates the potential of TED from pipelines differing in diameter and thus volume flow. The article states that the potential of TED is mainly in large transport pipelines for drinking water and so-called pre-treated raw water. Based on the assumption of a temperature change of 2 °C, the following scale sizes were distinguished:

- Raw water transport pipelines for dune infiltration (1,000 - 5,000 m^3/hour); capacity TED: 5,000 to 10,000 kWth (1,750 – 3,500 homes).
- Transport pipes for drinking water (primary network; 100 - 500 m^3/hour); capacity TED: 500 – 2,000 kWth (175 - 700 homes).
- Supplying distribution pipes in residential areas (secondary network; 10 - 50 m^3/hour); capacity TED: 50 - 200 kWth (15 - 70 homes).
- Pipelines in the street (tertiary network) capacity TED: < 50 kWth (< 15 homes).

So, according to De Fockert et al. (2022), the potential varies, assuming an average volume flow in a pipeline, from 50 kWth (approximately 15 homes) with a larger distribution pipeline to 10,000 kWth with a large raw water pipeline (approximately 3,500 homes) (de Fockert et al., 2022).

2.1.2. Generic construction and characteristics of a TED system

A schematic principle of the building blocks of a TED system is shown in **Figure 2.2.** and elaborated as follows:

The TED source.
1. This is the drinking water that flows through a drinking water pipeline.

A bypass of the pipeline (primary circuit).
2. This enables supply and discharge of drinking water to the HE. The connection to a thermal source in the drinking water system is realized with a bypass, because it should be possible to carry out maintenance on the TED system without affecting the most important task of a drinking water company, being the supply of clean and safe drinking water. In other words, installing a TED system should not affect the operational management of the drinking water supply network. (Oesterholt & Moerman, 2022)

A (double plated) HE in the drinking water system.
3. A double plated titanium HE is recommended against corrosion and leakage.
4. **The connection to a DHN or a TES (secondary circuit).**

Additionally, circulation pumps are included in the installation, for transporting the water through the circuits. Moreover, sensors and a technical room with the purpose of monitoring the installation are included. A photo of the oldest TED installation in the Netherlands is provided in **Figure 2.3**. An important note is that without using a heat buffer or thermal energy storage system, TED can only supply heat when the supply and demand of heat match throughout the days and seasons (Moerman et al., 2021). Anothers important note is that the drinking water pipeline network and the DH pipeline network are two separate systems. This means that the drinking water is never in direct contact with the DH liquid.

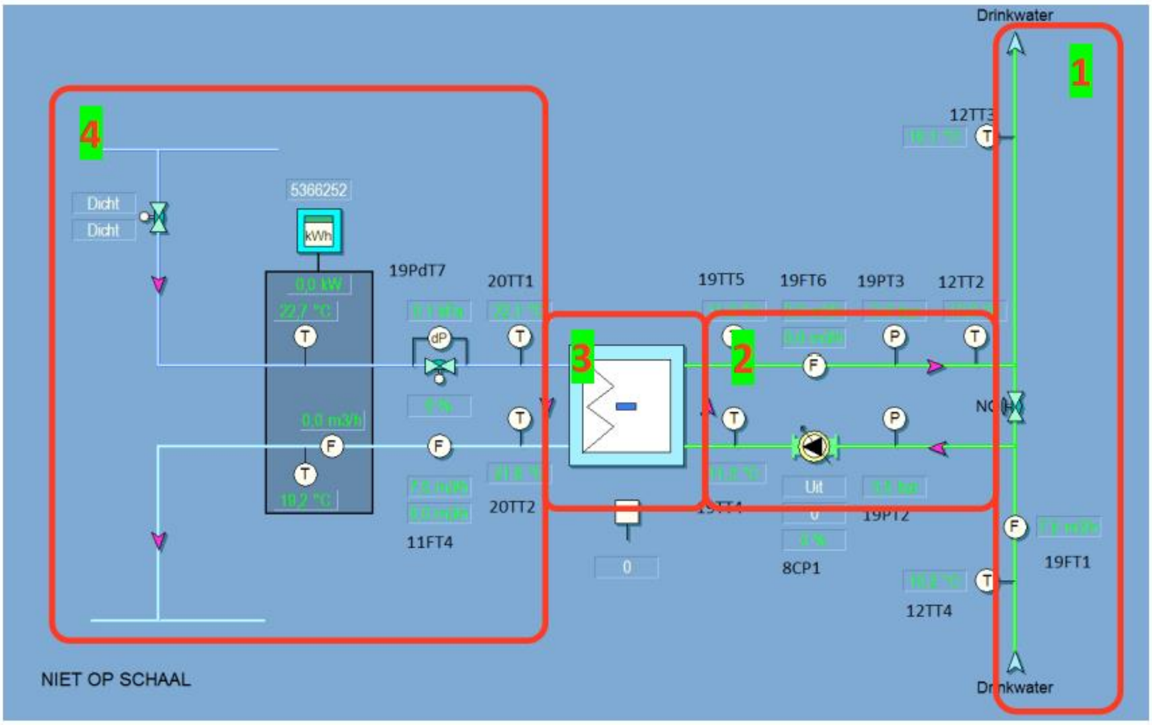

Figure 2.2. *Schematic principle of a TED system of which the source is a drinking water pipeline. The building blocks are as follows: (1) TED source, (2) By-pass unit, (3) HE, (4) DHN. (Figure from Oesterholt & Moerman, 2022).*

Figure 2.3. *A photo of the oldest TED installation in the Netherlands, including a heat exchanger (HE) (left) and a heat pump (HP) (right), that is owned by an energy corporation and extracts heat from a drinking water company's clean water reservoir. (Figure from KWR, 2022).*

There are different variables that affect the potential outcome of the TED installation, being temperature, volume flow (or pipeline diameter) and operating hours. Below, you find an elaboration on these variables and how they affect the outcome of the installation.

Temperature

To understand the potential of TED, it is important to understand the temperature dynamics of drinking water within the pipeline network. The temperature of drinking water undergoes changes while being transported through the distribution system. Research indicates that by the time drinking water reaches the consumer, it tends to reach the approximate temperature of the surrounding soil. This is due to heat exchange occurring between the water and the soil during the transportation process. As the soil temperature is different at different depths, also, the depth of the pipes affects the temperature of the drinking water (Alam et al., 2015). The impact of soil on the drinking water temperature is most significant in smaller pipes within the distribution network, while larger transport pipes experience a smaller influence. How fast the drinking water will reach the soil temperature depends on the material of the pipe, the diameter of the pipe and the velocity of the drinking water flow through the pipes (Blokker et al., 2013). Depending on the water source (groundwater, surface water) and the season, the drinking water may heat up or cool down as it travels from the source to the consumer, which implies that the drinking water distribution network can act as a collector of geothermal energy. (de Fockert et al., 2022) (Moerman et al., 2021) In general, for smaller drinking water pipes it can be assumed that the drinking water has the same temperature as the surrounding soil. For transport pipelines, the temperature depends on the source (for example groundwater or surface water) and the residence time in the transport network. (Moerman et al., 2021)

The thermal energy that can be extracted (T) depends on a few variables: (1) the temperature of the water at the site, (2) the system used to extract heat from the water, and (3) local conditions such as regulations, that for example affect the maximum and minimum temperature of the water.

1. The temperature of the water on site is influenced by location, as downstream locations have a temperature equal to that of the soil. At the treatment plant and some parts of the transport network, the temperature of the water when it enters the pipeline is more significant.
2. Specifications of the double-walled plate HE or countercurrent device. S. Mol explains the concept of a HE as follows (personal communication, July 19, 2023): in a HE, a cold and a hot stream flow counter currently and exchange heat. These flows are coming from the drinking water pipeline (hot flow) and the ATES (cold flow). The temperature difference between the countercurrent flows causes this heat exchange. The speed of the volume flow through the HE, which is regulated by pumps and determines for how long the flows are going through the HE, affects the outcome temperature. The longer it stays in the HE, the closer the cold source input temperature will get to the hot source input temperature. The temperature difference that you want to achieve is therefore regulated by these pumps. For an infinite size HE, the two flows will have an equal temperature when they leave the HE, but in practice a maximum temperature that is reached is the temperature of the hot source minus one degree, and the minimum temperature that is reached is the cold source plus one degree. To conclude, the temperature of the countercurrent flow, in combination with specifications of the HE, determines the temperature change of the water;
3. Drinking water companies establish prerequisites for heating and cooling of drinking water, because of maintenance and protection of the drinking water quality (Moerman et al., 2021).

According to S. Mol (personal communication, July 5, 2023), when heat from TED is transferred to a HP, it is important to understand that the input temperature into a HP affects the efficiency of the HP. The bigger the temperature difference between the HP input temperature and the HP output temperature, the lower the efficiency of the HP. The temperature difference is used to calculate the thermal heat [kWh] and the power [W] of the HP that is available, and the temperature itself affects the efficiency of the HP. That is why TED installations with the purpose of extracting heat are suggested to run during summer, when the temperature of the drinking water is highest.

Volume flow

For most pipes close to the consumers, the volume flows of drinking water fluctuate strongly during a 24-hour period. This is because drinking water consumption at the customer determines the flow in the mains network and drinking water consumption is not constant throughout the day. If there is a buffer, clean water reservoir (for example a water tower), downstream of a water pipe, this pipe will have a more constant volume flow because the reservoir stabilizes and equalizes fluctuations. Such constant operational management is usually only the case with (very) large transport pipelines, for example for the transport of groundwater or pre-treated raw water to a treatment plant. Clean water reservoirs are usually found at the location of a drinking water treatment plant in order to operate a treatment process as constantly as possible. Reservoirs are also found downstream of the treatment in some locations. Besides, the flow in the pipes close to and downstream of a water treatment plant (WTP) are normally constant. (Moerman et al., 2021) Concerning the diameter of the pipeline, the larger the diameter is, the larger the water flow and the larger the energy availability are. So, the smaller the diameter, the smaller the supply capacity. (Blokker et al., 2013)

Operating hours

In practice, TED systems often operate at partial capacity, and the number of full load hours (A representative number at full capacity utilization of the installation) they achieve strongly depends on the system choices made for the installation and the variability of the TED heat source. For instance, when TED is employed as a regeneration system for a Thermal Energy Storage (TES) system, where the TES system serves as the primary heat supply, the capacity of the TED installation (and the corresponding full load hours) is highly influenced by the source capacity of the TES system and the timing of heat supply from the TED installation to the TES system. (Moerman et al., 2021)

TED and TES

According to S. Mol (personal communication, July 5, 2023), heat from a TED installation can for instance be transferred to an ATES or to a HP. The seasons influence the ratio of supply to the ATES compared to the HP. In summer, the heat demand is low to zero, which means it is not logical to have a direct supply from the TED installation to the HP. Therefore, in summer the heat supply to the ATES is 100% of all supply. In this report, an energy loss of 10% of the ATES has been assumed, based on existing ATES systems in the Netherlands (personal communication with Stefan Mol, August 2, 2023). In winter, the SH demand is high, but there is no heat supply from the TED installation (the installation is off), as the drinking water temperature is relatively low. Regeneration of heat energy into the ATES happens in summer, when the HP is not being supplied with heat from the TED installation. For example in autumn, both the HP and the ATES could need heat and power supply from the TED installation, as there is expected to be some SH demand for multi-family residential buildings in autumn. So, only in summer, and maybe a bit in autumn, it is possible to deliver heat from TED to the HP to directly be used for heating purposes. However, the SH demand in summer is expected to be low or close to zero.

2.1.3. Existing TED projects

Currently in the whole of the Netherlands, there are about twelve TED systems operational, varying in size and characteristics (KWR, 2022). Below, two projects are further explained to illustrate the concept of TED.

At the moment, the drinking water company in Amsterdam (Waternet) has 2 TED projects running:

1. Sanquin blood bank in Amsterdam: regeneration of a thermal storage system in a cooling system using winter cold from drinking water;
2. Residential area Plantage De Sniep in Diemen: regeneration of an ATES from a source network using summer heat from drinking water. (de Fockert et al., 2022)

Regarding the first project, drinking water company Waternet delivers thermal energy extracted from their drinking water distribution pipeline system to Dutch blood bank and pharmaceutical company Sanquin. At the Sanquin site, cold is extracted in winter from an 800 mm pipeline and used to cool its facilities and pharmaceutical production processes. This cooling delivery achieves CO_2 savings of about 1100 tons a year, which is over two percent of Waternet's current climate footprint. (van der Hoek et al., 2018)

At the residential area De Sniep in Diemen, the Netherlands, energy supplier Eneco supplies sustainable heat by means of an ATES. The drinking water source at the location is surface water, and therefore the temperature of the drinking water is affected by the different seasons. There are certain locations in the distribution network in the Diemen area where the water temperature in summer approaches the legal limit of 25°C. This is undesirable, which was the reason for investigating potential heat transfer between Waternet and Eneco (Waternet, 2010).

The project is visualized in **Figure 2.4**. In winter, heat from the hot source is transferred to the room heating distribution network and feeds heat pumps at the households that provide SH and DHW preparation. This cools the water down. The cooled water is stored in the cold well. In summer, the local distribution network is fed from the cold source and provides the residential area with cooling. The heated water is stored in the hot well. Due to a greater heat demand in the winter than the cooling demand in the summer, the ATES system has an imbalance (heat is needed, or in other words, there is a surplus of cold.). Heat from low temperatures is sufficient and could be extracted from drinking water. This cools down the drinking water. In the summer months, heat is extracted from the drinking water and the ATES of the Plantage De Sniep residential area is balanced. For Plantage De Sniep, the wells of the ATES are constructed until a depth of 150 – 175 m. The temperature of the hot and cold source is 15°C and 8°C respectively. (Waternet, 2010)

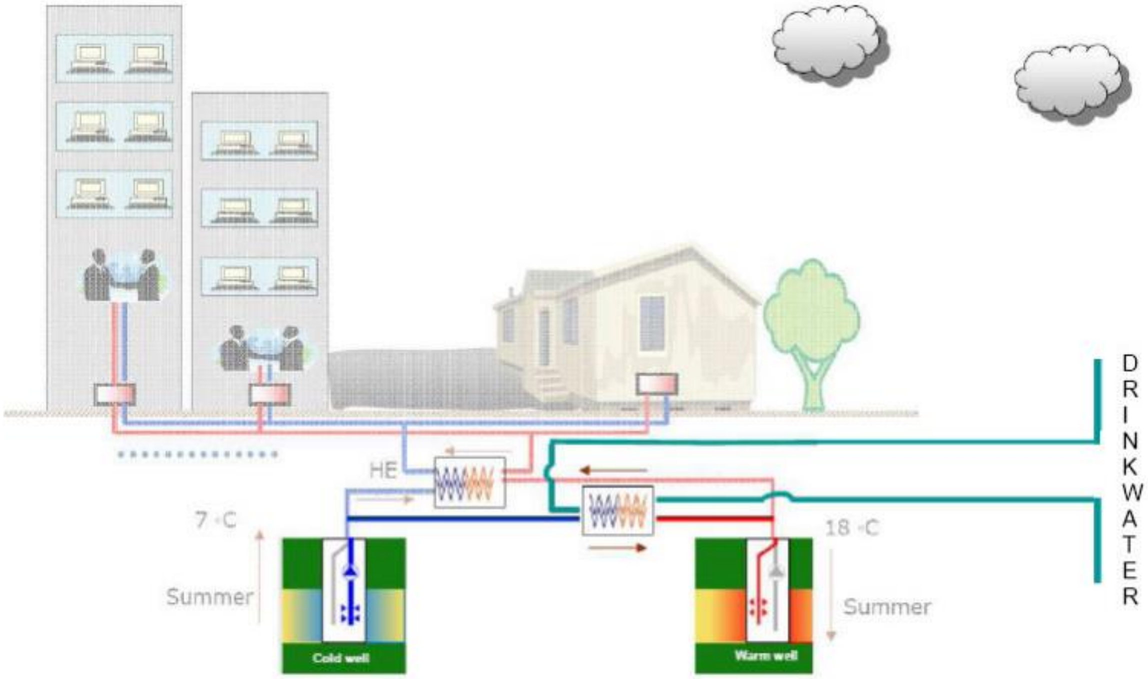

Figure 2.4. *ATES in combination with TED from drinking water at De Sniep in Diemen, the Netherlands. (Figure from Waternet, 2010).*

2.2. Thermal energy demand and supply in Sweden

Heating and cooling comprises 48% of the final energy demand of Sweden (Vad Mathiesen, 2015). The final energy demand (or consumption) is defined as the overall energy utilization by end-users, including households, industrial processes, and agricultural activities. This refers to the energy that is delivered to the final consumer and does not encompass the energy consumed within the energy sector's internal operations (Eurostat, 2018). Sweden exhibits an energy profile characterized by a limited cooling requirement, but a substantial demand for space and process heating. The industrial sector in Sweden is predominantly dominated by process heating, representing a significant proportion of energy consumption. Conversely, space heating (SH) is more prevalent in other sectors. In comparison to the EU28, the energy mix in Sweden displays a reduction in the reliance on gas and oil, with a corresponding increase in the utilization of biomass and DH. Notably, the use of fossil fuels for heating purposes is virtually nonexistent in Swedish households, highlighting the country’s commitment to sustainable and RE alternatives. (Swedish Energy Agency, 2021) (Vad Mathiesen, 2015)

In comparison to DH systems, district cooling (DC) systems are notably smaller in scale. The Swedish heat market has become a testing ground for the impact of high costs associated with fossil fuels in the heating sector, leading to the emergence of long-term market solutions. In densely populated urban regions, district heating has gained preference as a sustainable and efficient heating option, supported by robust legislative measures. On the other hand, suburban and rural areas have witnessed the adoption of local heat pumps as an alternative solution. Unlike mandatory connections, customers in Sweden have the freedom to choose their heat supply from various options, including district heating provided by heat distribution systems. This competitive environment encourages innovation and ensures customer satisfaction. Currently, Sweden boasts a widespread presence of DH systems across major cities and towns. National statistics indicate the existence of around 500 DH systems, encompassing both large-scale systems in urban areas and smaller systems serving small towns and villages (Werner, 2017). As DH is more common than DC, in this report the focus is on the potential of heating instead of cooling with TED.

In Swedish DH systems, the typical average temperature of the supplied hot water is around 86 °C, while the temperature of the returned water is approximately 47 °C (Averfalk et al., 2017). Swedish DH systems are known for their diverse range of fuel sources and technologies used to generate heat, with a focus on utilizing local waste heat resources. The main composition of the generation portfolio consists of a combination of combined heat and power (CHP) plants, heat pumps (HPs), and heat-only boilers (HOBs). In 2013, CHP plants generated about 40% of the total heat generation in DH systems and approximately 8% was generated by HPs. This strategic use of CHP plants and HPs creates a strong interdependence between the heat and electricity systems within DH systems (Romanchenko et al., 2017).

2.2.1. DH in Göteborg

In Sweden, DH is embraced as the primary heating solution for multi-family residential buildings (Swedish Energy Agency, 2021). In Göteborg, the DH system, operated by municipal-utility Göteborg Energi, stands as the second largest in the country, featuring an extensive network of piping of approximately 1000 km. Covering over 90% of multi-family dwellings and 9000 single-family houses in the city, the DH network also connects with two smaller networks in neighboring municipalities. As multi-family residential buildings are considered the main user of DHNs, this report focuses on the potential of TED for meeting the heating demand of residential multi-family or multi-dwelling buildings in a DHN.

Multi-dwelling buildings are the majority (51 percent) of all dwellings and the size of the average size of these is 68 m^2 (SCB Statistics Sweden, 2016). Besides, the average SH demand is 138 kWh/m^2 (Werner, 2017). Moreover, Bagge et al. (2014) states that the Swedish average annual domestic hot water

(DHW) heating was 20.1 kWh/$\boldsymbol{m^2}$ in one bedroom apartments and 22.8 kWh/$\boldsymbol{m^2}$ in two bedroom apartments. The average SH demand and the average DHW demand for two bedroom apartments were calculated and are provided in **Table 2.1.** These numbers are used for the calculations in **sub-chapter 4.4.**

Table 2.1. The average SH and DHW demand for multi-family residential houses, the most common user category of district heat in Sweden.

User category	**Average annual SH demand [kWh]**	**Average annual DHW demand [kWh]**	**Total annual heat demand [kWh]**
One apartment in a multi-dwelling building	9384 [1, 2]	1550 [1, 3]	10,934

1. (Werner, 2017), 2 (SCB Statistics Sweden, 2016), 3 (Bagge et al., 2014)

Heat deliveries in Göteborg peaked at around 4200 GWh per year in 2001 (Göteborg Energi AB, 2015), gradually decreasing thereafter. By 2015, the amount had reduced to 3300 GWh (Göteborg Energi AB, 2016), primarily due to energy efficiency measures implemented in the local building stock (Romanchenko et al., 2017).

Energy sources

In Göteborg Energi's 2022 annual and sustainability report (Göteborg Energi, 2022), the energy sources of the DH system in Göteborg are categorized (**Figure 2.5**). Besides, in **Figure 2.6**, key figures per energy source of the DH system are provided.

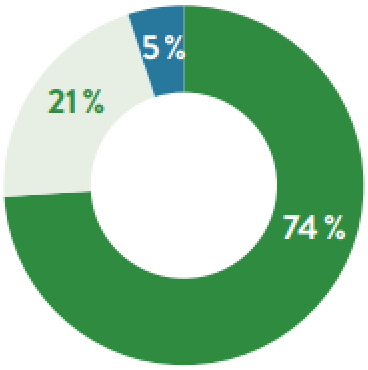

Figure 2.5. *DH sources. 74% Recycled energy, 21% Renewable energy, 5% Fossil energy. (Figure adapted from Göteborg Energi AB, 2022).*

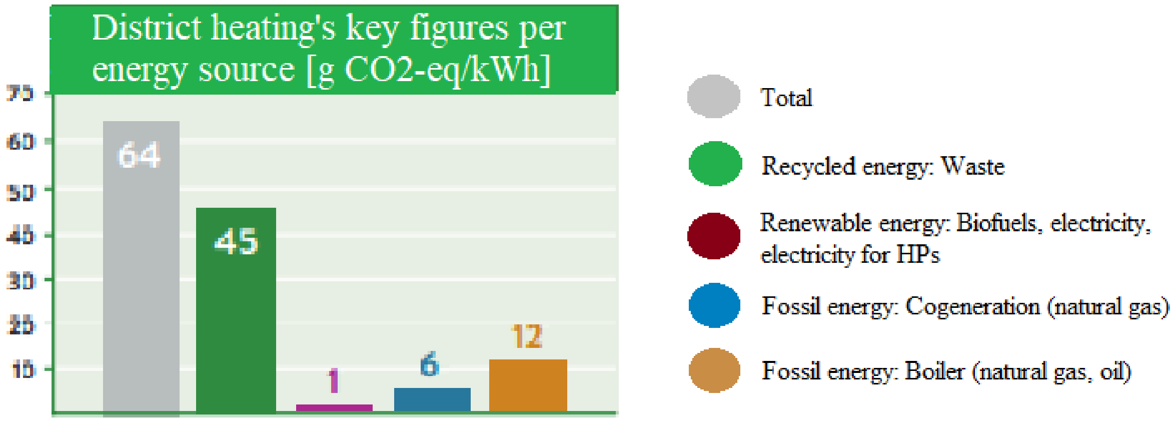

Figure 2.6. *District heating's key figures per energy source in 2022 according to 'Värmemarknadskommittén' (VMK) ('The Heating Market Committee') [g* CO_2*-eq/kWh]. (Figure adapted from Göteborg Energi AB, 2022).*

Averfalk et al. (2017) states that the specific waste heat sources in the DH system in Göteborg can be classified into different categories: industrial excess heat, ambient water, sewage water, and other heat sources (which are flue gas condensate where latent heat in the flue gases are recovered by condensation of flue gas vapor, geothermal water which is in use at one location in southern Sweden, and district cooling which provides increased return temperature as cooling is supplied to customers). Low-temperature heat recovered from industrial processes, known as industrial excess heat, typically falls within the temperature range of 15 to 40 °C. Saline sea water, lake and river water, and to a lesser extent groundwater, serve as the primary sources of ambient water for heat exchange purposes. The temperature of ambient water varies with the seasons, spanning from 2 to 14 °C. Treated municipal sewage water, has temperatures ranging between 12 and 20 °C. On average, approximately 17% of this sewage water is combined with district cooling systems.

Pisani (2018) states that the sewage water temperature in Göteborg is approximately 11 °C, fluctuating between 8 and 14 °C. To efficiently increase the temperature of the heating medium, a cascading technique involving four HPs is employed. The HPs ensure that the temperature of the sewage water remains above 3 °C when it exits the system. The final output temperature, which is supplied to the DH system, is maintained at around 80 °C. Additionally, the system is connected to two hot water boilers that use pellets to raise the temperature, if necessary, specifically when the temperature from the last heat pump is around 65 °C. The DH grid receives the heat delivered by the plant, and the returning temperature from the grid typically ranges from 40 to 55 °C. As per the data provided by Göteborg Energi, the plant has the capacity to produce 150 MW of heat with a COP of 3.4 without needing to use the hot water boilers to increase the temperature to 80 °C (Pisani, 2018).

Averfalk et al. (2017) writes about large-scale heat pumps in Swedish district heating systems and mentions that most probably the two largest mechanical heat pump units in the world are located in Göteborg, having a capacity of 50 MW each. However, most of the capacity installed is based on capacities belonging to the middle group between 10 and 30 MW. The HPs in the DH system are fed with electricity from the grid and use heat from the municipal sewage sludge plant (Romanchenko et al., 2017).

When additional heating is required, it is recommended to decrease the output temperature from the heat pump. This approach leads to an improved COP compared to when the heat pump operates at higher output temperatures. Ideally, the heat pump and the supplementary heating system should not run simultaneously at all times. Instead, the supplementary heating should only be employed when the heat pump cannot fully meet the building's heating demands. (Pisani, 2018)

Energy storage

Regarding TES, Romanchenko et al., (2018) investigated the advantages of implementing TES in DH systems to reduce fluctuations in heat demand by applying their models to the DHN in Göteborg, while comparing the use of a hot water tank for storage and the thermal inertia of buildings. To briefly explain the second principle, utilizing the thermal inertia of structures in the form of Building Inertia Thermal Energy Storage (BITES) relies on exploiting instances of temporary over-heating or under-heating of the building. BITES holds the potential to mitigate the day-to-day fluctuations in heat loads within the DH system (Ingvarson & Werner, 2008).

Romanchenko et al., (2018) states that the findings of their comparison indicate that both the hot water tank and BITES offer benefits to the DHN and exhibit similar utilization patterns. However, when comparing their performance, the hot water tank stores more than twice the amount of heat over the modeled year due to lower energy losses, unlike BITES. Consequently, the hot water tank is preferred for long-term heat storage (more than 48 hours). Additionally, the hot water tank maintains its full capacity for charging and discharging consistently, while BITES relies on heat transfer between the building core, indoor air, and internals. Furthermore, incorporating the thermal inertia of buildings results in a 1% reduction in the total yearly operating cost of the system, while including the hot water tank leads to a 2% decrease, as compared to the scenario without any storage.

DH prices

On the website of Göteborg Energi AB (2023), the current annual costs for DH are shared. The annual costs per house for DH in Göteborg with an annual consumption of 10,000 kWh is 14,000 SEK when renting and 9380 SEK when owning. The pricing of DH in Göteborg follows a cost-centered pricing model, where the price is influenced by both the expenses associated with supplying DH and the desired returns of the city of Göteborg. The components that determine the price are: production costs, operating costs, capital costs and the return requirement. The DH operations need to achieve a return on total capital ranging from 8% to 10% over a certain period.

3. Methodology

In this chapter, first of all the method for defining criteria for assessing a TED installation is described. Next, a brief introduction on the characteristics and tasks of the drinking water company Göteborg Kretslopp och vatten in Göteborg, Sweden is given. Thereafter, the case study being the candidate location at Göteborg Kretslopp och vatten for TED implementation is described. Lastly, a description of the three scenarios that are being compared in this research are introduced and elaborated. As already mentioned before, these three scenarios are:

1. TED in a DHN in Göteborg – in combination with natural gas
2. TED in a DHN in Göteborg - without natural gas
3. Conventional DH in Göteborg.

3.1. Criteria research and selection

For decision-making for sustainable energy, multi-criteria decision analysis (MCDA) methods have become increasingly popular, because of the multiple dimensions that sustainable energy matters entail and the complexity that comes with multi-dimensionality (Wang et al., 2009). MCDA combines both qualitative and quantitative evaluations to compare alternatives based on many criteria. MCDA is useful for solving issues with multiple objectives, criteria, and stakeholders, aiming to reduce uncertainty and find the best solution for complex decisions (Kumar et al., 2017). Implementation of TED as a sustainable energy source might benefit from the use of the MCDA tool, when making complex decisions around the topic.

Backeström & Ceder (2022) have established a general list of sustainability indicators or criteria commonly used in MCDAs. Their criteria list covers as many distinguishable sustainability aspects as possible. Through an additional literature study in online databases using keywords ‘drinking water sustainability’, ‘thermal energy’ and TED related studies, general criteria for sustainability assessments on these particular topics have been explored and investigated. Combining the findings from the report by Backeström & Ceder (2022) and the additional literature study, a list of criteria specifically relevant for MCDAs concerning TED was established and categorized into the different categories mostly used for sustainability indicators evaluated with MCDA tools as described in a literature review by Campos-Guzmán et al. (2019) (see **Table 4.1.)**. The list was evaluated to assess the relevance of each criterion in decision making, to check if important criteria were missing and to check data availability in the Göteborg case study. Additionally, it was checked if the criteria fit within the system boundaries and were expected to be affected by implementing TED. This resulted in a final list of criteria that can be used for analyzing the sustainability of TED and to assess the potential of TED in a specific location (see **Table 4.2.)**.

3.2. Introduction on Göteborg Kretslopp och vatten

Göteborg Kretslopp och vatten is a municipal administration in the City of Göteborg and is led by the Göteborg Kretslopp och vatten board. Since 1787, Göteborg Kretslopp och vatten has been providing inhabitants of Göteborg with drinking water and in 2013 it was officially founded as the largest water and waste utility in Sweden that is operated as a department and not as a company (IWA, 2021). The responsibilities of Göteborg Kretslopp och vatten are managing and cleaning stormwater, cleaning and producing drinking water in Göteborg and several neighboring municipalities, and developing, fixing and maintaining the drinking water pipeline network in Göteborg. Besides, they maintain sewer pipelines to ensure that the wastewater is transported to the treatment plant. The treatment plant, which is operated by Gryaab, purifies the wastewater before it is released into the River Göta älv. Additionally, Göteborg Kretslopp och vatten is responsible for waste management in the city of Göteborg, such as sorting and reducing garbage through collecting residual and food waste from households and businesses. Göteborg Kretslopp och vatten operates five recycling centers in the city and runs Återbruket, where you can hand in and buy used building materials. (Göteborgs Stad, 2023)

When addressing Gothenburg’s urban water challenges, the International Water Association (IWA) suggests, cited from IWA (2021): “Innovation and daring to implement untested solutions is a necessity for the future.”. This would ask for an open mind towards new technologies and innovations. Göteborg Kretslopp och vatten emphasizes the need for collaboration between and understanding of needs and goals of different disciplines and sectors, such as traffic planning and city planning, in order to succeed with sustainable management of the water network in Göteborg (IWA, 2021).

3.2.1. Characteristics of the drinking water network

The drinking water pipeline network in Göteborg is 176 km long (Göteborgs Stad, 2023). In **Figure 3.1**, a rough sketch of the drinking water pipeline network in Göteborg is provided, including the location of the main pipes and of the water treatment plants (WTPs) Lackarebäcks WTP and Alelyckan WTP which provide clean drinking water for Göteborg. Besides, in **Figure 3.1,** Delsjöarna (The Delsjö lakes) is shown, which is an intermediate storage of the raw water pumped from River Göta älv, at the raw water intake Lärjeholm, that provides raw water to both WTPs. Lake Rådasjön is the reserve raw water source for Göteborg (and main raw water source for the City of Mölndal, south of Göteborg). Also B. Haidarian, who is an operations engineer at Göteborg Kretslopp och vatten, explains that the drinking water in Göteborg is from surface water (personal communication, May 16, 2023). As the drinking water source is surface water, the temperature of the drinking water is affected by the different seasons (Waternet, 2010).

In Swedish cities, on average there are six to seven meters of drinking water pipes per person. In the countryside, this is on average more than 90 meters. These numbers include drinking water, wastewater (sewage) and stormwater pipes. The average share of the total pipe length in Sweden is 42% for drinking water, so about two and a half to three meters pipe per person in cities, and more than 38 meters in the countryside. (Bashir & Mohamud, 2021) On average, there is 2.16 individuals per household in Sweden (Statista Research Department, 2022). This gives, $2.16 \cdot 3 = 6.48$ meters of drinking water pipeline per household. Besides, according to B. Haidarian (personal communication, May 16, 2023) the minimum temperature of the drinking water is 2.9 °C, the median is 8.7 °C and the maximum is 20.2 °C. Currently there exists no formal regulation for the maximum allowed drinking water temperature. A previous maximum allowed drinking water temperature as defined by the Swedish Food Agency is 20 °C which is used “informally” today, even though this limit is exceeded at times. More numbers and information on characteristics of the drinking water network in Göteborg are provided in **Table C.1.**

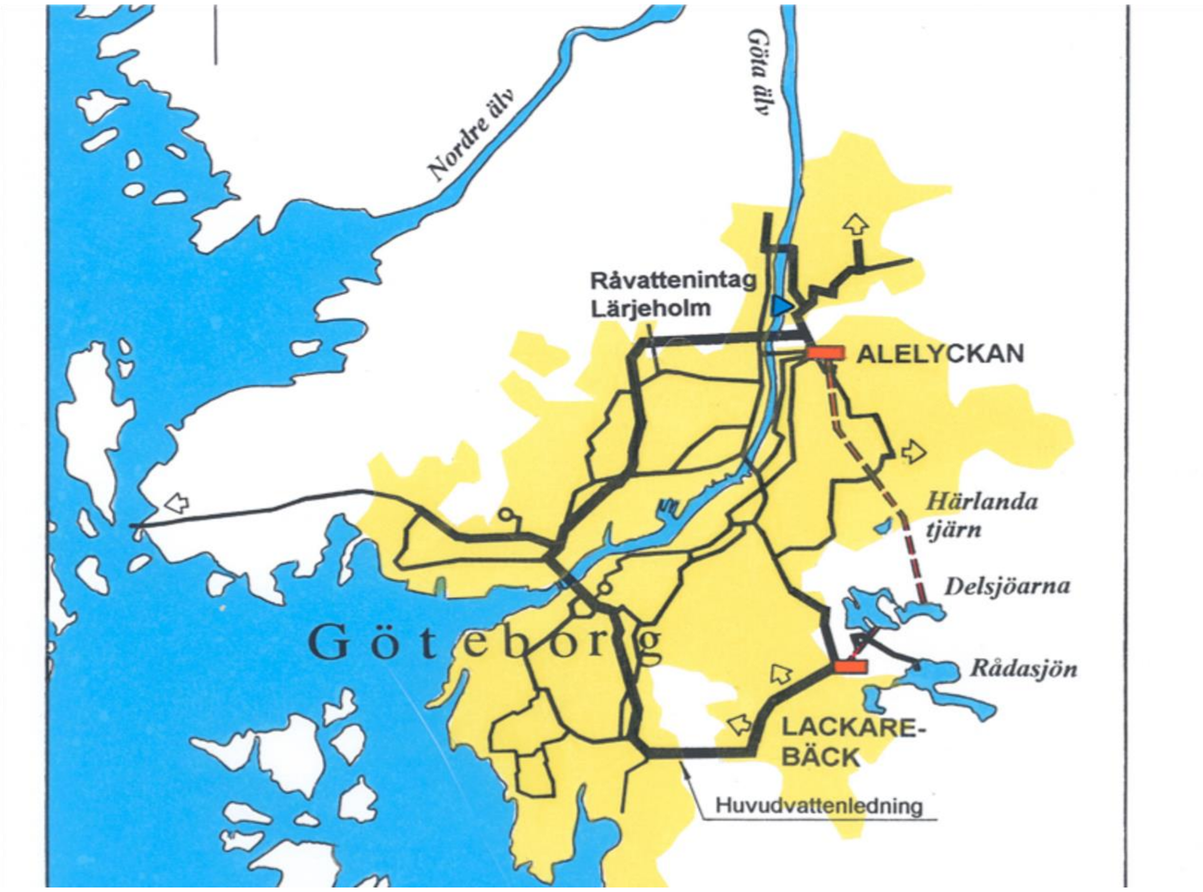

Figure 3.1. *A sketch of the drinking water pipeline network in Göteborg, including the two Water treatment plants (WTPs) in Göteborg: Lackarebäcks WTP (in the south) and Alelyckan WTP (in the north). (Figure from personal communication with T. Pettersson, July 17, 2023).*

3.3. The case study

To start with, as in Göteborg DH is more common than DC (Werner, 2017), and DH is embraced as the primary solution for multi-family residential buildings (Swedish Energy Agency, 2021), the potential of TED as an input to a local DHN for residential houses is analyzed.

The specific location that is being studied is a candidate location at Göteborg Kretslopp och vatten for implementation of TED, which here is proposed to be the heat input into a DHN of 70 °C in Göteborg. The specific location that is studied was determined by B. Haidarian (personal communication, May 16, 2023) who is working for Göteborg Kretslopp och vatten. The choice of the location was based on the criterion (that was derived from existing TED projects in the Netherlands) that the drinking water distribution pipeline should have a diameter of at least 700 mm. The pipeline at the location is a concrete drinking water pipe with an 800 mm diameter and is located close to a drinking water pump station. A sketch of the TED setup at that location is presented below in **Figure 3.2**. Additionally, data on the temperature of the drinking water through the pipeline over time and the volume flow over time provided by Göteborg Kretslopp och vatten is presented in **Appendix A**.

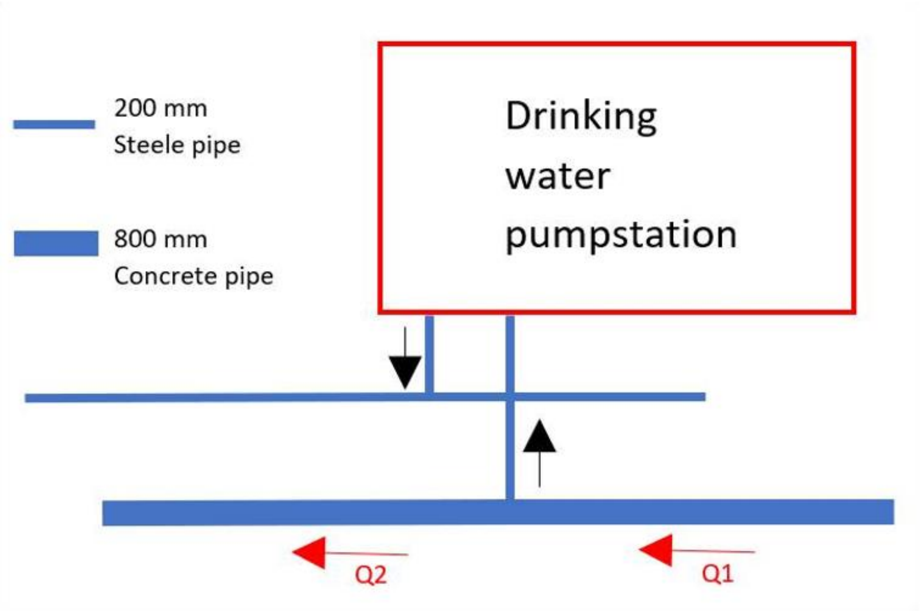

Figure 3.2. *A sketch of the setup of the TED system candidate location in the drinking water pipes system at Göteborg Kretslopp och vatten. (Figure from personal communication with B. Haidarian, May 16, 2023)*

Concerning regulations on thermal energy extraction from drinking water in Göteborg, the ABVA document describes the law and regulations on public water services. Translated from chapter 9 of the ABVA 2017 document (‘the property's use of drinking water’), water delivered through a public water system may only be used for heat extraction if the system owner has agreed in writing after the application been sent in. In the case of limited water availability, property owners are obliged to reduce their water consumption according to the principal's instructions (Kretslopp och vatten, 2017). Besides, according to B. Haidarian (personal communication, May 16, 2023) currently there exists no formal regulation for maximum allowed drinking water temperature. Previous maximum allowed drinking water temperature as defined by the Swedish Food Agency is 20 °C which is used “informally” today, even though Kretslopp och vatten exceeds this limit at times.

So, after a written approval from the principal of the municipality of Göteborg, the first step for a TED installation is that the connection to a thermal source in the drinking water system should be realized with a bypass (as explained in **sub-chapter 2.3.1**). In other words, the HE and pumps of the TED installation should not be placed within the main drinking water transport pipe (the 800 mm concrete pipe where Q1 and Q2 flow through). Based on the data from Göteborg Kretslopp och vatten, the flow through Q1 is bigger than the flow through Q2 (see **Table A.2.**). In order to retrieve the most from the available thermal energy, it is suggested to construct a bypass of 800 mm through which all of Q1 can flow. This means that all of Q1 can go through the HE. In **Figure 3.3.** a sketch of the TED installation at the candidate location of Göteborg Kretslopp och vatten is provided. Sensors for measuring for example the drinking water temperature and pressure in the pipes are not shown in the sketch. Also, pumps that are pumping the drinking water through the bypass are not drawn. Moreover, the cold source of the HE is not included.

To choose the size of the HE, the maximum available flow could be leading. However, also for example the average flow could be used. The bigger the flow, the bigger the required size of the HE. According to S. Mol (personal communication, July 5, 2023), the price of the HE is not increasing linearly with the size of the flow it can handle. Installing a HE that can handle the biggest flow when necessary means that the full potential of the thermal energy from Q1 can be retrieved. However, it should be taken into consideration that the largest measured flow only goes through the HE when the drinking water flow through the main drinking water pipe is largest. According to the data provided by Göteborg Kretslopp och vatten (see **Table A.2.**), this occurs once a week. This may affect the final efficiency of the HE. In this report, both the largest flow and the average flow are calculated and presented. Calculations using he largest flow show the maximum potential of the TED installation. Using the average flow shows the average potential of the TED installation. According to the data on Q1 (see **Table A.2.**), the average and highest number for Q1 are 0.173 m^3/s and 0.193 m^3/s respectively.

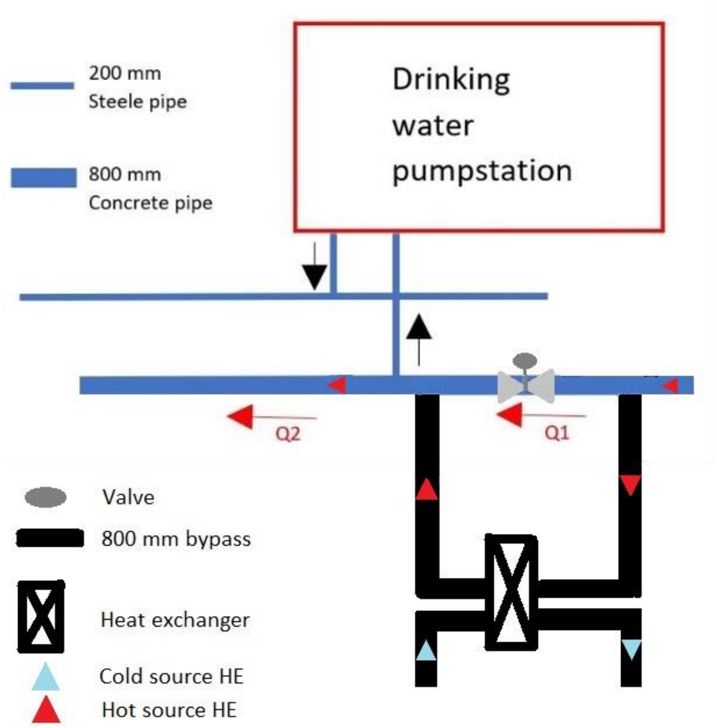

Figure 3.3. *A sketch of the candidate location for implementation of a TED system in a bypass at Göteborg Kretslopp och vatten. (Figure adapted from personal communication with B. Haidarian, May 16, 2023)*

As mentioned above, the cold water source of the HE is not included in **Figure 3.3**. In this report, the cold source of the HE in the TED installation is coming from an ATES. Usually, the cold water source of an ATES is around 8 °C. On the other hand, the hot water source of an ATES is around 15 °C. This is important to realize when determining the temperature that can be extracted by the TED installation. As in this report TED in the DHN provides heat input into an ATES (and directly to a HP) the delivery temperature needs to be at least 15 °C so the hot ATES source is actually heated or regenerated at the right temperature. So, when the temperature of the drinking water of flow Q1 is above 15 °C, a temperature difference of 5 °C is extracted. According to the data provided in **Appendix A** on the water temperature at the candidate location at Göteborg Kretslopp och vatten in Göteborg, the temperature of the drinking water is above 15 °C for about 100 days per year. It is then assumed that the TED installation runs continuously 24 hours per day. This gives $100 \cdot 24 = 2400$ full load hours. This means that during these 2400 hours, all of the drinking water is flowing through the bypass instead of the main drinking water pipeline.

3.3. The heat and power chain template for comparison of DH

In this sub-chapter, the heat and power chain template, provided by S. Mol (personal communication, June 7, 2023), that is used to formulate the different scenarios and analyze and compare them is described. A general block scheme of the different units of the heat and power chain is provided below in **Figure 3.4**. In **Appendix B.3.** snapshots of the spreadsheet calculations template have been attached and assumptions, estimations and choices that are made and key figures used are provided. The template consists following units: the TED installation, an ATES, a HP, a peak boiler, a buffer (water reservoir) and the district heat network including distribution pipes and the end users being residential houses.

Next, a few of these choices that are made on the standard default flows from the TED installation in the heat and power chain are explained. After that, the heat and power chain of the three scenarios that are compared in this report are presented and visualized.

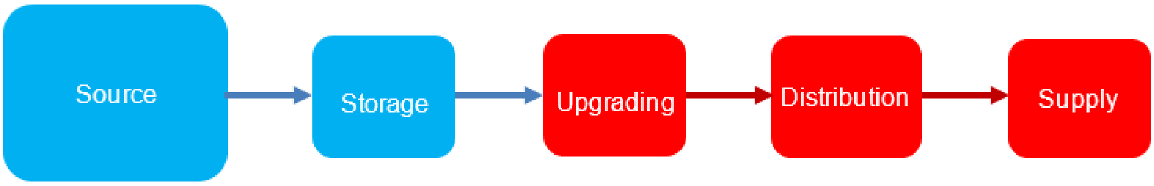

Figure 3.4. *A general block scheme of the different units of the heat and power chain.*

Firstly, regarding the calculations on the chain in this report, as can be seen in the photo of the spreadsheet for the heat and power chain calculations in **Appendix B.3**, the heat and power chain consists of two different chains being SH and DHW (which are one pipeline network in real life, but two separate calculations in the spreadsheet). SH and DHW are separated, because the heating demands for SH and DHW differ in time periods, fluctuations and levels and therefore accompany different levels of heat demand and supply and power input and output.

Secondly, an estimation has been done on the ratio of heat supply from TED to the HP (for upgrading the temperature so that it can directly be used for heating purposes) versus heat supply from TED to the ATES for regeneration. As mentioned before, the seasons influence the ratio of supply to the ATES compared to the HP. To repeat, in summer, the heat demand is low to zero, which means it is not logical to have a direct supply from the TED installation to the HP. Therefore, in summer the heat supply to the ATES is 100% of all supply. In winter, the heat demand is high, but there is no heat supply from the TED installation (the installation is off), as the drinking water temperature is relatively low. Regeneration of the ATES happens in summer, when the HP is not being supplied with heat from the TED installation. For example in autumn, both the HP and the ATES could need heat supply, and power, from the TED installation. So, only in summer, and maybe a bit in autumn, it is possible to deliver heat directly from TED to the HP. However, also important to note is that the different heating demands of a multi-family residential house, being SH and DHW demand, are also influencing the ratio of heat supply from TED to the HP versus to the ATES. for example the SH demand in summer is expected to be low or close to zero. Therefore, in this report it is estimated that the direct input from TED into the HP over the year is 10% and that the other 90% is going from the TED installation to the ATES to the HP. In other words, it is estimated that the SH demand in summer (during the 2400 full load hours) is about 10% of the total SH demand. At the same time, the DHW demand is about constant throughout the different seasons. Therefore, regarding the DHW, it is estimated that the TED output is supplied directly to the HP when it is available, which is in summer (during the 2400 full load hours). The rest of the time the TED installation supplies heat to the ATES for regeneration. The percentage of DHW heat that is supplied directly to the HP then is $\frac{100}{365} \cdot 100\% = 27\%$, which gives a percentage of $100\% - 27\% = 73\%$ that is supplied from TED to the ATES.

3.3.1. Scenario 1: TED in a DHN

Scenario 1 represents a TED installation in a 70 °C DHN in Göteborg.
In **Table 3.1**, an overview of the components of the heat and power chain are presented. **Figure 3.5.** provides a block scheme, to visualize the heat and power chain.

Table 3.1. Selected heat and power chain for a 70 °C DHN with TED as input.

Source	**Extraction**	**Storage**	**Upgrading/ transport**	**Supply**
TED, electricity and gas	HE	ATES	Heat pump to 70 °C and peak boiler	Radiators

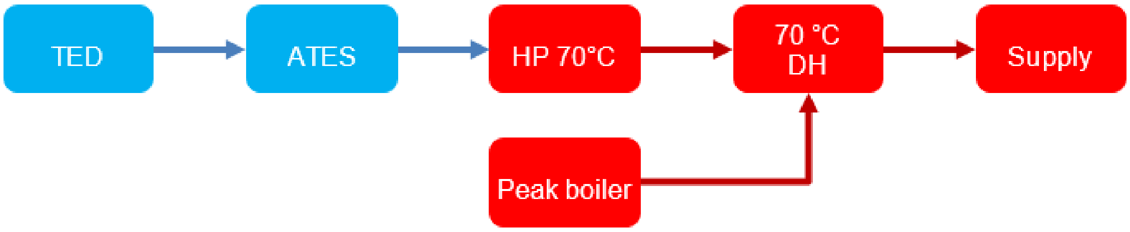

Figure 3.5. *Technical scheme scenario 1: energy and water sector are integrated - TED in a 70 °C DHN.*

3.3.2. Scenario 2: TED in a DHN - without gas

Scenario 2 represents a TED installation in a 70 °C DHN in Göteborg, without the use of gas in the heat and power chain. In **Table 3.2**, an overview of the components of the heat and power chain are presented. **Figure 3.6.** provides a block scheme, to visualize the heat and power chain.

Table 3.2. Selected heat and power chain for a 70 °C DHN with TED as input - without gas.

Source	**Extraction**	**Storage**	**Upgrading/ transport**	**Supply**
TED and electricity	HE	ATES	Heat pump to 70 °C	Radiators

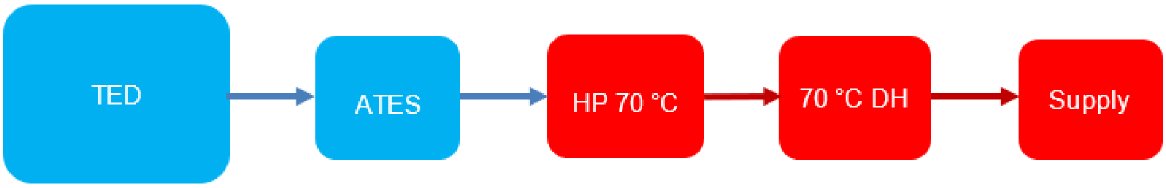

Figure 3.6. *Technical scheme scenario 2: energy and water sector are integrated - TED in a 70 °C DHN.*

3.3.3. Scenario 3: conventional DH

Scenario 3 represents the current DHN of 86 °C DHN in Göteborg. In **Table 3.3**, an overview of the components of the heat and power chain are presented. **Figure 3.7.** provides a block scheme, to visualize the heat and power chain.

Table 3.3. Selected heat and power chain for the current 86 °C DHN.

Source	**Storage**	**Upgrading/ transport**	**Supply**
Waste incineration, thermal energy from wastewater (TEW), waste heat	Hot water tank	Heat pump to 86 °C	Radiators

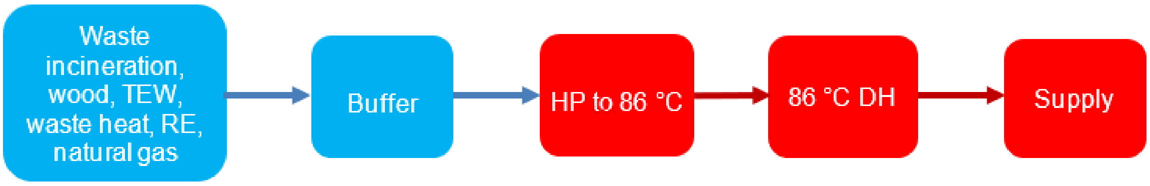

Figure 3.7. *Technical scheme scenario 3: energy and water sector are not integrated - conventional 86 °C DHN.*

3.4. Calculations

In this sub-chapter, the methods for the calculations in this study, including equations that are used, are provided. Approaches for the calculations on potential energy supply, TCO and CO_2 emissions are presented.

3.4.1. Energy supply

Van der Hoek et al. (2018) describes that the energy potential of TED is affected by the water source of the drinking water and the volume flow size in the drinking water pipelines transporting the drinking water. Next to the volume flow, the available potential is strongly determined by the temperature difference that can be realized at the location of a TED installation, which is strongly dependent on local parameters and starting points how cold or warm the drinking water is legally allowed to be at a certain location as a result of a TED installation (Moerman et al., 2021). The potential thermal power (P_{th}, [W]) is calculated using **equation 3.1.**

$$P_{th} = Q_w \cdot c_p \cdot \rho \cdot \Delta T \qquad \text{(Eq. 3.1)}$$

In which:
Q_w is the volume flow in the water pipe in cubic meters per second (m³/s);
c_p is the specific heat capacity of water; 4186 J/kg.K;
ρ is the density of water; 1000 kg/m³
ΔT is the temperature difference that can be achieved. (Moerman et al., 2021)

The volume flow in the water pipe (Q_w, [m³/s]) is affected by different variables such as the diameter of the pipeline. A larger water flow would result in a larger energy availability.

The thermal capacity can be converted to energy per year (E_{year},[GJ]) using equation 3.2.

$$E_{year} = \frac{(P_{th} \cdot t \cdot 3600)}{1 \cdot 10^9} \qquad \text{(Eq. 3.2)}$$

Where
t is the achievable full load in hours per year;
3600 is the factor to convert from J/s $\cdot\ t$ to J/year;
$1 \cdot 10^9$ is the factor to convert from J/year to GJ/year. (Moerman et al., 2021)

3.4.2. Total cost of ownership (TCO)

Considering implementations to achieve sustainability must also be cost-effective. To make a proper assessment of the cost-effectiveness, different options can be assessed on total cost of ownership (TCO). The TCO shows all the costs of a certain installation over a certain time period: purchase, operation, maintenance and interest costs (van Bel et al., 2017). Basically, for a certain time period, capital and operational costs are calculated (van der Hoek et al., 2018). A general equation for calculating the TCO is:

$$TCO = P + Net\ Present\ Value\ of\ (O + M + E - R) \qquad \text{(Eq. 3.5)}$$

Where
P is purchase costs
O is operating costs
M is maintenance costs
E is environmental costs
R is residual value. (van der Hoek et al., 2018)

Due to this research being a first exploratory research on the potential of TED for Göteborg Kretslopp och vatten, a simplified version of Eq. 3.5 is used in which for example bank loans and interest rates are not included. The final result for the TCO is expressed in costs per year [SEK/year]. The simplified version to calculate the TCO that is used in this report is presented below:

$$TCO = P + O + M + E \qquad \text{(Eq. 3.6)}$$

Where
P is purchase costs
O is operating costs
M is maintenance costs
E is environmental costs.

The annual costs per house are calculated by dividing the TCO by the amount of houses that are supplied by the DH system.

To calculate the costs of the total TED system at Göteborg Kretslopp och vatten, estimations are done on the total purchase (or investment), operation and maintenance costs. Estimations are based on Dutch cost indicators of different components of the system. These indicators are expressed in [€/kW] and later converted to [SEK/kW], with a factor of 12. Important to realize is that the power of the system influences the costs. Also estimations are done on the lifetimes of the different components of the system. Assumptions that are made for the TCO calculations are presented in the appendix in **Figure B.3**.

3.4.3. CO_2 emissions

In this research, the CO_2-eq emission is defined by the amount of CO_2-eq that is emitted by the electricity and gas consumption of the DHN. Subsequently, the CO_2 emissions of the conventional DH system and DH with TED are compared.

The emissions are calculated by multiplying the electricity and gas consumption of the system with the CO_2 emission coefficient for electricity and gas, and is expressed in kg CO_2 -eq per year. The change in CO_2 emission (reduction or increase) is calculated by equation 3.6.

$$CO_2\, reduction = (e_{beforeTED} - e_{afterTED}) \cdot e_f \qquad \text{(Eq. 3.6.)}$$

Where
$e_{beforeTED}$ is the yearly electricity or gas consumption before installation of TED [kWh/year];
$e_{afterTED}$ is the yearly electricity or gas consumption after installation of TED [kWh/year];
e_f = emission factor for electricity or gas [kg CO_2-eq/kWh].

Below, in **Table 3.4.** key figures that are used for calculations are presented. Additional key figures, assumptions, estimations and choices that are made in this report are provided in **Appendix B**.

Table 3.4. Key figures used for calculations.

Component	**Value**
Emission factor for electricity (e_f) in Sweden	0.028 kg CO_2-eq/kWh [1]
Emission factor for natural gas in Sweden	0.012 kg CO_2-eq/kWh [2]
Total emission factor for DH in Göteborg	0.064 kg CO_2-eq/kWh [2]
Swedish natural gas price households	51.80 öre/kWh [3]
Swedish fixed electricity price bulk consumers	146.75 öre/kWh [4]
COP of a HP to 70 °C	3.6 [5]
COP of a HP to 86 °C	3.4 [6]

1 (Nowtricity, 2023), 2 (Göteborg Energi AB, 2022), 3 (ApportGas, 2023), 4 (personal communication with Göteborg Energi kundservice, July 14, 2023), 5 (personal communication with Stefan Mol, August 2, 2023), 6 (Pisani, 2018)

4. Results

4.1. Sustainability assessment criteria

In **Table 4.1**, the first generated list of potential sustainability criteria for assessing a TED system is provided.

Table 4.1. First generated list of potential sustainability criteria for assessing a TED system.

	Sustainability indicator	**Definition**
Social	1. Working conditions	The working environment conditions (e.g. stress levels).
	2. Amount of jobs created	How many jobs are created operating and maintaining the system [fte/year]
	3. Security	Security of availability and supply of the drinking water flow and therefore of availability and supply of TED
	4. Drinking water quality	Bacterial growth (Legionella) in the drinking water [CFU/L]
Environmental	1. Local impact	Effects on surrounding biodiversity and human environment by operation of the installations. E.g. smell, aesthetics, noise.
	2. Carbon emissions saved	The amount of greenhouse gas emissions saved by installation of this system [CO_2-eq/year]
Economic	1. Operating costs	Yearly operating costs for drinking water supply (incl. for example cost of CO_2 savings and thermal energy supply costs) [€/year]
	2. Maintenance costs	Yearly maintenance costs for the drinking water plant [€/year]
	3. Estimated lifetime	Estimated lifetime of drinking water plant [year]
Technical & Political	1. Political support	Potential effect of laws on the scenarios or effects of scenarios on helping to achieve political goals
	2. Energy supply	Amount of thermal energy that can be supplied.
	3. Stakeholder motivation	Willingness of (potential) stakeholders to start, invest in and/or contribute to operation of TED projects.

4.2. Sustainability assessment criteria for assessing TED

From the first list of criteria in **Table 4.1**, a final list of criteria relevant for assessing a TED system is generated and provided below in **Table 4.2**. The final list of criteria was chosen based on the relevance of each criterion in decision making. Also, the data for these criteria was available for the Göteborg case study. Additionally, the chosen criteria fit within the system boundaries and were expected to be affected by implementing TED, based on their use in assessments on existing TED projects.

Table 4.2. Final list of criteria for assessing the sustainability of a TED system.

	Sustainability indicator	**Definition**
Social	-	-
Environmental	CO_2 emissions	Amount of CO_2 emitted by the total system [CO_2-eq].
Economic	TCO	All the costs of an installation over a certain time period. In this report [SEK/year].
Technical & Political	Potential energy supply	The available potential thermal energy that can be extracted by an installation [kWh].

4.3. TED versus conventional DH in Göteborg

In this sub-chapter, the results from the analysis on the potential of implementation of a TED installation for Göteborg Kretslopp och vatten is presented. Results of the calculations on the potential energy supply and TCO of the candidate TED system location and the CO_2 that are achieved by implementing the system are presented and explained. Criteria for the DHN including a TED installation both with and without the use of natural gas are compared to the current DHN in Göteborg. The results for the highest flow of Q1 (0.193 m^3/s) and the average flow of Q1 (0.173 m^3/s) are presented.

Energy supply

Regarding energy supply calculations, a photo of the spreadsheet calculations on the potential thermal energy is provided in **Appendix B**. The heat output of the TED installation was subsequently used as an input into the heat and power chain template, imitating a DHN. Based on the average annual SH demand of a dwelling in a multi-family building and the average DHW demand of an average household, which is about 11,000 kWh in total annually (see **Table 2.1.**), the number of multi-family residential houses of which its heating demand can be met through the DH system including TED is 1126 dwellings for the highest Q1 and 927 dwellings for the average Q1. The results are provided in **Table 4.3**.

TCO

Besides, the results from the TCO calculations for the different sscenarios are provided in **Table 4.3**. The calculated annual costs per house for both DH scenarios are also presented. The TCO for the conventional DH system is unknown, and falls outside of the boundaries of this research. Therefore, further research should be done to enable comparison based on this TCO. On the other hand, a rough comparison could be made based on the annual costs for DH from the website of Göteborg Energi AB (2023). The annual costs per house for DH in Göteborg with an annual consumption of 10,000 kWh is 14,000 SEK when renting and 9380 SEK when owning (Göteborg Energi AB, 2023).

CO_2 emissions

Lastly, also in **Table 4.3**, the annual CO_2 emissions per house are presented for the different DH scenarios. Using Eq. 3.6, the CO_2 reduction after implementing TED would be $3260 - 145 = 3115$ kg

$\boldsymbol{CO_2}$-eq per house when comparing conventional DH to TED in DH in combination with natural gas, and $3260 - 137 = 3123$ kg $\boldsymbol{CO_2}$-eq per house when comparing conventional DH to TED in DH without the use of natural gas.

4.4. Overview of the results

An overview of the results of all criteria in this research for all three scenarios is provided in **Table 4.8**. To sum up, a TED installation at the proposed location at Göteborg Kretslopp och vatten 9.7 million kWh of thermal heat can be supplied. As a heat input into a DHN in Göteborg, this could meet the total heat demand of 1126 and 927 houses for DH with gas and without gas respectively. Considering that the average number for leakage in the drinking water pipeline system in Gothenburg is approximately 20 %, the specific daily consumption per person is 150 liters (personal communication with Behroz Haidarian, September 11, 2023), with the Q1 flow (average is 173 liters per second approximately 80,000 people per day can be supplied. This means that the drinking water supply to 80,000 people could fulfill the heating demand of about 1000 apartments in multi-family buildings. Conventional DH with a 9.7 million kWh input from the current energy sources can meet de heat demand of 532 houses. Regarding costs of the TED installation in the DHN, 14,800 SEK with the use of gas and 15,300 SEK without the use of gas. The annual costs per house for DH in Göteborg with an annual consumption of 10,000 kWh is 14,000 SEK when renting and 9380 SEK when owning (Göteborg Energi AB, 2023). However, further research must be done to determine to what level this comparison can be done, as for example different research approaches, key figures, assumptions and boundaries might have been applied.

Concerning CO_2 emissions, the DHNs including TED show a yearly emission of 145 and 137 kg CO_2-eq per house for with gas and without gas respectively, and 3260 kg CO_2-eq for conventional DH. The CO_2 reduction after implementing TED would be $3260 - 145 = 3115$ kg $\boldsymbol{CO_2}$-eq per house when comparing conventional DH to TED in DH with gas, and $3260 - 137 = 3123$ kg $\boldsymbol{CO_2}$-eq per house when comparing conventional DH to TED in DH without gas.

Table 4.3. Overview of the annual results on the sustainability criteria for the three different scenarios on DH in Göteborg. 8.7 million kWh of thermal energy can be extracted from the average flow through Q1 (0.173 m^3/s), 9.7 million kWh of thermal energy can be extracted from the highest flow through Q1 (0.193 m^3/s).

DH system	Thermal energy output (from TED in scenario 1 & 2 and from other DH sources in scenario 3) [kWh]	# of dwellings of which total annual heat demand is met	TCO [SEK]	Costs per house [SEK]	Annual CO_2 emissions per house [kg]
Scenario 1: TED in a 70 °C DHN – in combination with natural gas	8.7 million	1010	177 million	14,600	145
	9.7 million	1126	202 million	14,800	145
Scenario 2: TED in a 70 °C DHN - without natural gas	8.7 million	831	156 million	15,000	137
	9.7 million	927	180 million	15,300	137
Scenario 3: Conventional 86 °C DH	8.7 million	460	-	-	3380
	9.7 million	532	-	-	3260

5. Discussion

When drawing conclusions from the results in this report, there are numerous important matters to consider. First of all, it should be kept in mind that numerous key figures used in this report are from existing TED projects in the Netherlands; for example, in the TCO calculations economic evaluations of TED projects depend significantly on the local situation (Reinstra et al., 2019). Thus, for a more precise and realistic economic evaluation on the specific location in Göteborg, key figures for Göteborg or Sweden in general should be applied. Furthermore, the TCO was calculated using a simplified method in this report. In this simplified calculation, bank loans and interest rates are not included. Additionally, 2000 kWh is the general number for heat loss at every connection in the Netherlands, and this number is used for the heat and power chain calculations in this report. As heat loss is a function of the temperature difference with the surroundings, the bigger the temperature difference the bigger the heat loss. In Sweden the heat loss might be bigger than in the Netherlands, because of colder surroundings.

Another matter worth mentioning is the used CO_2emission factors for natural gas in Sweden from (Göteborg Energi, 2022), which is remarkably low compared to data from for example (Swedish Environmental Protection Agency, 2022). More research should be done on these emission factors to generate the most realistic results. Moreover, in this research, an ATES is utilized in the heat chain of the DH scenarios. The possibilities and potential of ATES systems, also financially, in Göteborg should be investigated and determined to create a more realistic result.

Additionally, more research should be done on mechanical engineering related microbiological risks to generate complete advice on the potential implementation of TED. The more corners and bends in a distribution drinking water system, which are created by the installation of a bypass in the pipeline system, the bigger the chance for microbes to grow and thus microbiological risks might increase (personal communication with Stefan Mol, August 2, 2023). For example, Van der Hoek et al. (2018) found that after recovery of cold from the drinking water, the microbial drinking water quality was not affected, however, there was an increase of the biofilm formation in the pipes. Besides, Ahmad et al. (2021), states that increased drinking water temperatures caused the initial bacteria to multiply, but this did not result in a change in the overall diversity of microbes at the end of the study. Consequently, Ahmad et al. (2021) suggests more frequent monitoring of the microbiological water quality in DWDSs with cold recovery during the months in which the TED system is in operation. Concluding, sufficient local research should be done on microbiological drinking water quality before implementation of TED and microbial growth should be monitored thoroughly when operating TED.

Besides, it is important to note that the use of TED increases electricity consumption, which largely determines the total environmental impact. When TED is applied, it is important to opt for green electricity, to reduce the environmental impact as much as possible (van Bel et al., 2017).

Another issue to keep in mind is that the average temperature on earth will rise and precipitation patterns will change, causing mild winters and hot summers to occur more often (Vewin, 2022). This will have an effect on the temperature of the drinking water sources such as surface water, and therefore on the drinking water running through the distribution pipes. As the temperature of the drinking water has an effect on the potential energy that can be supplied with TED, when calculating potential energy from TED installations, the effect of the predicted average temperature rise should be taken into account.

6. Conclusion

The three relevant criteria for sustainability assessments on TED installations that were generated from this research are: energy supply, TCO and CO_2emissions. This report compared three DH scenarios based on the results of these three criteria. The three scenarios that were compared are TED in a DHN of 70 °C with the use of gas, TED in a DHN of 70 °C without the use of gas and the current conventional DHN of 86 °C in Göteborg.

From the results of this report, it can be concluded that a DHN including a TED installation at the location of the case study can meet the heat demand of approximately 1000 multi-family houses in Göteborg, which is about 500 houses more when comparing the number of houses that can be heated with the same thermal energy input from energy sources into the current DHN. Besides, further research must be done on the costs of the DH scenarios in order to enable comparison. Moreover, a DHN including TED, both with and without the use of gas, have lower levels of CO_2 emissions. Thus, based on two of the three criteria, a TED installation is a more sustainable option in a DH system in Göteborg than DH using conventional thermal energy sources in Göteborg. In other words, based on two of the three criteria in this research, TED is a more sustainable option for multi-family residential housing in Göteborg when comparing it to the current DH system.

6.1. Further research

As already mentioned above, more research can be done on the (energy) costs/house for current DH in Göteborg, to be able to make a comparison on DH with TED and without TED based on the costs. Besides, for a more advanced economic evaluation results a more elaborate TCO calculation should be conducted, including bank loans and interest rates. Additionally, in this report, no social criteria were included in the analysis. For completeness of assessing the sustainability of TED projects, it should be considered to include social criteria as well.

Additionally, more research should be done on the possibilities for building TES systems such as an ATES in Göteborg and combining TED systems with these TES systems. This can create more realistic results on the application of TED in a DHN in Göteborg.

Besides, building on the results showing TED as a sustainable heating option, exploration of other TED locations in Göteborg could benefit from its implementation. In Göteborg, TED presents itself as a feasible strategy to offer sustainable heating solutions for existing multi-residential family houses. Mapping out other potential TED locations can be a next step in showing the potential contribution to making the shift towards sustainable approaches to heating and increase the sustainability of the whole building sector in Göteborg.

There are also some other research ideas that are building on this research and topic in general and that could be of interest. For example, in this report the focus is on utilizing a TED installation for heating only. Concerning cooling, in 1992, Sweden's first district cooling system was established in Västerås, driven by the prohibition of chlorofluorocarbon (CFC) refrigerants in existing chillers, creating an opportunity to invest in new cooling capacity as a replacement. Since then, major district cooling systems have been adopted in multiple Swedish cities. Although, important to realize, district cooling is smaller than district heating, since year 2000, district cooling has grown by an average of 8% per year. The prevalence of space cooling, which includes district cooling, can be linked to the significant focus on heating when designing and constructing new buildings in Sweden. This approach aims to reduce heat loss, unintentionally limiting heat dissipation on hot summer days and consequently driving up the need for cooling (Werner, 2017). This increasing need for cooling suggests an additional research focus. It might be interesting to conduct further research on the potential of cooling using TED in Göteborg. An important matter to include when doing research on both heating and cooling is the seasonal performance factor (SPF) (van Bel et al., 2017). Van Bel et al. (2017) states that the energy performance of the sustainable installation as a whole is made transparent using the seasonal performance factor (SPF). The entire installation is assessed for energy performance, with a distinction being made between cooling and heating operation. Cooling can usually be done directly from the source, especially TED installations in which drinking water is prepared from groundwater, which requires minimal utilization of a HP. Therefore, the average COP of a TED installation that mainly supplies cooling will automatically be higher than if the installation also supplies heat, while the latter may perform better and/or save more energy. To do justice to all systems in the assessment, a distinction should therefore be made between cooling and heating operation.

Moreover, in this research the DHN that was designed for the calculations in this research were utilizing a centralized HP. The change of the results on the sustainability assessments when choosing for decentralized HPs (at the end users) compared to centralized HPs might be of interest to explore further. Decentralized HPs in a TED project is not a new idea, in one of the TED projects ran by the drinking water company in Amsterdam (Waternet), residential area Plantage De Sniep in Diemen, the decentralized HPs are utilized (Waternet, 2010).

Lastly, as implementation of TED as a new sustainable energy source in Göteborg, complex decision making is logically expected to be a part. As already mentioned, for decision-making for sustainable energy, MCDA methods have become increasingly popular, because of the multiple dimensions that sustainable energy matters entail and the complexity that comes with multi-dimensionality (Wang et al., 2009). Implementation of TED as a sustainable energy source might benefit from the use of the MCDA tool, when making complex decisions around the topic. MCDA combines both qualitative and quantitative evaluations to compare alternative scenarios based on many criteria. In MCDA, the process begins with organizing multiple criteria based on their significance. Following this, diverse values or alternatives for these criteria undergo evaluation, scoring, and assigning of weights. Subsequently, the aggregated outcomes are compared and ranked. In the scoring phase, the extent to which a scenario contributes to or promotes sustainability is assessed. Each scenario is scored for all criteria. The average score for each scenario is computed by adding up the scores for each criterion and dividing by the total number of criteria. Moving to the weighting stage, the focus shifts to determining the level of impact each criterion has on sustainability. Weighing the various criteria allows us to distinguish between more influential and less influential ones. In essence, weighting helps us identify criteria that are believed to wield a greater influence compared to others (Kumar et al., 2017). Further research on the use of MCDA tools for TED projects might be beneficial.

6.2. Recommendations for Göteborg Kretslopp och Vatten

Practically speaking of installing TED, the infrastructure is already built and the technology is already developed. Only, a technical room including the HE, a HP, a bypass and distribution pumps should be installed. Something that might be more advanced is any TES system if necessary to be installed. There are two valuable lessons learned from existing TED projects in the Netherlands to consider for Göteborg Kretslopp och vatten and any other drinking water company when implementing a TED installation (personal communication with Stefan Mol, August 7, 2023). According to Stefan Mol (personal communication, August 7, 2023), firstly, be cautious and thoughtful when it comes to resource allocation, to avoid unnecessary risks or mistakes. This is for example referring to the choice of the material of the HE, which should be titanium instead of stainless steel to prevent corrosion as already explained in **sub-chapter 2.2.2**. When being thoughtful about these choices from the start, risks can be minimized and mistakes prevented. Secondly, it is important to refrain from economizing on sensors and data points in the TED installation, to enable a comprehensive system analysis and thorough monitoring capability.

As technologies and best practices continue to evolve, TED can play an essential role in advancing sustainability efforts in the building sector. While TED presents a promising option for sustainable heating in Göteborg, its successful implementation requires careful planning, collaboration between various stakeholders, and consideration of local conditions and regulations. Therefore, I suggest investigating the different local and national stakeholders that would be involved in the implementation of TED in Göteborg, including their roles and influence. Within this framework, drinking water utilities are recognized as caretakers of renewable heat reservoirs. This necessitates a proactive reaction from the drinking water sector, potentially involving a structured organizational strategy and the establishment of an informational hub to address inquiries (KWR, 2022). By fulfilling this new role as energy supplier, I recommend Göteborg Kretslopp och vatten to do further research on how to best fulfill this role. Also, mapping out other potential TED locations will give insights into the total potential of TED in Göteborg. The framework presented in this research gives insights into the theoretical potential of TED in a specific location and can be a good start for determining the theoretical potential of a TED project in a certain location and comparison of the sustainability of TED projects to other TED projects and other heating systems.

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Appendix A.

A.1. Data on the candidate TED implementation location of Göteborg Kretslopp och vatten

Table A.1. Drinking water temperatures through the pipe at the candidate location for TED implementation of Göteborg Kretslopp och vatten. The dates in green represent the period in which a temperature difference of 5 °C can be extracted, as the drinking water temperature is around and above 15 °C then. Note: commas are used as decimal points.

Year 1			Year 2			Year 3	
Date	T (°C)		Date	T (°C)		Date	T (°C)
2021-01-05	4,3		2022-01-11	3		2023-01-16	3,9
2021-01-12	3,3		2022-01-19	2,8		2023-01-23	3,4
2021-01-18	3,1		2022-01-25	2,4		2023-02-03	3
2021-01-25	3,1		2022-02-04	2,9		2023-02-10	2,8
2021-02-01	3,1		2022-02-08	3		2023-02-14	3
2021-02-09	3,2		2022-02-18	3,5		2023-02-21	3,2
2021-02-15	3		2022-02-21	3		2023-02-27	3
2021-02-22	3,4		2022-02-28	3,3		2023-03-08	3,6
2021-03-01	3,3		2022-03-08	3,6		2023-03-14	3,6
2021-03-08	3,7		2022-03-15	4,4		2023-03-21	3,7
2021-03-15	4,1		2022-03-21	4,6		2023-03-28	4,7
2021-03-22	4,5		2022-03-28	5,5		2023-04-04	4,7
2021-03-29	5,2		2022-04-08	6,4		2023-04-11	5,5
2021-04-07	6,2		2022-04-11	5,7		2023-04-17	6,7
2021-04-15	6,6		2022-04-19	8,7		2023-04-24	7,9
2021-04-23	8,7		2022-04-27	8,3		2023-05-02	9,9
2021-04-29	8,5		2022-05-03	10,2		2023-05-08	10,2
2021-05-04	8,9		2022-05-10	11,5			
2021-05-10	9,8		2022-05-17	13			
2021-05-18	10,6		2022-05-24	12,3			
2021-05-24	10,9		2022-06-01	13,2			
2021-06-01	12,9		2022-06-07	13,5			
2021-06-08	14		2022-06-14	14			
2021-06-14	15		2022-06-20	14,9			
2021-06-23	17,3		2022-06-28	16,1			
2021-06-29	18		2022-07-07	17,3			
2021-07-06	19		2022-07-14	18,3			
2021-07-15	20,1		2022-07-19	18,4			
2021-07-22	20,8		2022-07-28	18,6			
2021-07-28	21,4		2022-08-02	18,5			
2021-08-05	20		2022-08-09	18,5			
2021-08-12	20		2022-08-16	18,6			
2021-08-19	19,1		2022-08-25	19,1			

2021-08-24	18,6		2022-08-30	19,7			
2021-09-02	17,6		2022-09-08	18,6			
2021-09-06	17,5		2022-09-12	17,9			
2021-09-07	17,3		2022-09-22	16,1			
2021-09-17	17,8		2022-09-30	14,9			
2021-09-21	16,1		2022-10-03	14,2			
2021-09-28	14,7		2022-10-10	13,7			
2021-10-04	14,1		2022-10-18	12,7			
2021-10-11	13,5		2022-10-26	11,7			
2021-10-18	12,2		2022-10-31	12			
2021-10-25	10,9		2022-11-07	11,3			
2021-11-02	10,5		2022-11-14	11,2			
2021-11-12	9,6		2022-11-22	9			
2021-11-15	9,1		2022-11-29	7,2			
2021-11-23	8,3		2022-12-06	5,6			
2021-11-30	------		2022-12-13	4,7			
2021-12-10	2,9		2022-12-19	4,1			
2021-12-13	3		2022-12-28	4			
2021-12-21	3		2023-01-03	3,7			
2021-12-28	3,2		2023-01-11	3,7			
2022-01-05	3,2						

Table A.2. Drinking water volume flow [Q] through the drinking water pipe at the proposedoccas location for TED implementation of Göteborg Kretslopp och vatten. The provided flow numbers were measured hourly, for a total time of 7 weeks (168 hours).

Q1 [l/s]	**Q1 [m3/s]**		**Q2 [l/s]**	**Q2 [m3/s]**
185	0,185		109	0,109
167	0,167		93	0,093
165	0,165		92	0,092
162	0,162		88	0,088
157	0,157		83	0,083
162	0,162		84	0,084
172	0,172		90	0,09
182	0,182		98	0,098
181	0,181		98	0,098
183	0,183		100	0,1
187	0,187		105	0,105
188	0,188		106	0,106
188	0,188		106	0,106
186	0,186		104	0,104
182	0,182		99	0,099
182	0,182		99	0,099
183	0,183		98	0,098

186	0,186		100	0,1
189	0,189		102	0,102
186	0,186		98	0,098
180	0,18		94	0,094
181	0,181		95	0,095
180	0,18		96	0,096
175	0,175		95	0,095
164	0,164		88	0,088
152	0,152		77	0,077
153	0,153		78	0,078
150	0,15		75	0,075
147	0,147		73	0,073
149	0,149		72	0,072
165	0,165		82	0,082
174	0,174		90	0,09
175	0,175		92	0,092
179	0,179		95	0,095
181	0,181		99	0,099
185	0,185		103	0,103
187	0,187		103	0,103
185	0,185		102	0,102
182	0,182		99	0,099
180	0,18		97	0,097
182	0,182		96	0,096
185	0,185		98	0,098
188	0,188		101	0,101
183	0,183		95	0,095
179	0,179		93	0,093
181	0,181		95	0,095
179	0,179		96	0,096
175	0,175		95	0,095
164	0,164		87	0,087
151	0,151		77	0,077
152	0,152		78	0,078
149	0,149		75	0,075
148	0,148		74	0,074
151	0,151		73	0,073
165	0,165		82	0,082
176	0,176		92	0,092
176	0,176		92	0,092
178	0,178		95	0,095
180	0,18		97	0,097
184	0,184		101	0,101
186	0,186		102	0,102

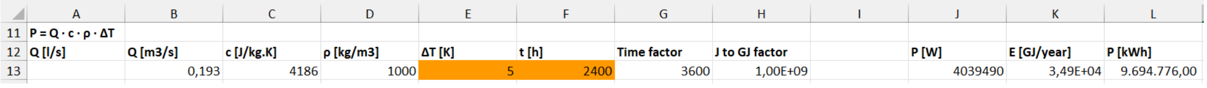
184	0,184		101	0,101
184	0,184		100	0,1
184	0,184		100	0,1
186	0,186		100	0,1
189	0,189		103	0,103
190	0,19		104	0,104
181	0,181		95	0,095
172	0,172		88	0,088
172	0,172		88	0,088
172	0,172		88	0,088
169	0,169		88	0,088
169	0,169		90	0,09
160	0,16		84	0,084
154	0,154		79	0,079
149	0,149		74	0,074
146	0,146		71	0,071
143	0,143		69	0,069
143	0,143		67	0,067
144	0,144		66	0,066
160	0,16		76	0,076
179	0,179		90	0,09
189	0,189		99	0,099
193	0,193		102	0,102
190	0,19		101	0,101
188	0,188		103	0,103
188	0,188		104	0,104
189	0,189		104	0,104
189	0,189		104	0,104
192	0,192		106	0,106
191	0,191		105	0,105
190	0,19		105	0,105
181	0,181		97	0,097
170	0,17		86	0,086
175	0,175		91	0,091
171	0,171		90	0,09
167	0,167		88	0,088
160	0,16		83	0,083
153	0,153		78	0,078
148	0,148		74	0,074
145	0,145		71	0,071
143	0,143		68	0,068
141	0,141		65	0,065
141	0,141		63	0,063
154	0,154		72	0,072

174	0,174		86	0,086
187	0,187		96	0,096
188	0,188		97	0,097
188	0,188		99	0,099
186	0,186		101	0,101
186	0,186		101	0,101
186	0,186		101	0,101
186	0,186		99	0,099
188	0,188		100	0,1
189	0,189		101	0,101
192	0,192		104	0,104
186	0,186		99	0,099
177	0,177		92	0,092
184	0,184		100	0,1
175	0,175		94	0,094
160	0,16		83	0,083
148	0,148		73	0,073
149	0,149		74	0,074
147	0,147		72	0,072
145	0,145		70	0,07
147	0,147		70	0,07
165	0,165		81	0,081
173	0,173		90	0,09
173	0,173		90	0,09
175	0,175		92	0,092
177	0,177		94	0,094
178	0,178		95	0,095
181	0,181		97	0,097
178	0,178		95	0,095
175	0,175		92	0,092
176	0,176		92	0,092
179	0,179		94	0,094
184	0,184		97	0,097
187	0,187		100	0,1
183	0,183		95	0,095
177	0,177		90	0,09
179	0,179		92	0,092
178	0,178		94	0,094
172	0,172		91	0,091
163	0,163		86	0,086
150	0,15		75	0,075
151	0,151		76	0,076
147	0,147		73	0,073
145	0,145		70	0,07

147	0,147		70	0,07
165	0,165		82	0,082
173	0,173		89	0,089
172	0,172		89	0,089
177	0,177		94	0,094
178	0,178		96	0,096
179	0,179		97	0,097
178	0,178		95	0,095
178	0,178		95	0,095
174	0,174		91	0,091
175	0,175		92	0,092
176	0,176		91	0,091
182	0,182		95	0,095
186	0,186		98	0,098
183	0,183		96	0,096
179	0,179		92	0,092
178	0,178		92	0,092
178	0,178		92	0,092
171	0,171		91	0,091
161	0,161		85	0,085

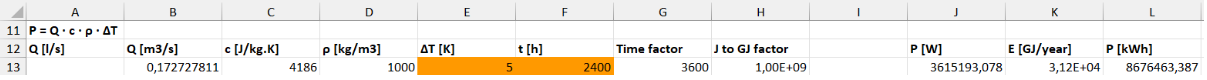
Appendix B.

B.1. Spreadsheet calculations on energy supply for Göteborg Kretslopp och vatten



	A	B	C	D	E	F	G	H	I	J	K	L
11	P = Q · c · ρ · ΔT											
12	Q [l/s]	Q [m3/s]	c [J/kg.K]	ρ [kg/m3]	ΔT [K]	t [h]	Time factor	J to GJ factor		P [W]	E [GJ/year]	P [kWh]
13		0,193	4186	1000	5	2400	3600	1,00E+09		4039490	3,49E+04	9.694.776,00

Figure B.1. Calculated energy potential from TED for the highest Q1.



	A	B	C	D	E	F	G	H	I	J	K	L
11	P = Q · c · ρ · ΔT											
12	Q [l/s]	Q [m3/s]	c [J/kg.K]	ρ [kg/m3]	ΔT [K]	t [h]	Time factor	J to GJ factor		P [W]	E [GJ/year]	P [kWh]
13		0,172727811	4186	1000	5	2400	3600	1,00E+09		3615193,078	3,12E+04	8676463,387

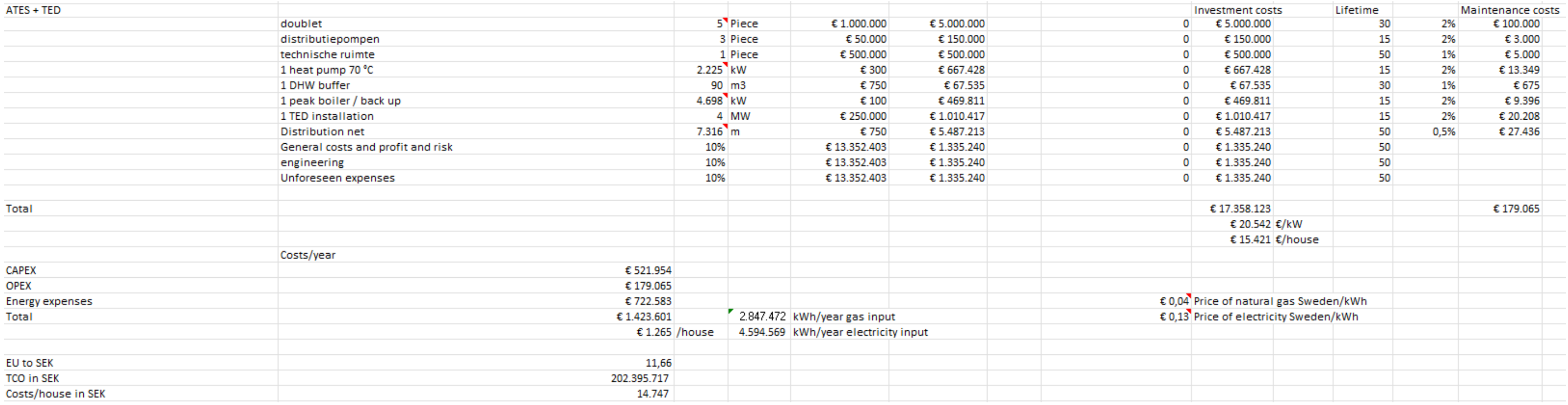
Figure B.2. Calculated energy potential from TED for the highest Q1.

B.2. Spreadsheet calculations on TCO for Göteborg Kretslopp och vatten

In **Figure B.3**, a screenshot of the spreadsheet calculations on the TCO and costs per house for a DHN including TED in combination with natural gas are presented. The costs per component and lifetime per component are included.

Assumptions that are made:

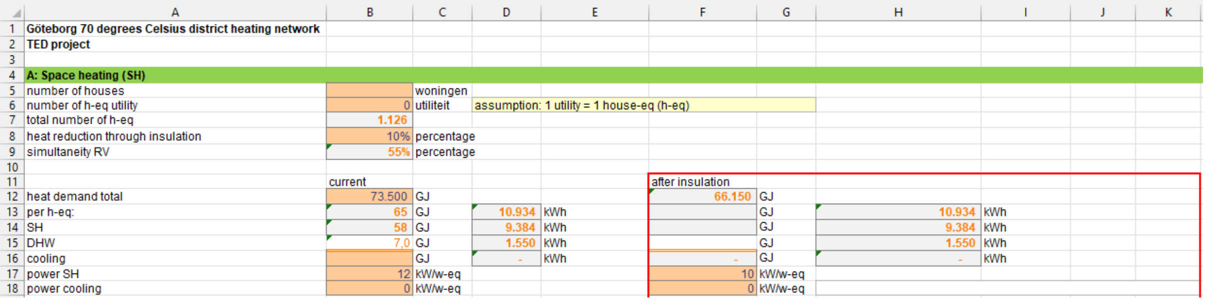
- One doublet supplies 1MW. This is based on the power of a doublet in Hilversum, the Netherlands which supplies 1 MW. In Amsterdam, one doublet supplies 2MW, in Utrecht one doublet supplies 0.5 MW.
- The DHW demand is supplied from the buffer, so the boiler is only used for fulfilling the SH demand. This is economically better as a boiler has a lower cost indicator [€/kW] than a heat pump. However, this is a choice.
- The size of the DHW buffer (m^3) is determined by estimation based on the average amount of liters per shower in the Netherlands (which is 40 liters) and there are on average two showers per day per household, according to S. Mol (personal communication, July 5, 2023). This is then multiplied by the amount of houses that the DHN is supplying heat to.
- Regarding the number of heat pumps, it is important to install an extra heat pump in case another heat pump breaks down.
- The costs for the heat exchanger are included in the 'TED installation' costs.
- Electrical engineering is included in the key figures.
- The price used for electricity is the price for large consumers, the gas price is the average gas price in Sweden.
- All costs are excl. VAT.
- The assumed life times of the different components of the district heating system are presented in **Figure B.3.**



ATES + TED									Investment costs		Lifetime		Maintenance costs
	doublet		5	Piece	€ 1.000.000	€ 5.000.000		0	€ 5.000.000		30	2%	€ 100.000
	distributiepompen		3	Piece	€ 50.000	€ 150.000		0	€ 150.000		15	2%	€ 3.000
	technische ruimte		1	Piece	€ 500.000	€ 500.000		0	€ 500.000		50	1%	€ 5.000
	1 heat pump 70 °C		2.225	kW	€ 300	€ 667.428		0	€ 667.428		15	2%	€ 13.349
	1 DHW buffer		90	m3	€ 750	€ 67.535		0	€ 67.535		30	1%	€ 675
	1 peak boiler / back up		4.698	kW	€ 100	€ 469.811		0	€ 469.811		15	2%	€ 9.396
	1 TED installation		4	MW	€ 250.000	€ 1.010.417		0	€ 1.010.417		15	2%	€ 20.208
	Distribution net		7.316	m	€ 750	€ 5.487.213		0	€ 5.487.213		50	0,5%	€ 27.436
	General costs and profit and risk		10%		€ 13.352.403	€ 1.335.240		0	€ 1.335.240		50		
	engineering		10%		€ 13.352.403	€ 1.335.240		0	€ 1.335.240		50		
	Unforeseen expenses		10%		€ 13.352.403	€ 1.335.240		0	€ 1.335.240		50		
Total									€ 17.358.123				€ 179.065
									€ 20.542	€/kW			
									€ 15.421	€/house			
	Costs/year												
CAPEX		€ 521.954											
OPEX		€ 179.065											
Energy expenses		€ 722.583						€ 0,04	Price of natural gas Sweden/kWh				
Total		€ 1.423.601		2.847.472	kWh/year gas input			€ 0,13	Price of electricity Sweden/kWh				
		€ 1.265	/house	4.594.569	kWh/year electricity input								
EU to SEK		11,66											
TCO in SEK		202.395.717											
Costs/house in SEK		14.747											

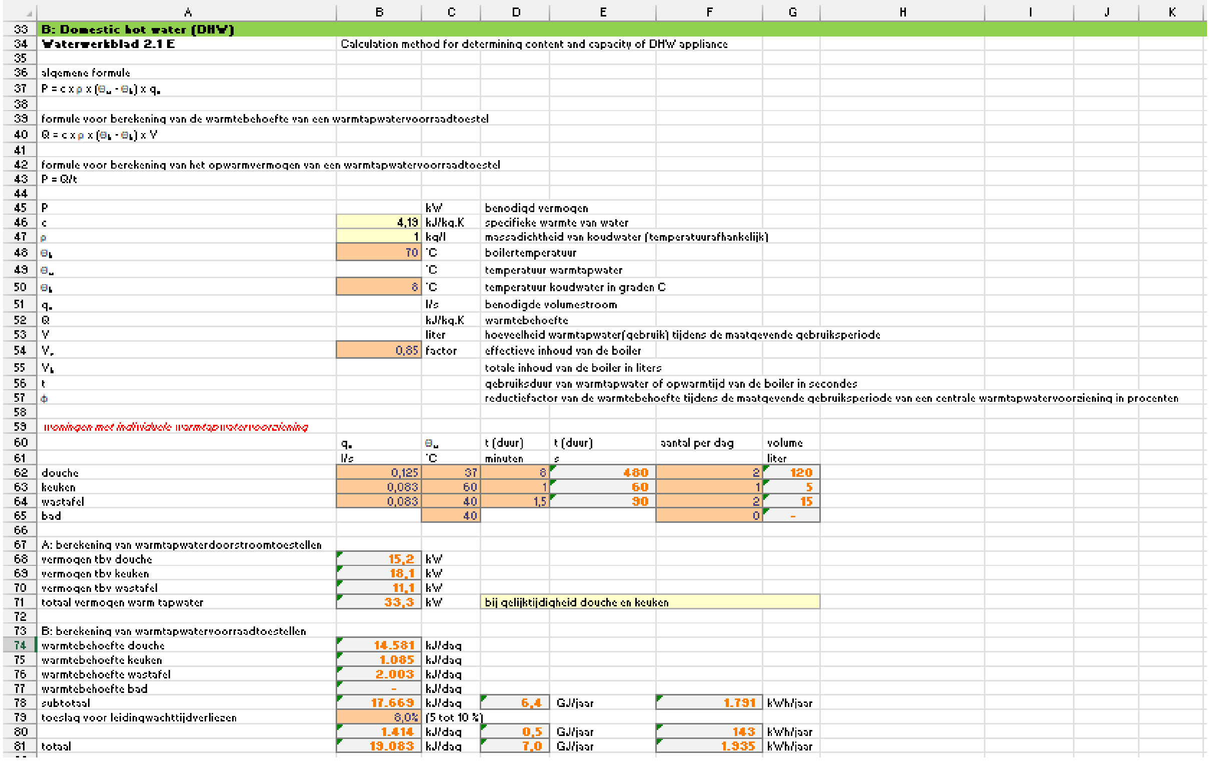
Figure B.3. Spreadsheet calculations on the TCO and costs per house for a DHN including TED in combination with natural gas.

B.3. Spreadsheet calculations on the heat and power chain of the DHN



	A	B	C	D	E	F	G	H	I	J	K
1	**Göteborg 70 degrees Celsius district heating network**										
2	**TED project**										
3											
4	**A: Space heating (SH)**										
5	number of houses		woningen								
6	number of h-eq utility	0	utiliteit	assumption: 1 utility = 1 house-eq (h-eq)							
7	total number of h-eq	1.126									
8	heat reduction through insulation	10%	percentage								
9	simultaneity RV	55%	percentage								
10											
11		current				after insulation					
12	heat demand total	73.500	GJ			66.150	GJ				
13	per h-eq:	65	GJ	10.934	kWh		GJ	10.934	kWh		
14	SH	58	GJ	9.384	kWh		GJ	9.384	kWh		
15	DHW	7,0	GJ	1.550	kWh		GJ	1.550	kWh		
16	cooling		GJ	-	kWh	-	GJ	-	kWh		
17	power SH	12	kW/w-eq			10	kW/w-eq				
18	power cooling	0	kW/w-eq			0	kW/w-eq				

Figure B.4. Worksheet for SH demand.



	A	B	C	D	E	F	G	H	I	J	K
33	**B: Domestic hot water (DHW)**										
34	**Waterwerkblad 2.1 E**	Calculation method for determining content and capacity of DHW appliance									
35											
36	algemene formule										
37	$P = c \times \rho \times (\theta_w - \theta_k) \times q_w$										
38											
39	formule voor berekening van de warmtebehoefte van een warmtapwatervoorraadtoestel										
40	$Q = c \times \rho \times (\theta_b - \theta_k) \times V$										
41											
42	formule voor berekening van het opwarmvermogen van een warmtapwatervoorraadtoestel										
43	P = Q/t										
44											
45	P		kW	benodigd vermogen							
46	c	4,19	kJ/kg.K	specifieke warmte van water							
47	ρ	1	kg/l	massadichtheid van koudwater (temperatuurafhankelijk)							
48	θ_b	70	°C	boilertemperatuur							
49	θ_w		°C	temperatuur warmtapwater							
50	θ_k	8	°C	temperatuur koudwater in graden C							
51	q_w		l/s	benodigde volumestroom							
52	Q		kJ/kg.K	warmtebehoefte							
53	V		liter	hoeveelheid warmtapwater(gebruik) tijdens de maatgevende gebruiksperiode							
54	V_e	0,85	factor	effectieve inhoud van de boiler							
55	V_b			totale inhoud van de boiler in liters							
56	t			gebruiksduur van warmtapwater of opwarmtijd van de boiler in secondes							
57	ϕ			reductiefactor van de warmtebehoefte tijdens de maatgevende gebruiksperiode van een centrale warmtapwatervoorziening in procenten							
58											
59	*woningen met individuele warmtapwatervoorziening*										
60		q_w	θ_w	t (duur)	t (duur)	aantal per dag	volume				
61		l/s	°C	minuten	s		liter				
62	douche	0,125	37	8	480	2	120				
63	keuken	0,083	60	1	60	1	5				
64	wastafel	0,083	40	1,5	90	2	15				
65	bad		40			0	-				
66											
67	A: berekening van warmtapwaterdoorstroomtoestellen										
68	vermogen tbv douche	15,2	kW								
69	vermogen tbv keuken	18,1	kW								
70	vermogen tbv wastafel	11,1	kW								
71	totaal vermogen warm tapwater	33,3	kW	bij gelijktijdigheid douche en keuken							
72											
73	B: berekening van warmtapwatervoorraadtoestellen										
74	warmtebehoefte douche	14.581	kJ/dag								
75	warmtebehoefte keuken	1.085	kJ/dag								
76	warmtebehoefte wastafel	2.003	kJ/dag								
77	warmtebehoefte bad	-	kJ/dag								
78	subtotaal	17.669	kJ/dag	6,4	GJ/jaar	1.791	kWh/jaar				
79	toeslag voor leidingwachttijdverliezen	8,0%	(5 tot 10 %)								
80		1.414	kJ/dag	0,5	GJ/jaar	143	kWh/jaar				
81	totaal	19.083	kJ/dag	7,0	GJ/jaar	1.935	kWh/jaar				

Figure B.5. Worksheet for DHW demand.

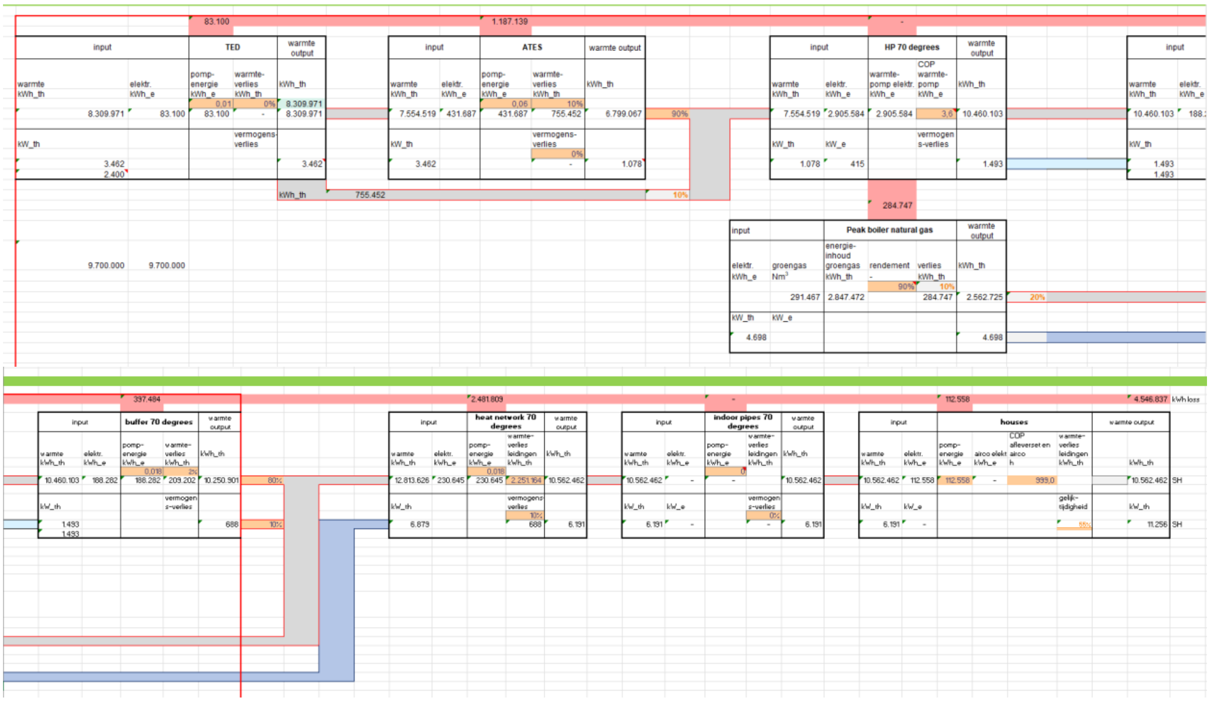


Figure B.6. Heat and power chain for SH.

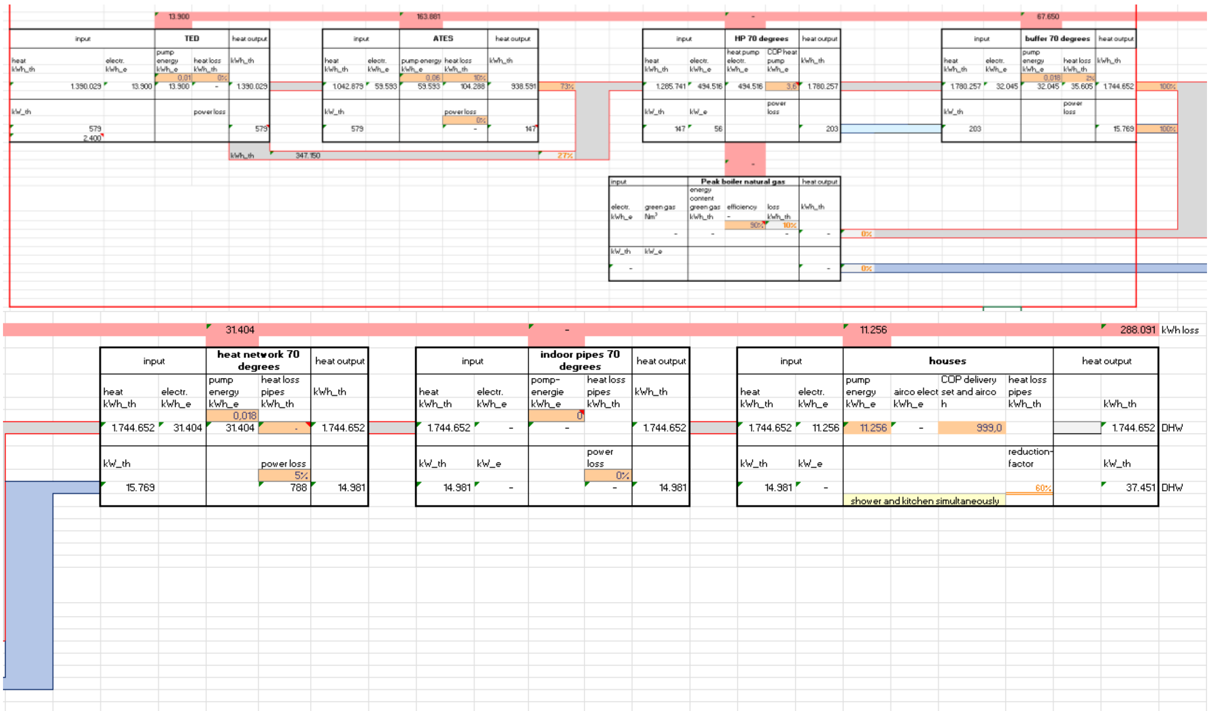
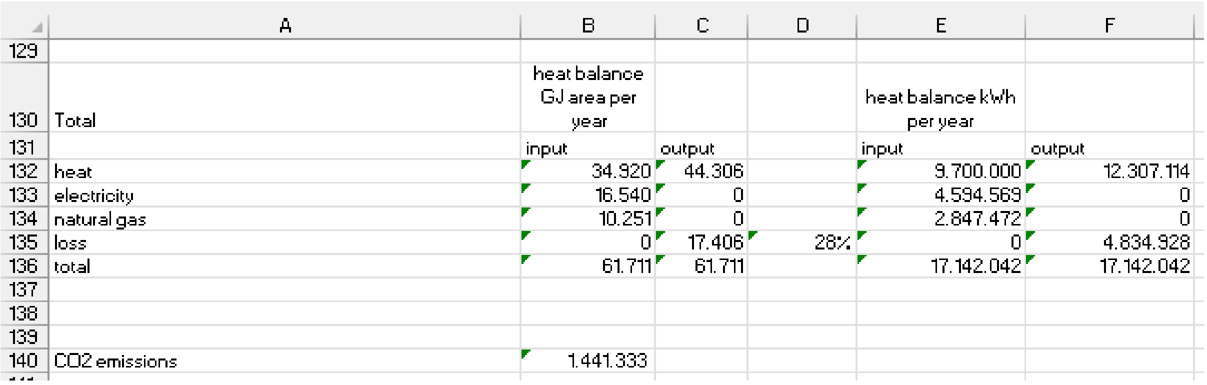


Figure B.7. Heat and power chain for DHW.



	A	B	C	D	E	F
129						
130	Total	heat balance GJ area per year			heat balance kWh per year	
131		input	output		input	output
132	heat	34.920	44.306		9.700.000	12.307.114
133	electricity	16.540	0		4.594.569	0
134	natural gas	10.251	0		2.847.472	0
135	loss	0	17.406	28%	0	4.834.928
136	total	61.711	61.711		17.142.042	17.142.042
137						
138						
139						
140	CO2 emissions	1.441.333				

Figure B.8. Heat balance of the total system.

How to use the spreadsheet:

- There is a heat and power chain for SH demand and a heat and power chain for DHW demand. The TED input is divided among the inputs of these two chains, based on the average SH and DHW demand for multi-family houses in Göteborg which is inserted at the end of the heat and power chain.
- If you use the heat and power chain to do calculations starting at the end and calculating back towards the front, you are calculating the discharging of the ATES or in other words the supply of the different units.
  If you use the heat and power chain to do calculations starting at the front and calculating towards the end, you are calculating the charging of the ATES.
  I.e. for the highest Q1 calculations: the ATES is being charged with a power of 3.4 MW and discharged with a power of 1 MW. More power is needed to charge the ATES, because charging is only happening during 100 out of 365 days in a year. While discharging is constantly happening over the year. The discharging power is related to the heat demand of the houses that are connected to the DHN.
  Both directions of calculations in the heat and power chain are applied at the same time.
- Power [W] input and output of a unit do not always have to be equal. For example, when a buffer is being charged, which happens at a constant pace over the whole year, less power is needed than when you want to use the buffer output. SH and DHW demand is fluctuating throughout the days. The power says something about *when* you need the heat [kWh].
- Power input and output per unit is checked with the full load hours (when the temperature of the drinking water is high enough).
- Always choose the least (e.g. economically) favorable power option. In other words, if the power output of a unit is higher than the power input, change the power input so that it is equal to the (higher) power output. The charging or discharging power that is the highest is determinative.
- The power input and output of the TED installation should be equal, which should be equal to the input of the ATES.
- The power input of a unit such as a buffer does not necessarily have to be equal to the power output.

Assumptions, estimations, choices and key figures for ATES + TED + DHN:

- DHN of 70 °C, because this is the situation in the NL so maybe also possible in the Sweden. Low temperature heating networks have less loss and are more efficient with low temperature energy sources.
- ATES heat loss = 10%
- COP HP = 3.6 (Romanchenko et al., 2017).
- Cell AD95 is a power calculation of the buffer for SH. This calculation is based on the power that the buffer is supposed to be able to supply, which is 10%. This 10% is estimated based on: in winter in Göteborg, when heat demand has been relatively high for weeks in a row, the buffer must have discharged a lot of power already and is not being charged by the HP because the

HP will be delivering directly to the DHN in this situation. In such a situation there will not be a lot of power left to be delivered by the buffer. In practice, the heat supplied by a HP is always going through the buffer, also when it is delivered "directly" to the DHN. Heat is always going through a buffer, to make sure that the HP is not turned on and off all the time, which increases its inefficiency. It is more efficient to let the HP run at its optimum regulations constantly.
So, 10% of the power that needs to go into the DHN is supplied by the buffer. The power that is needed for this output is necessary as input also. This is a choice. For example, it can also be decided that the buffer is charged faster, so more power on the input side would be needed then. The time period in which you want to charge your buffer depends on its thermal capacity, which is set at 80% in this calculation. The buffer can only be charged when the HP is not delivering directly to the DHN. It is estimated that 20% of the time throughout the year the HP is delivering directly to the DHN. In other words, over the year 20% of the power of the HP is delivered directly to the DHN and 80% of the power is delivered to the buffer, available for charging of the buffer. So, the buffer needs to have this amount of charging power. It takes less power for a buffer to discharge, but this power should be available (charged) in the limited time (80% of the time). So a higher power is required to charge the buffer than to discharge the buffer.

- Cell AD123 is a power calculation of the buffer for DHW. Apparently less power is required for charging the buffer then for discharging the buffer. Therefore, it is determined that the buffer delivers 100% of its power to the DHN, instead of a direct power supply by the HP. The power output of the HP is then made equal to the power input of the buffer. Apparently, the power of the buffer for SH is decisive, as the power input for the buffer in that chain is higher.
  The input to the buffer for DHW is constant, as charging can happen all year long. The DHW demand is fluctuating a lot, so the buffer for DHW is required to deliver at different times, not constantly. This means a lot of power is needed for discharging, compared to charging. The same amount of heat is being transferred, but the time in which this is required influences the power that is required.
- In a DHN with TED and gas: the HP delivers power at its full capacity, the buffer at 10% and the peak boiler covers the rest.

Assumptions, estimations, choices and key figures for the conventional DHN:

- COP HP = 3.4 when the temperature of the DHN is 86 °C (Pisani, 2018).
- Three energy sources: waste incineration, TEW and waste heat (Göteborg Energi AB, 2022).
- Regarding waste incineration and waste heat, there is a direct heat supply, without installation (assumption based on personal communication with Stefan Mol, August 2, 2023).
- Sewage water has a temperature of around 10 °C throughout the whole year, so full load hours for sewage water is 8760 hours per year (estimation based on personal communication with Stefan Mol, August 2, 2023).
- Renewable energy input (kWh thermal) is equal to renewable energy output (kWh thermal) (assumption based on personal communication with Stefan Mol, August 2, 2023).

Appendix C.

C.1. Drinking water pipeline system characteristics for the Netherlands, Sweden and Göteborg

Table C.1. Drinking water pipeline system characteristics per country (the Netherlands and Sweden).

Drinking water pipe system characteristic	**The Netherlands**	**Sweden**	**Göteborg, Sweden**
Source	Groundwater or (infiltrated) surface water [1]	Groundwater, surface water or infiltrated surface water [3]	According to B. Haidarian (personal communication, May 16, 2023), surface water.
Total length pipeline system	120,244 km (in 2020) [2]	67 000 km. These figures do not include the private house connections. If these were to be included the figure could double. [3]	According to B. Haidarian (personal communication, May 16, 2023), 1800 km. This figure includes only mains, does not include service connections.
Average length of pipeline per household	According to S. Mol (personal communication, July 5, 2023) 7 m.		6-7 m pipe per person in Swedish cities and 0n average > 90 m in the countryside. These numbers include drinking water, wastewater (sewage) and stormwater pipes. The average share of the total pipe length in Sweden is 42% for drinking water, so i.e. 2.5-3.0 m pipe per person in cities and >38 m in the countryside area. (Bashir & Mohamud, 2021) 2.16 individuals per household in Sweden (Statista Research Department, 2022), so $2.16 \cdot 3 = 6.48$ m per household.
Construction of pipe system and its diameters	**Transport pipes** (300 – 1500 mm) transport		According to B. Haidarian (personal communication, May

	the drinking water to a ring structure of **secondary pipes** (160 – 300 mm) feed **tertiary pipes** (< 160 mm) distribute to connecting pipes to customers [1]		16, 2023), 1400 mm down to 32 mm
Pipe material	The material used for the transportation pipelines in the Netherlands usually is PVC. [4]	55 % cast iron, 19 % PVC, 14 % PE and the rest other materials. PE is the dominating material in new pipes.	According to B. Haidarian (personal communication, May 16, 2023): 34 % cast iron, 30 % plastic (PE, PEH, PEM), 24 % ductile iron and the rest other materials. PE is the dominating material in new pipes.
Yearly amount of drinking water produced and distributed	1,225 million m^3 (in 2020) [2] Yearly total interruption time 18:19 min in 2019 [2]	* 7.7 million customers * 365 = 928 million litres = 928 million m^3 [3]	63 million m^3 per year is produced at the water works and delivered to the water distribution network. Around 13.5 million m^3 per year is lost due to leakage in the distribution system.
Volume peaks	7 a.m. - 8 a.m. and 5 p.m. - 7 p.m. [1]	-	7 a.m. - 8 a.m. and 5 p.m. - 7 p.m.
Average temperature drinking water in distribution pipelines near customer	Winter: 8-10 ℃ Summer: 20 ℃	-	According to B. Haidarian (personal communication, May 16, 2023): Minimum: 2.9 ℃ Median: 8.7 ℃ Maximum: 20.2 ℃
Maximum allowed drinking water temperature	25 ℃ [2]	-	According to B. Haidarian (personal communication, May 16, 2023) currently there exists no formal regulation for maximum allowed drinking water temperature. Previous maximum allowed drinking water

			temperature as defined by the Swedish Food Agency: 20 ℃ which is used “informally” today, even though we exceed this limit at times.

Sources: 1 (Moerman et al., 2021), 2 (Vewin, 2022), 3 (Vatten, 2000), 4 (Blokker et al., 2013)